Environmental Science

Environmental Science

a Canadian perspective

BILL FREEDMAN

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Contents

Bill Freedman: an appreciation vii

Preface ix

Part I: Ecosystems and Humans

Chapter 1 ~ Ecosystems and Humans 2

Part II: The Biosphere: Characteristics and Dynamics

Chapter 2 ~ Science as a Way of Understanding the Natural World 27
Chapter 3 ~ The Physical World 37
Chapter 4 ~ Energy and Ecosystems 60
Chapter 5 ~ Flows and Cycles of Nutrients 78
Chapter 6 ~ Evolution 96
Chapter 7 ~ Biodiversity 114
Chapter 8 ~ Biomes and Ecozones 133
Chapter 9 ~ Ecology: From Individuals to the Biosphere 156

Part III: The Human Population

Chapter 10 ~ Global Populations 182
Chapter 11 ~ The Canadian Population 218

Part IV: Natural Resources

Chapter 12 ~ Resources and Sustainable Development 240
Chapter 13 ~ Non-Renewable Resources 265
Chapter 14 ~ Renewable Resources 293

Part V: Environmental Damages

Chapter 15 ~ Environmental Stressors 336
Chapter 16 ~ Gaseous Air Pollution 366
Chapter 17 ~ Atmospheric Gases and Climate Change 395
Chapter 18 ~Toxic Elements 426
Chapter 19 ~ Acidification 450
Chapter 20 ~ Additional Problems of Surface Waters 490

Chapter 21 ~ Oil Spills 520
Chapter 22 ~ Pesticides 544
Chapter 23 ~ Environmental Effects of Forestry 590
Chapter 24 ~ Agriculture and the Environment 624
Chapter 25 ~ Urban Ecology 649
Chapter 26 ~ War 686
Chapter 27 ~ The Biodiversity Crisis 726

Part VI: Ecologically Sustainable Development

Chapter 28 ~ Ecologically Sustainable Development 765

Glossary 795

Bill Freedman: an appreciation

Bill Freedman (1950-2015) was a colleague at Dalhousie University and was also a neighbor down the street from me. I was chair of the committee that recommended him for a position in the Biology Department in 1979 and later Bill became my department chair. We shared many ecological interests and often walked together. So I knew Bill both personally and professionally.

When Bill arrived at Dalhousie University in 1979, he threw himself into intensive field work. His graduate students became well versed in field skills and many have gone on to play key environment-related roles in Nova Scotia and elsewhere. Bill was a superb supervisor.

Bill authored or co-authored over 100 refereed research papers. Collectively they could be described as quantitative descriptions of natural and human-stressed habitats and their associated flora and fauna. Those studies continue to provide invaluable reference or baseline data on the state of a wide range of aquatic and terrestrial sites in a world changing ever more rapidly under the influence of humans. Many of the quantitative examples Bill provides in this book are drawn from those papers.

A lot of Bill's earliest work focused on effects of acid rain on surface waters and forests and relationships of aquatic plants and amphibians to acidity. He ventured into assessment of carbon storage in forests well before it became an important topic, subject to international agreements related to GHGs, and he was one of the first environmentalists to highlight the potential of protected areas for carbon storage. In later years, he took an interest in urban ecology. He was especially passionate about the Canadian Arctic, Sable Island and birds.

Bill was a collector, intellectually and physically. His intellectual collection was encyclopedic. There was very little on land and in fresh waters world-wide that Bill could not make a comment on or cite his own observations.

Bill and George-Anne's house, strategically located "half way between the Biology Dept. and the squash courts" as Bill would say, hosted an incredible collection of artifacts including for example, hundreds of old Nova Scotia bottles, probably a hundred or more wooden decoys, animal carvings, stuffed birds (100 years and older) and all manner of sea floats and pieces of old fishing gear; their walls were covered with large bird prints, and bookshelves were replete with old volumes on natural history. Nothing was new; most of the items came from a local flea market which Bill visited regularly.

Bill walked the talk as an environmentalist. He was a vegetarian for his last 30 years or so because of concerns about impacts of livestock on environment. He filled the small spaces around his house with native plants. He had a small Canadian built car. He volunteered for 25 years on the board of the Nature Conservancy of Canada, several as chair and conducted related field work as a volunteer. I frequently think about the story I was told by one NCC board member about the time they all wore horn rimmed glasses with Einstein-like moustaches to one of their meetings, an expression of their strong affection for Bill, who bore more than a little facial resemblance to Einstein.

Bill never took any kind of conventional holiday. His rest and recovery days were spent birdwatching locally or in the jungles of Peru or New Guinea, or as a guide on Adventure-Canada tours including their first NW passage tour, or weeding his native plant garden. He was an inveterate reader and he loved The Blues.

Bill surprised the Biology Dept in 2000 when he volunteered to be chair at a time when no one really wanted to volunteer because we were all 'busy' with our own teaching and research. He served as chair until 2007 with aplomb, while barely detracting from his research and teaching activities. I never saw Bill get visibly angry; outraged about some injustice perhaps, but not angry.

As Bill was approaching the retirement days that he looked forward to as more time to pursue his passions, he got the news of a possibly terminal cancer. He treated it as a learning experience to be shared, which he did on Facebook, always with a kind of self-deprecating humour full of “Bill Puns”. He would die within a year.

Bill spent a good three months or more of that last year updating his textbook, also editing a book on Sable Island, both labours of love because he knew there was slim chance he would be around much longer.

Bill believed strongly that people are capable of rational action in relation to environmental issues if given “the facts” and given some options. He was also Canadian to the core. That’s what drove him to write Environmental Sciences, A Canadian Perspective. It was the first Canadian text on Environmental Science, and he updated it 5 times. The 6th edition was headed for publication by a prominent academic press, but delays and miscommunications following his passing led Bill’s spouse, George-Anne, to withdraw it and seek to have it published as a free online text available from Dalhousie. I strongly encouraged that initiative in part because I think no one would be happier about it than Bill.

It is a wonderful gift: 1097 highly readable, referenced, well-illustrated pages organized under five sections and twenty-two chapters. The literature cited goes up to mid-2015. With the information and references given, it would require little effort to assemble the more recent research on any particular topic, e.g., using Google Scholar. I think the book will be widely and well used by Canadians from coast to coast to coast, and thank George-Anne, Dalhousie University and of course my friend and much missed colleague Bill for it being so-available.

David Graham Patriquin
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Preface

Environmental Literacy

Environmental literacy can be defined as: "the degree to which people have an objective and well-informed understanding of environmental issues." Today, it is extremely important to have a understanding of environmental issues. This is because the human economy is engaged in a wide range of activities that are causing enormous damage to the ecosystems that sustain both our species and Earth's legacy of biodiversity. All around us, this is witnessed by pollution, climate warming, collapsing fisheries, deforestation, the degradation of agricultural soil, extinctions and endangerment of species, and other damages.

Nevertheless, we need not be overly pessimistic. If our society takes constructive actions now, or at least soon, it will not be too late to prevent or repair many of these important environmental problems, which threaten the welfare of people and most other species. Within limits, humans are prescient creatures, and our society is capable of implementing a sustainable economy that can support our livelihoods as well as healthy ecosystems.

It is clear, however, that any sustainable economy will involve ways of doing business that are different from those that have recently been dominant. It will also require fundamental changes in the lifestyles of many people, especially those living in wealthy countries such as Canada. Ultimately, such socio-economic transformations must involve much less use of energy, materials, and other resources, in comparison with what many of us take for granted today. A more respectful attitude toward the natural world is also badly needed.

Achieving such a transformation will depend on citizens having a sound understanding of environmental issues. Any imposition of restrictions on access to resources will initially be uncomfortable for many people. Nevertheless, I believe that people will be more willing to soften their lifestyle if they understand the reasons for those changes in the context of the livelihoods of future generations and ecological sustainability more generally. With such an understanding, most people will support economic and social changes that conserve the quality of their own and future environments.

A broad-based environmental literacy will be a key requirement if a country such as Canada is to achieve the difficult transition into an ecologically sustainable economy. Within that context, this book was developed to help Canadian students in universities and colleges to have an objective and well-informed understanding of important environmental issues.

A Canadian Textbook

This textbook is intended to provide the core elements of a curriculum for teaching environmental science at the introductory level in Canadian colleges and universities. This book is suitable for students beginning a program in environmental science, environmental studies, or sustainability. It is also appropriate for arts students who require a science elective, and for science students who require a non-major elective. Not many introductory textbooks in environmental science are written in a way that provides a deep examination of issues that are particularly important in Canada, and the ways they are being dealt with by governments and society-at-large. Canada has unique national and regional perspectives that should be understood by Canadian students, and it is regrettable that many of them are studying from textbooks whose focus is not their own country.

This book, however, was written from the ground-up to provide Canadian information and examples. This national context is integrated throughout the text, along with North American and global data that provide a broader perspective. Special Canadian Focus boxes illustrate important examples of environmental issues in our national context. At the same time, Global Focus boxes enhance the international context for learning about issues, while In Detail boxes examine particular topics in greater depth.

Approach and Organization of the Book

Environmental science draws on knowledge and methods from many fields of the sciences and social sciences, including biology, chemistry, economics, ethics, geography, geology, medicine, physics, political science, sociology, and statistics. Many environmental specialists adopt an interdisciplinary approach to integrate these different ways of knowing in order to help understand and prevent environmental damage. This book also adopts an interdisciplinary approach by drawing on a variety of disciplines. At the same time, however, the choice of topics and the interpretations offered reflect my own experience and world view as an ecologist – one who has had a rather specialized career examining the ecological dimensions of environmental problems.

The book is organized into twenty-eight chapters that are grouped into six parts:

Part I

"Ecosystems and Humans" serves as an introduction to the broad field of environmental science. It defines environmental science, explains the principles of the ecosystem approach, gives an overview of environmental stressors caused by human activities, and describes various world views.

Part II

"The Biosphere: Characteristics and Dynamics" consists of eight chapters that provide a scientific foundation for much of what follows:

- Chapter 2 explains the scientific approach to identifying and understanding environmental problems
- Chapter 3 examines the geological, hydrological, and atmospheric characteristics of planet Earth
- Chapter 4 provides a basic understanding of the kinds and transformations energy, along with practical implications
- Chapter 5 explains the flows and cycles of nutrients
- Chapter 6 examines the overarching implications of evolution for biological and ecological change
- Chapter 7 is an overview of the various levels at which biodiversity can be examined, while also explaining why it is important for intrinsic reasons as well as the welfare of humans
- Chapter 8 described the major biomes of Earth, from both a global perspective, as well as a Canadian one
- Chapter 9 provides an explanation of the realm of ecology, while also explaining the underlying context of that subject area to many environmental problems

Part III

"The Human Population" deals with the growth and implications of the human population. It consists of two chapters:

- Chapter 10 examines global population growth and its causes
- Chapter 11 focuses on Canadian population issues, at both national and provincial/territorial levels

Part IV

"Natural Resources" deals with the resources that humans and all other species need to sustain their livelihoods. It consists of three chapters:

- Chapter 12 examines the relationship between resources and sustainable development, within the context of the fields of economics and the more recently emerged perspectives of ecological economics
- Chapter 13 looks at the limited supplies of non-renewable resources, and their place in a sustainable human economy
- Chapter 14 examines renewable resources, and explains why they are the basic underpinning of any economy that is sustainable over the longer term

Part V

"Environmental Damages" consists of thirteen chapters that deal with important damages that are being caused by human activities.

- Chapter 15 explains the broader topics of environmental stressors, as well as the various kinds of pollution and disturbance
- Chapter 16 examines gaseous air pollution and the kinds of damage that are caused
- Chapter 17 looks at climate change and how its recent dynamics appear to be forced by anthropogenic increases in greenhouse gases
- Chapter 18 focuses on metals and other toxic elements and some of their environmental effects
- Chapter 19 explains the causes of acidification, with particular attention to surface waters that have been affected by "acid rain", or the deposition of acidifying gases and precipitation
- Chapter 20 examines problems of surface waters that are not covered in other chapters, such as eutrophication and hydroelectric development
- Chapter 21 looks at oil spills and the damage caused to marine and terrestrial environments
- Chapter 22 explains the various kinds of pesticides and their used, and described case studies of environmental damages that are associated with their use
- Chapter 23 looks at forestry operations and their environmental effects, with particular attention to ecological damages
- Chapter 24 examines the environmental effects of agricultural activities
- Chapter 25 explains urban ecology and the benefits that could be achieves by taking a more ecological approach to planning and the management of green spaces
- Chapter 26 looks at the causes and consequences of warfare, including those that are socioeconomic and others

that represent environmental damages
- Chapter 27 examines the biodiversity crisis, including extinctions and endangerment of species and even entire kinds of ecological communities, as well as mitigations that can be applied, such as the designation of protected areas and the use of softer management practices on working landscapes.

Part VI

"Ecologically Sustainable Development" consists of one chapter that provides a synthesis and conclusion for the book.

- Chapter 28 discusses the process of assessing environmental impacts, provides a synthetic overview of ecologically sustainable development, and it considers the prospects for Canada and for spaceship Earth

New to This Edition

One completely new chapter has been added to this sixth edition – chapter 26 examines the causes and consequences of warfare. This is a topic that is not often included in environmental textbooks, despite the fact that warfare has devastating impacts on people, their economy, and the natural world. This chapter has a global focus, but particular attention is paid to conflicts in which Canada played a significant role.

Of course, a lot of effort has gone into updating the information in this data-rich textbook. This has been done wherever new data were available, and as a result the information content is fresh and current. Lastly, all of the boxes have been reviewed and updated, and new ones have been added that highlight emerging issues that are relevant to Canada, within an international context.

In addition, the book has been thoroughly edited to improve the clarity and accessibility of its language and format, with an eye to making the content more appealing to undergraduate students.

Features

A special effort has been made to incorporate features that will facilitate learning and enhance an understanding of environmental science:

- Chapter Objectives are presented at the beginning of each chapter that summarize the anticipated learning outcomes
- Key terms are boldfaced where defined in the text, and are listed in a comprehensive glossary
- Canadian Focus boxes illustrate the application of important concepts to Canadian case studies
- Global Focus boxes enhance the international context for learning about environmental issues
- In Detail and Environmental Issues boxes provide additional technical information on selected topics
- Images, Figures, and Tables are abundant throughout, many of them being original analyses of publically available data, and all with an explanatory caption that is further developed within the text
- Questions for Review are presented at the end of each chapter that provide opportunities to test students' factual and conceptual understanding of the material presented in the chapter (sample answers are provided in the Instructor's Manual; see below)

- Questions for Discussion are also presented at the end of each chapter to provide thought-provoking queries that help to stimulate careful reflection and class discussion
- Exploring Issues questions at the end of each chapter provide activities and exercises that help students to delve deeper into environmental issues
- References are listed, by chapter, at the end of the book to help guide users to further reading
- A comprehensive Index makes looking up topics easy
- An Instructor's Manual is available that includes suggested answers to all the questions for review and discussion at the end of each chapter
- Lecture Templates in a PowerPoint format are available for all chapters, consisting of bulleted lecture notes and full-colour versions of images, figures, and tables

Acknowledgements

I am grateful for the help that many busy colleagues and other professionals have provided over the years and editions during which this book has been developed. These helpful persons offered an extremely valuable service by informally reviewing draft material and by making important ideas and information available to me. Inevitably, I was not able to incorporate all of the criticisms and suggestions, sometimes because they did not correspond with my own interpretation of the subject matter. However, the overwhelming majority of suggestions and criticisms offered by these people resulted in beneficial changes, and they improved the quality of the material.

These helpful colleagues are: Gordon Beanlands, Christine Beauchamp, Stephen Beauchamp, Karen Beazley, Marian Binkley, Chris Corkett, Ray Cote, Roger Cox, Les Cwynar, Roger Doyle, Peter Duinker, William Ernst, Peter Feige, Tracy Fleming, George Francis, David Gauthier, Chuck Geale, William Gizyn, Patricia Harding, Chris Harvey-Clarke, Owen Hertzman, Jeff Hutchings, Adrian Johnston, Joseph Kerekes, Allan Kuja, Roshani Lacoul, Patriia Lane, Brian Le, Judy Loo, Annette Luttermann, Paul Mandell, Moira McConnell, Ian McLaren, Chris Miller, Pierre Mineau, Gunther Muecke, Neil Munro, Ram Myers, David Nettleship, David Patriquin, Allan Pinder, Stephen Price, Nigel Roulet, Robert Scheibling, Tara Steeves, Donald Stewart, Kate Turner, Tony Turner, Torgney Viegerstad, Richard Wassersug, Peter Wells, Mary-Anne White, Hal Whitehead, Sheilagh Whitley, Martin Willison, Stephen Woodley, and Vince Zelazney.

In addition, the publisher asked instructors at universities and colleges in Canada to provide formal reviews of parts of the book, in each of its editions. I am grateful to the following instructors for providing that invaluable help and constructive criticisms. They are: Susan Bare, Linda Campbell, Daniel Catt, Danielle Fortin, Scott Gilbert, Jon Hornung Richard A. Jarrell, Trudy Kavanagh, Patrick Lane, Cindy Mehlenbacher, Stephen Murphy, Michael Pidwirny, Roberto Quinlan, Lawton Shaw, Sue Vajoczki, Frank Williams, and Carl Wolfe.

Several personal acknowledgements are also in order. I thank my spouse, George-Anne Merrill, for her patient and uncomplaining tolerance of my work habits and lifestyle, and for being my best friend in spite of everything I do and don't do. Also, my grown children, Jonathan and Rachael, for mysterious motivations that succeeding generations engender in their parents.

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PART I: ECOSYSTEMS AND HUMANS

Chapter 1 ~ Ecosystems and Humans

Key Concepts

After completing this chapter, you will be able to:

1. Define environmental science and distinguish it from related fields such as environmental studies, ecology, and geography.
2. Explain the complexity of the universe through a hierarchical framework that includes consideration of Earth, life, and ecosystems at various scales.
3. Identify key principles of the ecosystem approach to conserving natural resources.
4. Describe how environmental stressors and disturbances can affect species and ecosystems.
5. Explain the history of human cultural evolution in terms of an increasing ability to cope with environmental constraints on the availability of natural resources and other aspects of economic development.
6. List at least three ways in which humans directly influence environmental conditions.
7. Identify four broad classes of environmental values.
8. Describe five important world views.
9. Understand the diverse issues of the environmental crisis by classifying them into three categories, and give several examples within each of them.
10. Discuss the environmental effects of humans as a function of two major influences: increases of population and intensification of lifestyle (per-capita effects).
11. explain the differences between economic growth and ecologically sustainable development.

Environmental Science and Its Context

Every one of us is sustained by various kinds of natural resources – such as food, materials, and energy that are harvested or otherwise extracted from the environment. Our need for those resources is absolute – we cannot survive without them. Moreover, the same is true of all other species – every organism is a component of an ecosystem that provides the means of subsistence.

Collectively, the needs and activities of people comprise a human economy. That economy operates at various scales, ranging from an individual person, to a family, to communities such as towns and cities, nation-states (such as Canada), and ultimately the global human enterprise. While an enormous (and rapidly growing) number of people are supported by the global economy, a lot of environmental damage is also being caused. The most important of the damages are the depletion of vital natural resources, various kinds of pollution (including climate change), and widespread destruction of natural habitats to the extent that the survival of many of the natural ecosystems and species of Earth are at grave risk.

These issues are of vital importance to all people, and to all life on the planet. Their subject matter provides the context for a wide-ranging field of knowledge called environmental studies, an extremely broad field of knowledge that examines the scientific, social, and cultural aspects of environmental issues. As such, the subject matter of environmental studies engages all forms of understanding that are relevant to identifying, understanding, and resolving environmental problems. Within that context, environmental science examines the science-related implications of environmental issues (this is explained in more detail in the following section). The subject matter of environmental science is the focus of this book.

Issues related to environmental problems are extremely diverse and they interact in myriad ways. Despite this complexity, environmental issues can be studied by aggregating them into three broad categories:

1. the causes and consequences of the rapidly increasing human population
2. the use and depletion of natural resources
3. damage caused by pollution and disturbances, including the endangerment of biodiversity

These are extremely big issues – their sustainable resolution poses great challenges to people and their economy at all scales. Nevertheless, it is important to understand that the study of environmental issues should not be regarded as being a gloomy task of understanding awful problems – rather, the major goal is to identify problems and find practical ways to repair them and prevent others from occurring. These are worthwhile and necessary actions that represent real progress towards an ecologically sustainable economy. As such, people who understand and work towards the resolution of environmental problems can achieve high levels of satisfaction with their contribution, which is something that helps to make life worth living.

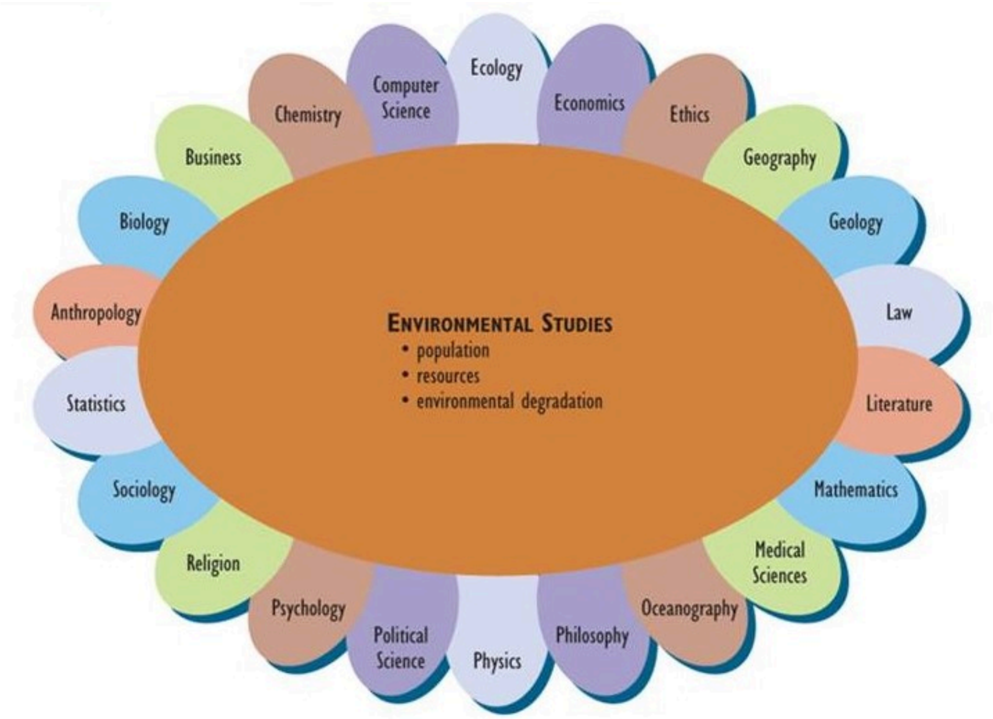
Typical questions that might be examined in environmental science include the following:

1. How large is the human population likely to be in Canada, or on Earth, in 50 or 200 years?
2. How can the use of fossil fuels be integrated into a sustainable economy, in view of the fact that they are non-renewable resources that do not regenerate?
3. How can we harvest renewable resources (which do have the potential to regenerate) in ways that do not degrade their stocks, such as cod in Atlantic Canada, wild salmon in British Columbia, wheat and other grains in the Prairie provinces, and forest resources across much of the country?
4. What ecological damages are caused by various kinds of pollution, such as acid rain, ozone, pesticides, and sulphur dioxide, and how can these effects be prevented or repaired?
5. Are human influences affecting global climate, and if so, what are the causes and consequences of this effect?
6. Where and how quickly are species and natural habitats becoming endangered or extinct, and how can these calamities be prevented?

Image 1.1. Planet Earth. Earth is the third closest planet to the Sun, and it is the only place in the universe that is definitely known to sustain life and ecosystems. Other than sunlight, the natural resources needed to sustain the human economy are restricted to the limited amounts that can be extracted on Earth. This image of the Western Hemisphere was taken from a distance of 35-thousand km from the surface of Earth. Source: R. Stöckli, N. El Saleous, and M. Jentoft-Nilsen, NASA GSFC; http://earthobservatory.nasa.gov/IOTD/view.php?id=885

Specialists examining these and other questions related to environmental issues may come from many specific areas of study, each of which is referred to as a discipline. However, the various ways of understanding each issue may be integrated into comprehensive studies of the subject matter – this is why environmental studies is referred to as interdisciplinary field. For environmental science, the most relevant of the disciplinary subjects are atmospheric science, biology, chemistry, computer science, ecology, geography, geology, mathematics, medical science, oceanography, physics, and statistics. This is illustrated in Figure 1.1, which suggests that all fields of scientific knowledge are relevant to understanding the causes, consequences, and resolution of environmental problems.

Figure 1.1. Environmental science has an interdisciplinary character. All scientific disciplines are relevant to the identification and resolution of environmental issues. However, the work requires an interdisciplinary approach that engages many disciplines in a coordinated manner. This integration is suggested by the overlaps among the disciplinary fields.



This book deals with the key subject areas of environmental science. To some degree, however, certain non-science topics are also examined because they are vital to understanding and resolving environmental issues. These non-science fields include ethics, philosophy, and economics.

Of all of the academic disciplines, ecology is the most relevant to environmental science, and in fact the terms are often confused. Ecology may be defined simply as the study of the relationships of organisms with their environment. Ecology is itself a highly interdisciplinary field of study – it mostly involves biology, but knowledge of chemistry, computer science, mathematics, physics, geology, and other fields is also important. Geography is another interdisciplinary field that is central to environmental science. Geography can be simply defined as the study of natural features of Earth's surface, including climate, soil, topography, and vegetation, as well as intersections with the human economy. Obviously, ecology and geography are closely related fields.

Increasing numbers of scientists are studying human (or anthropogenic) influences on ecosystems, occurring as a result of pollution, disturbances, and other stressors. Examples of the major subject areas are:

1. The extraction, processing, and use of non-renewable resources, such as fossil fuels and metals, in ways that do

not cause unacceptable environmental damage, while also moderating their depletion to some possible degree (for example, by re-cycling certain materials)
2. The harvesting and management of biological resources, such as those in agriculture, fisheries, and forestry, in ways that allow them to fully regenerate so their stocks can be sustained into the future
3. The growth of renewable sources of energy, such as the various forms of solar energy (including biomass fuels, hydroelectricity, photovoltaics, and wind), as a way of replacing non-renewable fossil fuels and thereby making the energy economy more sustainable
4. The prevention and repair of ecological damages, such as those related to endangered biodiversity, degraded land or water, and the management of greenhouse gases

An environmental scientist is a generalist who uses science-related knowledge relevant to environmental quality, such as air or water chemistry, climate modelling, or the ecological effects of pollution. Several well-known environmental scientists who have worked in Canada are: William Rees of the University of British Columbia, who studies ecological economics and footprints, David Schindler of the University of Alberta, who studies the effects of pollution and climate change on lakes, Bridget Stutchbury of York University, who examines factors affecting bird conservation, and Andrew Weaver of the University of Victoria, who studies the causes and consequences of climate change.

Another group of people, known as environmentalists, is also involved with these sorts of issues, especially in the sense of advocacy. This involves taking a strong public stance on a particular environmental issue, in terms of the need to address the problem. David Suzuki is perhaps the most famous environmentalist in Canada, because he has so effectively influenced the attitudes of people through books, television, and other media. Elizabeth May is another well-known Canadian environmentalist, who has worked to deal with many issues as the director of the Sierra Club of Canada, and more recently as the head of the Green Party of Canada and a Member of Parliament. A final example is Paul Watson, a direct-action environmentalist who has worked through the Sea Shepherd Society. He has been involved in non-governmental "policing" actions, such as the sabotage of vessels engaged in illegal whaling and fishing.

However, any person can be called an environmentalist if they care about the quality of the environment and work towards changes that would help to resolve the issue. Environmentalists may work as individuals, and they often pursue their advocacy through non-governmental organizations (NGOs; see Chapter 27 for an explanation of the role of NGOs in Canada and internationally).

Canadian Focus 1.1. David Suzuki – A Canadian Environmentalist

David Suzuki was born in Vancouver in 1936. In 1964, he became a biology professor at the University of British Columbia, where he studied the genetics of fruit flies. Beginning in the mid-1970s, Suzuki became engaged in media ventures designed to popularize knowledge about scientific issues important to society, most notably through the Quirks and Quarks (radio) and Nature of Things (television) series of the Canadian Broadcasting Corporation.

Through these media efforts, as well as his many books, magazine and newspaper articles, and public lectures, Suzuki has been instrumental in informing a broad public in Canada and other countries about the gravity of environmental problems, including their scientific and socio-economic dimensions. This is not to say that everyone agrees with his interpretation of environmental issues. Such issues are always controversial, and there are people who believe that some environmental problems – even climate change and the effects of pesticides – are not important. But despite this disagreement, David Suzuki is a highly respected spokesperson on a wide range of environmental topics. His work is now being advanced through the activities of the David Suzuki Foundation, an advocacy and research organization founded in 1990 with the aim of enhancing progress toward an ecologically sustainable human economy (see http://www.davidsuzuki.org/). Suzuki has built a worldwide following of a broad constituency of people concerned about environmental damage and social equity. By doing this, he has contributed greatly to the identification and resolution of environmental problems in Canada and the world.

Earth, Life, and Ecosystems

The universe consists of billions of billions of stars and probably an even larger number of associated planets. Our Earth is one particular planet, located within a seemingly ordinary solar system, which consists of the Sun, eight planets, three "dwarf" planets, and additional orbiting bodies, such as asteroids and comets.

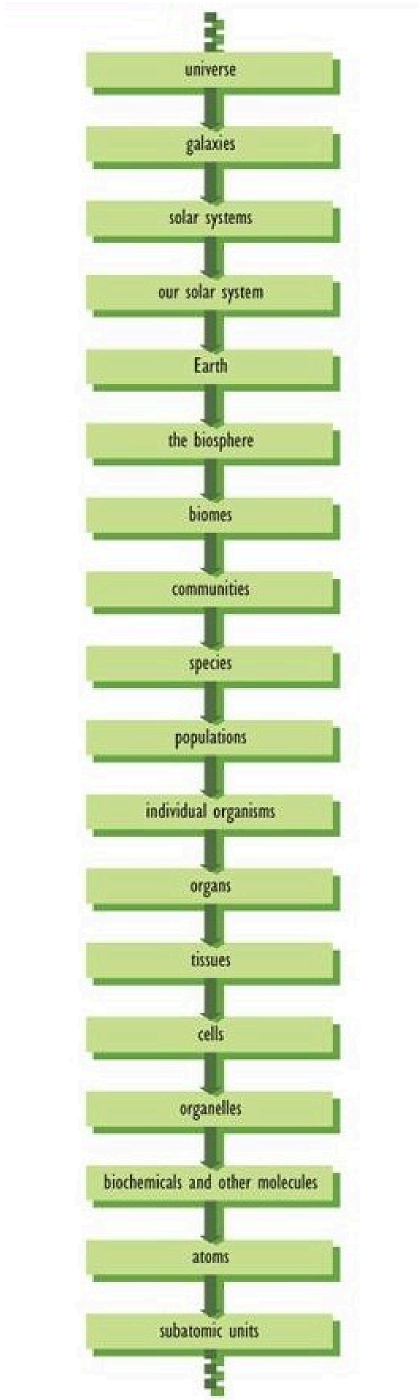
Earth is the third closest planet to the sun, orbiting that medium-sized star every 365 days at an average distance of 149 million kilometres, and revolving on its own axis every 24 hours. Earth is a spherical body with a diameter of 12,700 kilometres. About 70% of its surface is covered with liquid water, and the remaining terrestrial area of exposed land and rock is covered mostly with vegetation. With so much of its surface covered with water, one might wonder why our planet was not named "Water" instead of "Earth."

The most singularly exceptional characteristic of Earth is the fact that certain qualities of its environment have led to the genesis and subsequent evolution of organisms and ecosystems. These favourable environmental factors include aspects of Earth's chemistry, surface temperature, and strength of gravity.

The beginning of life occurred about 3.5 billion years ago, only 1 billion years following the origin of Earth during the formation of the solar system. It is not exactly known how life first evolved from inanimate matter, although it is believed to have been a spontaneous event. On other words, the genesis of life happened naturally, as a direct result of appropriate physical and chemical conditions.

Aside from the musings of science fiction, Earth is celebrated as the only place in the universe that is known to sustain life and its associated ecological processes. Of course, this observation simply reflects our present state of knowledge. We do not actually know that organisms do not exist elsewhere – only that life or its signals have not yet been discovered anywhere else in the universe. In fact, many scientists believe that because of the extraordinary diversity of environments that must exist among the innumerable planets of the multitudinous solar systems of the universe, it is likely that life forms have developed elsewhere. Nevertheless, the fact remains that Earth is the only planet definitely known to support organisms and ecosystems. This makes Earth an extraordinarily special place. We can consider the universe at various hierarchical levels (Figure 1.2). The scale ranges from the extremely small, such as subatomic particles and photons, to the fantastically large, such as galaxies and, ultimately, the universe.

Figure 1.2. Hierarchical Organization of the Universe.



Life on Earth occupies intermediate levels of this hierarchy. The realm of ecology encompasses the following levels:

1. individual organisms, which are living entities that are genetically and physically discrete
2. populations, or individuals of the same species that occur together in time and space
3. communities, or populations of various species, also co-occurring at the same time and place
4. landscapes and seascapes (collectively, these are ecoscapes), which are spatial integrations of various communities over large areas

5. and the biosphere in its entirety, which is composed of all life and ecosystems on Earth

Species and Ecosystems

A species is defined as individuals and populations that can potentially interbreed and produce fertile offspring (see Chapter 7). The word ecosystem is a generic term that is used to describe one or more communities of organisms that are interacting with their environment as a defined unit. As such, ecosystems can be organized in a hierarchy – they may range from small units occurring in discrete microhabitats (such as an aquatic ecosystem contained within a pitcher plant or in a garden surrounded by pavement) to much larger scales (such as a landscape or seascape). Even the biosphere can be viewed as being a single ecosystem.

Ecological interpretations of the natural world consider the web-like connections among the many components of ecosystems in a holistic manner. This ecosystem approach does not view the system as a random grouping of individuals, populations, species, communities, and environments. Rather, it confirms all of these as being intrinsically connected and mutually dependent, although in varying degrees, and also as having emergent properties (In Detail 1.1).

An important ecological principle is that all species are sustained by environmental resources: the "goods and services" that are provided by their ecosystem. All organisms require specific necessities of life, such as inorganic nutrients, food, and habitat with particular biological and physical qualities. Green plants, for example, need access to an adequate supply of moisture, inorganic nutrients (such as nitrate and phosphate), sunlight, and space. Animals require suitable foods of plant or animal biomass (organic matter), along with habitat requirements that differ for each species.

It is important to understand that humans are no different in this respect from other species. Although this dependence may not always seem to be immediately apparent as we live our daily lives, we nevertheless depend on environmental resources such as food, energy, shelter, and water to sustain ourselves and our larger economies.

It follows that the development and growth of individual people, their populations, and their societies and cultures are limited to some degree by environmental factors. Examples of such constraints include excessively cold or dry climatic conditions, mountainous or otherwise inhospitable terrain, and other factors that influence food production by agriculture or hunting.

However, humans are often able to favourably manipulate their environmental circumstances. For example, crop productivity may be increased by irrigating agricultural land, by applying fertilizer, or by managing pests. In fact, humans are enormously more capable of overcoming their environmental constraints than any other species. This ability is a distinguishing characteristic of our species.

The human species is labelled by the scientific term Homo sapiens, a two-word name (or binomial) that is Latin for "wise man." Indeed, humans are the most intelligent of all the species, with an enormous cognitive ability (that is, an aptitude for solving problems). When humans and their societies perceive an environmental constraint, such as a scarcity of resources, they often have been able to understand the limiting factors and to then use insight and tools to manipulate the environment accordingly. The clever solutions have generally involved management of the environment or other species to the benefit of humans, or the development of social systems and technologies that allow a more efficient exploitation of natural resources.

Humans are not the only species that can cope with ecological constraints in clever ways. A few other species have learned to use rudimentary tools to exploit the resources of their environment more efficiently. For example, the woodpecker finch of the Galapagos Islands uses cactus spines to pry its food of insects out of fissures in bark and rotting wood. Chimpanzees modify twigs and use them to extract termites, a favourite food, from termite mounds.

Egyptian vultures pick up stones in their beak and drop them on ostrich eggs, breaking them and allowing access to the rich food inside.

A few such innovations or “discoveries” by other species have even been observed. About 60 years ago in England, milk was hand-delivered to homes in glass bottles that had a bulbous compartment at the top to collect the cream as it separated. A few great tits (chickadee-like birds) discovered that they could feed on the cream by tearing a hole in the cardboard cap of the bottle. Other great tits observed this behavioural novelty and adopted it. The feeding tactic became widespread and was even adopted by several other species, such as the blue tit. Cream-eating was a clever innovation, allowing access to a new and valuable food resource.

Although other species have developed behavioural changes that allow more efficient exploitation of their environment, none have approached the number and variety of innovations developed by humans. Moreover, no other species has developed a cumulative expertise for exploiting such a broad range of resources. And no other species has managed to spread these adaptive capabilities as extensively as humans have, in an increasingly global culture. Unfortunately, humans also have developed an unparalleled ability to degrade resources and ecosystems and to cause the extinction of other species. The intense damage caused by humans and our economy is, of course, a major element of the subject matter of environmental science.

In Detail 1.1. Systems and Complexity

The concept of systems is important in the hierarchical organization of environmental science. For this purpose, a system may be defined as a group or combination of regularly interacting and interdependent elements that form a collective entity, but one that is more than the mere sum of its constituents. A system can be isolated for purposes of study. Systems occur in various spheres of life, including the following: • biosystems, which are represented by any of the levels of organization of life, ranging from biochemistry to the biosphere • ecosystems, which are biosystems that consist of ecological communities that interact with their environment as a defined unit • economic systems, or integrated activities that produce goods and services in an economy • socio-cultural systems, which consist of ways that specialized people, information, and technologies are organized to achieve some goal • and numerous others, including musical symphonies, physical art such as paintings, and for that matter, the words and data in this book

Note, however, that these various systems are not mutually exclusive. For example, an agroecosystem includes elements of biosystems, ecosystems, and socio-cultural systems.

Systems have collective properties, which are based on the summation of their parts. One such property might be the total number of organisms present in a defined area, which might be measured as the sum of all of the individual plants, animals, and microorganisms that are estimated to be present.

Systems also have emergent properties, which are revealed only when their components interact to develop functional attributes that do not exist at simpler, lower levels. For example, harmonies and melodies are emergent properties of music, as occurs when vocalists, a drummer, a bass and lead guitarist, and a keyboard player of a rock band all integrate their activities to perform a song. Emergent properties are complex and may be difficult to predict or manage.

Biological systems provide numerous examples of emergent properties (see Chapter 9). For example, certain kinds of fungi and algae join together as a life form known as a lichen, which is an intimate, mutually beneficial relationship (a mutualism). The biological properties of a lichen are different from those of the partner species (which cannot live apart in nature), and they are impossible to predict based only on knowledge of the alga and the fungus.

Similarly, assemblages of various species occurring in the same place and time (an ecological community) develop emergent properties based on such interactions as competition, disease, herbivory, and predation. This complexity makes it difficult to predict changes caused by the introduction of a new disease or predator to a community (including the harvesting of certain species by humans). Assemblages of communities over large areas, known as ecoscapes, also have emergent properties, as does the biosphere as a whole.

Emergent properties are extremely difficult to predict and often emerge as "surprises," for example, occurring when ecosystems are stressed by some human influence. The interconnections within systems are particularly important: any effects on particular components will inevitably affect all of the others. This extreme complexity is one of the defining attributes of life and ecosystems, in contrast with physical (or non-biological) systems, which are less complex.

Systems analysis is the study of the characteristics of systems, including their components, the relationships among those elements, and their collective and emergent properties. Systems analysis is used to study commercial, industrial, and scientific operations, usually with the goal of improving their efficiency. It can also be applied to improve the management of ecosystems being exploited to provide goods and services for use by the human economy. Ecologists also use systems analysis to better understand the organization and working of natural ecosystems, regardless of any direct relationship to the harvesting of natural resources. A key result of many such analyses is that the complexity of the system often precludes accurate predictions.

To see a remarkable example of a musical system with emergent properties, have a look at the video, Stringfever Bolero at http://www.youtube.com/watch?v=H5MLNMgpywk

Stressors and Responses

The development and productivity of organisms, populations, communities, and ecosystems are naturally constrained by environmental factors. These constraints can be viewed as being environmental stressors (or stressors). For example, an individual plant may be stressed by inadequate nutrition, perhaps because of infertile soil or competition with nearby plants for scarce resources. Less-than-optimal access to nutrients, water, or sunlight results in physiological stress, which causes the plant to be less productive than it is genetically capable of being. One result of this stress–response relationship is that the plant may develop relatively few seeds during its lifetime. Because reproductive (and evolutionary) success is related to the number of progeny an organism produces to carry on its genetic lineage, the realized success of this individual plant is less than its potential.

Similarly, the development and productivity of an animal (including any human) are constrained by the environmental conditions under which it lives. For instance, an individual may have to deal with stresses caused by food shortage or by difficult interactions with other animals through predation, parasitism, or competition for scarce resources.

The most benign (or least stressful) natural environments are characterized by conditions in which factors such as moisture, nutrients, and temperature are not unduly constraining, while disturbances associated with disease, wildfire, windstorm, or other cataclysms are rare. These kinds of relatively benevolent conditions allow the most complex and biodiverse ecosystems to develop, namely old-growth rainforest and coral reefs. Other environments, however, are characterized by conditions that are more stressful, which therefore limits their development to less complex ecosystems, such as prairie, tundra, or desert.

All ecosystems are dynamic, in the sense that they change profoundly, and quite naturally, over time. Many ecosystems are especially dynamic, in that they regularly experience large changes in their species, amounts of biomass, and rates of productivity and nutrient cycling. For example, ecosystems that occur in seasonal climates usually have a discrete growing season, which is followed by a dormant period when little or no growth occurs. To varying degrees, all of the natural ecosystems of Canada are seasonally dynamic: a warm growing season is followed by a cold dormant period when no plant productivity or growth occurs. Animals may survive the hard times of winter by migrating, hibernating, or feeding on plant biomass remaining from the previous growing season.

Ecosystems that have recently been affected by a disturbance (an episode of destruction) are particularly dynamic because they are undergoing a process of ecological recovery known as succession. Succession occurs in response to changes associated with natural disturbances such as a wildfire, windstorm, or insect or disease epidemic. These cataclysmic stressors kill many of the dominant organisms in an ecosystem, creating opportunities for relatively short-lived species, which may dominate the earlier years of the post-disturbance recovery. Succession also occurs after anthropogenic disturbances, such as a deliberately lit wildfire or a clear-cut of mature timber.

The dynamics of natural disturbances can be far-reaching, in some cases affecting extensive landscapes. For example, in most years, millions of hectares of the boreal forest of northern Canada are disturbed by wildfires. Similarly, great areas may be affected by sudden increases of spruce budworm, a moth that can kill most mature trees in fir–spruce forest, or by the mountain pine beetle, which kills pine trees. An even more extensive cataclysm ended about 12,000 years ago, when glaciation covered virtually all of Canada with enormous ice sheets up to several kilometres thick. However, disturbances can also be local in scale. For example, the death of a large tree within an otherwise intact forest creates a local zone of damage, referred to as a microdisturbance. This small-scale disturbance induces a local succession of vigorously growing plants that attempt to achieve individual success by occupying the newly available gap in the forest canopy.

Even highly stable ecosystems such as tropical rainforest and communities of deep regions of the oceans change inexorably over time. Although catastrophic disturbances may affect those stable ecosystems, they are rare under natural conditions. Nevertheless, as with all ecosystems, these stable types are influenced by pervasive changes in climate and by other long-term dynamics, such as evolution.

In fact, natural environmental and ecological changes have caused the extinction of almost all of the species that have ever lived on Earth since life began about 3.5 billion years ago. Many of the extinctions occurred because particular species could not cope with the stresses of changes in climate or in biological interactions such as competition, disease, or predation. However, many of the extinctions appear to have occurred synchronously (at about the same time) and were presumably caused by an unpredictable catastrophe, such as a meteorite colliding with the Earth. (See Chapters 7 and 26 for descriptions of natural extinctions and those caused by human influences.)

Environmental stressors and disturbances have always been an important, natural context for life on Earth. So, too, have been the resulting ecological responses, including changes in species and the dynamics of their communities and ecosystems.

> Image 1.2. Modern consumerism results in huge demands for material and energy resources to build and run homes and to manufacture and operate machines and other goods. In an environmental context, this is

sometimes referred to as “affluenza”. Source: B. Freedman

Human Activities are Environmental Stressors

These days, of course, ecosystems are influenced not just by “natural” environmental stressors. In many situations, anthropogenic influences have become the most important constraining influence on the productivity of species and on ecosystems more generally. These direct and indirect influences have intensified enormously in modern times.

Humans affect ecosystems and species in three direct ways: (a) by harvesting valuable biomass, such as trees and hunted animals; (b) by causing damage through pollution; and (c) by converting natural ecosystems to into land-uses for the purposes of agriculture, industry, or urbanization.

These actions also engender many indirect effects. For example, the harvesting of trees alters the habitat conditions for the diversity of plants, animals, and microorganisms that require forested habitat, thereby affecting their populations. At the same time, timber harvesting indirectly changes functional properties of the landscape, such as erosion, productivity, and the quantity of water flowing in streams. Both the direct and indirect effects of humans on ecosystems are important.

Humans have always left “footprints” in nature – to some degree, they have always influenced the ecosystems of which they were a component. During most of the more than 100,000 years of evolution of modern Homo sapiens, that ecological footprint was relatively shallow. This was because the capability of humans for exploiting their environment was not much different from that of other similarly abundant, large animals. However, during the cultural evolution of humans, the ecological changes associated with our activities progressively intensified. This process of cultural evolution has been characterized by the discovery and use of increasingly more sophisticated methods, tools, and social organizations to secure resources by exploiting the environment and other species.

Certain innovations occurring during the cultural evolution of humans represented particularly large increases in capability. Because of their great influence on human success, these advances are referred to as "revolutions." The following are examples of early technological revolutions:

- the discovery of ways of making improved weapons for hunting animals
- domestication of the dog, which also greatly facilitated hunting
- domestication of fire, which provided warmth and allowed for cooked, more digestible foods
- ways of cultivating and domesticating plants and livestock, which resulted in huge increases in food availability
- techniques for working raw metals into tools, which were much better than those made of wood, stone, or bone
  The rate of new discoveries has increased enormously over time. More recent technological revolutions include the following:
- methods of using machines and energy to perform work previously done by humans or draught animals
- further advances in the domestication and cultivation of plants and animals
- discoveries in medicine and sanitation
- extraordinary strides in communications and information-processing technologies

These and other revolutionary innovations all led to substantial increases in the ability of humans to exploit the resources of their environment and to achieve population growth (Chapter 10). Unfortunately, enhanced exploitation has rarely been accompanied by the development of a compensating ethic that encourages conservation of the resources needed for survival. Even early hunting societies of more than about 10,000 years ago appear to have caused the extinction of species that were hunted too effectively (Chapter 26).

The diverse effects of human activities on environmental quality are vital issues, and they will be examined in detail in later chapters. For now, we emphasize the message that intense environmental stress associated with diverse human activities has become the major factor causing ecological changes on Earth. Many of the changes are degrading the ability of the environment and ecosystems to sustain humans and their economies. Anthropogenic activities are also causing enormous damage to natural ecosystems, including to habitats needed to support most other species.

In fact, the environmental and ecological damage caused by humans has become so severe that an appropriate metaphor for the human enterprise may be that of a malignancy, or cancer. This is a sobering image. It is useful to dwell on it so that its meaning does not escape our understanding. Humans and their activities are endangering species and natural ecosystems on such a tremendous scale and rate that the integrity of Earth's life-support systems is at risk.

From an ecological perspective, the pace and intensity of these changes is staggering. Moreover, the damage will become substantially worse before corrective actions are (hopefully) undertaken to reverse the damage and allow an ecologically sustainable human enterprise to become possible. From a pessimistic standpoint, however, it may prove to be beyond the capability of human societies to act effectively to fix the damage and to design and implement solutions for sustainability.

These are, of course, only opinions, albeit the informed views of many environmental specialists. Anticipating the future is always uncertain, and things may turn out to be less grim than is now commonly predicted. For example, we might be wrong about the availability of key resources needed to sustain future generations of humans. Still, the clear indications from recent patterns of change are that the environmental crisis is severe and that it will worsen in the foreseeable future.

But not all this damage is inevitable. There is sincere hope and expectation that human societies will yet make appropriate adjustments and will choose to pursue options that are more sustainable than many of those now being followed. In fact, no other outcome could be considered acceptable.

Ethics and World Views

The choice that people make can influence environmental quality in many ways – by affecting the availability of resources, causing pollution, and causing species and natural ecosystems to become endangered. Decisions influencing environmental quality are influenced by two types of considerations: knowledge and ethics.

In the present context book, knowledge refers to information and understanding about the natural world, and ethics refers to the perception of right and wrong and the appropriate behaviour of people toward each other, other species, and nature. Of course, people may choose to interact with the environment and ecosystems in various ways. On the one hand, knowledge provides guidance about the consequences of alternative choices, including damage that might be caused and actions that could be taken to avoid that effect. On the other hand, ethics provides guidance about which alternative actions should be favoured or even allowed to occur.

Because modern humans have enormous power to utilize and damage the environment, the influence of knowledge and ethics on choices is a vital consideration. And we can choose among various alternatives. For example, individual people can decide whether to have children, purchase an automobile, or eat meat, while society can choose whether to allow the hunting of whales, clear-cutting of forests, or construction of nuclear-power plants. All of these options have implications for environmental quality.

Perceptions of value (of merit or importance) also profoundly influence how the consequences of human actions are interpreted. Environmental values can be divided into two broad classes: utilitarian and intrinsic.

1. Utilitarian value (also known as instrumental value) is based on the known importance of something to the welfare of people (see also the discussion of the anthropocentric world view, below). Accordingly, components of the environment and ecosystems are considered important only if they are resources necessary to sustain humans—that is, if they bestow economic benefits, provide livelihoods, and contribute to the life-support system. In effect, people harvest materials from nature because they have utilitarian value. These necessities include water, timber, fish and animals hunted in wild places, and agricultural crops grown in managed ecosystems.

   Ecological values are somewhat broader utilitarian values—they are based on the needs of humans, but also on those of other species and natural ecosystems. Ecological values often take a longer-term view. Aesthetic values are also utilitarian but are based on an appreciation of beauty, but they are subjective and influenced by cultural perspectives. For instance, environmental aesthetics might value natural wilderness over human-dominated ecosystems, free-living whales over whale meat, and large standing trees over toilet paper. On the other hand, aesthetics that are heavily influenced by more anthropogenic considerations might result in the opposite preferences. Maintaining aesthetic values can provide substantial cultural, social, psychological, and economic benefits.

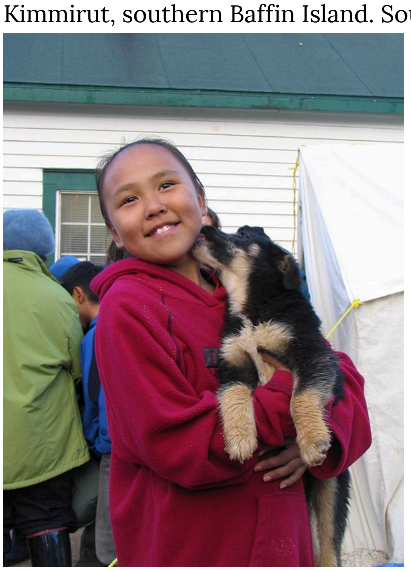
2. Intrinsic value is based on the belief that components of the natural environment (such as species and natural ecosystems) have inherent value and a right to exist, regardless of any positive, negative, or neutral relationships with humans. Under this system, it would be wrong for people to treat other creatures cruelly, to take actions that cause natural entities to become endangered or extinct, or to fail to prevent such occurrences.

As was noted previously, ethics concerns the perception of right and wrong and the values and rules that should govern human conduct. Clearly, ethics of all kinds depend upon the values that people believe are important. Environmental ethics deal with the responsibilities of present humans to both future generations and other species to ensure that the world will continue to function in an ecologically healthy way, and to provide adequate resources and livelihoods (this is also a key aspect of sustainable development; see the last section of this chapter). The environmental values described above underlie this system of ethics. Applying environmental ethics often means analyzing and balancing standards that may conflict, because aesthetic, ecological, intrinsic, and utilitarian values rarely all coincide (see In Detail 1.2).

There is also tension between ethical considerations that are individualistic and those that are holistic. For example, animal-rights activists are highly concerned with issues involving the treatment of individual organisms. Ecologists, however, are typically more concerned with holistic values, such as a population, species, or ecosystem. As such, an ecologist might advocate a cull of overabundant deer in a park in order to favour the survival of populations of endangered plants, whereas that action might be resisted by an animal-rights activist.

Values and ethics, in turn, support larger systems known as world views. A world view is a comprehensive philosophy of human life and the universe, and of the relationship between people and the natural world. World views include traditional religions, philosophies, and science, as well as other belief systems. In an environmental context, generally important world views are known as anthropocentric, biocentric, and ecocentric, while the frontier and sustainability world views are more related to the use of resources. The anthropocentric world view considers humans as being at the centre of moral consideration. People are viewed as being more worthy than any other species and as uniquely disconnected from the rest of nature. Therefore, the anthropocentric world view judges the importance and worthiness of everything, including other species and ecosystems, in terms of the implications for human welfare.

Image 1.3. According to the biocentric and ecocentric world views, all species have intrinsic value. This does not, however, mean that one species cannot exploit another. This image of a girl and her puppy was taken in Kimmirut, southern Baffin Island. Source: B. Freedman.



The biocentric world view focuses on living entities and considers all species (and individuals) as having intrinsic value. Humans are considered a unique and special species, but not as being more worthy than other species. As such, the biocentric world view rejects discrimination against other species, or speciesism (a term similar to racism or sexism).

The ecocentric world view considers the direct and indirect connections among species within ecosystems to be invaluable. It also includes consideration for non-living entities, such as rocks, soil, and water. It incorporates the biocentric world view but goes well beyond it by stressing the importance of interdependent ecological functions, such as productivity and nutrient cycling.

The frontier world view asserts that humans have a right to exploit nature by consuming natural resources in boundless quantities. This world view claims that people are superior and have a right to exploit nature. Moreover, the supply of resources to sustain humans is considered to be limitless, because new stocks can always be found, or substitutes discovered. The consumption of resources is considered to be good because it enables economies to grow. Nations and individuals should be allowed to consume resources aggressively, as long as no people are hurt in the process.

The sustainability world view acknowledges that humans must have access to vital resources, but the exploitation of those necessities should be governed by appropriate ecological, intrinsic, and aesthetic values. The sustainability world view can assume various forms. The spaceship world view is quite anthropocentric. It focuses only on sustaining resources needed by people, and it assumes that humans can exert a great degree of control over natural processes and can safely pilot "spaceship Earth." In contrast, ecological sustainability is more ecocentric. It considers people within an ecological context and focuses on sustaining all components of Earth's life-support system by preventing human actions that would degrade them. In an ecologically sustainable economy, natural goods and services should be utilized only in ways that do not compromise their future availability and do not endanger the survival of species or natural ecosystems.

The attitudes of people and their societies toward other species, natural ecosystems, and resources have enormous implications for environmental quality. Extraordinary damages have been legitimized by attitudes based on a belief in the inalienable right of humans to harvest whatever they desire from nature, without consideration of pollution, threats to species, or the availability of resources for future generations. Clearly, one of the keys to resolving the environmental crisis is to achieve a widespread adoption of ecocentric and ecological sustainability world views.

> Environmental Issues 1.1. Old-Growth Forest: Values in Competition Ethics and values are greatly influenced by cultural attitudes. Because the attitudes of people vary considerably, proposals to exploit natural resources as economic commodities often give rise to intense controversy. This can be illustrated by the case of old-growth rainforest on Vancouver Island.
>
> Old-growth forest in the coastal zone of British Columbia contains many ancient trees, some of which are hundreds of years old and of gigantic height and girth (see Chapter 23). The cathedral-like aesthetics of old-growth forest are inspiring to many people, providing a deeply natural, even spiritual experience. Elements of the culture of the First Nations of coastal British Columbia are based on values associated with old-growth forest. Whatever their culture, however, few people fail to be inspired by a walk through a tract of old-growth forest on Vancouver Island. Old-growth forest is also a special kind of natural ecosystem, different from other forests, and supporting species that cannot survive elsewhere. These ecological qualities give coastal old-growth forest an intrinsic value that is not replicated elsewhere in Canada. This ecosystem represents a distinct element of our natural heritage.
>
> Old-growth forest is also an extremely valuable resource because it contains large trees that can be harvested and manufactured into lumber or paper. If utilized in this manner, old-growth forest can provide livelihoods for people and revenues for local, provincial, and national economies. Old-growth forest also supports other economic values, including deer that can be harvested by hunters, and salmon by fishers, as well as birds and wildflowers that entice ecotourists to visit these special habitats. Intact old-growth forest also provides other valuable services, such as flows of clean streamwater and assistance in the regulation of atmospheric concentrations of vital gases such as carbon dioxide and oxygen. At one time, old-growth forest was widespread on Vancouver Island, but it is now endangered both there and almost everywhere else in Canada. This has happened largely because old-growth forest has been extensively harvested and replaced by younger, second-growth stands. The secondary forest is harvested as soon as it becomes economically mature, which happens long before it can develop into an old-growth condition. The net result is a rapidly diminishing area of old-growth forest and endangerment of both the ecosystem and some of its dependent species.

Obviously, the different values concerning old-growth forest on Vancouver Island are in severe conflict. Industrial schemes to harvest old-growth trees for manufacturing into lumber or paper are incompatible with other proposals to protect this special ecosystem in parks and wilderness areas. The conflicting perceptions of values have resulted in emotional confrontations between loggers and preservationists, in some cases resulting in civil disobedience, arrests, and jail terms. Ultimately, these sorts of controversies can only be resolved by finding a balance among the utilitarian, ecological, aesthetic, and intrinsic values of old-growth forest, and by ensuring that all of these values are sustained.

The Environmental Crisis

The modern environmental crisis encompasses many issues. In large part, however, we can classify the issues into three categories: population, resources, and environmental quality. In essence, these topics are what this book is about. However, the core of their subject areas is the following:

- Population

  In 2015, the human population numbered more than 7.3 billion, including about 34 million in Canada . At the global level, the human population has been increasing because of the excess of birth rates over death rates. The recent explosive population growth, and the poverty of so many people, is a root cause of much of the environmental crisis. Directly or indirectly, large population increases result in extensive deforestation, expanding deserts, land degradation by erosion, shortages of water, change in regional and global climate, endangerment and extinction of species, and other great environmental problems. Considered together, these damages represent changes in the character of the biosphere that are as cataclysmic as major geological events, such as glaciation. We will discuss the human population in more detail in Chapters 10 and 11.

- Resources

  Two kinds of natural resources can be distinguished. A non-renewable resource is present in a finite quantity. As these resources are extracted from the environment, in a process referred to as mining, their stocks are inexorably diminished and so are available in increasingly smaller quantities for future generations. Non-renewable resources include metals and fossil fuels such as petroleum and coal. In contrast, a renewable resource can regenerate after harvesting, and if managed suitably, can provide a supply that is sustainable forever. However, to be renewable, the ability of the resource to regenerate cannot be compromised by excessive harvesting or inappropriate management practices. Examples of renewable resources include fresh water, the biomass of trees and agricultural plants and livestock, and hunted animals such as fish and deer. Ultimately, a sustainable economy must be supported by renewable resources. Too often, however, potentially renewable resources are not used responsibly, which impairs their renewal and represents a type of mining. The subject area of natural resources is examined in detail in Chapters 12, 13, and 14.

- Environmental Quality

  This subject area deals with anthropogenic pollution and disturbances and their effects on people, their economies, other species, and natural ecosystems. Pollution may be caused by gases emitted by power plants and vehicles, pesticides, or heated water discharged into lakes. Examples of disturbance include clear-cutting, fishing, and forest fires. The consequences of pollution and disturbance for biodiversity, climate change, resource availability, risks to human health, and other aspects of environmental quality are examined in Chapters 15 to 26.

Environmental Impacts of Humans

In a general sense, the cumulative impact of humans on the biosphere is a function of two major factors: (1) the size of the population and (2) the per-capita (per-person) environmental impact. The human population varies greatly among and within countries, as does the per-capita impact, which depends on the kind and degree of economic development that has occurred.

Paul Ehrlich, an American ecologist, has expressed this simple relationship using an "impact formula," as follows: I = P × A × T, where

- I is the total environmental impact of a human population
- P is the population size
- A is an estimate of the per-capita affluence in terms of resource use
- T is the degree of technological development of the economy, on a per-capita basis

Calculations based on this simple PAT formula show that affluent, technological societies have a much larger per-capita environmental impact than do poorer ones.

How does Canada's impact on the environment compare with that of more populous countries, such as China and India? We can examine this question by looking at two simple indicators of the environmental impact of both individual people and national economies: (a) the size of the human population, (b) the use of energy and (c) gross domestic product (GDP, or the annual value of all goods and services produced by a country). The use of energy is a helpful environmental indicator because power is needed to carry out virtually all activities in a modern society, including driving vehicles, heating or cooling buildings, manufacturing industrial products, and running computers. GDP represents all of the economic activities in a country, each of which results in some degree of environmental impact.

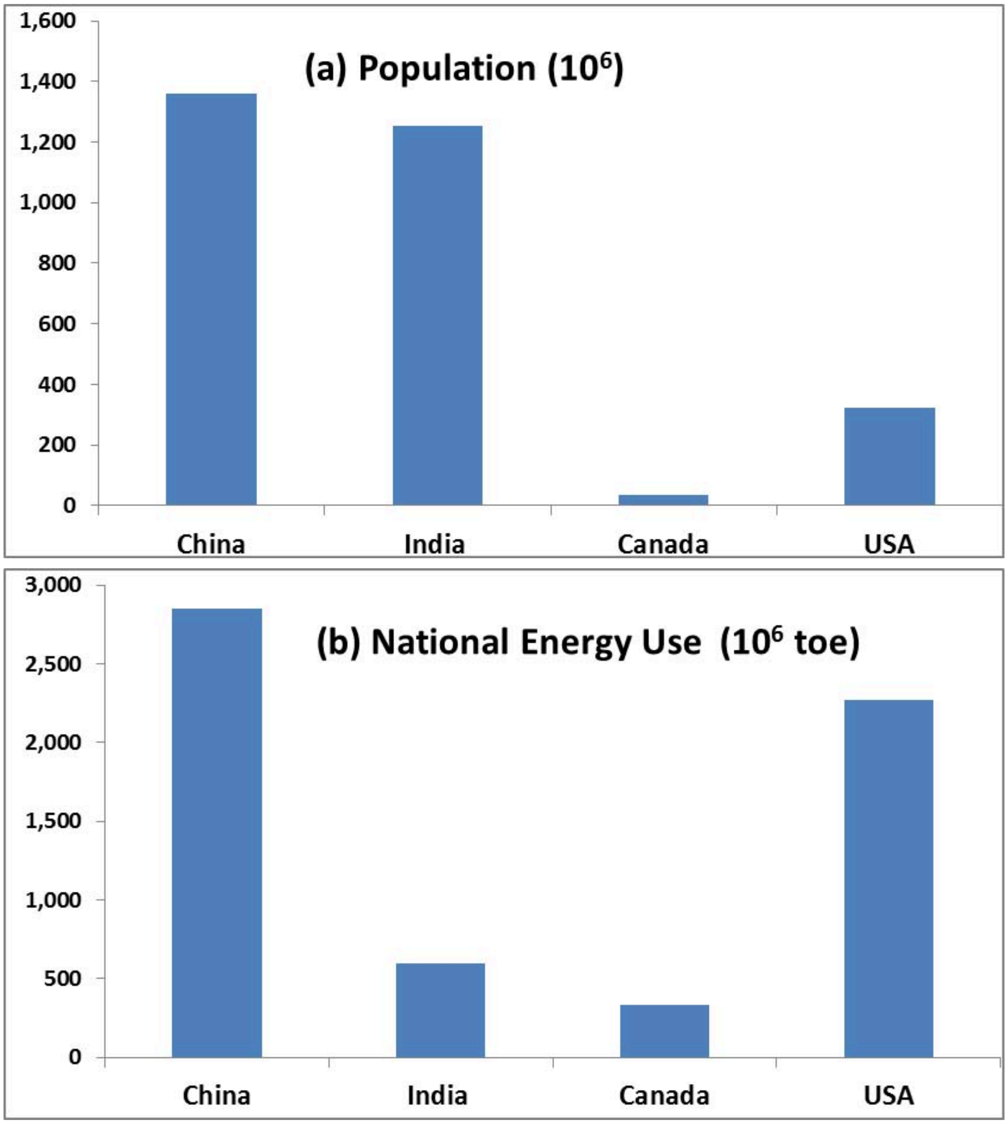
One of the major influences on the environmental impact of any human population is the number of people (the population size). In this respect, Canada has a much smaller population (35.1 million in 2015) compared to China (1.3 billion), India (1.1 billion), or the United States (321 million) (Figure 1.3a).

However, on a per-person basis, people living in Canada or the U.S. have much larger environmental impacts than do those living in China or India, as indicated by both per-capita energy use (Figure 1.3c) and per-capita GDP (Figure 1.3e). This difference is an inevitable consequence of the prosperous nature of the lifestyle of North Americans and other wealthier people, which on a per-capita basis is achieved by consuming relatively large amounts of natural resources and energy, while generating a great deal of waste materials. Sometimes this environmental effect of a wealthier population is referred to as "affluenza".

However, the per-capita environmental impact is only part of the environmental influence of a country, or of any human population. To determine the national effect, the per-capita value must be multiplied by the size of the population. When this is done for energy, China and the U.S. have by far the largest values, while Canada and India are much less (Figure 1.3b). Still, it is remarkable that the national energy use of Canada, with its relatively small population, is close to that of India and within an order of magnitude of China, which have enormously larger populations. The same pattern is true of national the GDPs of those countries.

These observations drive home the fact that the environmental impact of any human population is a function of both (a) the number of people and (b) the per-person environmental impact. Because of this context, relatively wealthy countries like Canada have much larger environmental impacts than might be predicted based only on the size of their population. On the other hand, the environmental impacts of poorer countries are smaller than might be predicted based on their population. We can conclude that the environmental crisis is due to both overpopulation and excessive resource consumption.

Figure 1.3. The relative environmental impacts of China, India, Canada, and the United States. The environmental impacts of countries, and of their individual citizens, can be compared using simple indicators, such as the use of energy and the gross domestic product. Canada's relatively small population, compared with China and India, is somewhat offset by its higher per-capita GDP and use of energy. However, because the per-capita data for the U.S. and Canada are similar, relative population sizes are the key influence on the environmental impacts of these two countries. Sources of data: population data are for 2015 (U.S. Census Bureau, 2015); energy use (all commercial fuels) for 2013 (BP, 2013); GDP for 2013 (CIA, 2014).



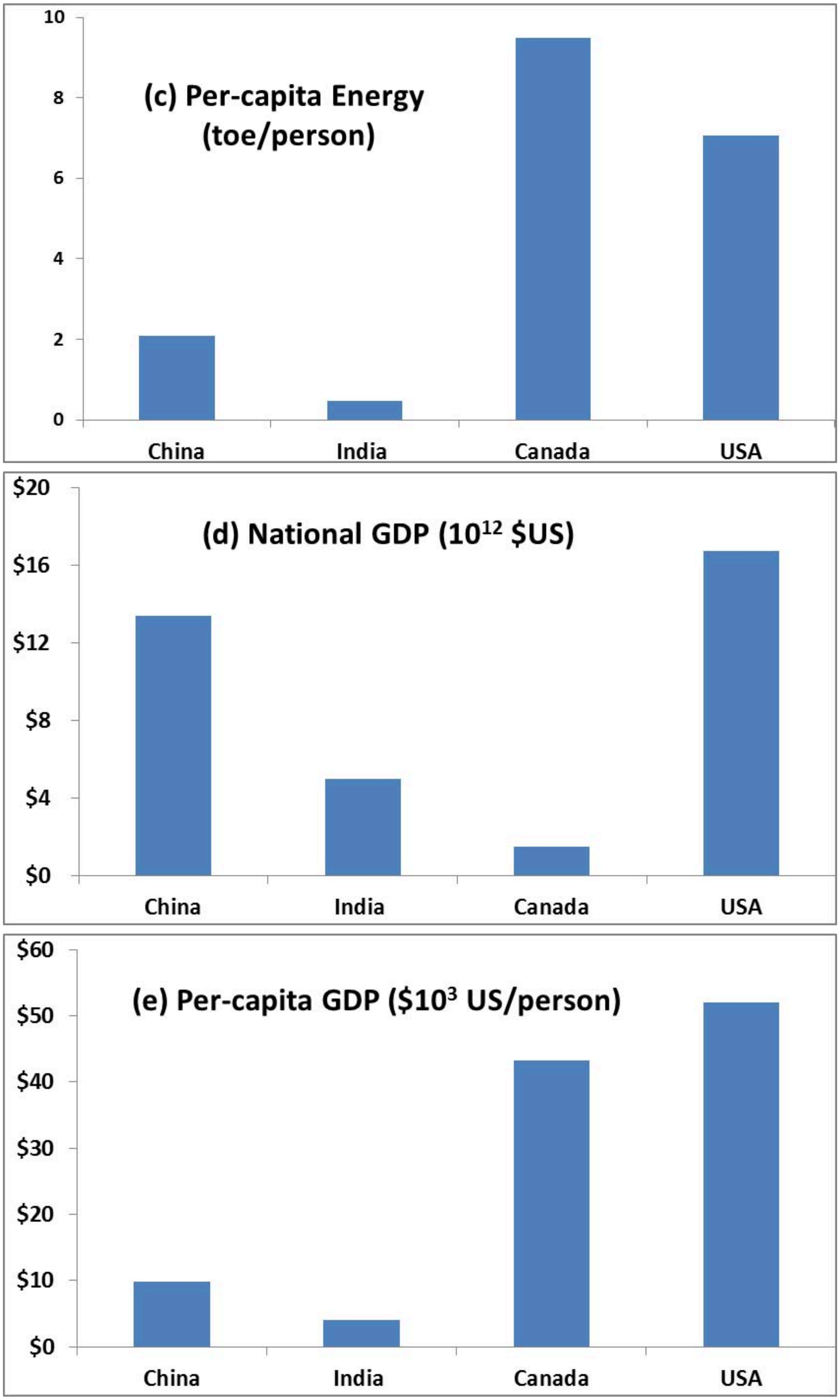

(c) Per-capita Energy (toe/person)
10
8
6
4
2
0
China
India
Canada
USA
(d) National GDP (10^12 $US)
$20
$16
$12
$8
$4
$0
China
India
Canada
USA
(e) Per-capita GDP ($10^3 US/person)
$60
$50
$40
$30
$20
$10
$0
China
India
Canada
USA

Image 1.4. Places where people live, work, grow food, and harvest natural resources are affected by many kinds of anthropogenic stressors. These result in ecosystems that are not very natural in character, such as the pavement and grassy edges of this major highway in Toronto. Source: B. Freedman.

Ecologically Sustainable Development

Sustainable development refers to development of an economic system that uses natural resources in ways that do not deplete them or otherwise compromise their availability to future generations. In this sense, the present human economy is clearly non-sustainable. The reason for this bold assertion is that the present economy achieves rapid economic growth through vigorous depletion of both non-renewable and renewable resources (see Chapters 12-14). Economic growth and development are different phenomena. Economic growth refers to increases in the size of an economy because of expansions of both population and per-capita resource use. This growth is typically achieved by increasing the consumption of natural resources, particularly non-renewable ones such as fossil fuels and metals. The rapid use results in an aggressive depletion of vital non-renewable resources, and even renewable ones. In Canada, for example, considerable economic growth is being achieved by the huge investments of capital needed to mine and process the great oil-sand resources of northern Alberta (see Canadian Focus 13.1). In contrast, a comparable scale of investment in renewable energy initiatives, such as wind or solar power, or in energy conservation, would have contributed more so to sustainable development.

Almost all national economies have been growing rapidly in recent times. Moreover, most politicians, economic planners, and business people hope for additional growth of economic activity, in order to generate more wealth and to provide a better life for citizens. At the same time, however, most leaders of society have publicly affirmed their support of sustainable development. However, they are confusing sustainable development with "sustainable economic growth." Unfortunately, continuous economic growth is not sustainable because there are well-known limits due to finite stocks of natural resources, as well as a limited ability of the biosphere to absorb wastes and ecological damage without suffering irreversible degradation. This limit is a fundamental principle of ecological economics (see Chapter 12).

Economic development is quite different from economic growth. Development implies a progressively improving efficiency in the use of materials and energy, a process that reflects socio-economic evolution toward a more sustainable economy. Within that context, so-called developed countries have a relatively well-organized economic infrastructure and a high average per-capita income (because of their latter characteristic, they may also be referred to as high-income countries). Examples include Canada, the United States, Japan, countries of western Europe, and Australia. In contrast, less-developed or low-income countries have much less economic infrastructure and low per-capita earnings. Examples include Afghanistan, Bolivia, Myanmar, and Zimbabwe. A third group is comprised of rapidly developing or middle-income countries, such as Brazil, Chile, China, India, Malaysia, Russia, and Thailand.

A sustainable economy must be fundamentally supported by the wise use of renewable resources, meaning they are not used more quickly than their rate of regeneration. For these reasons, the term sustainable development should refer only to progress being made toward a sustainable economic system. Progress in sustainable development involves the following sorts of desirable changes:

- increasing efficiency of use of non-renewable resources, for example, by careful recycling of metals and by optimizing the use of energy
- increasing use of renewable sources of energy and materials in the economy (to replace non-renewable sources)
- improving social equity, with the ultimate goal of helping all people (and not just a privileged minority) to have reasonable access to the basic necessities and amenities of life

Despite abundant public rhetoric, our society has not yet made much progress toward true sustainability. This has happened because most actions undertaken by governments and businesses have supported economic growth, rather than sustainable development. We will further examine these issues in Chapter 12 and other parts of this book.

Sustainable development is a lofty and necessary goal for society to pursue. But if a sustainable human economy is not attained, then the non-sustainable one will run short of resources and could collapse. This would cause terrible misery for huge numbers of people and colossal damage to the biosphere.

The notion of sustainability can be further extended to that of ecologically sustainable development. This idea includes the usual aspect of sustainable development in which countries develop without depleting their essential base of natural resources, essentially by basing their economy on the wise use of renewable sources of energy and materials. Beyond that, however, an ecologically sustainable economy runs without causing an irretrievable loss of natural ecosystems or extinctions of species, while also maintaining important environmental services, such as the provision of clean air and water. Ecological sustainability is a reasonable extension of sustainability, which only focuses on the human economy. By expanding to embrace the interests of other species and natural ecosystems, ecological sustainability provides an inclusive vision for a truly harmonious enterprise of humans on planet Earth. Identifying and resolving the barriers to ecological sustainability are the fundamental objectives and subject matter of environmental studies. It provides a framework for all that we do.

Conclusions

Environmental science is a highly interdisciplinary field that is concerned with issues associated with the rapidly increasing human population, the use and diminishing stocks of natural resources, damage caused by pollution and disturbance, and effects on biodiversity and the biosphere. These are extremely important issues, but they involve complex and poorly understood systems. They also engage conflicts between direct human interests and those of other species and the natural world.

Ultimately, the design and implementation of an ecologically sustainable human economy will require a widespread adoption of new world views and cultural attitudes that are based on environmental and ecological ethics, which include consideration for the needs of future generations of people as well as other species and natural ecosystems. This will be the best way of dealing with the so-called "environmental crisis," a modern phenomenon that is associated with rapid population growth, resource depletion, and environmental damage. This crisis is caused by the combined effects of population increase and an intensification of per-capita environmental damage.

Finally, it must be understood that that the study of environmental issues is not just about the dismal task of understanding awful problems. Rather, a major part of the subject is to find ways to repair many of the damages that have been caused, and to prevent others that might yet occur. These are helpful and hopeful actions, and they represent necessary progress toward an ecologically sustainable economy.

Questions for Review

1. Define environmental science, environmental studies, and ecology. List the key disciplinary fields of knowledge that each includes.
2. Describe the hierarchical structure of the universe and list the elements that encompass the realms of biology and ecology.
3. Identify the key environmental stressors that may be affecting an ecosystem in your area (e.g., a local park). Make sure that you consider both natural and anthropogenic stressors.
4. What is the difference between morals and knowledge, and how are these conditioned by personal and societal values?
5. Explain how cultural attributes and expressions can affect the ways that people view the natural world and interact with environmental issues.

Questions for Discussion

1. Describe how you are connected with ecosystems, both through the resources that you consume (food, energy, and materials) and through your recreational activities. Which of these connections could you do without?
2. How are your personal ethical standards related to utilitarian, ecological, aesthetic, and intrinsic values? Think about your world view and discuss how it relates to the anthropocentric, biocentric, and ecocentric world views.
3. According to information presented in this chapter, Canada might be regarded as being as overpopulated as India and China. Do you believe this is a reasonable conclusion? Justify your answer.
4. Make a list of the most important cultural influences that have affected your own attitudes about the natural world and environmental issues.

Exploring Issues

1. You have been asked by the United Nations to devise an index of national and per-capita environmental impacts that will be used to compare various developed and less-developed countries. Until now, the United Nations has used extremely simple indicators, such as energy use and gross domestic product, but they now want to use more realistic data. How would you design better indicators? What do you think would be the most important components of the indicators, and why?

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PART II: THE BIOSPHERE: CHARACTERISTICS AND DYNAMICS

Chapter 2 ~ Science as a Way of Understanding the Natural World

Key Concepts

After completing this chapter, you will be able to

1. Describe the nature of science and its usefulness in explaining the natural world.
2. Distinguish among facts, hypotheses, and theories.
3. Outline the methodology of science, including the importance of tests designed to disprove hypotheses.
4. Discuss the importance of uncertainty in many scientific predictions, and the relevance of this to environmental controversies.

The Nature of Science

Science can be defined as the systematic examination of the structure and functioning of the natural world, including both its physical and biological attributes. Science is also a rapidly expanding body of knowledge, whose ultimate goal is to discover the simplest general principles that can explain the enormous complexity of nature. These principles can be used to gain insights about the of the natural world and to make predictions about future change.

Science is a relatively recent way of learning about natural phenomena, having largely replaced the influences of less objective methods and world views. The major alternatives to science are belief systems that are influential in all cultures, including those based on religion, morality, and aesthetics. These belief systems are primarily directed toward different ends than science, such as finding meaning that transcends mere existence, learning how people ought to behave, and understanding the value of artistic expression.

Modern science evolved from a way of learning called natural philosophy, which was developed by classical Greeks and was concerned with the rational investigation of existence, knowledge, and phenomena. Compared with modern science, however, studies in natural philosophy used unsophisticated technologies and methods and were not particularly quantitative, sometimes involving only the application of logic.

Modern science began with the systematic investigations of famous 16th- and 17th-century scientists, such as:

- Nicolaus Copernicus (1473-1543), a Polish astronomer who conceived the modern theory of the solar system
- William Gilbert (1544-1603), an Englishman who worked on magnetism
- Galileo Galilei (1564-1642), an Italian who conducted research on the physics of objects in motion, as well as astronomy
- William Harvey (1578-1657): an Englishman who described the circulation of the blood
- Isaac Newton (1642-1727): an Englishman who made important contributions to understanding gravity and the nature of light, formulated laws of motion, and developed the mathematics of calculus

Inductive and Deductive Logic

The English philosopher Francis Bacon (1561-1626) was also highly influential in the development of modern science. Bacon was not an actual practitioner of science but was a strong proponent of its emerging methodologies. He promoted the application of inductive logic, in which conclusions are developed from the accumulating evidence of experience and the results of experiments. Inductive logic can lead to unifying explanations based on large bodies of data and observations of phenomena. Consider the following illustration of inductive logic, applied to an environmental topic:

- Observation 1: Marine mammals off the Atlantic coast of Canada have large residues of DDT and other chlorinated hydrocarbons in their fat and other body tissues.
- Observation 2: So do marine mammals off British Columbia.
- Observation 3: As do those in the Arctic Ocean, although in lower concentrations.

Inductive conclusion: There is a widespread contamination of marine mammals with chlorinated hydrocarbons. Further research may demonstrate that the contamination is a global phenomenon. This suggests a potentially important environmental problem.

In contrast, deductive logic involves making one or more initial assumptions and then drawing logical conclusions from those premises. Consequently, the truth of a deductive conclusion depends on the veracity of the original assumptions. If those suppositions are based on false information or on incorrect supernatural belief, then any deduced conclusions are likely to be wrong. Consider the following illustration of deductive logic:

- Assumption 1: TCDD, an extremely toxic chemical in the dioxin family, is poisonous when present in even the smallest concentrations in food and water—even a single molecule can cause toxicity.
- Assumption 2: Exposure to anything that is poisonous in even the smallest concentrations is unsafe.
- Assumption 3: No exposure that is unsafe should be allowed.

Deductive conclusion 1: No exposure to TCDD is safe.
Deductive conclusion 2: No emissions of TCDD should be allowed.

The two conclusions are consistent with the original assumptions. However, there is disagreement among highly qualified scientists about those assumptions. Many toxicologists believe that exposures to TCDD (and any other potentially toxic chemicals) must exceed a threshold of biological tolerance before poisoning will result (see Chapter 15). In contrast, other scientists believe that even the smallest exposure to TCDD carries some degree of toxic risk. Thus, the strength of deductive logic depends on the acceptance and truth of the original assumptions from which its conclusions flow.

In general, inductive logic plays a much stronger role in modern science than does deductive logic. In both cases, however, the usefulness of any conclusions depends greatly on the accuracy of any observations and other data on which they were based. Poor data may lead to an inaccurate conclusion through the application of inductive logic, as will inappropriate assumptions in deductive logic.

Goals of Science

The broad goals of science are to understand natural phenomena and to explain how they may be changing over time.

To achieve those goals, scientists undertake investigations that are based on information, inferences, and conclusions developed through a systematic application of logic, usually of the inductive sort. As such, scientists carefully observe natural phenomena and conduct experiments.

A higher goal of scientific research is to formulate laws that describe the workings of the universe in general terms. (For example, see Chapter 4 for a description of the laws of thermodynamics, which deal with the transformations of energy among its various states.) Universal laws, along with theories and hypotheses (see below), are used to understand and explain natural phenomena. However, many natural phenomena are extremely complex and may never be fully understood in terms of physical laws. This is particularly true of the ways that organisms and ecosystems are organized and function.

Scientific investigations may be pure or applied. Pure science is driven by intellectual curiosity – it is the unfettered search for knowledge and understanding, without regard for its usefulness in human welfare. Applied science is more goal-oriented and deals with practical difficulties and problems of one sort or another. Applied science might examine how to improve technology, or to advance the management of natural resources, or to reduce pollution or other environmental damages associated with human activities.

Facts, Hypotheses, and Experiments

A fact is an event or thing that is definitely known to have happened, to exist, and to be true. Facts are based on experience and scientific evidence. In contrast, a hypothesis is a proposed explanation for the occurrence of a phenomenon. Scientists formulate hypotheses as statements and then test them through experiments and other forms of research. Hypotheses are developed using logic, inference, and mathematical arguments in order to explain observed phenomena. However, it must always be possible to refute a scientific hypothesis. Thus, the hypothesis that "cats are so intelligent that they prevent humans from discovering it" cannot be logically refuted, and so it is not a scientific hypothesis.

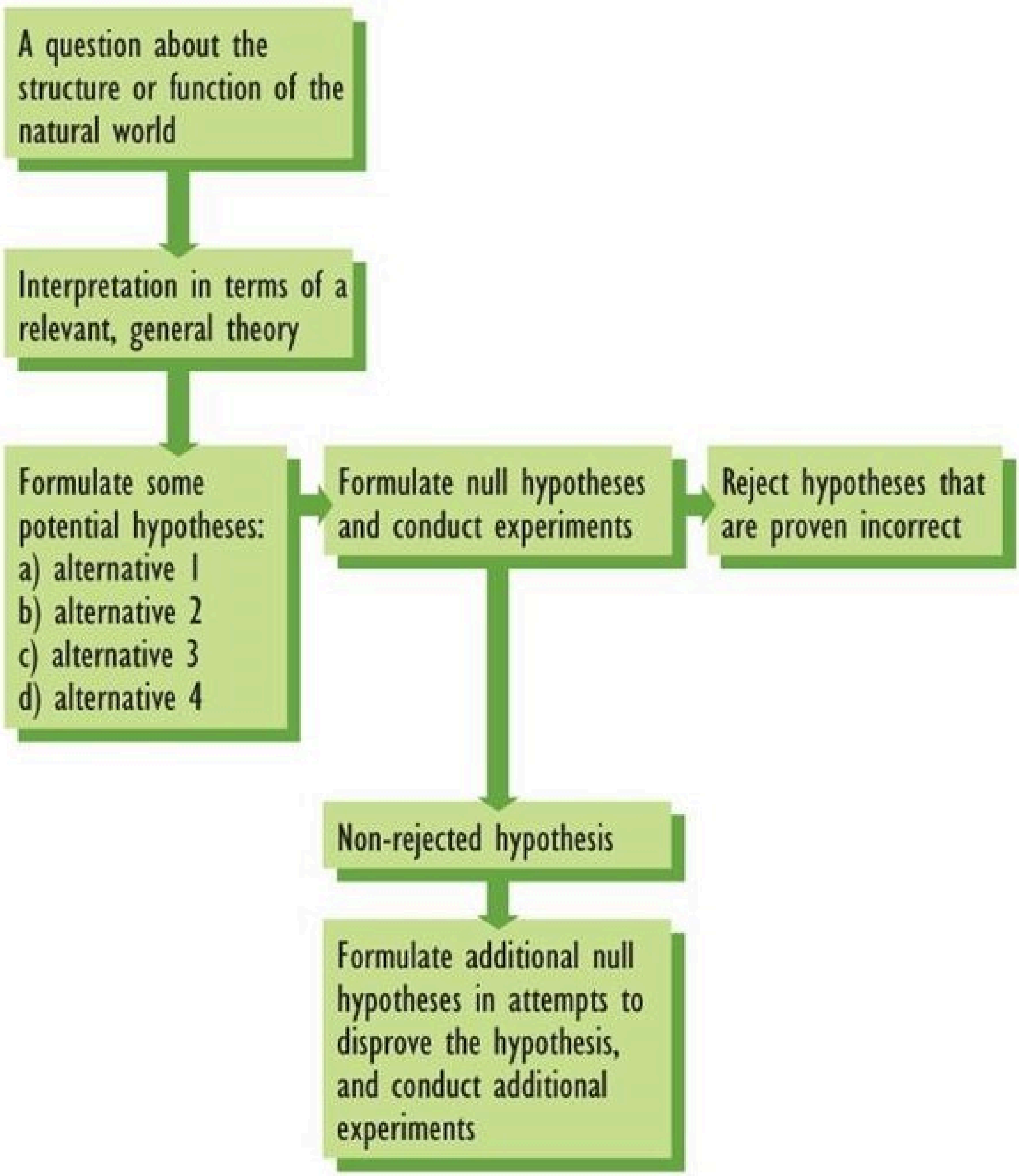
A theory is a broader conception that refers to a set of explanations, rules, and laws. These are supported by a large body of observational and experimental evidence, all leading to robust conclusions. The following are some of the most famous theories in science:

- the theory of gravitation, first proposed by Isaac Newton (1642-1727)
- the theory of evolution by natural selection, published simultaneously in 1858 by two English naturalists, Charles Darwin (1809-1882) and Alfred Russel Wallace (1823-1913)
- the theory of relativity, identified by the German–Swiss physicist, Albert Einstein (1879-1955)

Celebrated theories like these are strongly supported by large bodies of evidence, and they will likely persist for a long time. However, we cannot say that these (or any other) theories are known with certainty to be true –some future experiments may yet falsify even these famous theories.

The scientific method begins with the identification of a question involving the structure or function of the natural world, which is usually developed using inductive logic (Figure 2.1). The question is interpreted in terms of existing theory, and specific hypotheses are formulated to explain the character and causes of the natural phenomenon. The research might involve observations made in nature, or carefully controlled experiments, and the results usually give scientists reasons to reject hypotheses rather than to accept them. Most hypotheses are rejected because their predictions are not borne out during the course of research. Any viable hypotheses are further examined through additional research, again largely involving experiments designed to disprove their predictions. Once a large body of evidence accumulates in support of a hypothesis, it can be used to corroborate the original theory.

Figure 2.1. Diagrammatic Representation of the Scientific Method. The scientific method starts with a question, relates that question to a theory, formulates a hypothesis, and then rigorously tests that hypothesis. Source: Modified from Raven and Johnson (1992).



The scientific method is only to investigate questions that can be critically examined through observation and experiment. Consequently, science cannot resolve value-laden questions, such as the meaning of life, good versus evil, or the existence and qualities of God or any other supernatural being or force.

An experiment is a test or investigation that is designed to provide evidence in support of, or preferably against, a hypothesis. A natural experiment is conducted by observing actual variations of phenomena in nature, and then developing explanations by analysis of possible causal mechanisms. A manipulative experiment involves the deliberate alteration of factors that are hypothesized to influence phenomena. The manipulations are carefully planned and controlled in order to determine whether predicted responses will occur, thereby uncovering causal relationships.

By far the most useful working hypotheses in scientific research are designed to disprove rather than support. A null hypothesis is a specific testable investigation that denies something implied by the main hypothesis being studied. Unless null hypotheses are eliminated on the basis of contrary evidence, we cannot be confident of the main hypothesis.

This is an important aspect of scientific investigation. For instance, a particular hypothesis might be supported by many confirming experiments or observations. This does not, however, serve to "prove" the hypothesis – rather, it only supports its conditional acceptance. As soon as a clearly defined hypothesis is falsified by an appropriately designed and well-conducted experiment, it is disproved for all time. This is why experiments designed to disprove hypotheses are a key aspect of the scientific method.

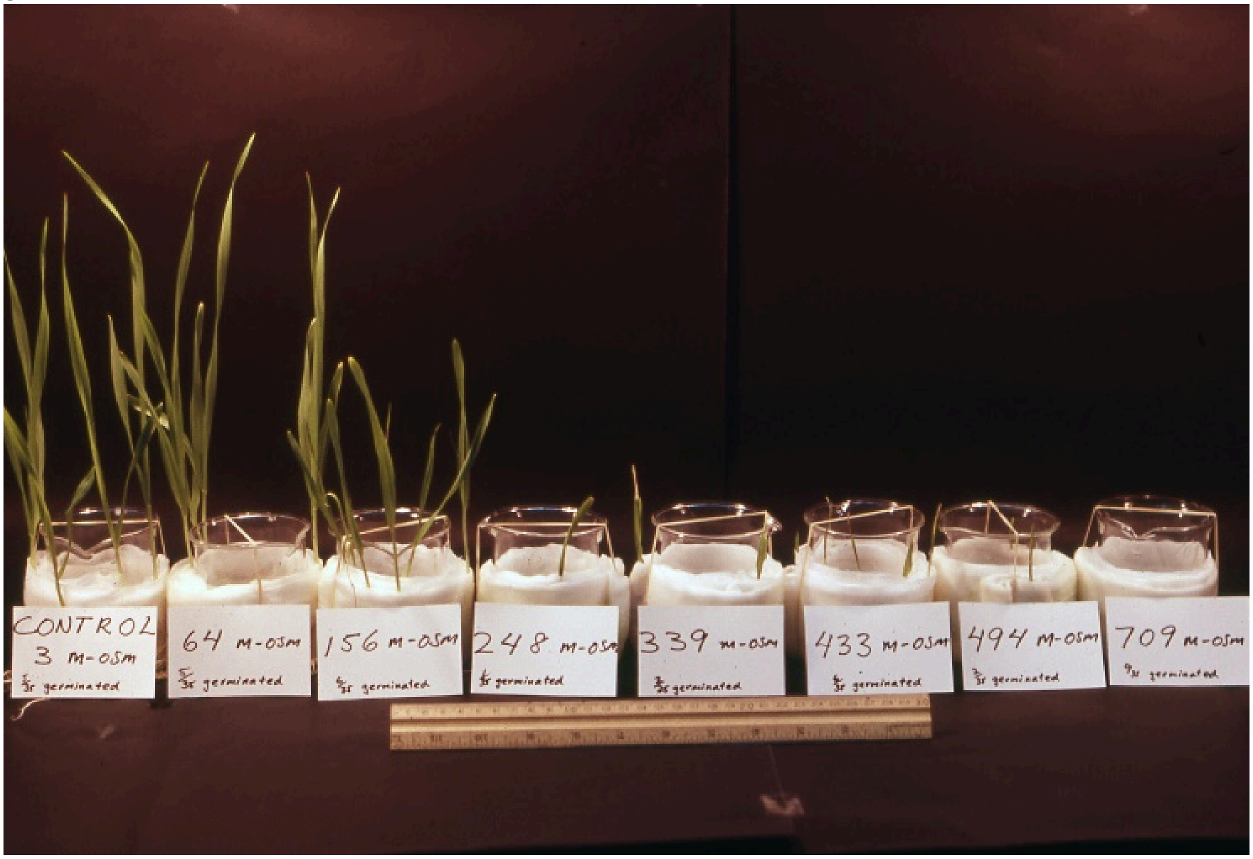
Revolutionary advances in understanding may occur when an important hypothesis or theory are rejected through discoveries of science. For instance, once it was discovered that the Earth is not flat, it became possible to confidently sail beyond the visible horizon without fear of falling off the edge of the world. Another example involved the discovery by Copernicus that the planets of our solar system revolve around the Sun, and the related concept that the Sun is an ordinary star among many – these revolutionary ideas replaced the previously dominant one that the planets, Sun, and stars all revolved around the Earth.

Thomas Kuhn (1922-1995) was a philosopher of science who emphasized the important role of "scientific revolutions" in achieving great advances in our understanding of the natural world. In essence, Kuhn (1996) said that a scientific revolution occurs when a well-established theory is rigorously tested and then collapses under the accumulating weight of new facts and observations that cannot be explained. This renders the original theory obsolete, to be replaced by a new, more informed paradigm (i.e., a set of assumptions, concepts, practices, and values that constitutes a way of viewing reality and is shared by an intellectual community).

A variable is a factor that is believed to influence a natural phenomenon. For example, a scientist might hypothesize that the productivity of a wheat crop is potentially limited by such variables as the availability of water, or of nutrients such as nitrogen and phosphorus. Some of the most powerful scientific experiments involve the manipulation of key (or controlling) variables and the comparison of results of those treatments with a control that was not manipulated. In the example just described, the specific variable that controls wheat productivity could be identified by conducting an experiment in which test populations are provided with varying amounts of water, nitrogen, and phosphorus, alone and in combination, and then comparing the results with a non-manipulated control.

In some respects, however, the explanation of the scientific method offered above is a bit uncritical. It perhaps suggests a too-orderly progression in terms of logical, objective experimentation and comparison of alternative hypotheses. These are, in fact, important components of the scientific method. Nevertheless, it is important to understand that the insights and personal biases of scientists are also significant in the conduct and progress of science. In most cases, scientists design research that they think will "work" to yield useful results and contribute to the orderly advancement of knowledge in their field. Karl Popper (1902-1994), a European philosopher, noted that scientists tend to use their "imaginative preconception" of the workings of the natural world to design experiments based on their informed insights. This means that effective scientists must be more than knowledgeable and technically skilled – they should also be capable of a degree of insightful creativity when forming their ideas, hypotheses, and research.

Image 2.1. An experiment is a controlled investigation designed to provide evidence for, or preferably against, a hypothesis about the working of the natural world. This laboratory experiment exposed test populations of a grass to different concentrations of a toxic chemical.



Uncertainty

Much scientific investigation involves the collection of observations by measuring phenomena in the natural world. Another important aspect of science involves making predictions about the future values of variables. Such projections require a degree of understanding of the relationships among variables and their influencing factors, and of recent patterns of change. However, many kinds of scientific information and predictions are subject to inaccuracy. This occurs because measured data are often approximations of the true values of phenomena, and predictions are rarely fulfilled exactly. The accuracy of observations and predictions is influenced by various factors, especially those described in the following sections.

Predictability

A few phenomena are considered to have a universal character and are consistent wherever and whenever they are accurately measured. One of the best examples of such a universal constant is the speed of light, which always has a value of 2.998×10^8 meters per second, regardless of where it is measured or of the speed of the body from which the light is emitted. Similarly, certain relationships describing transformations of energy and matter, known as the laws of thermodynamics (Chapter 4), always give reliable predictions.

However, most natural phenomena are not so consistent–depending on circumstances, there are exceptions to general predictions about them. This circumstance is particularly true of biology and ecology, related fields of science in which almost all general predictions have exceptions. In fact, laws or unifying principles of biology or ecology have not yet been discovered, in contrast to the several esteemed laws and 11 universal constants of physics. For this reason, biologists and ecologists have great difficulties making accurate predictions about the responses of organisms and ecosystems to environmental change. This is why biologists and ecologists are sometimes said to have "physics envy."

In large part, the inaccuracies of biology and ecology occur because key functions are controlled by complexes of poorly understood, and sometimes unidentified, environmental influences. Consequently, predictions about future values of biological and ecological variables or the causes of changes are seldom accurate. For example, even though ecologists in eastern Canada have been monitoring the population size of spruce budworm (an important pest of conifer forests) for some years, they cannot accurately predict its future abundance in particular stands of forest or in larger regions. This is because the abundance of this moth is influenced by a complex of environmental factors, including tree-species composition, age of the forest, abundance of its predators and parasites, quantities of its preferred foods, weather at critical times of year, and insecticide use to reduce its populations (see Chapter 21). Biologists and ecologists do not fully understand this complexity, and perhaps they never will.

Variability

Many natural phenomena are highly variable in space and time. This is true of physical and chemical variables as well as of biological and ecological ones. Within a forest, for example, the amount of sunlight reaching the ground varies greatly with time, depending on the hour of the day and the season of the year. It also varies spatially, depending on the density of foliage over any place where sunlight is being measured. Similarly, the density of a particular species of fish within a river typically varies in response to changes in habitat conditions and other influences. Most fish populations also vary over time, especially migratory species such as salmon. In environmental science, replicated (or independently repeated) measurements and statistical analyses are used to measure and account for these kinds of temporal and spatial variations.

Accuracy and Precision

Accuracy refers to the degree to which a measurement or observation reflects the actual, or true, value of the subject. For example, the insecticide DDT and the metal mercury are potentially toxic chemicals that occur in trace concentrations in all organisms, but their small residues are difficult to analyze chemically. Some of the analytical methods used to determine the concentrations of DDT and mercury are more accurate than others and therefore provide relatively useful and reliable data compared with less accurate methods. In fact, analytical data are usually approximations of the real values – rigorous accuracy is rarely attainable.

Precision is related to the degree of repeatability of a measurement or observation. For example, suppose that the actual number of caribou in a migrating herd is 10,246 animals. A wildlife ecologist might estimate that there were about 10,000 animals in that herd, which for practical purposes is a reasonably accurate reckoning of the actual number of caribou. If other ecologists also independently estimate the size of the herd at about 10,000 caribou, there is a good degree of precision among the values. If, however, some systematic bias existed in the methodology used to count the herd, giving consistent estimates of 15,000 animals (remember, the actual population is 10 246 caribou), these estimates would be considered precise, but not particularly accurate.

Precision is also related to the number of digits with which data are reported. If you were using a flexible tape to measure the lengths of 10 large, wriggly snakes, you would probably measure the reptiles only to the nearest centimetre. The strength and squirminess of the animals make more precise measurements impossible. The reported average length of the 10 snakes should reflect the original measurements and might be given as 204 cm and not a value such as 203.8759 cm. The latter number might be displayed as a digital average by a calculator or computer, but it is unrealistically precise.

Significant figures are related to accuracy and precision and can be defined as the number of digits used to report data from analyses or calculations (see also Appendix A). Significant figures are most easily understood by examples. The number 179 has three significant figures, as does the number 0.0849 and also 0.000794 (the zeros preceding the significant integers do not count). However, the number 195,000,000 has nine significant figures (the zeros following are meaningful), although the number 195×10^6 has only three significant figures.

It is rarely useful to report environmental or ecological data to more than 2-4 significant figures. This is because any more would generally exceed the accuracy and precision of the methodology used in the estimation and would therefore be unrealistic. For example, the approximate population of Canada in 2015 was 35.1 million people (or 35.1×10^6; both of these notations have three significant figures). However, the population should not be reported as 33,100,000, which implies an unrealistic accuracy and precision of eight significant figures.

A Need for Scepticism

Environmental science is filled with many examples of uncertainty—in present values and future changes of environmental variables, as well as in predictions of biological and ecological responses to those changes. To some degree the difficulties associated with scientific uncertainty can be mitigated by developing improved methods and technologies for analysis and by modelling and examining changes occurring in different parts of the world. The latter approach enhances our understanding by providing convergent evidence about the occurrence and causes of natural phenomena.

However, scientific information and understanding will always be subject to some degree of uncertainty. Therefore, predictions will always be inaccurate to some extent, and this uncertainty must be considered when trying to understand and deal with the causes and consequences of environmental changes. As such, all information and predictions in environmental science must be critically interpreted with uncertainty in mind (In Detail 2.1). This should be done whenever one is learning about an environmental issue, whether it involves listening to a speaker in a classroom, at a conference, or on video, or when reading an article in a newspaper, textbook, website, or scientific journal. Because of the uncertainty of many predictions in science, and particularly in the environmental realm, a certain amount of scepticism and critical analysis is always useful.

Environmental issues are acutely important to the welfare of people and other species. Science and its methods allow for a critical and objective identification of key issues, the investigation of their causes, and a degree of understanding of the consequences of environmental change. Scientific information influences decision making about environmental issues, including whether to pursue expensive strategies to avoid further, but often uncertain, damage.

Scientific information is, however, only one consideration for decision makers, who are also concerned with the economic, cultural, and political contexts of environmental problems (see Environmental Issues 1.1 and Chapter 27). In fact, when deciding how to deal with the causes and consequences of environmental changes, decision makers may give greater weight to non-scientific (social and economic) considerations than to scientific ones, especially when there is uncertainty about the latter. The most important decisions about environmental issues are made by politicians and senior bureaucrats in government, or by private managers, rather than by environmental scientists. Decision makers typically worry about the short-term implications of their decisions on their chances for re-election or continued employment, and on the economic activity of a company or society at large, as much as they do about the consequences of environmental damage (see also Chapter 27).

> In Detail 2.1. Critical Evaluation of an Overload of Information
> More so than any previous society, we live today in a world of easy and abundant information. It has become remarkably easy for people to communicate with others over vast distances, turning the world into a "global village" (a phrase coined by Marshall McLuhan (1911-1980), a Canadian philosopher, to describe the phenomenon of universal networking). This global connectedness has been facilitated by technologies for transferring ideas

and knowledge—particularly electronic communication devices, such as radio, television, computers, and their networks. Today, these technologies compress space and time to achieve a virtually instantaneous communication. In fact, so much information is now available that the situation is often referred to as an "information overload" that must be analyzed critically. Critical analysis is the process of sorting information and making scientific enquiries about data. Involved in all aspects of the scientific process, critical analysis scrutinizes information and research by posing sensible questions such as the following:

- Is the information derived from a scientific framework consisting of a hypothesis that has been developed and tested, within the context of an existing body of knowledge and theory in the field?
- Were the methodologies used likely to provide data that are objective, accurate, and precise? Were the data analyzed by statistical methods that are appropriate to the data structure and to the questions being asked?
- Were the results of the research compared with other pertinent work that has been previously published? Were key similarities and differences discussed and a conclusion deduced about what the new work reveals about the issue being investigated?
- Is the information based on research published in a refereed journal—one that requires highly qualified reviewers in the subject area to scrutinize the work, followed by an editorial decision about whether it warrants publication?
- If the analysis of an issue was based on incomplete or possibly inaccurate information, was a precautionary approach used in order to accommodate the uncertainty inherent in the recommendations? All users of published research have an obligation to critically evaluate what they are reading in these ways in order to decide whether the theory is appropriate, the methodologies reliable, and the conclusions sufficiently robust. Because so many environmental issues are controversial, with data and information presented on both sides of the debate, people need to be able to formulate objectively critical judgments. For this reason, people need a high degree of environmental literacy—an informed understanding of the causes and consequences of environmental damages. Being able to critically analyze information is a key personal benefit of studying environmental science.

Conclusions

The procedures and methods of science are important in the identifying, understanding, and resolving environmental problems. At the same time, however, social and economic issues are also vital considerations. Although science has made tremendous progress in helping us to understand the natural world, the extreme complexity of biology and ecosystems makes it difficult for environmental scientists to make reliable predictions about the consequences of many human economic activities and other influences. This context underscores the need for continued study of the scientific and socio-economic dimensions of environmental problems, even while practical decisions must be made to deal with obvious issues as they arise.

Questions for Review

1. Outline the reasons why science is a rational way of understanding the natural world.
2. What are the differences between inductive and deductive logic? Why is inductive logic more often used by scientists when formulating hypotheses and generalizations about the natural world?
3. Why are null hypotheses an efficient way to conduct scientific research? Identify a hypothesis that is suitable for examining a specific problem in environmental science and suggest a corresponding null hypothesis that could be examined through research.
4. What are the causes of variation in natural phenomena? Choose an example, such as differences in the body

weights of a defined group of people, and suggest reasons for the variation.

Questions for Discussion

1. What are the key differences between science and a less objective belief system, such as religion?
2. What factors result in scientific controversies about environmental issues? Contrast these with environmental controversies that exist because of differing values and world views.
3. Explain why there are no scientific "laws" to explain the structure and function of ecosystems.
4. Many natural phenomena are highly variable, particularly ones that are biological or ecological. What are the implications of this variability for understanding and predicting the causes and consequences of environmental changes? How do environmental scientists cope with this challenge of a variable natural world?

Exploring Issues

1. Devise an environmental question of interest to yourself. Suggest useful hypotheses to investigate, identify the null hypotheses, and outline experiments that you might conduct to provide answers to this question.
2. During a research project investigating mercury, an environmental scientist performed a series of chemical analyses of fish caught in Lake Canuck. The sampling program involved seven species of fish obtained from various habitats within the lake. A total of 360 fish of various sizes and sexes were analyzed. It was discovered that 30% of the fish had residue levels greater than 0.5 ppm of mercury, the upper level of contamination recommended by Health Canada for fish eaten by humans. The scientist reported these results to a governmental regulator, who was alarmed by the high mercury residues because of Lake Canuck's popularity as a place where people fish for food. The regulator asked the scientist to recommend whether it was safe to eat any fish from the lake or whether to avoid only certain sizes, sexes, species, or habitats. What sorts of data analyses should the scientist perform to develop useful recommendations? What other scientific and non-scientific aspects should be considered?

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Chapter 3 ~ The Physical World

Key Concepts

After completing this chapter, you will be able to

1. Explain the geological structure and dynamics of planet Earth.
2. Describe the importance of glaciation and other geological forces in modifying the landscapes of Canada.
3. Outline the four major elements of Earth's water cycle.
4. Describe the atmosphere and its circulation.
5. Explain the elements of climate and weather.

Introduction

In this chapter we examine various aspects of the physical world, including the origin of planet Earth and the nature and dynamics of its physical attributes. Understanding these subjects is important in environmental science because they provide a context for interpreting many of the changes that are being caused by human activities.

Planet Earth

The universe is thought to have originated as many as 12-15 billion years ago during a ginormous cataclysm known as the "big bang." Initially, virtually all of the mass of the nascent universe consisted of the two lightest elements, hydrogen and helium, which existed as an extremely diffuse gaseous mass. Eventually, under the pervasive influence of gravity, the hydrogen and helium were aggregated into immense masses that became increasingly compressed under enormously high pressure and temperature. When the pressure and temperature were sufficiently intense, nuclear fusion reactions began to occur within the masses, at which point they had become young stars. In addition to releasing immense quantities of energy, the fusion reactions caused the formation of heavier elements. Because of these processes, there are now 88 naturally occurring elements. Hydrogen and helium are still, however, the most abundant elements, comprising more than 99.9% of the mass of the universe.

The Sun is an ordinary star, one of billions of billions that exist in the universe. The Sun, its eight orbiting planets, plus miscellaneous comets, meteors, asteroids, and other materials (such as space dust) are collectively known as the solar system. This particular region of the universe is organized and held together by a balance of the attractive force of gravitation and counteracting influences associated with rotation and orbiting (these same forces, along with continuing expansion from the initial big bang, also organize the universe). The age of the solar system (and of Earth) is at least 4.6 billion years.

Earth is the third-closest planet to the Sun. Earth is a dense planet, as are other so-called terrestrial planets located relatively close to the Sun: Mercury, Venus, and Mars. The mass of these planets consists almost entirely of heavier elements such as iron, nickel, magnesium, aluminum, and silicon. These inner planets were formed by a selective condensing of heavier elements out of the primordial planetary nebula (the disk of gases and other matter that slowly rotated around the Sun during the early stages of formation of its solar system). This happened because the inner planets were subjected to relatively intense heating by solar radiation, which caused lighter gases such as hydrogen and helium to disperse further away, to the extent that they ended up mostly in the outer, cooler planets. Meanwhile the terrestrial planets retained heavier elements. Consequently, the more distant planets in the solar system, such as Jupiter and Saturn, are relatively large, gaseous, and diffuse in character. Most of their volume is composed of an extensive atmosphere of hydrogen and helium, although these planets may contain heavier elements in their core.

Earth is the only place in the universe that is definitely known to sustain life. It is quite possible, however, that other planets in the cosmos also sustain life. Although there is no direct evidence of this, many scientists consider it likely that life has evolved elsewhere. One estimate suggests that the universe contains 10^{22} (10,000 billion billion) stars, with perhaps 10% of them having planetary systems (10^{21}systems). With such incredibly large numbers, it is highly probable that at least some of the billions of billions of other planetary systems support suitable conditions for a genesis of life, in addition to what occurred on Earth.

Earth is a spherical body with a diameter of about 12,740 km. It revolves around the Sun in an elliptical orbit, at an average distance of about 149 million km, completing an orbit in 365.26 days, or one year. Earth also rotates on its axis every 24 hours, or one day. Its single moon has a diameter of about 3,474 km and a mass about 2% that of Earth. The Moon revolves around Earth in an elliptical orbit at an average distance of about 385,000 km, completed every 27.3 days (the lunar month).

The sphere of Earth is composed of four layers—the core, mantle, lithosphere, and crust—arranged in concentric layers like an onion. The massive core has a diameter of about 3,500 km and is composed of hot, molten metals, particularly iron and nickel. The internal heat of Earth is thought to be generated by the slow, radioactive decay of unstable isotopes of certain elements, such as uranium.

The mantle is a less dense region that encloses the core. It is about 2,800 km thick and composed of minerals in a plastic, semi-liquid state known as magma. The mantle contains relatively light elements, notably silicon, oxygen, and magnesium, occurring as various mineral compounds. Magma from the upper mantle sometimes erupts to the surface at mountainous vents known as volcanoes and is usually spewed to the surface as lava, which cools to form basaltic rock.

The next layer, the lithosphere, is only about 80 km thick and is made of rigid, relatively light rocks, especially basaltic, granitic, and sedimentary ones. These rocks contain elements found in the mantle as well as enriched quantities of aluminum, carbon, calcium, potassium, sodium, sulphur, and other lighter elements.

The outermost layer is known as the crust. Oceanic crust is relatively thin, averaging 10–15 km, while continental crust is 20–60 km thick. Earth's crust has an extremely complex mineralogical composition, in contrast to the mantle and especially the core, which are thought to be relatively uniform in structure and constitution. The most abundant elements in the crust are oxygen (45%), silicon (27%), aluminum (8.0%), iron (5.8%), calcium (5.1%), magnesium (2.8%), sodium (2.3%), potassium (1.7%), titanium (0.86%), vanadium (0.17%), hydrogen (0.14%), phosphorus (0.10%), and carbon (0.032%).

The rocks forming the crust can be grouped into three basic types: igneous, sedimentary, and metamorphic. Igneous rocks include basalt and granite, which are formed by the cooling of molten magma. The mineral forms depend on the rate of cooling plus other factors. Basalt is a heavy, dark, extremely fine-grained rock that sometimes forms vertical, columnar structures. Basaltic rocks are the major constituent of oceanic crust, originating in submarine places where magmic lava erupts to the sea-floor surface, such as deep-ocean spreading zones and abyssal volcanoes. Basalt can also be formed at terrestrial volcanoes – for instance, it is the basement rock of the Hawaiian archipelago and other volcanic islands. Granitic rocks dominate the continental crust, are typically relatively light in colour and density, and are coarser-grained, with readily distinguishable crystals. The complex crystalline structure includes the minerals quartz and feldspar, and mica and hornblende are often present.

Sedimentary rocks include limestone, dolomite, shale, sandstone, and conglomerates. These form from particles eroded from other rocks or from precipitated minerals such as calcite ($CaCO_3$) that become lithified (turned into stone) under great pressure in deep oceanic deposits. Sedimentary rocks typically overlie basaltic or granitic rocks.

Metamorphic rocks are formed from igneous or sedimentary ones that were changed under the combined influences of massive geological heat and pressure. These conditions were encountered when the primary rocks were carried deep into the lithosphere by crustal movements, such as those associated with mountain building (described below). Gneiss, for example, is a metamorphic rock derived from granite, while marble is derived from limestone, and slate from shale. About 30% of Earth's surface is covered by the solid substrates of continents and islands. The other 70% of Earth's surface is liquid water, almost all of which is oceanic. In addition, Earth's dense sphere is immersed in a gaseous envelope known as the atmosphere, which extends to a distance of about 1,000 km. However, about 99% of the mass of the atmosphere occurs within 30 km of the planet's surface.

Geological Dynamics

Throughout its history, Earth has been subject to enormous geological forces that have greatly affected its mineralogical composition and surface features. The predominant influences are tectonic forces, which are associated with crustal movements and other processes that cause structural deformation of rocks and minerals. Geological forces also cause the continents and their underlying plates to slowly move about Earth's surface, much like rafts of solid rock riding upon a sea of plastic magma. Mountain ranges are built where crustal plates collide and push up surface rocks.

Earthquakes and volcanoes are also tectonic phenomena, which influence Earth's crust and surface with extremely powerful, sometimes disastrous events. Other massive geological forces include rare, cataclysmic strikes into our planet by meteorites and extensive glaciation associated with cooling of the climate. Slower but still pervasive geological forces are erosion (caused by water, wind, and gravity) and weathering (the fracturing of rocks and dissolution of minerals).

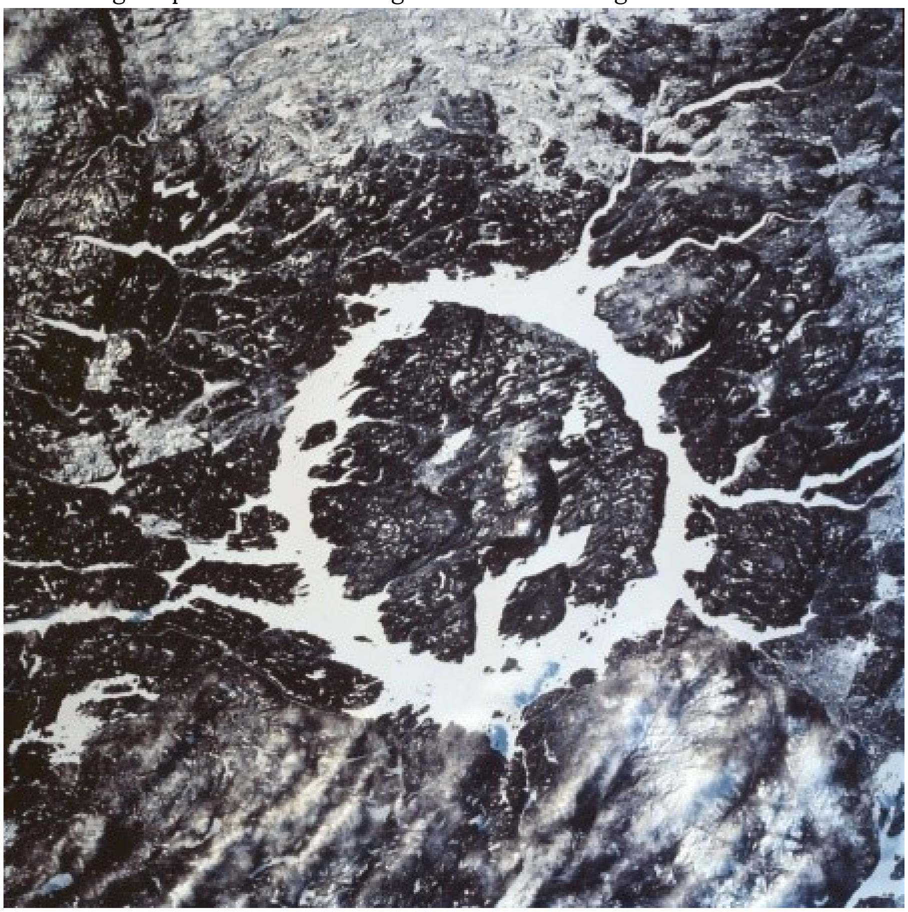
Over geological time, these various physical processes have profoundly influenced the character of Earth. Geological forces continue to have enormous influences on Earth and its ecosystems, over both short- and long-term time scales. Environmental changes associated with these geological dynamics provide a natural context for the substantial changes that humans are now causing through their economic activities.

Meteorites

Earth is frequently struck by fast-moving rocky or metallic objects from space known as meteorites. Although meteorites are relatively small objects (by planetary standards), they have immense momentum because of their speed, which typically ranges from 10-100 km/s. The smallest, most numerous meteorites reaching Earth typically burn up or explode in the atmosphere because of heat generated by friction, but larger ones may survive to impact the surface. It has been estimated that each day a meteorite weighing at least 100 g strikes the surface somewhere in Canada.

Very large meteorites are extremely rare, but if the impact the surface enormous damage is caused. The impact site is typically obliterated and a large crater is formed because vast amounts of crustal materials are ejected into the atmosphere. Immense sea waves can also be caused by a meteorite impact. Several dozen large meteorite craters are known in Canada. The largest is an ovoid depression with a diameter of 140 km near Sudbury, Ontario, caused by a meteorite strike occurring about 1,850 million years ago (Mya), and a doughnut-shaped lake with a diameter of 70 km at Manicouagan, Quebec, from an impact about 215 Mya ago. These extraordinary events must have caused tremendous damage to the species and ecosystems of the time.

Image 3.1. View of Lake Manicouagan, Quebec. This doughnut-shaped lake is an impact crater from a meteorite impact that occurred about 215 million years ago. This image was taken from the space shuttle Endeavour on May 25, 2011. Source: NASA photo 714196. http://www.dvidshub.net/image/714196/earth-observations-lake-manicouagan-quebec-taken-during-sts-99#.VBCO4VIg99A



Earth's evolutionary history has been punctuated by a number of catastrophic events of mass extinction, during which most of the existing biota disappeared in a short period of time, to be later replaced by new species (see Chapter 6). Paleontologists recognize these cataclysms by the occurrence of rapid changes in the fossil record, which point to a transition between stages in the geological time scale (Table 3.1). According to surviving evidence, the most intense mass extinction event occurred 245 million years ago at the end of the Permian period, when an astonishing 96% of species may have become extinct. Another mass extinction occurred 65 million years ago at the end of the Cretaceous period, when perhaps 76% of species became extinct, including the last of the dinosaurs. According to one theory, the end-of-Cretaceous extinctions were caused when a 10–15 km wide meteorite impacted the Earth. This resulted in that huge amounts of fine dust being spewed into the upper atmosphere, which caused a severe cooling of the climate that large animals and many ecosystems could not tolerate. Some geologists believe that the impact site was near the Yucatan coast of Mexico, where a buried, 170-km-wide ring structure exists, dated to about 65 million years old. Although controversial, the theory of rare, meteorite-caused catastrophes has also been used to explain other mass extinctions in the geological record.

Table 3.1. The Geological Time Scale. The divisions between geological time stages are assigned on the basis of

rapid changes in mineralogy and in species composition of the fossil record. These are related to events of mass extinction, which were followed by the evolutionary radiation of new species and families. The record is most detailed for relatively recent times, because the fossil remains are more complete. Time is given in Mya (millions of years ago) and indicates the beginning of each time stage. For example, the Holocene epoch ranges from 0.01 Mya (10,000 years ago) to the present; the Pleistocene ranges from 1.6 million years ago to 0.01 Mya.

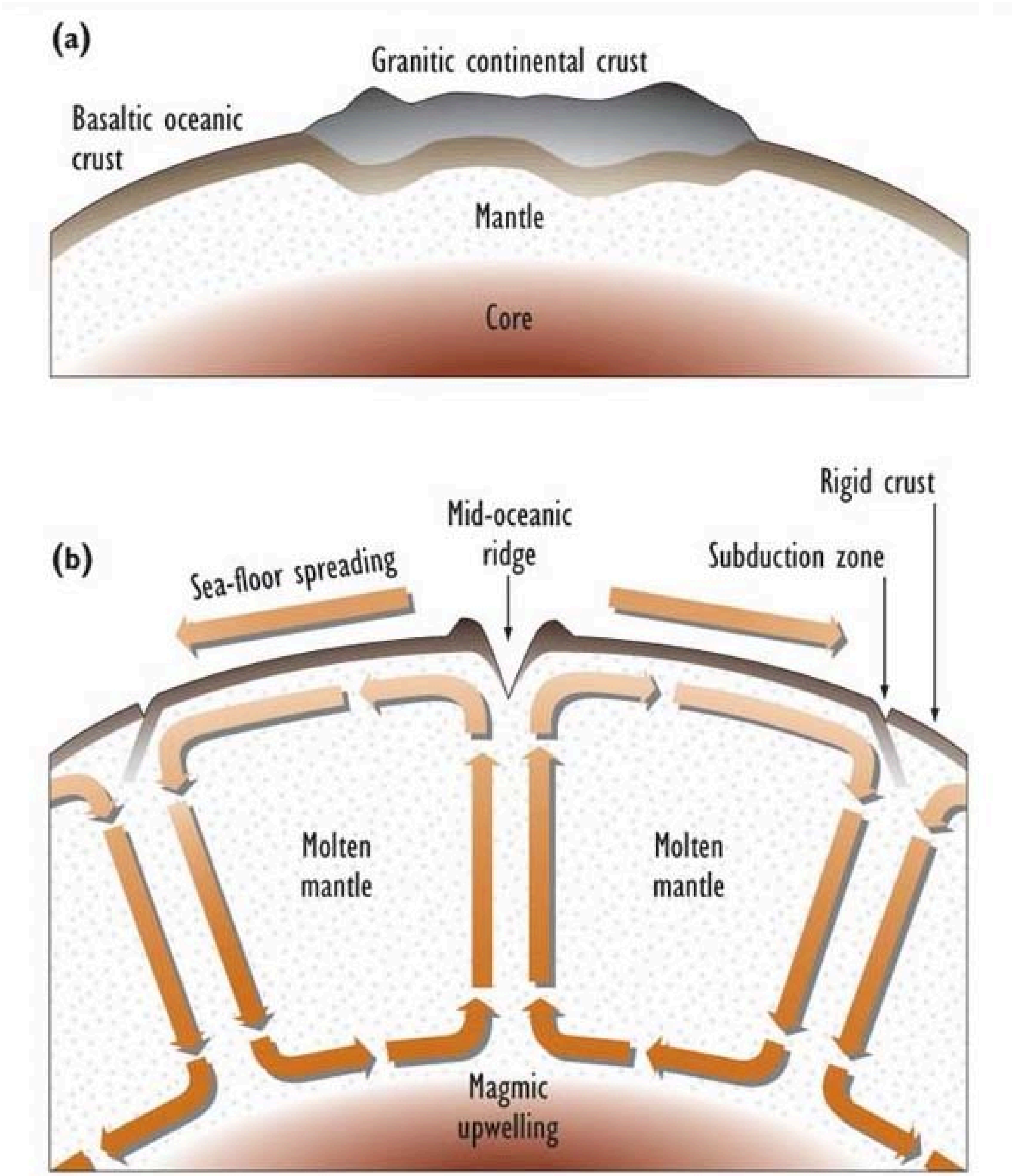
Era	**Period**	**Epoch**	**Time (Mya)**
Cenozoic	Quaternary	Holocene	0.01
		Pleistocene	1.6
	Tertiary	Pliocene	5
		Miocene	26
		Oligocene	38
		Eocene	54
		Paleocene	65
Mesozoic	Cretaceous		140
	Jurassic		210
	Triassic		245
Paleozoic	Permian		290
	Carboniferous		365
	Devonian		413
	Silurian		441
	Ordovician		504
	Cambrian		570
Precambrian	Proterozoic		2,400
	Archaean		>4,500

Plate Tectonics

The theory of plate tectonics concerns the dynamics of surface crustal materials. In simple terms, this theory suggests that the crust and mantle behave as an enormous convecting system that, at the surface, is characterized by extremely slow movements of huge plates of rigid crustal material. The plates move from zones where they are created by an upwelling of magma from the upper mantle, toward other zones where they are destroyed by downward movement into the upper the mantle. In the creation zones, the plastic magma rises to the surface, solidifies, and then extends laterally in a process known as sea-floor spreading. In the down-welling zones, there is a subduction of sea-floor crust back down into the mantle, where it is re-melted and convected laterally. The magma may eventually reach another upwelling region and again be carried to the crust. The slowly moving, rigid plates of surface crust have a basement of basaltic rock, with lighter, granitic-based continents rafting on the surface of some of the oceanic plates (Figure 3.1).

Figure 3.1. Tectonic Forces. (a) The continents are viewed as granitic islands that are rafting upon underlying plates of basaltic oceanic crust. (b) Heat and density gradients in the mantle cause a slow, convective circulation to develop in the molten magma. This circulation forms new basaltic crust at zones of magmic upwelling known as mid-oceanic ridges, followed by lateral sea-floor spreading and eventual subduction back to the mantle at

the boundary with another crustal plate.



For example, in the Atlantic Ocean, about halfway between the Americas and Europe and Africa, a deep-sea geological structure called the Mid-Atlantic Ridge runs in a roughly north to south direction. This abyssal ridge is a zone of sea-floor spreading, from which the two continental regions are diverging at a slow but steady rate of 2-4 cm/year. In essence, the Atlantic ocean is widening at this rate, which is equivalent to 2-4 meters per century.

In contrast, parts of the continental landmass in the western Americas are riding on regions of plates that are subducting beneath the oceanic Pacific Plate. However, along most of southwestern North America, the Pacific and North American Plates are moving in opposite but parallel directions. This is causing southern California and the Baja

Peninsula to slowly move northward relative to the rest of the continent. This process is occurring along an extended but narrow zone of contact between the plates (a fault) known as the San Andreas Fault.

These tectonic forces result in frequent earthquakes and volcanic eruptions along the Pacific coasts of North and South America, the Aleutians, and eastern Asia. This geologically active region around the Pacific Ocean is referred to as the "ring of fire" because of its many volcanoes. In addition to these discrete but intense geological events, there is active building of the relatively young mountains in this region. The mountain building is caused by crustal materials being pushed upward in regions where continents and oceanic plates are colliding with each other. In a similar manner, the lofty Himalayas of southwestern Asia were and still are being created by immense uplifting forces that are generated as the northward-drifting Indian subcontinent pushes into the larger Asian landmass.

It is thought that the continents were a single contiguous mass during the Permian period, about 290 million years ago. This primeval super-continent, referred to as Pangaea, was surrounded by a single, global ocean. However, divergent forces of crustal plates moving in different directions then pulled Pangaea apart, initially into two masses known as Laurasia and Gondwanaland, and then into the existing continents of North and South America, Africa, Eurasia, Australia, and Antarctica.

An earthquake is a trembling or movement of the Earth caused by a sudden release of geological stresses at some point within the crust or upper mantle. Earthquakes are most often caused when crustal plates slip across or beneath each other at their faults, but they can also be caused by a volcanic explosion. Although their seismic energy can affect a large area, earthquakes have a spatial focus, known as the epicentre and defined as the surface position lying above the deep point of energy release. An intense earthquake can cause great damage to buildings, and the collapsing structures, fires, and other destruction can take a great toll on people. In 1556 an earthquake struck Shanxi Province in China and caused about 830,000 deaths, making it the most deadly earthquake in recorded history. The most famous catastrophic earthquake in North America was the San Francisco event in 1906, caused by slippage along the San Andreas Fault, which killed 503 people and resulted in tremendous physical damage. However, other earthquakes during the twentieth century resulted in much greater losses of human lives, including one in 1976 that killed 242,000 people in Tangshan, China; another in 1927 that killed 200,000 in Nan-Shan, China; and one in Tokyo–Yokohama, Japan, that killed 200,000 in 1926. Notable recent earthquakes include one in Kobe, Japan (1995) that killed 5,500 people, another in Kashmir (2005) that killed 79,000 people, one in Sichuan, China (2008) that killed 70,000 people, and one in the Tohuku region of Japan (2011) that generated a tsunami (seismic sea wave) that killed 16,000 people.

The events in San Francisco (1906) and Tokyo (1926) affected large cities. The powerful tremors caused great damage, partly because of weak architectural designs that were unable to withstand the strong forces. In both cases, however, about 90% of the actual destruction resulted from fires. Earthquakes can also cause soil to lose some of its mechanical stability, resulting in destructive landslides and subsidence (sinking) of land and buildings.

Undersea earthquakes can trigger a fast-moving, sea-surface phenomenon known as a tsunami or seismic sea wave. A tsunami is barely noticeable at sea, but it can become gigantic when the wave reaches shallow water and piles up to heights that can swamp coastal villages and towns. In 1929, an earthquake off eastern Canada generated a seismic sea wave that killed 29 people in Newfoundland and Cape Breton. In 1946, a large earthquake centred on Umiak Island in the Aleutian Islands caused a tsunami to strike Hawaii, 4,500 km away, with an 18 m crest. In 2004, a tsunami in the Indian Ocean killed more than 225,000 people (see Global Focus 3.1).

> Global Focus 3.1. A Killer Tsunami
> A tsunami, or seismic sea wave, is a great surge of the ocean's surface caused by an underwater earthquake. A tsunami may be almost indiscernible in deep water of the open ocean, but it can become enormous when it reaches shallow coastal water and builds to a height capable of causing massive destruction. The greatest tsunami of recent times was triggered by an undersea, so-called "megathrust" earthquake on December 26, 2004. Its epicentre was located about 40 km off the coast of Aceh in northern Sumatra, an Indonesian island,

and it registered a massive 9.2 on the Richter scale (making it the largest earthquake in 40 years). The tremor generated an immense tsunami (actually, a close series of individual waves) that gathered to a height up to 30 m when it impacted shallow-sloping coasts of countries fringing the Indian Ocean. Unfortunately, none of the countries that bore the brunt of the devastation were forewarned of the impending catastrophe, so no action was taken to move people from low-lying coastal areas to higher ground. This happened mostly because there was no tsunami-detection system in the Indian Ocean, although negligence was also involved because the extremely large earthquake should have alerted civil authorities to a potential catastrophe.

The colossal tsunami waves were moving at speeds of about 60 km/hr when they impacted the shore. They caused widespread devastation and more than 225,000 deaths by drowning and injuries caused by floating debris and collapsing buildings. The hardest-hit places were Sumatra (which suffered at least 168,000 dead and missing), Sri Lanka (35,000), the eastern coast and islands of India (18,000), and Thailand (8,000). At least 7,000 of the deaths were tourists from developed countries who were visiting coastal resorts during their holiday break. In addition to the mortality, tens of millions of people were displaced from their homes and livelihoods by the flooding. In many of the worst-hit places, the damage was made much more severe because of increased coastal vulnerability caused by the removal of previously abundant mangrove forest, mostly to develop tourist resorts and brackish ponds for shrimp aquaculture. Where mangroves remained intact, the coastal forest provided a sea-wall that helped to absorb much of the force of the tsunami, providing a measure of protection to areas further inland.

Responding to the overwhelming toll of death and destruction, citizens and governments of many non-affected countries delivered large donations of aid for rescue and subsequent recovery, including money (pledges totalled about US$5.4 billion), specialized rescue personnel, food and water, and materials for reconstruction. From the environmental perspective, important lessons to be learned from this devastating tsunami include the facts that natural disasters are unpredictable and inevitable, and that the ensuing destruction can be made much worse by inappropriate land-use practices and a lack of emergency planning and response capability.

Image 3.2. A devastated village on the coast of Aceh, Sumatra, after the killer tsunami of December 26, 2004. Source: image by P.A. McDaniel, United States Navy, ID 050102-N-9593M-040; https://commons.wikimedia.org/wiki/File%3AUS_Navy_050102-N-9593M-040_A_village_near_the_coast_of_Sumatra_lays_in_ruin_after_the_

Tsunami_that_struck_South_East_Asia.jpg

A volcano is a vent in the surface from which molten lava flows onto the ground and liquid, solid, and gaseous materials are ejected into the atmosphere. The largest eruptions can literally explode a volcanic mountain, ejecting immense quantities of material into the environment and causing enormous damage and loss of life. For example, an eruption of Mount Vesuvius in the year 79 CE (Common Era) buried the Roman city of Pompeii, killing almost all of its inhabitants. A 1902 explosion of Mont Pelée on the Caribbean island of Martinique killed 30,000 people.

The greatest eruption of modern times was that of Tambora, a volcano in Indonesia that exploded in 1815 and blew more than 300 km^3 of material into the atmosphere (including the top 1,300 m of the mountain). Some of the finer particulates of this massive eruption were blown into the upper atmosphere (the stratosphere), causing an increase in Earth's reflectivity that resulted in global cooling. The year 1816 became known as the "year without a summer" in Europe and North America because of its unusually cool and wet weather, including frost and snowfall during the summer months.

Another famous Indonesian eruption was that of Krakatau in the Sunda Strait in 1883, which ejected 18-21 km^3 of material as high as 50-80 km into the atmosphere. The 30-m tsunami associated with this eruption killed about 36,000 people in coastal villages.

Large volcanic eruptions can also disturb great expanses of forest and other ecosystems. For instance, the 1980 explosion of Mount St. Helen's in the state of Washington blew down about 21,000 hectares of coniferous forest and otherwise damaged another 40,000 ha. Mudslides also devastated large areas, and a vast region was covered by particulate debris (known as tephra) that settled from the atmosphere.

Some volcanoes produce chronic lava flows and venting of gases. These volcanoes tend to form distinctive, cone-shaped mountains from their accumulated lava, which solidifies into finely crystalline, glassy rocks. An active example of this spectacular process is Mount Kilauea in Hawaii, which sometimes erupts continuously for years. The slowly flowing lava from these volcanoes can destroy buildings and vegetation but is not otherwise dangerous because people and animals can avoid the molten streams.

Glaciation

Glaciers, or persistent sheets of ice, are common features in high-latitude environments of the Arctic and Antarctic. They also occur at high altitude on mountains, even in tropical countries such as New Guinea and Peru. Glaciers are formed from a deep, persistent snowpack, which becomes compressed into ice as its weight accumulates. Most glaciers occur on land, but some also extend onto the ocean. At the present time, about 10% of the land surface of Earth is covered with glaciers, the largest of which are the continental ice sheets of Antarctica. The largest glaciers in the Northern Hemisphere are in Greenland, but parts of Baffin and Ellesmere Islands in the Canadian Arctic are also covered with glacial ice, as are some mountainous areas in western Canada.

Glaciation refers to an extensive advance of ice sheets, caused by a period of extended global cooling sometimes referred to as an ice age. There have been a number of glacial periods during geological history, although details are known only about the most recent glaciation because it obliterated most traces of earlier events. The most recent glacial period, known as the Wisconsin, began about 85,000 years ago and ended about 11,000 years ago.

At the height of the Wisconsin glaciation, ice covered about 30% of Earth's land surface, including almost all of what is now Canada, as well as extensive areas of the continental shelf that are now beneath the ocean. The latter occurred because sea level was about 120 m lower during that glaciation as a result of so much water being tied up in ice on land. The greatest ice mass in Canada was the Laurentide Ice Sheet, which reached a thickness of about 4 km. The Cordilleran Ice Sheet of the western mountains contained ice up to 2 km thick.

The present Holocene (recent; Table 3.1) epoch is relatively warm and ice-free and is referred to as an interglacial stage. Climate has not, however, been uniformly warm during the present interglacial. For example, the period of about 1450 to 1850 is known as the Little Ice Age because of its relatively cool climate. During that period there was a moderate expansion of glaciers and snowfields in many parts of the world, including the Arctic regions and western mountains of Canada.

Glaciers are extremely erosive forces that crush, scour, and excavate the underlying terrain with their massive weight and ponderous movements. Glaciers also transport huge quantities of excavated debris around the landscape. These solid materials are eventually deposited when the glaciers melt, tumbling from the ablating (melting) ice mass or being carried away by meltwater running in streams and rivers. Extensive deposits of glacial debris are common over almost all of Canada, often occurring as distinctive landforms, such as the following:

- moraines, which are a series of long, mounded hills, usually lying perpendicular to the flow of the regional glacier, and containing mixed rocky debris known as till
- drumlins, or teardrop-shaped hills that are elongated in the direction of movement of the glacier and are composed of a mixture of rocky materials
- eskers, which are long, serpentine mounds of crudely sorted debris that was deposited by a river flowing beneath a glacier
- erratics, or rounded boulders of various sizes that are incongruously scattered over the landscape
- long U-shaped valleys in mountainous terrain, which were carved from pre-existing river valleys by the erosive forces of a glacier
- fiords, which are long, narrow, steep-sided inlets of the ocean that were carved by outlet glaciers descending from a much larger ice sheet at higher altitude
- outwash plains, which contain a mixture of materials, ranging in size from rocks to sand or clay, that were

deposited over a relatively wide area by streams and rivers fed by glacial meltwaters

- the former basins of large lakes of glacial meltwater, which today are characterized by flat, fine-grained, often fertile plains (Southern Manitoba has extensive former lakebeds of postglacial Lake Agassiz, while flat areas in southern Ontario and Quebec were once part of the postglacial basins of what are now the Great Lakes and St. Lawrence River.)

The tremendous ice sheets that once obliterated almost all of Canada were largely gone by 8,000 to 10,000 years ago, although glacial remnants still occur on islands in the Arctic and on mountains of western Canada. The Canadian landscape has been profoundly shaped by the impressive geological signatures of the advance and retreat of the immense continental glaciers of times past. Since then, the terrain and landforms have been greatly modified by other geological forces, such as erosion and weathering, and by the redevelopment of ecosystems after the retreat of the immense ice sheets. However, compared with the effects of the Wisconsin and previous glaciers, those forces have had a relatively small influence on the enduring character of the landscapes and coastal seascapes of Canada.

Image 3.3. During the most recent, Wisconsin glaciation, almost all of Canada was covered by glaciers. Remnant glaciers still occur, such as this ice cap on Ellesmere Island. Source: B. Freedman.

Weathering and Erosion

Meteorite impacts, earthquakes, volcanic explosions, and glaciation are all tremendous geological forces – they are capable of obliterating both natural and anthropogenic ecosystems. However, less forceful geological dynamics are also important, although they exert their influences more pervasively, by operating relatively slowly over longer time scales rather than as extremely destructive events.

Weathering refers to physical and chemical processes by which rocks and minerals are broken down by environmental agents. Non-biological (abiotic) forces of weathering include rain, wind, and temperature changes (especially freeze-thaw cycles). Biological forces include the rock-cracking powers that are exerted by plant roots. Weathering proceeds by the fracturing of rocks and by the solubilization (chemical decomposition) of minerals by acidic rainwater and by corrosive excretions of plant roots and microorganisms.

Erosion refers to the removal of rocks and soil through the actions of gravity, flowing water, ice, and wind. Erosion is a pervasive geological process, occurring at various rates in all environments. Usually it is gradual, occurring as particles are slowly removed by flowing water or blowing wind, or when dissolved minerals are carried away by underground flows of water. However, erosion also occurs as mass events, such as a landslide in steep terrain. Over extremely long periods of time, weathering and erosion tend to influence the landscape towards a relatively flat and homogeneous condition known as a peneplain.

Even geological features as immense as mountains are slowly eroded away, with their enormous mass gradually descending to be deposited in lower regions. For instance, the Precambrian Shield that is so extensive in regions of Canada is composed of the granitic basement rocks of ancient mountains that were slowly eroded away by the actions of water, wind, and glaciers. The somewhat less ancient hills of the Appalachians of eastern North America, which extend into New Brunswick, Nova Scotia, and Newfoundland, are also the eroded relics of a once-great mountain range. The youngest mountain range in North America, the Rocky Mountains, extends from the western United States north into Alberta, British Columbia, the Yukon, and the western Northwest Territories. The Rockies still have many towering, sharp peaks because they have not yet been much reduced by the inexorable, mass-wasting forces of erosion.

The rates of natural weathering and erosion is influenced by many factors, including the hardness of rocks, degree of consolidation of soil and sediment, amount of vegetation cover, rate of water flow, slope of the land, speed and direction of winds, and frequency of storm events and other disturbances. Some of these factors can be greatly influenced by human actions. For example, when the local vegetation is disturbed, its moderating influence on erosion is reduced or eliminated. In fact, human activities associated with agriculture, forestry, and road-building have greatly increased the rates of erosion in almost all regions of the world. In many cases, the increased losses of soil have had serious consequences for the productivity of agricultural land and for natural biodiversity (see Chapters 14, 20, 23, and 24).

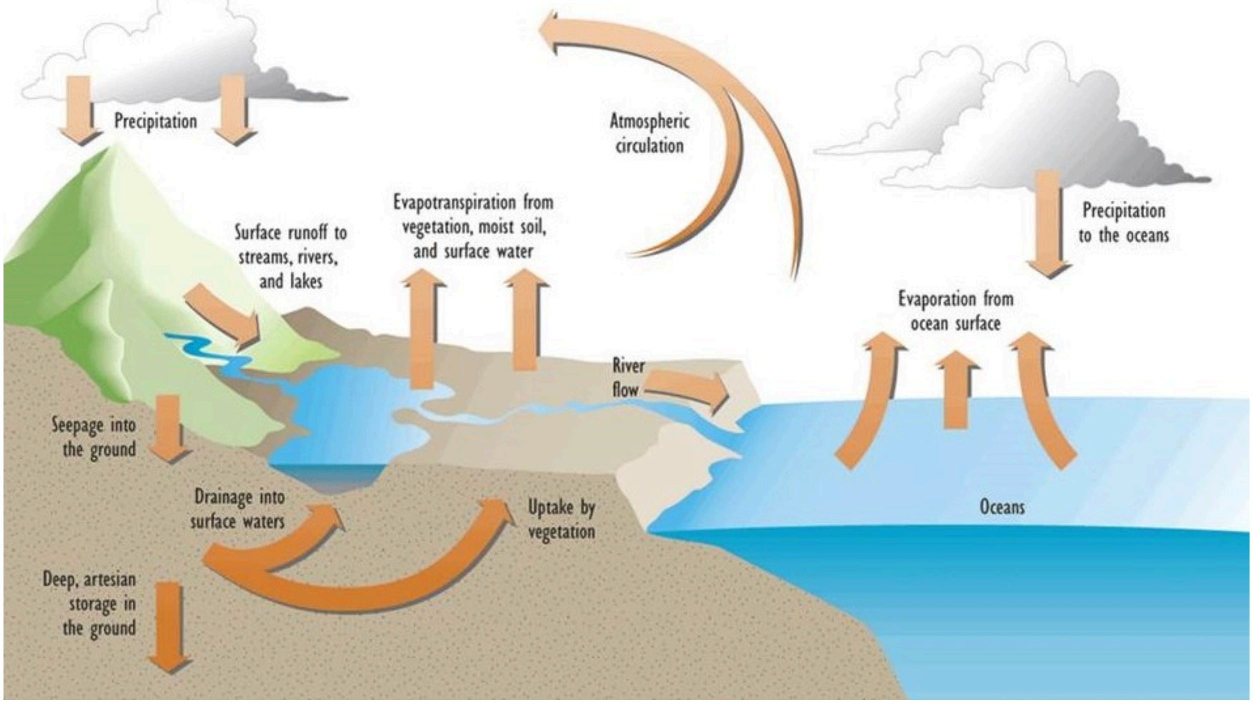
Rocks, sand, clays, and other debris eroded from mountains and other uplands must, of course, go somewhere. These materials are carried to lower altitude, and eventually much of the mass is deposited in the oceans, where they settle to the bottom in a process known as sedimentation. Over extremely long periods of time (tens or more millions of years), the mass of sedimented material builds up to the extent that intense pressure is exerted on lower levels of the sediment, which causes it to become more densely packed and fuse into sedimentary rock in a process called lithification. Examples of sedimentary rocks are mudstone, sandstone, shale, limestone, and mixtures of these known as conglomerates (the latter may also contain eroded non-sedimentary rocks, such as granite and basalt).

Eventually, under the influence of tectonic forces, enormously slow and powerful collisions of crustal plates can cause areas of deep-oceanic sedimentary rocks to uplift, sometimes raising them to great altitude and contributing to the formation of new mountain ranges underwater or on the continents. As such, geological uplift is the means by which marine rocks and fossils find their way to the tops of the highest mountains. Uplift and mountain building are important stages in the geological recycling of some of the continental mass that was wasted downslope during millions of years of erosion.

The Hydrosphere

The hydrosphere is the portion of Earth that contains water (H_2O), including in the oceans, atmosphere, land surface, and underground. The hydrologic cycle (or water cycle) refers to the rates of movement (fluxes) of water among these various reservoirs (compartments). The hydrologic cycle functions at all scales, ranging from local to global. The major elements of the global hydrologic cycle are illustrated in Figure 3.2.

Figure 3.2. Major Elements of the Hydrologic Cycle. The hydrologic cycle includes the influences of oceans and other kinds of surface water (such as lakes and rivers), as well as groundwater and atmospheric moisture (occurring as clouds and humidity). Water evaporates, precipitates as rain and snow, and flows in various kinds of channels, both along the surface as well as underground.



Each compartment of the hydrologic cycle has both input and output fluxes, and the sum of all of these elements comprises the cycle. If the rate of input to a compartment equals the rate of output, then there is a flow-through equilibrium and the amount of water present does not change. Of course, if input exceeds output, the compartment increases in size over time, and it decreases if input is less than output.

On the global scale, the major compartments of the hydrologic cycle are in a long-term equilibrium condition. However, this is not generally true on a local scale, especially over shorter intervals of time. For example, a particular area may temporarily flood or dry out. In addition, local hydrological conditions can change over the long term. Glaciation, for example, stores immense quantities of solid water on land, and excessive use of groundwater can deplete an artesian reservoir (aquifer).

Image 3.4. The global hydrologic cycle involves water movement through the atmosphere, on the surface, and underground, as well as storage in oceans, lakes, glaciers, and groundwater. Ultimately, rivers like the Niagara River, which flows north from Lake Erie to Lake Ontario, represent a flow to the ocean of water that had been deposited to the landscape as rain or snow. Niagara Falls is located on the Niagara River. Source: B. Freedman

Although the hydrologic cycle is an exceedingly complex phenomenon, it can be examined in the context of four major compartments (Table 3.2):

1. The oceans are the largest hydrological compartment, accounting for about 97.4% of all water on the planet.
2. Surface waters occur on the landmasses and account for 2.3% of global water. Almost all that amount is tied up in glaciers, mostly in Antarctica and Greenland, with lakes, ponds, rivers, streams, and other surface bodies of liquid water amounting to only 0.002%.
3. Groundwater accounts for 0.32% of global water. Groundwater can occur in relatively shallow soil horizons, where it is accessible for uptake by plants, or it can drain laterally into surface waters such as lakes and streams. Deeper groundwater is inaccessible for these purposes and it forms artesian reservoirs in spaces within porous or fractured bedrock. Such aquifers receive water infiltrating by deep drainage from above or by long-distance underground transport from nearby upland areas.
4. Atmospheric water accounts for only about 0.001% of the global total. It can occur as a gas, vapour (tiny, suspended droplets), or solid (ice crystals), all of which are highly variable over space and time. A cloud is a dense aggregation of liquid or solid water in the atmosphere, while gaseous water is invisible. Note that the maximum amount of water a volume of atmosphere can hold is highly dependent on temperature, with warmer air having a much greater water-storage capacity than cold air. The term humidity refers to the actual concentration of water in the atmosphere (measured in g/m3), while relative humidity expresses actual humidity as a percentage of the saturation value for a particular temperature.

Table 3.2. The Hydrologic Cycle. This table shows the quantity of water involved in various global

compartments and fluxes. Source of data: Botkin and Keller (2014).

Compartments	Quantity (10^{14} t)	Percent of Total
oceans	12300	97.4
glaciers	286	2.3
groundwater (to 0.8 km)	40	0.32
inland waters	0.25	0.002
atmosphere	0.13	0.001
Fluxes	**Quantity (10^{14} t/y)**	
evaporation:	4.4	
from oceans	3.8	
from land surfaces	0.6	
total precipitation:	4.4	
to oceans	1	
to land surfaces	4.4	
atmospheric transfer oceans to land	0.4	
surface runoff from land	0.2	

Evaporation is a change of state of water from a liquid to a gas, or from a solid directly to a gas (evaporation directly from ice or snow is more properly referred to as sublimation). Globally, about 86% of evaporation is from the oceans, and the rest is from terrestrial surfaces. On terrestrial landscapes, water can evaporate from bodies of surface water, from moist soil and rocks, and from vegetation. Transpiration refers specifically to the evaporation of water from plants, while evapotranspiration refers to all sources of evaporation from a landscape.

Precipitation is the deposition of water from the atmosphere, occurring as liquid rain or as solid snow or hail. In addition, vapour-phase atmospheric water can condense or freeze onto surfaces as dew or frost, respectively. As previously noted, most global evaporation is from the oceans, much of which precipitates back to them. However, some is transported by moving air masses over the continents, resulting in a net import of evaporated water from the oceans to the land surfaces. Precipitation volumes can be especially large in mountainous areas facing an ocean, a phenomenon known as orographic precipitation (In Detail 3.1).

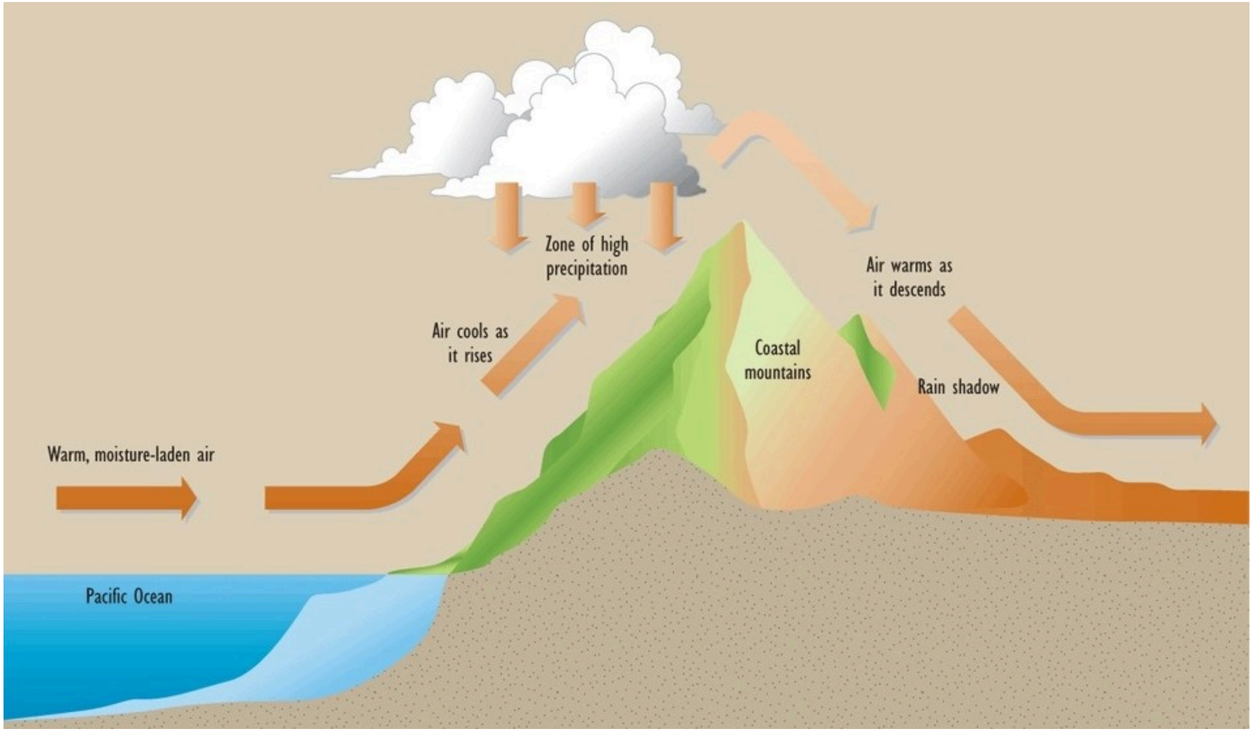
Surface flows involve water that is transported in streams and rivers. In contrast, lakes and ponds are relatively static storage reservoirs. Surface flows move in response to gravitational descents associated with altitude – in other words, water flows downhill. Ultimately, most surface flows carry water to the oceans, thereby helping to balance the net import of moisture evaporated from the oceans.

In Detail 3.1. Orographic Precipitation along a Transect through Coastal British Columbia
The spatial pattern of precipitation in coastal British Columbia illustrates the phenomenon of orographic precipitation. It occurs as moisture-laden air masses, blown by the prevailing westerly winds from the Pacific Ocean, encounter the mountains of the Coast Range. As the air masses rise, they cool (by 0.5 to 0.8°C for every 100 m increase in elevation), which greatly reduces their ability to hold water. This causes much of the moisture to condense into clouds and to then precipitate from the atmosphere as snow and rain.

As the air mass passes to the other side of the mountains and starts to descend, it warms again, which increases its moisture-holding capacity. Therefore, precipitation is much sparser on the rain-shadow side of the mountains.

Consequently, coastal Vancouver has much more rainfall (about 110 cm/y) than Penticton in the inland Okanagan Valley (28 cm/y). However, local orographgic effects are also considerable in the Greater Vancouver area, where rainfall is only about 50 cm/y in the southern suburbs of Delta, but as much as 250 cm/y in places nearer the mountains, such as North Vancouver.

Figure 3.3. A diagrammatic model of orographic precipitation.



Groundwater drainage involves the infiltration of water into the ground. Shallow groundwater can move laterally, eventually draining into surface waters. It can also be taken up by plant roots to later be transpired into the atmosphere through foliage. However, deeper groundwater is not available for plant uptake or to recharge surface waters. It accumulates in underground artesian reservoirs, which can be very large. The biggest such aquifer in North America is the Ogallala, which underlies about 450,000 km^2 of the western U.S.

The hydrologic cycle is extremely important. Water is needed by natural ecosystems for the metabolic needs of organisms, for cooling, and as a ubiquitous solvent that allows water-soluble nutrients to be absorbed by organisms. Water is also required by people for use in agriculture, industry, and recreation. Unfortunately, in many regions water and its biological resources (such as fish) have been used excessively, and water quality has been degraded through pollution. Damages caused to water and its resources, and ways of mitigating those effects, are common themes in many chapters in this book.

The Atmosphere

The atmosphere is an envelope of gases that surrounds the Earth and is held in place by the attractive forces of gravity. The density of the atmospheric mass is much greater close to the surface and decreases rapidly with increasing altitude. The atmosphere consists of four layers, the boundaries of which are inexact because they may vary over time and space:

1. The troposphere (or lower atmosphere) contains 85-90% of the atmospheric mass and extends from the surface to

an altitude of 8-20 km. It is thinner at high latitudes, and thicker at equatorial latitudes, but also varies seasonally, at any place being thicker during the summer than in the winter. It is typical for air temperature to decrease with increasing altitude within the troposphere, and convective air currents (winds) are common. Consequently, the troposphere is sometimes referred to as the "weather layer."
2. The stratosphere extends from the troposphere to as high as about 50 km, depending on the season and latitude. Air temperature varies little with altitude within the stratosphere, and there are few convective air currents.
3. The mesosphere extends beyond the stratosphere to about 75 km.
4. The thermosphere extends to 450 km or more.

Image 3.5. The atmosphere is composed of a mixture of gases, fine particulates, and water vapour occurring as clouds. This view of a foggy tropical forest was taken in the highlands of Peru. Source: B. Freedman

Beyond the atmosphere is outer space, an immeasurably vast region where the Earth exerts no detectable chemical or thermal influences.

About 78% of the mass of the atmosphere is composed of nitrogen gas (N_2), while 21% is oxygen (O_2), 0.9% argon (Ar), and 0.04% carbon dioxide (CO_2). The rest is various trace gases, including potentially toxic ones such as ozone (O_3) and sulphur dioxide (SO_2) (see Chapter 16). The atmosphere also contains highly variable concentrations of water vapour, which can range from only 0.01% in frigid winter air in the Arctic to 5% in warm, humid, tropical air. On average, the total weight of the atmospheric mass exerts a pressure at sea level of around 1.0×10^5 pascals (Pa; or one atmosphere), which is equivalent to 1.0 kg per cm^2.

The atmosphere is a highly dynamic medium, being variable over space and time. This is particularly true of the troposphere, within which gradients of temperature and energy are most pronounced. To even out the energy gradients, there is a streaming of atmospheric mass from regions of relatively high pressure to those with lower pressure. These more-or-less lateral atmospheric movements are known as wind. The vigour and speed of winds can range from barely perceptible to several hundred kilometres per hour in extremely turbulent, rotating air masses such as a tornado or hurricane. In general, winds are caused when air heated by the sun becomes less dense and rises in altitude, to be replaced at the surface by an inflow of cooler, denser air from elsewhere. Simply interpreted, this movement of atmospheric mass represents an enormous gaseous convective cell. These atmospheric movements occur on both local and global scales and are extremely variable over space and time. At the global level, however, a broad general pattern of circulation is discernible.

As was noted above, wind directions are influenced by the relative locations of high and low atmospheric pressures. Wind directions are also influenced by the Coriolis effect, which is caused by the west-to-east rotation of Earth. For example, in the mid-latitudes of the Northern Hemisphere, the distribution of pressure in the lower atmosphere provides a northward force on wind direction. The Coriolis force, which deflects motions to the right in that hemisphere, balances the pressure-gradient force so that the winds tend to blow from west to east. In comparison, in the mid-latitudes of the Southern Hemisphere, the pressure gradient force is directed toward the south, while the Coriolis force deflects motions to the left. On balance, this again results in winds tending to blow from west to east. Local patterns of wind flow are also influenced by surface topography—mountains are barriers that deflect winds upward or around, while valleys can channel wind flows.

Prevailing winds blow relatively continuously in a dominant direction. There are three major classes of prevailing winds:

1. trade winds are tropical airflows that blow from the northeast (to the southwest) in the Northern Hemisphere, and from the southeast in the Southern Hemisphere
2. westerlies are mid-latitude winds that blow from the southwest in the Northern Hemisphere, and from the northwest in the Southern Hemisphere
3. polar easterlies blow from the northeast at high northern latitudes, and from the southeast near Antarctica.

Climate and Weather

Climate refers to the prevailing atmospheric conditions of temperature, precipitation, humidity, wind speed and direction (together, these are wind velocity), insolation (incoming solar radiation), visibility, fog, and cloud cover in a place or region. Climatic data are usually calculated as statistics (such as averages or ranges of values), using data obtained from at least several decades of monitoring (the preferred period for the calculation of "normal" climatic parameters is at least 30 years).

In contrast, weather refers to day-to-day or instantaneous meteorological conditions (the latter is referred to as "real-time" weather). Because weather is related to short-term conditions, it is much more variable over time and space than climate. Most aspects of climate are functions of solar insolation and of how this incoming energy is absorbed, reflected, and re-radiated by the atmosphere, oceans, and terrestrial surfaces. The complex subject of physical energy budgets is described in Chapter 4. For the present purpose, it is worthwhile to examine several ecologically important aspects:

- **Give Thanks to the Sun.** If it were not for the warming influence of solar radiation, the temperature of the surface and atmosphere would approach the coldest that is physically possible – this is absolute zero, or -273°C (or 0o on the Kelvin scale). Although Earth has a limited ability to generate its own heat by the decay of radioactive elements in its core, this is insufficient to provide much warming at the surface. Therefore, solar energy is critical to maintaining the surface temperature within a range that organisms can tolerate.

- **Atmospheric Reflection and Absorption.** Conditions in the atmosphere have a great influence on climatic factors. For instance, cloud cover and tiny particulates are highly reflective of many visible wavelengths of solar radiation and so have a marked cooling effect on the lower atmosphere and the surface. In addition, the atmosphere contains trace concentrations of certain gases that absorb some of the infrared radiation that the planet emits to cool itself of the heat obtained by absorbing solar radiation. The most important of these so-called "greenhouse gases" are water vapour, carbon dioxide, and methane. This influence is called the greenhouse effect, and it maintains the surface temperature of Earth at an average of about 15°C, or 33°C warmer than the -18°C it would be without this moderating effect (see Chapters 4 and 17).
- **Night and Day.** At any place on the surface, the input of solar radiation is high during the day and low at night. (At night, the only radiation inputs are from distant stars and from solar radiation reflected by atmospheric particulates and the moon—these sparse inputs are known as "skylight.") The daily, 24-hour (diurnal) variations in energy input result in large changes in weather. However, this effect varies greatly between tropical and polar latitudes. Tropical regions have approximately equal day and night lengths of about 12 hours each, which do not vary much during the year. In contrast, polar latitudes are much more seasonal, with almost continuous light during much of the summer, and constant night during part of the winter. Temperate latitudes are intermediate, with longer day lengths during the summer and shorter ones during winter.
- **Effects of Latitude.** Places at tropical latitudes tend to face incoming solar radiation on a relatively perpendicular angle (closer to 90° at noon). Polar latitudes have a more oblique angle of solar incidence, and temperate latitudes are intermediate in this regard. The more perpendicular the angle of incidence of solar radiation is, the smaller the surface area over which the incoming energy is distributed and the more intense the resulting heating. The angle of solar incidence has a strong influence on the amounts of unit-area solar radiation that are received at various latitudes, and is a major reason (along with seasonality) why the tropics are warmer than polar regions.
- **Seasons.** Earth's axis tilts at a 23.5° angle relative to the incidence of solar radiation. Consequently, during the planet's annual revolution around the Sun, there are seasonal differences in energy received between the Northern and Southern Hemispheres. In the Northern Hemisphere, the angle of incidence is closer to perpendicular from March 21 to September 22, giving relatively warmer conditions, while the angle is more oblique from September 22 to March 21, resulting in cooler conditions. These seasons are reversed in the Southern Hemisphere. Because Earth's orbit is elliptical, climatic seasons are also influenced by the varying distance from the Sun. However, this effect is relatively small compared with that of the inclination of the axis.
- **Aspect.** On a local scale, the direction that a slope faces (known as its aspect) has a substantial influence on the amount of solar radiation received. In the Northern Hemisphere, south-facing, and to a lesser degree west-facing slopes are relatively warm, while north- and east-facing slopes are cooler. In the Southern Hemisphere, north-facing slopes are warmer.
- **Slope.** The degree of slope, or the angle of inclination of the land, also affects the amount of energy received. The closer the slope approximates a perpendicular angle to incoming solar radiation, the greater is the energy input per unit of surface area. In the Northern Hemisphere, this effect is greatest on south-facing slopes.
- **Soil and Vegetation Cover.** Darker surfaces absorb much more solar radiation than do lighter surfaces. This is the reason why a black asphalt surface gets much hotter during the day than one made of light-coloured cement. Plant canopies also vary in their absorption and reflection characteristics, depending on the colour of the foliage and the angle at which it is oriented to incoming solar radiation. Major changes in the character of vegetation, as occur when forest is converted into agricultural or urban land-use, can affect local, and sometimes regional, weather and climate.
- **Snow and Ice Cover.** Because snow and ice are highly reflective of solar radiation, surfaces covered by those materials absorb relatively little insolation. The melting of snow cover in the springtime exposes a much more absorptive ground surface, and warming then accelerates.

- **Evaporation of Water.** Moist surfaces are cooled by the evaporation of water, a process that absorbs thermal energy. Therefore, the transpiration of water from plant foliage has a cooling effect, similar to the evaporation of sweat from the body surface of a human.

The above factors influence the input, reflection, absorption, and dissipation of solar radiation, resulting in large variations of air, water, and surface temperatures over the surface of Earth. The energy gradients that develop result in global processes that attempt to distribute the energy more evenly, by movements of air masses in the atmosphere (winds) and currents of water in the oceans. In addition, prevailing wind directions can interact with oceanic currents to generate circular water flows known as gyres. Subtropical gyres rotate clockwise in the Northern Hemisphere and counter-clockwise in the Southern Hemisphere, while subpolar gyres rotate in the opposite directions.

Climate has an important influence on the character of ecological development in any region or place. Climatic conditions can vary on a large scale, called macroclimate, which affects the nature of ecosystems over a large area. Climatic conditions can also vary on much smaller scales, called microclimate, which may be affected by local topography, proximity to the ocean or a large lake, or understorey conditions beneath a dense canopy of tree foliage. Four climatic factors particularly affect the development of ecosystems (see Chapter 8). Of these, variations of precipitation and temperature generally have the greatest influence. The amounts of precipitation are greatly affected by the flow of prevailing winds, the humidity of air masses, and the influence of topography (see In Detail 3.1). A dry climate may only support desert vegetation, whereas wetter conditions may allow old-growth forest and wetlands to develop.

Temperature is relatively warm in tropical latitudes and at lower altitude in mountainous terrain, while it is cooler at high latitude and high altitude. In general, places with cold temperatures develop tundra vegetation, whereas warmer temperatures may support forest. Temperate and polar latitudes have large seasonal fluctuations in temperature. Tropical forest develops in moist regions where temperature remains uniformly warm, while temperate and boreal forests are dominated by tree species that can tolerate cold temperatures during the winter. Wind can also have a substantial ecological influence, although this is typically less important than that of precipitation and temperature. Very windy locations may not be able to support forest, even though precipitation and temperature are otherwise favourable. This occurs in many coastal habitats in Canada, where windy conditions result in shrub-dominated ecosystems rather than the forest that occurs farther inland.

Extreme events of weather, such as drought, flooding, a hurricane, or a tornado, can also be important. Severe disturbances have a large influence on ecological development, especially where they occur frequently. For example, frequent drought or severe windstorms may restrict the development of forest in some regions, even though the average climatic conditions may be favourable.

Major elements of the climates of Canada are described in Canadian Focus 3.1. Their relationship with ecological development is examined in Chapter 8.

Canadian Focus 3.1. Climates of Canada

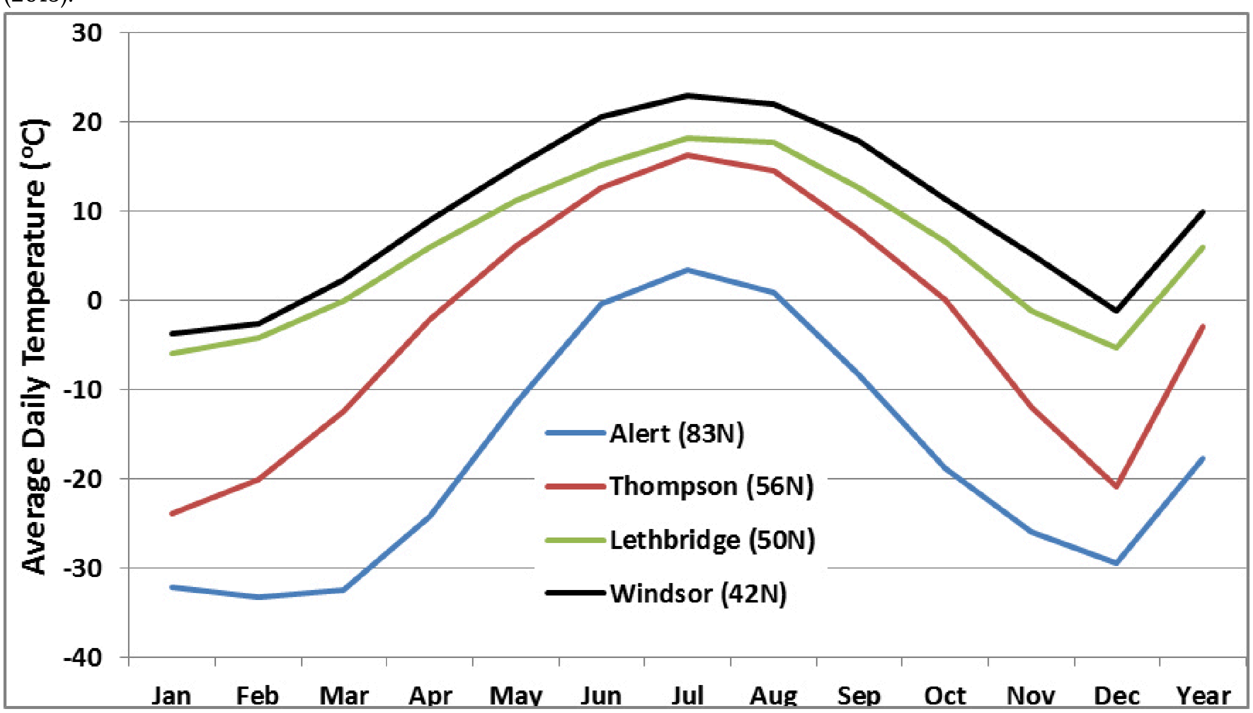
Canada is a huge country, the second largest in the world after Russia. The wide range of latitude means that local and regional climates vary from cold polar in the High Arctic to warm temperate in southern Ontario and southern British Columbia. Canada also has extremely varied topography, with extensive low regions and many areas at high elevation, particularly in the mountains of Labrador, the eastern Arctic Islands, and the Rocky Mountains. Therefore, the regions of Canada are characterized by huge differences in climate.

The figure shows seasonal patterns of change, using temperature as an indicator. Note that the high-Arctic station at Alert (82° N) on far-northern Ellesmere Island is much colder and has a brief growing season compared with the southerly stations. Thompson (55° N) is in the boreal zone of northern Manitoba and it also has a relatively cold climate with a short growing season. Lethbridge, in the prairie region of southern Alberta, has a temperate prairie climate with a relatively warm and extended growing season. Windsor (42^o N) is the most southern location shown, and it has the warmest climate and longest growing season.

Table 3.3 Normal climate values (longer-term averages) calculated for the period 1981 to 2010 (Environment Canada, 2015).

	St. John's, NL	Halifax, NS	Montreal, QC	Toronto, ON	Winnipeg, MB	Regina, SK	Edmonton, AB	Penticton, BC	Vancouver, BC	Iqaluit, NU
Temperature (°C)										
Annual average	5	6.6	6.8	8.2	3	3.1	2.6	9.5	10.4	-9.3
Days >20° C	53	89	117	122	110	108	87	129	77	44
Days <-10° C	35	45	63	39	102	102	99	11	2	182
Days frost-free	139	163	165	168	121	115	110	159	237	74
Growing Degree-Days										
days > 10 °C	559	922	1260	1325	1018	913	611	1234	966	24
Precipitation (cm/y)										
Annual total	154	141	100	79	52	39	45	29	119	40
As rain	121	119	79	68	42	31	34	22	115	20
As snow	33	22	21	11	10	8	9	7	4	20
Days rainy	163	128	119	113	78	72	77	99	165	52
Days snowy	79	58	59	45	54	56	53	26	9	114
Wind (kph)										
Average wind	21.9	16.5	14.4	15	17.1	18.4	12.2	10.9	12.2	15.7
Days wind >63	16	3	<1	6	1	9	0	<1	2	10

Figure 3.4. Average daily temperature for a range of places in Canada. Source: Data from Environment Canada (2015).



Conclusions

Knowledge of the physical world is a central aspect of environmental science – it provides essential context for understanding the causes and consequences of almost all changes that are caused by human activities. The physical and structural attributes of Earth influence the geological and geographical forces affecting its surface (both water and land) and atmosphere. In addition, the amount and spectral quality of incoming sunlight have a profound influence on the energy budget and climates of the planet. Increasingly, anthropogenic influences are having a large, cumulative effect on these natural effects and are transforming the surface attributes of Earth by affecting erosion, surface cover, environmental chemistry, and even global climate.

Questions for Review

1. What are the various layers of Earth's solid sphere and atmosphere? Briefly describe the characteristics of these layers.
2. What causes tectonic forces, and what are their consequences on crustal dynamics?
3. What is glaciation? Describe the major surface features that it leaves behind.
4. What are key factors affecting regional climate and microclimate?

Questions for Discussion

1. Explain how geological forces have influenced landscape features in the region where you live.
2. Where does your drinking water come from? Trace its origins and disposal in terms of the hydrologic cycle.
3. Explain the differences between climate and weather. Discuss the influences of climate and weather on your daily and annual life.
4. Natural disasters, such as extreme weather caused by a windstorm or massive rain event, are rare but inevitable occurrences. What is the recent history of natural disasters in the place where you live? Do you think that land-use and other human influences may have increased the possibility of worse damage being caused by these unpredictable events?

Exploring Issues

1. You are part of a research team that is investigating the potential environmental effects of climate change in a region of hilly topography. Your responsibility is to characterize the climatic conditions in the study area, giving sufficient detail so the team can understand the overall conditions as well as the local ones, such as in valleys, on slopes, and on hilltops. What kinds of factors would you have to consider when designing the climate-monitoring program? Consider the following aspects: (a) the number of monitoring sites, (b) where monitoring sites should be located, (c) what variables to measure (such as wind, temperature, precipitation, sunlight), and (d) how long you must monitor conditions before determining the normal climate (as opposed to the weather).

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Chapter 4 ~ Energy and Ecosystems

Key Concepts

After completing this chapter, you will be able to

1. Describe the nature of energy, its various forms, and the laws that govern its transformations.
2. Explain how Earth is a flow-through system for solar energy.
3. Identify the three major components of Earth's energy budget.
4. Describe energy relationships within ecosystems, including the fixation of solar energy by primary producers and the passage of that fixed energy through other components of the ecosystem.
5. Explain why the trophic structure of ecological productivity is pyramid-shaped and why ecosystems cannot support many top predators.
6. Compare the feeding strategies of humans living a hunting and gathering lifestyle with those of modern urban people.

Introduction

None of planet Earth, its biosphere, or ecosystems at any scale are self-sustaining with respect to energy. In fact, without continuous access to an external source of energy, all of these entities would quickly deplete their quantities of stored energy and would rapidly cool, and in the case of the biosphere and ecosystems, would cease to function in ways that support life. The external source of energy to those systems is solar energy, which is stored mainly as heat and biomass. In effect, solar energy is absorbed by green plants and algae and is utilized to fix carbon dioxide and water into simple sugars through a process known as photosynthesis. This biological fixation of solar energy provides the energetic basis for almost all organisms and ecosystems (the few exceptions are described later). Energy is critical to the functioning of physical processes throughout the universe, and of ecological processes in the biosphere of Earth. In this chapter we will examine the physical nature of energy, the laws that govern its behaviour and transformations, and its role in ecosystems.

The Nature of Energy

Energy is a fundamental physical entity and is simply defined as the capacity of a body or system to accomplish work. In physics, work is defined as the result of a force being applied over a distance. In all of the following examples of work, energy is transformed and some measurable outcome is achieved:

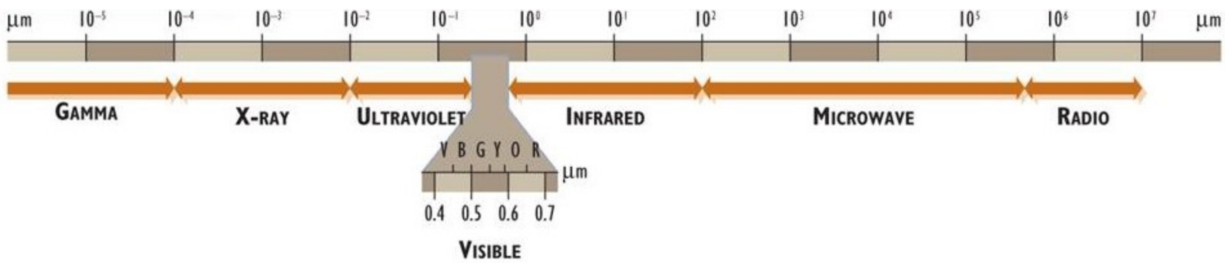
- A hockey stick strikes a puck, causing it to speed toward a target
- A book is picked up from the floor, lifted, and then laid on a table
- A vehicle is driven along a road
- Heat from a stove is absorbed by water in a kettle, causing it to become hotter and eventually to boil
- The photosynthetic pigment chlorophyll absorbs sunlight, converting the electromagnetic energy into a form that plants and algae can utilize to synthesize sugars

Energy can exist in various states, each of which is fundamentally different from the others. However, under suitable conditions energy in any state can be converted into another one through physical or chemical transformations. The states of energy can be grouped into three categories: electromagnetic, kinetic, and potential.

Electromagnetic Energy

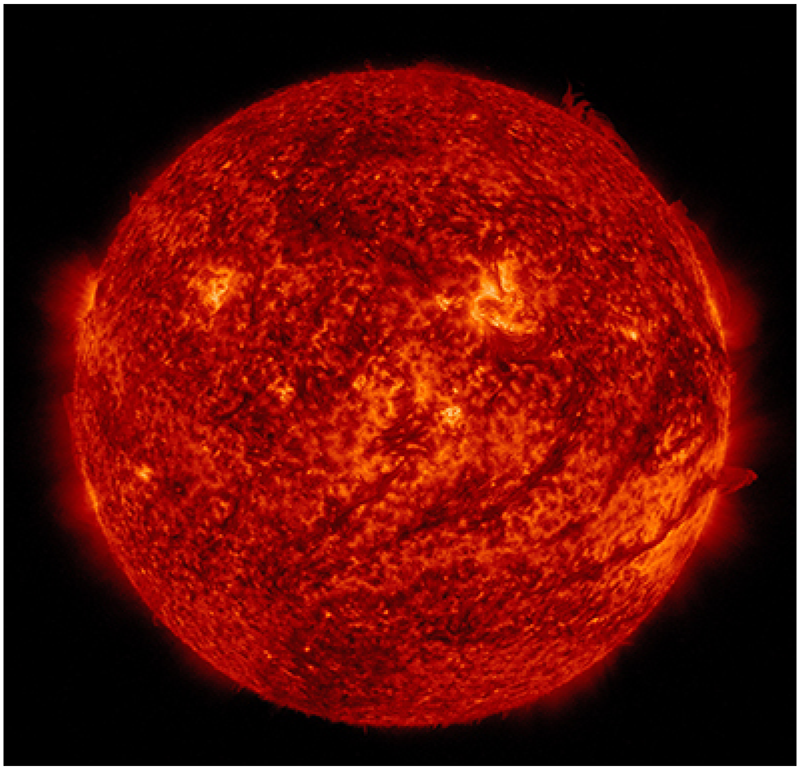
Electromagnetic energy (or electromagnetic radiation) is associated with photons. These have properties of both particles and waves and travel through space at a constant speed of 3×10^8 m/s (the speed of light). Electromagnetic energy exists as a continuous spectrum of wavelengths, which (ordered from the shortest to longest wavelengths) are known as gamma, X-ray, ultraviolet, visible light, infrared, microwave, and radio (Figure 4.1). The human eye can perceive electromagnetic energy over a range of wavelengths of about 0.4 to 0.7 µm, a part of the spectrum that is referred to as visible radiation or light (1 µm, or 1 micrometre, is 10^{-6} m; see Appendix A).

Figure 4.1. The Electromagnetic Spectrum. The spectrum is divided into major regions on the basis of wavelength and is presented on a logarithmic scale ($\log_{10}$) in units of micrometres (1 µm = 10^{-3}mm = 10^{-6} m). Note the expansion of the visible component and the wavelength ranges for red, orange, yellow, green, blue, and violet colours.



Electromagnetic energy is given off (or radiated) by all objects that have a surface temperature greater than absolute zero (greater than -273°C or 0°K). The surface temperature of a body determines the rate and spectral quality of the radiation it emits. Compared with a cooler body, a hotter one has a much larger rate of emission, and the radiation is dominated by shorter, higher-energy wavelengths. For example, the Sun has an extremely hot surface temperature of about 6000°C, and as a direct consequence most of the radiation it emits is ultraviolet (0.2 to 0.4 µm), visible (0.4 to 0.7 µm), and near infrared (0.7 to 2 µm). (Note that the interior of the Sun is much hotter than 6000°C, but it is the surface temperature that directly influences the emitted radiation.) Because the surface temperature of Earth averages much cooler at about 15°C, it radiates much smaller amounts of energy at longer wavelengths (peaking at a wavelength of about 10 µm).

Image 4.1. The energy of the Sun is derived from nuclear fusion reactions involving hydrogen nuclei. These reactions generate enormous quantities of thermal and electromagnetic energy. Solar electromagnetic radiation is the most crucial source of energy that sustains ecological and biological processes. Source: NASA image: http://sdo.gsfc.nasa.gov/assets/img/latest/latest_4096_0304.jpg



Kinetic Energy

Kinetic energy is associated with bodies that are in motion. Two classes of kinetic energy can be distinguished.

Mechanical kinetic energy is associated with any object that is in motion, meaning it is travelling from one place to another. For example, a hockey puck flying through the air, a trail-bike being ridden along a path, a deer running through a forest, water flowing in a stream, or a planet moving through space are all expressions of this kind of kinetic energy. The amount of mechanical kinetic energy is determined by the mass of an object and its speed.

Thermal kinetic energy is associated with the rate that atoms or molecules are vibrating. Such vibrations are frozen at -273°C (absolute zero), but are progressively more vigorous at higher temperatures, corresponding to a larger content of thermal kinetic energy, which is also referred to as heat.

Potential Energy

Potential energy is the stored ability to perform work. To actually perform work, potential energy must be transformed into electromagnetic or kinetic energy. There are a number of kinds of potential energy:

Gravitational potential energy results from gravity, or the attractive forces that exist among all objects. For example, water stored at any height above sea level contains gravitational potential energy. This can be converted into kinetic energy if there is a pathway that allows the water to flow downhill. Gravitational potential energy can be converted into electrical energy through the technology of hydroelectric power plants.

Chemical potential energy is stored in the bonds between atoms within molecules. Chemical potential energy can be liberated by exothermic reactions (those which lead to a net release of thermal energy), as in the following examples:

- Chemical potential energy is stored in the molecular bonds of sulphide minerals, such as iron sulphide (FeS_2), and some of this energy is released when the sulphides are oxidized. Specialized bacteria can metabolically tap the potential energy of sulphides to support their own productivity, through a process known as chemosynthesis (this is further examined later in this chapter).

- The ionic bonds of salts also store chemical potential energy. For example, when sodium chloride (table salt, NaCl) is dissolved in water, ionic potential energy is released as heat, which slightly increases the water temperature.
- Hydrocarbons store energy in the bonds between their hydrogen and carbon atoms (hydrocarbons contain only these atoms). The chemical potential energy of gasoline, a mixture of liquid hydrocarbons, is liberated in an internal combustion engine and becomes mechanically transformed to achieve the kinetic energy of vehicular motion.
- Organic compounds (biochemicals) produced metabolically by organisms also store large quantities of potential energy in their inter-atomic bonds. The typical energy density of carbohydrates is about 16.8 kJ/g, while that of proteins is 21.0 kJ/g, and lipids (or fats) 38.5 kJ/g. Many organisms store their energy reserves as fat because these biochemicals have such a high energy density.

Electrical potential energy results from differences in the quantity of electrons, which are subatomic, negatively charged particles that flow from areas of high density to areas where it is lower. When an electrical switch is used to complete a circuit connecting two areas with different electrical potentials, electrons flow along the electron gradient. The electric energy may then be transformed into uses as light, heat, or work performed by a machine. A difference in electrical potential is known as voltage, and the current of electrons must flow through a conducting material, such as a metal.

Elasticity is a kind of potential energy that is inherent in the physical qualities of certain flexible materials and that can perform work when released, as occurs when a drawn bow is used to shoot an arrow.

Compressed gases also store potential energy, which can do work if expansion is allowed to occur. This type of potential energy is present in a cylinder containing compressed or liquefied gas.

Nuclear potential energy results from the extremely strong binding forces that exist within atoms. This is by far the densest form of energy. Huge quantities of electromagnetic and kinetic energy are liberated when nuclear reactions convert matter into energy. A fission reaction involved the splitting of isotopes of certain heavy atoms, such as uranium-235 and plutonium-239 (U^{235} and ^{239}P), to generate smaller atoms plus enormous amounts of energy. Fission reactions occur in nuclear explosions and, under controlled conditions, in nuclear reactors used to generate electricity. A fusion reaction involves the combining of certain light elements, such as hydrogen, to form heavier atoms under conditions of extremely high temperature and pressure, while liberating huge quantities of energy. Fusion reactions involving hydrogen occur in stars and are responsible for the unimaginably large amounts of energy that these celestial bodies generate and radiate into space. It is thought that all heavy atoms in the universe were produced by fusion reactions occurring in stars (see Chapter 3). Fusion reactions also occur in a type of nuclear explosive device known as a hydrogen bomb. A technology has not yet been developed to exploit controlled fusion reactions to generate electricity; if and when available, controlled fusion could be used to generate virtually unlimited amounts of commercial energy (see Chapter 13).

Image 4.2. Organic matter and fossil fuels contain potential chemical energy, which is released during combustion to generate heat and electromagnetic radiation. This forest fire was ignited by lightning and burned the organic matter of a pine forest. Source: NASA image: Kari Greer, http://www.nasa.gov/images/

content/710937main_climate-fire-lg.jpg

Units of Energy

Although energy can exist in various forms, all of them can be measured in the same or equivalent units. The internationally accepted system for scientific units is the SI system (Système International d'Unités), and its recommended unit for energy is the joule (J). One joule is defined as the energy required to accelerate 1 kg of mass at 1 m/s^2 (1 metre per second per second) over a distance of 1 m.

A calorie (or gram-calorie, abbreviation cal) is another unit of energy. One calorie is equivalent to 4.184 J, and it is defined as the amount of energy required to raise the temperature of 1 g of pure water by 1°C (specifically, from 15°C to 16°C). Note, however, that the dietician's "Calorie" is equivalent to 1000 calories (1 Calorie = 1 kcal). However, the energy content of many food products is now listed in kJ in countries using the SI system of units, such as Canada.

Energy Transformations

As was previously noted, energy can be transformed among its various states. For example, when solar electromagnetic radiation is absorbed by a dark object, it is transformed into thermal energy and the absorbing body increases in temperature. The gravitational potential energy of water stored at a height is converted into the kinetic energy of flowing water at a waterfall, which may be harnessed using hydroelectric technology to spin a turbine and generate electrical energy. As well, visible wavelengths of solar radiation are absorbed by chlorophyll, a green pigment in plant foliage, and some of the captured energy is converted into chemical potential energy of sugars via the biochemistry of photosynthesis.

All transformations of energy must behave according to certain physical principles, which are known as the laws of thermodynamics. These are universal principles, meaning they are always true, regardless of the circumstances.

The First Law of Thermodynamics

The first law of thermodynamics, also known as the law of conservation of energy, can be stated as follows: Energy can undergo transformations among its various states but it is never created or destroyed; therefore, the energy content of the universe remains constant. A consequence of this law is that there is always a zero balance among the energy inputs to a system, any net storage within it, and the energy output from the system.

Consider the case of an automobile driving along a highway. The vehicle consumes gasoline, an energy input that can be measured. The potential energy of the fuel is converted into various other kinds of energy, including kinetic energy embodied in forward motion of the vehicle, electrical energy powering the lights and windshield wipers, heat from friction between the vehicle and the atmosphere and road surface, and hot exhaust gases (thermal energy) and unburned fuel (chemical potential energy) that are vented through the tailpipe. Overall, in accordance with the first law of thermodynamics, an accurate measuring of all of these transformations would find that, while the energy of the gasoline was converted into various other forms, the total amount of energy was conserved (it remained constant).

The Second Law of Thermodynamics

The second law of thermodynamics can be expressed as follows: Transformations of energy can occur spontaneously only under conditions in which there is an increase in the entropy of the universe. Entropy is a physical attribute related to disorder, and is associated with the degree of randomness in the distributions of matter and energy. As the randomness (disorder) increases, so does entropy. A decrease in disorder is referred to as negative entropy. Consider, for example, an inflated balloon. Because of the potential energy of its compressed gases, that balloon may slowly leak its contents to the surrounding atmosphere, and it may even burst. Either of these outcomes can occur in a spontaneously fashion, because both processes would represent an increase in the entropy of the universe. This is because compressed gases are more highly ordered than those widely dispersed in the atmosphere. In contrast, dispersed gases in the atmosphere would never spontaneously relocate to inflate a balloon. A balloon will only inflate only if energy is expended through a local application of work, such as by a person blowing into the balloon. In other words, energy must be expended to cause a local decrease of entropy in a system. However, note that this energy cost itself gives rise to an increase in the entropy of the universe. For instance, the effort of a person inflating a balloon involves additional respiration, which uses biochemical energy and results in heat being released into the environment.

Another example concerns planet Earth. The planet continuously receives solar radiation, almost all of which is visible and near-infrared wavelengths in the range of about 0.4 to 2.0 µm. Some of this electromagnetic energy is absorbed and converted to thermal energy, which heats the atmosphere and surface. The planet cools itself of the absorbed solar radiation in various ways, but ultimately that energy is dissipated by an emission of electromagnetic energy to outer space as longer-wave infrared radiation (of a spectral quality that peaks at a wavelength of 10 µm). In this case, relatively short-wavelength solar radiation is ultimately transformed into the longer-wavelength radiation emitted by Earth, a process that represents a degradation in quality of the energy and an increase in the entropy of the universe.

An important corollary (or secondary proposition) of the second law of thermodynamics is that energy transformations can never be completely efficient—some of the initial content of energy must always be converted to heat so that entropy increases. This helps to explain why, even when using the best available technology, only about 30% of the potential energy of gasoline can be converted into the kinetic energy of a moving automobile, and no more than about 40% of the energy of coal or natural gas can be transformed into electricity in a generating station. There are also thermodynamic limits to the efficiency of photosynthesis, the process by which plants convert visible radiation into biochemical, even when it is occurring under ideal conditions with optimal supplies of nutrients, water, and light.

A superficial assessment might suggest that life in general appears to contradict the second law of thermodynamics. Plants, for example, absorb visible wavelengths of electromagnetic radiation and use this highly dispersed form of energy to fix simple inorganic molecules (carbon dioxide and water) into extremely complex and energy-dense biochemicals. The plant biomass may then be consumed by animals and microbes, which synthesize their own complex biochemicals. These various bio-syntheses represent energy transformations that greatly decrease local entropy because relatively dispersed electromagnetic energy and simple inorganic compounds are being converted into the complex, highly ordered biochemicals of organisms. Do these biological transformations contravene the second law of thermodynamics?

This seeming paradox of life can be resolved using the following logic: the localized bio-concentration of negative entropy can only occur because the system (ultimately referring to the biosphere, or all life on Earth) receives a constant input of energy in the form of solar radiation. If this external source of energy were somehow terminated, all of the organisms and organic materials would spontaneously degrade, releasing simple inorganic molecules and heat and thereby increasing the entropy of the universe. Therefore, life and ecosystems cannot survive without continual inputs of solar energy, which are required to organize and maintain their negative entropy. In this sense, the biosphere can be viewed as representing an "island" of negative entropy, highly localized in space and time, and continuously fuelled by the Sun as an external source of energy.

Earth: An Energy Flow-Through System

Electromagnetic radiation emitted by the Sun is by far the major input of energy that drives ecosystems. Solar energy heats the planet, circulates its atmosphere and oceans, evaporates its water, and sustains almost all its ecological productivity. Eventually, all of the solar energy absorbed by Earth is re-radiated back to space in the form of electromagnetic radiation of a longer wavelength than what was originally captured. In other words, Earth is a flow-through system, with a perfect balance between the input of solar energy and output of re-radiated energy, and no net storage over the longer term.

In addition, almost all ecosystems absolutely depend on solar radiation as the source of energy that photosynthetic organisms (such as plants and algae) utilize to synthesize simple organic compounds (such as sugars) from inorganic molecules (carbon dioxide and water). Plants and algae then use the chemical potential energy in these sugars, plus inorganic nutrients (such as nitrate and phosphate), to synthesize a huge diversity of biochemicals through various metabolic reactions. Plants grow and reproduce by using these biochemicals and their potential energy. Moreover, plant biomass is used as food by the enormous numbers of organisms that are incapable of photosynthesis. These organisms include herbivores that eat plants directly, carnivores that eat other animals, and detritivores that feed on dead biomass. (The energy relationships within ecosystems are described later.)

Less than 0.02% of the solar energy received at Earth's surface is absorbed and fixed by photosynthetic plants and algae. Although this represents a quantitatively trivial component of the planet's energy budget, it is extremely important qualitatively because this biologically absorbed and fixed energy is the foundation of ecological productivity. Ultimately and eventually, however, the solar energy fixed by plants and algae is released to the environment again as heat and is eventually radiated back to outer space. This reinforces the idea of Earth being a flow-through system for energy, with a perfect baance between the input and output.

Earth's Energy Budget

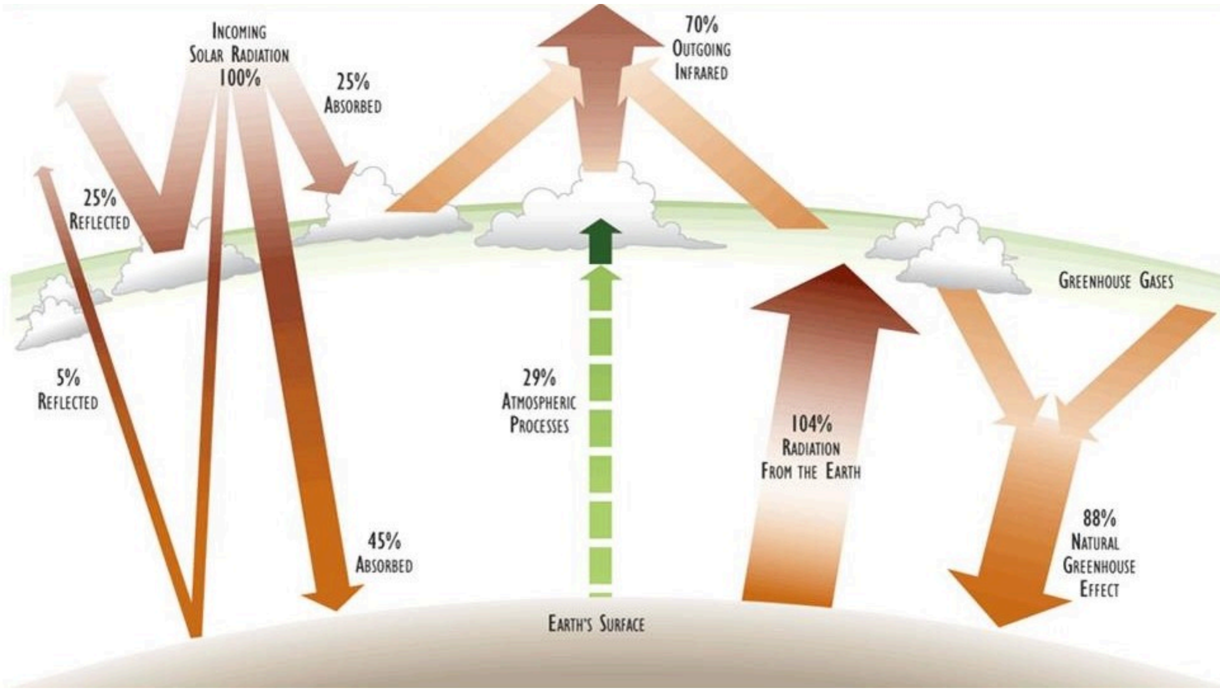
An energy budget of a system describes the rates of energy input and output as well as any internal transformations among its various states, including changes in stored quantities. Figure 4.2 illustrates key aspects of the physical energy budget of Earth.

The rate of input of solar radiation to Earth averages about 8.36 J/cm^2-minute (2.00 cal/cm^2-min), measured at the outer limit of the atmosphere. About half of this energy input is visible radiation and half is near infrared. The output of energy from Earth is also about 8.36 J/cm^2-min, occurring as longer-wave infrared. Because the rates of energy input and output are equal, there is no net storage of energy, and the average surface temperature of the planet remains stable. Therefore, as was previously noted, the energy budget of Earth can be characterized as a zero-sum, flow-through system.

However, the above is not exactly true. Over extremely long scales of geological time, a small amount of storage of solar energy has occurred through an accumulation of undecomposed biomass that eventually transformed into fossil fuels. In addition, relatively minor long-term fluctuations in Earth's surface temperature occur, representing an important element of climate change. Nevertheless, these are quantitatively trivial exceptions to the statement that Earth is a zero-sum, flow-through system for solar energy.

Figure 4.2. Important Components of Earth's Physical Energy Budget. About 30% of the incoming solar radiation is reflected by atmospheric clouds and particulates and by the surface of the planet. The remaining 70% is absorbed and then dissipated in various ways. Much of the absorbed energy heats the atmosphere and terrestrial surfaces, and most is then re-radiated as long-wave infrared radiation. Atmospheric moisture and greenhouse gases interfere with this process of re-radiation, keeping the surface considerably warmer than it would otherwise be (see also Chapter 17). The numbers refer to the percentage of incoming solar radiation. See the text for a more detailed description of important factors in this energy budget. Source: Modified from

Schneider (1989).



Even though the amount of energy emitted by Earth eventually equals the quantity of solar radiation that is absorbed, many ecologically important transformations occur between the initial absorption and eventual re-radiation. These are the internal elements of the physical energy budget of the planet (see Figure 4.2). The most important components are described below:

Reflection – On average, Earth's atmosphere and surface reflect about 30% of incoming solar energy back to outer space. Earth's reflectivity (albedo) is influenced by such factors as the angle of the incoming solar radiation (which varies during the day and over the year), the amounts of reflective cloud cover and atmospheric particulates (also highly variable), and the character of the surface, especially the types and amounts of water (including snow and ice) and darker vegetation.

Absorption by the Atmosphere – About 25% of incident solar radiation is absorbed by gases, vapours, and particulates in the atmosphere, including clouds. The rate of absorption is wavelength-specific, with portions of the infrared range being intensively absorbed by the so-called "greenhouse" gases (especially water vapour and carbon dioxide; see Chapter 17). The absorbed energy is converted to heat and re-radiated as infrared radiation of a longer wavelength than what has been initialy absorbed.

Absorption by the Surface – On average, about 45% of incoming solar radiation passes through the atmosphere and is absorbed at Earth's by living and non-living materials at the surface, a trabsformation that increases their temperature. However, this figure of 45% is highly variable, depending partly on atmospheric conditions, especially cloud cover, and also on whether the incident light has passed through a plant canopy. Although over the longer term (years) and even the medium term (days) the global net storage of heat is essentially zero, in some places there may be substantial changes in the net storage of thermal energy within the year. This occurs everywhere in Canada because of the seasonality of its climate, in that environments are much warmer during the summer than in the winter. Nevertheless, almost all of the absorbed energy is eventually dissipated by re-radiation from the surface as long-wave infrared.

Evaporation of Water – Some of the thermal energy of living and non-living surfaces causes water to evaporate in a process known as evapotranspiration. This process has two components: the evaporation of water from lakes, rivers, streams, moist rocks, soil, and other non-living substrates, and transpiration of water from any living surface, particularly from plant foliage, but also from moist body surfaces and lungs of animals.

Melting of Snow and Ice – Absorbed thermal energy can also cause ice and snow to melt, representing an energy transformation associated with a change of state of water from a solid to a liquid form.

Wind and Water Currents – There is a highly uneven distribution of the content of thermal energy at and near the surface of Earth, with some regions being quite cold (such as the Arctic) and others much warmer warm (the tropics). Because of this irregular allocation of heat, the surface develops processes to diminish the energy gradients by transporting mass around the globe, such as by winds and oceanic currents (see also Chapter 3).

Biological Fixation – A very small but ecologically critical portion of incoming solar radiation (globally averaging less than 0.02%) is absorbed by chlorophyll in plants and algae and used to drive photosynthesis. This biological fixation allows some of the solar energy to be temporarily stored as potential energy in biochemicals, thereby serving as the energetic basis for ecological productivity and life on Earth.

Energy in Ecosystems

An ecological energy budget focuses on the absorption of energy by photosynthetic organisms and the transfer of that fixed energy through the trophic levels of ecosystems ("trophic" refers to the means of organic nutrition). Ecologists classify organisms in terms of the sources of energy they utilize.

Autotrophs are capable of synthesizing their complex biochemicals using simple inorganic compounds and an external source of energy to drive the process. The great majority are photoautotrophs, which use sunlight as their external source of energy. Photoautotrophs capture solar radiation using photosynthetic pigments, the most important of which is chlorophyll. Green plants are the most abundant examples of photoautotrophs, but algae and some bacteria are also photoautotrophic.

A much smaller number of autotrophs are chemoautotrophs, which harness some of the energy content of certain inorganic chemicals to drive a process called chemosynthesis. The bacterium Thiobacillus thiooxidans, for example, oxidizes sulphide minerals to sulphate and uses some of the energy liberated during this reaction to chemosynthesize organic molecules.

Because autotrophs are the biological foundation of ecological productivity, ecologists refer to them as primary producers. The total fixation of solar energy by all of the primary producers within an ecosystem is known as gross primary production (GPP). Primary producers use some of this production for their own respiration (R) – that is, for the physiological functions needed to maintain their health and to grow. Respiration is the metabolic oxidation of biochemicals, and it requires a supply of oxygen and releases carbon dioxide and water as waste products. Net primary production (NPP) refers to the fraction of GPP that remains after primary producers have used some for their own respiration. In other words: NPP = GPP – R.

The energy fixed by primary producers is the basis for the productivity of all other organisms, known as heterotrophs, which heterotrophs rely on other organisms, living or dead, to supply the energy they need. Animal heterotrophs that feed on plants are known as herbivores (or primary consumers); three familiar examples are deer, geese, and grasshoppers. Heterotrophs that consume other animals are known as carnivores (or secondary consumers), such as timber wolf, peregrine falcon, sharks, and spiders. Some species feed on both plant and animal biomass and are known as omnivores –the grizzly bear is a good example, as is our own species. Many other heterotrophs feed primarily on dead organic matter and are called decomposers or detritivores, such as vultures, earthworms, and most fungi and bacteria.

Image 4.3. Plant productivity is sustained by solar energy, which is fixed by chlorophyll in the plant and used to combine carbon dioxide, water, and other simple inorganic compounds into the complex molecular structures of organic matter. These ecologists are studying the productivity of a plant community on Sable Island, Nova Scotia. Source: B. Freedman.

Productivity is production expressed as a rate function, that is, per unit of time and area. Productivity in terrestrial ecosystems is often expressed in units such as kilograms of dry biomass (or its energy equivalent) per hectare per year (kg/ha-y or kJ/ha-y), while aquatic productivity is often given as grams per cubic metre per year (g/m^3-y).

Many studies have been made of the productivity of the various trophic levels in ecosystems. For example, studies of a natural oak–pine forest found that the total fixation of solar energy by the vegetation (the annual gross primary production) was equivalent to 4.81 × 104 kJ/m2-y (48 100 kJ/m^2-y) (Odum, 1993). This fixation rate was equivalent to less than 0.1% of the annual input of solar radiation. Because the plants used 2.72 × 104 kJ/m^2-y during their respiration, the net primary productivity was 2.09 × 104 kJ/m^2-y, represented mainly by the growing biomass of the trees. The various heterotrophic organisms in the forest used 1.26 × 104 kJ/m^2-y to support their respiration. Ultimately, the net accumulation of biomass by all organisms in the ecosystem (referred to as the net ecosystem productivity) was equivalent to 0.83 × 104 kJ/m^2-y, or 8.3 × 103 kJ/m^2-y.

The primary productivities of the world's major classes of ecosystems are summarized in Table 4.1. Note that the rate of production is greatest in tropical forests, wetlands, coral reefs, and estuaries. The production for each ecosystem type is calculated as its productivity multiplied by its area. However, the largest amounts of production occur in tropical forests and the open ocean. Note that the open ocean has a relatively small productivity, but its global production is large because of its enormous area.

Table 4.1. Primary Production of Earth's Major Ecosystems. The ecosystems are listed in order of net primary productivity. Productivity is the rate of production, standardized to area and time, while production is the total amount of biomass (in dry tonnes) produced by the global area of an ecosystem. See Chapter 8 for descriptions of these biomes (major kinds of ecosystems). Source: modified from Whittaker and Likens (1975).

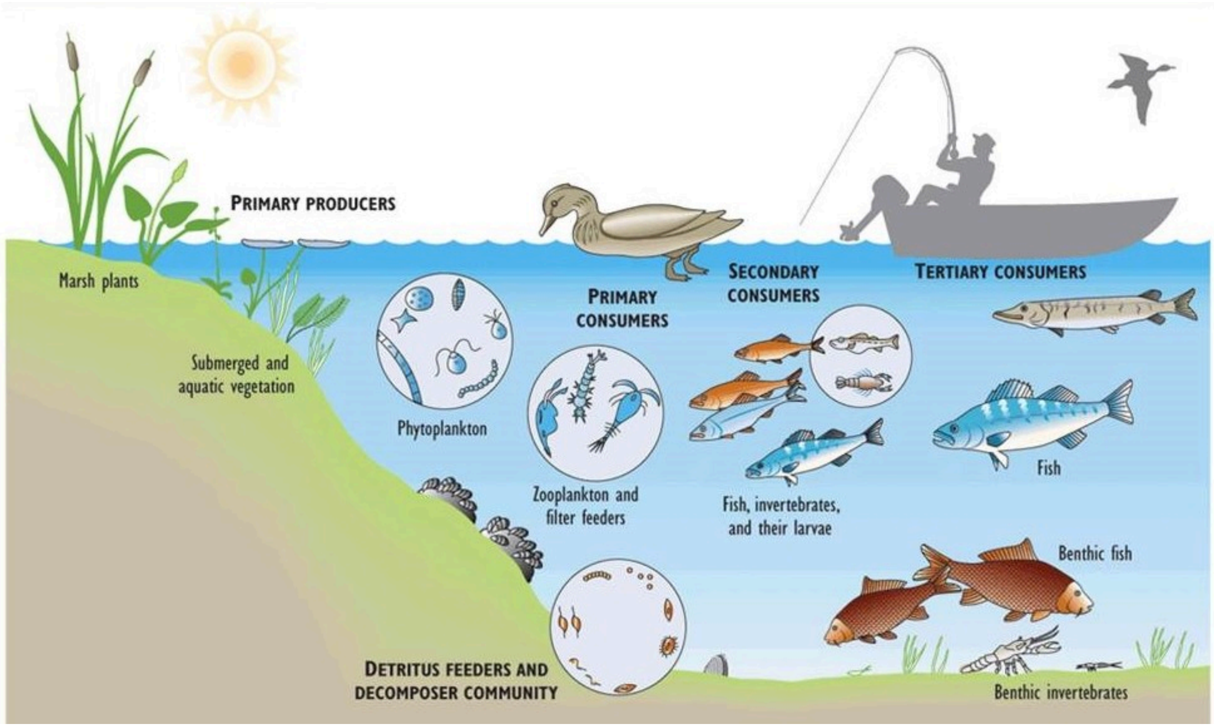
Biome (ecosystem)	Area (× 10^6 km^2)	Net Primary Productivity	Global Net Production (×10^9 t/y)
Wetlands	2	30	6
Tropical rain forest	17	22	37.4
Tropical seasonal forest	7.5	16	12
Temperate evergreen fores	5	13	6.5
Temperate deciduous fore	7	12	8.4
Savannah	15	9	13.5
Boreal forest	12	8	9.6
Open woodland	8.5	7	6
Cultivated land	14	6.5	9.1
Temperate grassland	9	6	5.4
Lake & stream	2	4	0.8
Tundra, arctic and alpine	2	4	0.8
Desert & semi-desert scrul	18	0.9	1.6
Extreme desert	24	<0.1	0.1
Total Continental	**149**	**7.8**	**117.5**
Reefs & estuaries	2	18	3.7
Shelf & upwelling	27	3.6	9.8
Open ocean	332	1.3	41.5
Total Marine	**361**	**1.5**	**55**
World Total	**510**	**3.4**	**172.5**

An ecological food chain is a linear model of feeding relationships among species. An example of a simple food chain in northern Canada is lichens and sedges, which are eaten by caribou, which are eaten by wolves. A food web is a more complex model of feeding relationships, because it describes the connections among all food chains within an ecosystem. Wolves, for instance, are opportunistic predators that may feed on snowshoe hare, voles, lemming, beaver, birds, and other prey in addition to their usual prey of deer, moose, and caribou. Therefore, wolves participate in various food chains within their ecosystem. However, no natural predators feed on wolves, which are therefore referred to as top carnivores or top predators.

Figure 4.3 illustrates important elements of the food web of Lake Erie, one of the Great Lakes. In this large lake, shallow-water environments support aquatic plants, while phytoplankton occur throughout the upper water column. The shallow-water plants are consumed by ducks, muskrat, and other herbivores, while phytoplankton are consumed by tiny crustaceans (zooplankton) and bottom-living filter-feeders such as clams. Zooplankton are eaten by small fish such as smelt, which are eaten by larger fish, which may eventually be eaten by cormorants, bald eagles, or humans. Dead biomass from any level of the food web may settle to the bottom, where it enters a detrital food web and is eaten by small animals and ultimately decomposed by bacteria and fungi.

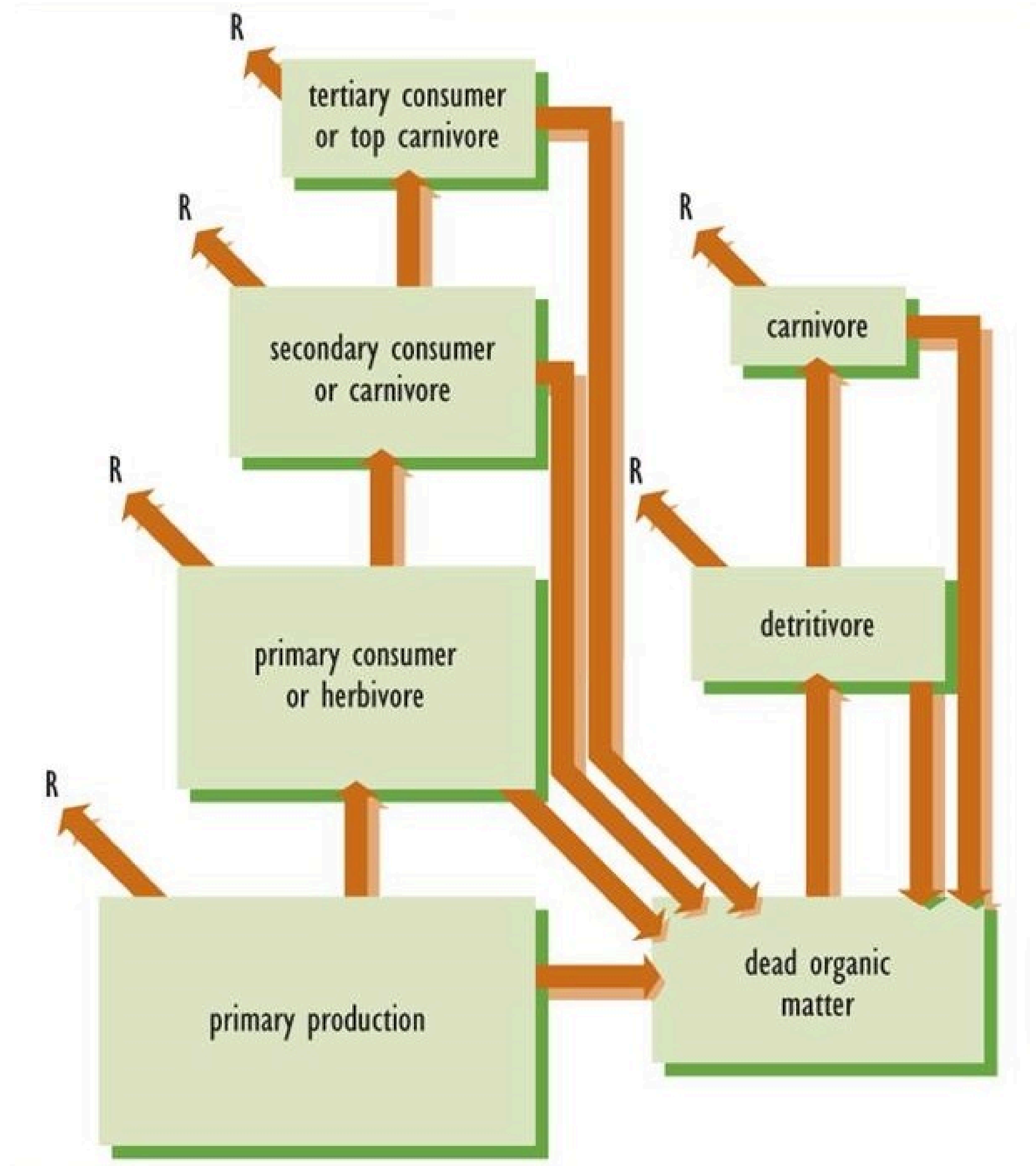
Figure 4.3. Major Elements of the Food Web in Lake Erie. Food webs are complex systems, involving many

species and various food chains.



In accordance with the second law of thermodynamics, the transfer of energy in food webs is always inefficient because some of the fixed energy must be converted into heat. For example, when a herbivore consumes plant biomass, only some of the energy content can be assimilated and transformed into its biomass. The rest is excreted in feces or utilized in respiration (Figure 4.4). Consequently, in all ecosystems the amount of productivity by autotrophs is always much greater than that of herbivores, which in turn is always much greater than that of their predators. As a broad generalization, there is about a 90% loss of energy at each transfer stage. In other words, the productivity of herbivores is only about 10% of that of their plant food, and the productivity of the first carnivore level is only 10% of that of the herbivores they feed upon.

Figure 4.4. Model of Energy Transfer in an Ecosystem. Lower levels of a food web always have a greater production than higher levels. For this reason, the trophic structure is roughly pyramidal. According to the second law of thermodynamics, some of the energy content in food webs is converted into heat or respiration (R). There is about a 90% loss of energy at each transfer stage.



These productivity relationships can be displayed graphically using a so-called ecological pyramid to represent the trophic structure of an ecosystem. Ecological pyramids are organized with plant productivity on the bottom, that of herbivores above the plants, and carnivores above the herbivores. If the ecosystem sustains top carnivores, they are represented at the apex of the pyramid. The sizes of the trophic boxes in Figure 4.4 suggest the pyramid-shaped structure of ecosystem productivity.

The second law of thermodynamics applies to ecological productivity, a function that is directly related to energy flow. The second law does not, however, directly explain the accumulated biomass of an ecosystem. Consequently, it is only the trophic structure of productivity that is always pyramid-shaped. In some ecosystems, other variables may have a pyramid-shaped trophic structure, such as the amounts of biomass (standing crop) present at specific times, or the sizes or densities of populations. However, these particular variables are not pyramid-shaped in all ecosystems.

For example, in the open ocean, phytoplankton are the primary producers, but they often maintain a biomass similar to that of the small zooplankton that feed upon them. The phytoplankton cells are relatively short-lived, and their biomass turns over quickly because of their high rates of productivity and mortality. In contrast, the individual zooplankton animals are longer-lived and much less productive than the phytoplankton. Consequently, the productivity of the phytoplankton is much larger than that of the zooplankton, even though at any particular time these trophic levels may have a similar biomass.

Some ecosystems may even have an inverted pyramid of biomass, characterized by a smaller biomass of plants than of herbivores. This sometimes occurs in grasslands, in which the dominant plants are relatively small herbaceous species that can be quite productive but do not maintain a large biomass. In comparison, some of the herbivores that feed on the plants are large, long-lived animals, which may maintain a greater total biomass than the vegetation. Some temperate and tropical grasslands have an inverted biomass pyramid, especially during the dry season when there may be large populations (and biomass) of long-lived herbivores such as antelope, bison, deer, elephant, gazelle, hippopotamus, or rhino. However, in accordance with the second law of thermodynamics, the annual (or long-term) productivity of the plants in these grasslands is always much larger than that of the herbivores.

In addition, the population densities of animals are not necessarily smaller than those of the plants that they eat. For instance, insects are the most important herbivores in many forests and they commonly maintain large populations. In contrast, the numbers of trees are much smaller, because each individual plant is large and occupies a great deal of space. Forests typically maintain many more herbivores than trees and other plants, so the pyramid of numbers is inverted in shape. As in all ecosystems, however, the pyramid of forest productivity is much wider at the bottom than at the top.

Because of the inefficiency of the energy transfer between trophic levels, there are energetic limits to the numbers of top carnivores (such as eagles, killer whales, sharks, and wolves) that can be sustained by an ecosystem. To sustain a viable population of top predators, there must be a suitably large production of prey that these animals can exploit. This prey must in turn be sustained by an appropriately high plant productivity. Because of these ecological constraints, only extremely productive or very extensive ecosystems can support top predators. Of all Earth's terrestrial ecosystems, none supports more species of higher-order carnivores than the savannahs and grasslands of Africa. The most prominent of these top predators are the cheetah, hyena, leopard, lion, and wild dog. This unusually high richness of top predators can be sustained because these African ecosystems are immense and quite productive of vegetation, except during years of drought. In contrast, the tundra of northern Canada can support only one natural species of top predator, the wolf. Although the tundra is an extensive biome, it is a relatively unproductive ecosystem.

Some pre-industrial human populations functioned as top predators. This included certain Aboriginal peoples of Canada, such as the Inuit of the Arctic and many First Nations cultures of the boreal forest. As an ecological consequence of their higher-order feeding strategy within their food web, these cultures were not able to maintain large populations. In most modern economies, however, humans interact with ecosystems in an omnivorous manner—we harvest an extremely wide range of foods and other biomass products of microbes, fungi, algae, plants, and invertebrate and vertebrate animals. One of the consequences of this kind of feeding is that a large human population can be sustained.

> Enviromental Issues 4.1. Vegetarianism and Energy Efficiency
>
> Most people have an omnivorous diet, meaning they eat a wide variety of foods of both plant and animal origin. Vegetarians, however, do not eat meat or other foods produced by killing birds, fish, mammals, or other animals. Some vegetarians, known as vegans, do not eat any foods of animal origin, including cheese, eggs,

honey, or milk. People may choose to adopt a vegetarian lifestyle for various reasons, including those that focus on the ethics of the rearing and slaughter of animals and the health benefits of a balanced diet that does not include animal products. In addition, there are large environmental benefits of vegetarianism. They are dues to avoiding certain air, water, and soil pollutants, and reducing the conversion of natural habitat into agroecosystems used for livestock rearing. In addition, it takes much less energy to feed a population of vegetarian humans than omnivorous ones.

Cultivated animals eat a great deal of food. In the industrial agriculture practised in developed countries, including Canada, livestock are raised mostly on a diet of plant products, including cultivated grain. Some vegetarians argue that if that grain were fed directly to people, the total amounts of cereals and agricultural land needed to support the human population would be much less. This argument is based on the inefficiency of energy transfer between trophic levels, which we examined in this chapter in a more ecological context. This energy-efficiency argument is most compelling for animals that are fed on grain and other concentrated foods. It is less relevant to livestock that spend all or part of their life grazing on wild rangeland – in that ecological context, ruminant animals such as cows and sheep are eating plant biomass that humans could not directly consume and so they are producing food that would not otherwise be available.

Similarly, many chickens, pigs, and other livestock are fed food wastes (for example, from restaurants) and processing by-products (such as vegetable and fruit culls and peelings, and grain mash from breweries) that are not suitable for human consumption. It has been estimated that about 25% of global cropland is being used to grow grain and other foods for livestock, and that 37% of the world's cereal production is fed to agricultural animals. In North America, however, about 70% of the grain production is fed to livestock. And there are immense numbers of agricultural animals: globally, there are more than 3 billion cows, goats, and sheep, and at least 20 billion chickens. The cows alone eat the equivalent of the caloric needs of 8–9 billion people.

Assimilation efficiency is a measure of the percentage of the energy content of an ingested food that is absorbed by the gut and therefore available to support the metabolic needs of an animal. This efficiency varies among groups of animals and also depends on the type of food being eaten. Herbivorous animals typically have an assimilation efficiency of 20–50%, with the smaller rate being for tough, fibrous, poor-quality foods such as grass and straw, and the larger one for higher-quality foods such as grain. Carnivores have a higher assimilation efficiency, around 80%, because their food is so dense in protein and fat. Overall, it takes about 16 kg of feed to produce 1 kg of beef in a feedlot. The ratios for other livestock are 6:1 for pork, 3:1 for chicken, and 2:1 to 3:1 for farmed fish. These assimilation inefficiencies would be avoided if people directly ate the grain consumed by livestock.

Ecological energetics is not the only consideration in the energy efficiency of vegetarianism. Huge amounts of energy are also used to convert natural ecosystems into farmland, to cultivate and manage the agroecosystems, to transport commodities, to process and package foods, and to transport, treat, or dispose of waste materials. These energy expenditures would also be substantially reduced if more people had a vegetarian diet and lifestyle. Clearly, vegetarians have a smaller "ecological footprint" associated with their feeding habits (see Table 25.1 in Chapter 25).

Conclusions

Energy can exist in various states, but transformations from one to another must obey the laws of thermodynamics. Organisms and ecosystems would spontaneously degrade if they did not have continuous access to external sources of energy. Ultimately, sunlight is the key source of energy that supports almost all life and ecosystems. Sunlight is used by photoautotrophs to combine carbon dioxide and water into simple organic molecules through the metabolic process of photosynthesis. The fixed energy of plant biomass supports ecological food webs. Plants may be eaten by herbivores and the energy obtained is used to support their own growth. Herbivores may then be eaten by carnivores. Dead biomass supports a decomposer food web. Sunlight also drives important planetary functions, such as the hydrologic and climatic systems. Human activities can have a large and degrading influence on food webs, and even on Earth's climatic system by influencing the intensity of the planet's greenhouse effect.

Questions for Review

1. What forms of energy are described in this chapter? How can each be changed into other forms?
2. What are the first and second laws of thermodynamics? How do they govern transformations of energy?
3. What are the major elements of Earth's physical energy budget?
4. Why is the trophic structure of ecological productivity pyramid-shaped?

Questions for Discussion

1. According to the second law of thermodynamics, systems always spontaneously move toward a condition of greater entropy. Yet life and ecosystems on Earth represent local systems where negative entropy is continuously being generated. What conditions allow this apparent paradox to exist?
2. Why are there no natural higher-order predators that kill and eat lions, wolves, and sharks?
3. Why would it be more efficient for people to be vegetarian? Discuss your answer in view of the pyramid-shaped structure of ecological productivity.
4. Make a list of the key sources and transformations of energy that support you and your activities on a typical day. What is the ultimate source of each of the energy resources you use (such as sunlight and fossil fuels)?

Exploring Issues

1. As part of a study of the cycling of pollutants, you have been asked to describe the food web of two local ecosystems. One of the ecosystems is a natural forest (or prairie) and the other is an area used to grow wheat (or another crop). How would you determine the major components of the food webs of these ecosystems, the species occurring in their trophic levels, and the interactions among the various species that are present?

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Chapter 5 ~ Flows and Cycles of Nutrients

Key Concepts

After completing this chapter, you will be able to

1. Explain what nutrients are and give examples.
2. Discuss the concept of nutrient cycling and describe important compartments and fluxes.
3. Describe factors that affect the development of major soil types.
4. Describe the cycles of carbon, nitrogen, phosphorus, and sulphur.

Nutrients

Nutrients are any chemicals that are needed for the proper functioning of organisms. We can distinguish two basic types of nutrients: (1) inorganic chemicals that autotrophic organisms require for photosynthesis and metabolism, and (2) organic compounds ingested as food by heterotrophic organisms. This chapter deals with the inorganic nutrients.

Plants absorb a wide range of inorganic nutrients from their environment, typically as simple compounds. For example, most plants obtain their carbon as gaseous carbon dioxide (CO_2) from the atmosphere, their nitrogen as the ions (charged molecules) nitrate (NO_3^-) or ammonium (NH_4^+), their phosphorus as phosphate (PO_4^{3-}), and their calcium and magnesium as simple ions (Ca^{2+} and Mg^{2+}). The ions are obtained in dissolved form in soil water absorbed by plant roots. Plants utilize these various nutrients in photosynthesis and other metabolic processes to manufacture all of the biochemicals they need for growth and reproduction.

Some inorganic nutrients, referred to as macronutrients, are needed by plants in relatively large quantities. These are carbon, oxygen, hydrogen, nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur. Carbon and oxygen are required in the largest amounts because carbon typically comprises about 50% of the dry weight of plant biomass and oxygen somewhat less. Hydrogen accounts for about 6% of dry plant biomass, while nitrogen and potassium occur in concentrations of 1-2% and those of calcium, phosphorus, magnesium, and sulphur are 0.1-0.5%. Micronutrients are needed in much smaller amounts, and they include boron, chlorine, copper, iron, manganese, molybdenum, and zinc. Each of these accounts for less than 0.01% of plant biomass and as little as a few parts per million (ppm, or 10^{-6}; 1 ppm is equivalent to 0.0001%; see Appendix A).

Image 5.1. The productivity of a natural ecosystem is often limited by the supply of nutrients. This can be investigated by experimentally adding fertilizer to the system. In this case, nitrogen fertilizer was added to a meadow in Arctic tundra on Ellesmere Island, resulting in increased productivity. The experimental plot is a slightly darker colour. Source: B. Freedman.

Heterotrophs obtain the nutrients they require from the food they eat, which may be plant biomass (in the case of a herbivore), other heterotrophs (carnivore), or both (omnivore). The ingested biomass contains nutrients in various organically bound forms. Animals digest the organic forms of nutrients in their gut and assimilate them as simple organic or inorganic compounds, which they use to synthesize their own necessary biochemicals through various metabolic processes.

Nutrient Flows and Cycles

Although Earth gains small amounts of material through meteorite impacts, these extraterrestrial inputs are insignificant in comparison with the mass of the planet. Essentially, at the global level, Earth is an isolated system in terms of matter. As a consequence of this fact, nutrients and other materials "cycle" within and between ecosystems. In contrast, energy always "flows through" ecosystems and the biosphere (Chapter 4). Nutrient cycling refers to the transfers, chemical transformations, and recycling of nutrients in ecosystems. A nutrient budget is a quantitative (numerical) estimate of the rates of nutrient input and output to and from an ecosystem, as well as the amounts present and transferred within the system.

The major elements of a nutrient cycle are shown in Figure 5.1. The outer boundary of the diagram defines the limits of an ecosystem. (It could even represent the entire biosphere, in which case there would be no inputs to or outputs from the system.) In ecological studies, the system is often defined as a particular landscape, lake, or watershed (a terrestrial basin from which water drains into a stream or lake). Each of these systems has inputs and outputs of nutrients, the rates of which can be measured.

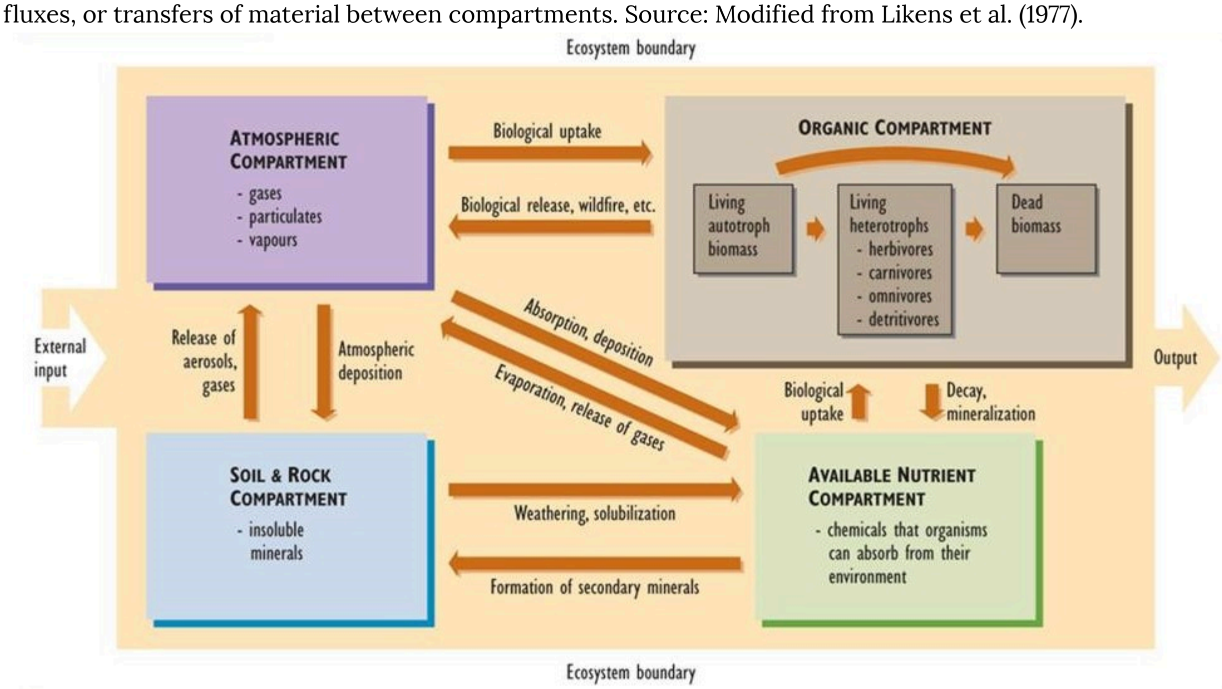
The boxes within the boundary represent compartments, each of which stores a quantity of material. Compartment sizes are typically expressed in units of mass per unit of surface area. Examples of such units are kilograms per hectare (kg/ha) or tonnes per hectare (t/ha). In aquatic studies, compartment sizes may be expressed per unit of water volume (such as g/m^3). The arrows in the diagram represent fluxes, or transfers of material between compartments. Fluxes are rate functions, and are measured in terms of mass per area per time (e.g., kg/ha-yr).

The system can be divided into four major compartments:

1. ***The atmosphere*** consists of gases and small concentrations of suspended particulates and water vapour.
2. ***Rocks and soil*** consist of insoluble minerals that are not directly available for uptake by organisms.
3. ***Available nutrients*** are present in chemical forms that are water soluble to some degree, so they can be absorbed by organisms from their environment and contribute to their mineral nutrition.
4. ***The organic compartment*** consists of nutrients present within living and dead organic matter. This compartment can be divided into three functional groups: (a) living biomass of autotrophs such as plants, algae, and autotrophic bacteria, (b) living heterotrophs including herbivores, carnivores, omnivores, and detritivores, and (c) and all forms of dead organic matter.

The major transfers of material between compartments, or fluxes, are also shown in Figure 5.1. These are important transfer pathways within nutrient cycles. For instance, insoluble forms of nutrients in rocks and soil become available for uptake by organisms through various chemical transformations, such as weathering, that render the nutrients soluble in water. This is reversed by reactions that produce insoluble compounds from soluble ones. These latter reactions form secondary minerals such as carbonates (e.g. limestone, $CaCO_3$, and dolomite, $MgCO_3$), oxides of iron and aluminum (Fe_2O_3 and $Al(OH)_3$), sulphides (e.g., iron sulphide, FeS_2), and other compounds that are not directly available for biological uptake.

Figure 5.1. Conceptual Diagram of a Nutrient Cycle. This diagram shows the major elements of a nutrient cycle for a particular ecosystem, such as a watershed. Each box represents a compartment (atmosphere, soil and rocks, organic material, and available nutrients) that contains a quantity of material. The arrows represent fluxes, or transfers of material between compartments. Source: Modified from Likens et al. (1977).



Other fluxes in nutrient cycles include the biological uptake of nutrients from the atmosphere or from the available pool in soil. For example, plant foliage assimilates carbon dioxide (CO_2) from air, and roots absorb nitrate (NO_3^-) and ammonium (NH_4^+) ions dissolved in soil water. Plants then metabolically fix these nutrients into their growing biomass. The organic nutrients may then enter the food web and are eventually deposited as dead biomass. Organic nutrients in dead biomass are recycled through decay and mineralization, which regenerate the supply of available nutrients.

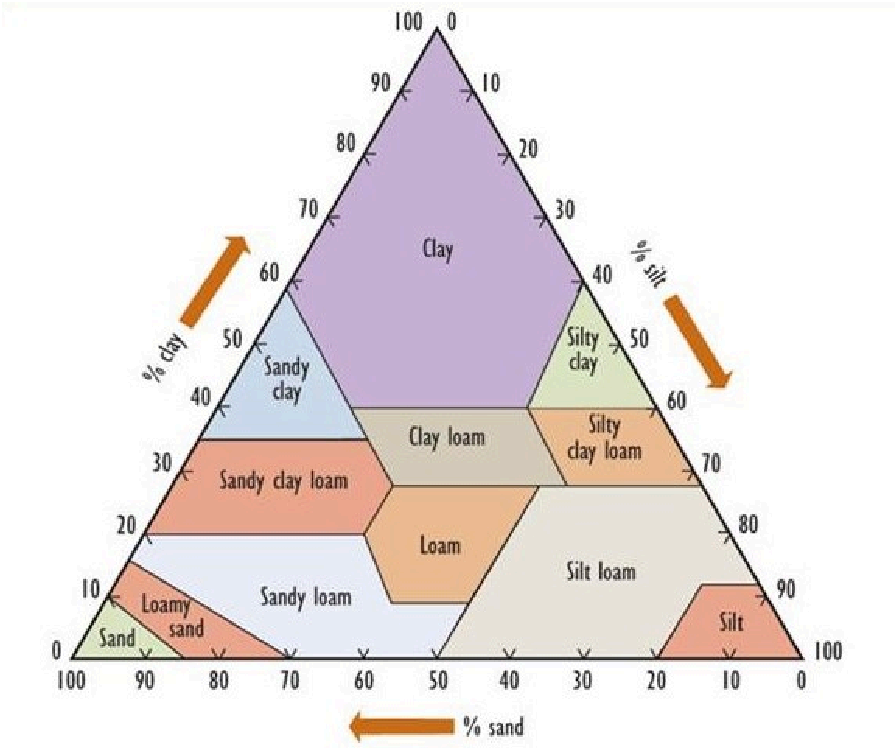
These concepts are examined in more detail in the following sections. Initially, we examine the soil ecosystem, which is where most nutrient cycling occurs within terrestrial habitats. We will then examine key aspects of the cycling of carbon, nitrogen, phosphorus, and sulphur.

The Soil Ecosystem

Soil is a complex and variable mixture of fragmented rock, organic matter, moisture, gases, and living organisms that covers almost all terrestrial landscapes. Soil provides mechanical support for growing, even for trees as tall as 100 m. Soil also stores water and nutrients for use by plants and provides habitat for the many organisms that are active in the decomposition of dead biomass and recycling of its nutrient content. Soil is a component of all terrestrial ecosystems, but it is also in itself a dynamic ecosystem.

Soil develops over long periods of time toward a mature condition. Fundamentally, soil is derived from a so-called parent material, which consists of rocks and minerals that occur within a metre or so of the surface. Parent materials in most of Canada were deposited through glacial processes, often as a complex mixture known as till, which contains rock fragments of various sizes and mineralogy. In some areas, however, the parent materials were deposited beneath immense inland lakes, usually in post-glacial times. Such places are typically flat and have uniform, fine-grained soils ranging in texture from clay to sand. (Clay particles have a diameter less than 0.002 mm, while silt ranges from 0.002 to 0.05 mm, sand from 0.05 to 2 mm, gravel from 2 to 20 mm, and coarse gravel and rubble are larger than 20 mm.) Figure 5.2 presents a textural classification of soil based on the percentage of clay-, silt-, and sand-sized particles.

Figure 5.2. A Textural Classification of Soils. The percentage composition of clay-, silt-, and sand-sized particles is used to classify soils into the 12 major types that are shown. Source: Modified from Foth (1990).



In other regions, parent materials known as loess are derived from silt that was transported by wind from other places. Because of their very small particle size, soil rich in clay has an enormous surface area, giving it important chemical properties such as the ability to bind many nutrient ions.

The characteristics of the parent material have an important influence on the type of soil that eventually develops. However, soil development is also profoundly affected by biological processes and climatic factors such as precipitation and temperature.

For example, water from precipitation dissolves certain minerals and carries the resulting ions downward. This process, known as leaching, modifies the chemistry and mineralogy of both the surface and deeper parts of the soil. In addition, inputs of litter (dead biomass) from plants increase the content of organic matter in soil. Fresh litter is a food substrate for many decomposer species of soil-dwelling animals, fungi, and bacteria. These organisms eventually oxidize the organic debris into carbon dioxide, water, and inorganic nutrients such as ammonium, although some material remaining as complex organic matter, known as humus. As soils develop, they assume a vertical stratification known as a soil profile, which has recognizable layers known as horizons. From the surface downward, the major horizons of a well-developed soil profile are as follows:

Horizon	Description
L	***Litter layer*** contains organic matter that is readily identifiable as plant litter
F	***Fermentation or duff layer*** contains partly decomposed organic matter with small litter fragments still visible
H	***Humus layer*** contains well-decomposed (humified) organic matter with few readily identifiable fragments
A_1	***Transitional A horizon*** has a high organic concentration mixed with inorganic materials
A_2 or A_e	***Eluviated A horizon*** has a relatively light colour with low concentrations of organic matter and certain minerals (such as iron and aluminum) that have been leached downward (or eluviated) with percolating water
B	***Accumulation horizon*** has a darker colour because of the deposition of clay, iron, and organic matter leached from the A horizon
C	***Parent material***, or the original mineral substrate, which has not been influenced by soil-forming processes
R	***Regolith*** or underlying bedrock

Soil that has been modified by human influences may be stratified differently. In cultivated land, for example, a homogeneous plough layer (A_p) of 15-20 cm develops at the surface. The plough layer is uniform in structure because it has been repeatedly mixed up for many years. In addition, the soil of agricultural land is often deficient in organic matter, compacted by the repeated passage of heavy machinery, and degraded in structure, nutrient concentration, and other qualities important to its ability to support crop productivity. These subjects are examined in more detail in Chapters 14 and 24.

Image 5.2. Soil in natural ecosystems often develops a vertical stratification. Typically, there are organic-rich horizons on the surface and mineral-rich ones below. This soil “pit” was dug in a spruce-dominated stand of boreal forest in Labrador. Beneath the darker organic surface layer is a light-coloured mineral horizon from which iron and aluminum ions have been leached downward by percolating water. The next reddish layer is part of the B horizon, where iron and aluminum are deposited. The lightish bottom layer is the parent material, which in this case is sand deposited by the Churchill River thousands of years ago. Source: B. Freedman

Broadly speaking, soil within a particular kind of ecosystem, such as tundra, conifer forest, hardwood forest, or prairie, tends to develop in a distinctive way. Soils are classified by the ecological conditions under which they developed. The highest level of classification arranges soils into groups called orders, which can themselves be divided into more detailed assemblies. The most important soil orders in Canada are:

Soil Order	Description
Chernozem	Forms in cool temperate climate with sufficient rainfall to support tall-grass and mixed-grass prairie. Has a thick, blackish, organic-rich A horizon, rich in calcium carbonate at the surface. The B horizon is lighter coloured, and the C horizon is rich in calcium carbonate.
Podzol	Forms in a cool temperate, humid climate, especially under coniferous and mixed conifer and hardwood forest. Has a thick, acidic, LFH layer, a highly leached A_e horizon, and often a reddish B horizon due to the deposition of iron oxides. Also known as spodosol.
Brunisol	Forms in a temperate, humid climate under hardwood forest, and usually from calcium-rich parent material. Little accumulation of litter, with a dark-brown A horizon and a lighter coloured B horizon. Also known as brown forest soil.
Luvisol	Develops under a range of climatic conditions from boreal to temperate, and under a range of forest types from coniferous to hardwood. Little accumulation of litter, with a slightly acidic A_e horizon and a neutral, clay-rich B horizon.
Regosol	Develops under various climatic conditions from poorly consolidated parent materials such as sand or silt. Has little profile development.
Gleysol	Develops in a cool temperate climate on sites that are subject to periodic waterlogging, usually because the C horizon is not permeable to downward movement of water. The waterlogged surface layers become anoxic (oxygen-depleted), which fosters the downward leaching of iron and manganese compounds, which deposit lower down in grey-red mottled
Solonetz	Develops in semi-desert to arid climates under moderate drainage and somewhat saline conditions that support salt-tolerant plants. Has a thin surface layer over a darker, alkaline
Organic	Develops in a cool, humid climate in wetlands such as bogs and fens. It is characterized by surface peat deposits that can be up to 10 m thick.

The Importance of Soil

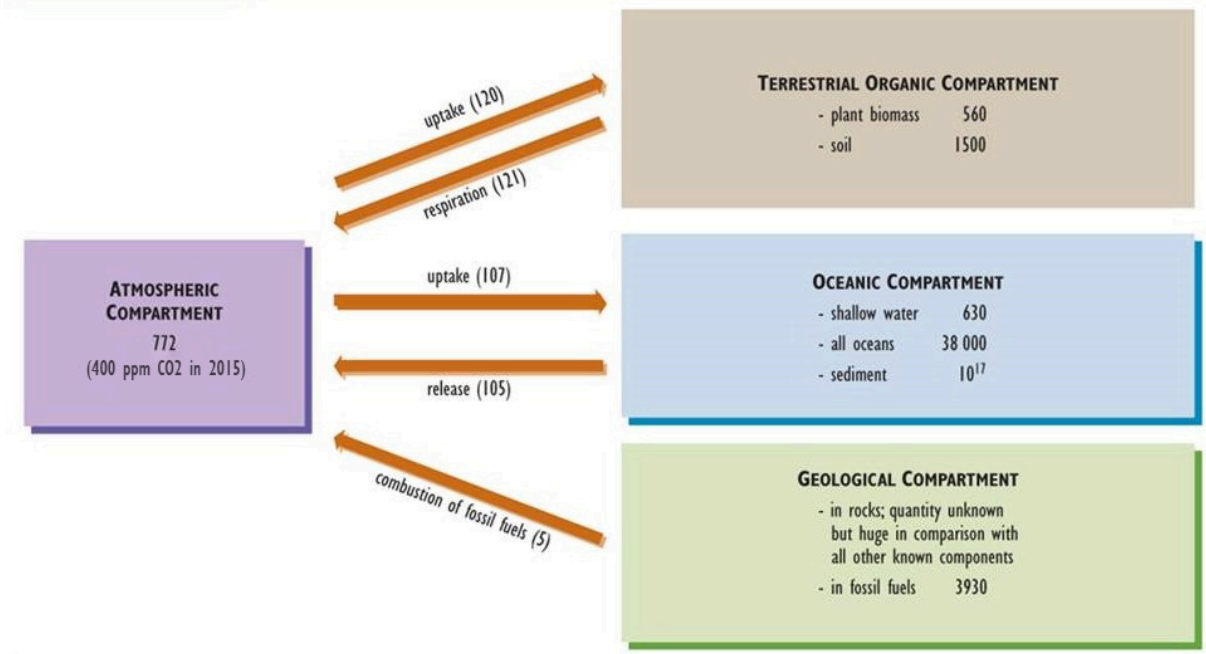
The soil ecosystem is extremely important. Terrestrial plants obtain their water and much of the nutrients they need from the soil, absorbing them through their roots. Soil also provides habitat for a great diversity of animals and microorganisms that play a crucial role in litter decomposition and nutrient cycling.

Soil is economically important because it critically influences the kinds of agricultural crops that can be grown (this topic is examined in Chapter 14). Some of the most productive agricultural soils are alluvial deposits found along rivers and their deltas, where periodic flooding and silt deposition bring in abundant supplies of nutrients. As long as they are not too stony, chernozem and brunisol are also fertile and useful for agriculture. Much prairie agriculture is developed on chernozem soils, while much of the fertile agricultural land of southern Quebec and Ontario has brunisol types.

The Carbon Cycle

Carbon is one of the basic building blocks of life and the most abundant element in organisms, accounting for about half of typical dry biomass. Key aspects of the global carbon cycle are presented in Figure 5.3 (see also Chapter 17 and Figure 17.1). Gaseous carbon dioxide (CO_2) is the most abundant form of carbon in the atmosphere, where it occurs in a concentration of about 400 ppm (0.04%), although methane (CH_4, 1.8 ppm) is also significant.

Figure 5.3. Model of the Global Carbon Cycle. Carbon is stored in the various compartments (atmosphere, organic material, oceans, and soil/rock) and moves from one box to another. The amounts of carbon in compartments are expressed in units of billions of tonnes of carbon (10^9 t or gigatonnes, Gt), while fluxes between them are in 10^9 t/y. Based on data from Blasing (1985), Solomon et al. (1985), and Freedman (1995).



Atmospheric CO_2 is a critical nutrient for photosynthetic organisms, such as plants and algae. Plants absorb this gas through tiny pores (called stomata) in their foliage, fix it into simple sugars, and then use the fixed energy to support their respiration and to achieve growth and reproduction. The biomass of autotrophs is available to be consumed by heterotrophs and passed through food webs. All organisms release CO_2 to the atmosphere as a waste product of their respiratory metabolism.

CO_2 is also the most common emission associated with the decomposition of dead organic matter. However, if this process occurs under anaerobic conditions (in which oxygen, O_2, is not present), then both CO_2 and CH_4 are emitted. Because anaerobic decomposition is relatively inefficient, dead organic matter often accumulates in wetlands such as swamps and bogs, eventually forming peat. Under suitable geological conditions of deep burial, high pressure and temperature, and a lack of oxygen, peat and other organic materials may be slowly transformed into carbon-rich fossil fuels such as coal, petroleum, and natural gas (see Chapter 13).

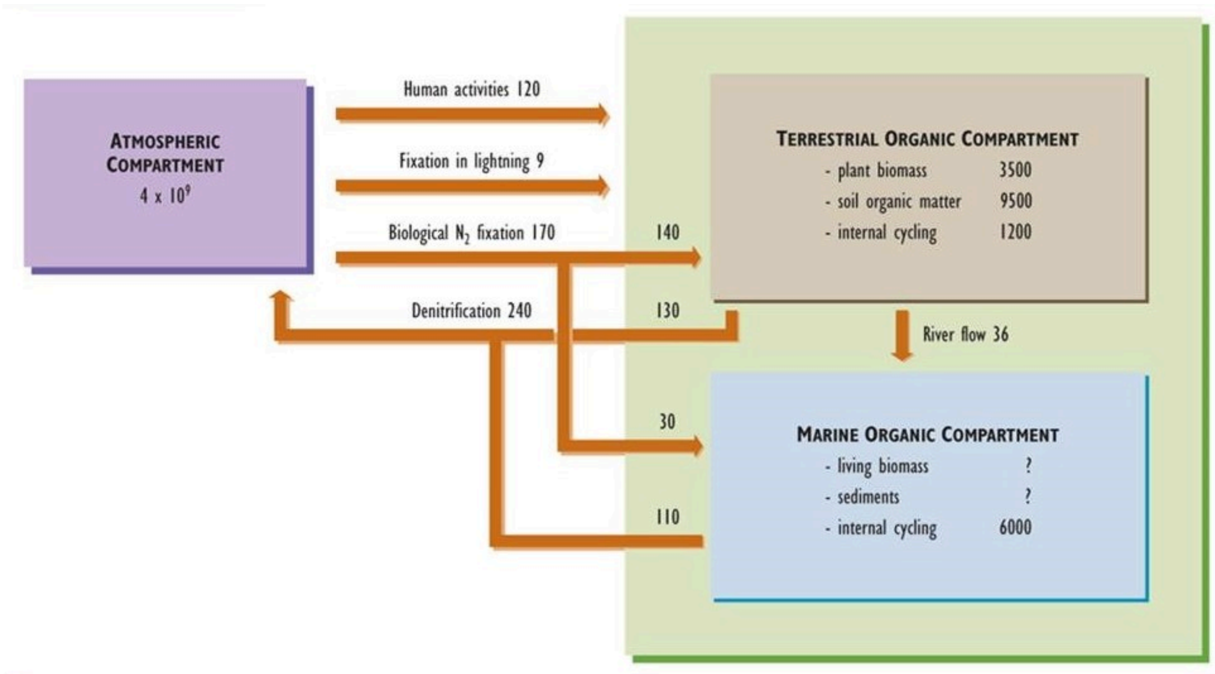
Atmospheric CO_2 also dissolves into oceanic water, forming the bicarbonate ion (HCO_3^-), which can be taken up and fixed by photosynthetic algae and bacteria, which are the base of the marine food web. Various marine organisms also use oceanic CO_2 and HCO_3^- to manufacture their shells of calcium carbonate ($CaCO_3$), an insoluble mineral that slowly accumulates in sediment and may eventually lithify into limestone (also $CaCO_3$).

Over almost all of geological time, the amount of CO_2 absorbed by the global biota from the atmosphere was similar to that released through respiration and decomposition. Consequently, the cycling of this nutrient can be viewed as a steady-state system. In modern times, however, anthropogenic emissions have changed the atmospheric carbon balance. Global emissions of CO_2 and CH_4 are now larger than the uptake of these gases, an imbalance that has resulted in increasing concentrations in the atmosphere. This phenomenon appears to be intensifying the greenhouse effect of Earth and resulting in global warming (see Chapter 17).

The Nitrogen Cycle

Nitrogen is another important nutrient for organisms, being an integral component of many biochemicals, including amino acids, proteins, and nucleic acids. Like the carbon cycle, that of nitrogen has an important atmospheric phase. However, unlike carbon, nitrogen is not a significant constituent of rocks and minerals. Consequently, the atmospheric reservoir plays a paramount role in the cycling of nitrogen (Figure 5.4).

Figure 5.4. Model of the Global Nitrogen Cycle. Nitrogen occurs in three main compartments: the atmosphere, terrestrial organic material, and oceanic organic material. The amounts of nitrogen stored in compartments are expressed in units of millions of tonnes of nitrogen (10^6 t or megatonnes, Mt), while fluxes are in 10^6 t/y. Based on data from Hutzinger (1982) and Freedman (1995).



Virtually all nitrogen in the atmosphere occurs in the form of nitrogen gas (N_2, sometimes referred to as dinitrogen), which is present in a concentration of 78%. Other gaseous forms of nitrogen are ammonia (NH_3), nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O). These trace gases typically occur in atmospheric concentrations much less than 1 ppm, although there may be larger amounts close to sources of anthropogenic emissions (see Chapter 16). Nitrogen also occurs in trace particulates containing nitrate (NO_3^-) and ammonium (NH_4^+), such as ammonium nitrate (NH_4NO_3) and ammonium sulphate ($(NH_4)_2SO_4$), both of which can be significant pollutants related to acid rain and haze (see Chapters 16 and 19).

Nitrogen occurs in many additional forms in terrestrial and aquatic environments. “Organic nitrogen” refers to the great variety of nitrogen-containing molecules in living and dead biomass. These chemicals range in character from simple amino acids, through proteins and nucleic acids, to large and complex molecules that are components of humified organic matter. Nitrogen in ecosystems also occurs in a small number of inorganic compounds, the most important of which are N_2 and NH_3 gases and the ions nitrate, nitrite (NO_2^-), and ammonium. The nitrogen cycle involves the transformation and cycling of the various organic and inorganic forms of nitrogen within ecosystems.

Because the two nitrogen atoms in dinitrogen gas are held together by a strong triple bond, N_2 is a highly unreactive compound. For this reason N_2 can be directly used by only a few specialized organisms, even though it is extremely abundant in the environment. These nitrogen-fixing species, all of which are microorganisms, have the ability to metabolize N_2 into NH_3 gas, which can then be used for their nutrition. More importantly, the NH_3 also becomes indirectly available to the great majority of autotrophic plants and microorganisms that cannot fix N_2 themselves.

Biological nitrogen fixation is a critical process – most ecosystems depend on it to provide the nitrogen that sustains their primary productivity. In fact, because nitrogen is not an important constituent of rocks and soil minerals, N_2 fixation is ultimately responsible for almost all of the organic nitrogen in the biomass of organisms and ecosystems throughout the biosphere. The only other significant sources of fixed nitrogen for ecosystems are the atmospheric deposition of nitrate and ammonium in precipitation and dustfall, and the uptake of NO and NO_2 gases by plants. However, these are generally minor sources in comparison with biological N_2 fixation.

The best known of the N_2-fixing microorganisms are bacteria called Rhizobium, which live in specialized nodules on the roots of leguminous plants, such as peas and beans. Some non-legumes, such as alders, also live in a beneficial symbiosis (a mutualism; see Chapter 9) with N_2-fixing microorganisms. So do most lichens, which are a mutualism between a fungus and an alga. Many other N_2-fixing microbes are free-living in soil or water, such as cyanobacteria (blue-green bacteria).

Non-biological nitrogen fixation also occurs, for instance during a lightning event when atmospheric N_2combines with O_2 under conditions of great heat and pressure. Humans can also cause N_2 to be fixed. For example, nitrogen fertilizer is manufactured by combining N_2 with hydrogen gas (H_2, which is manufactured from CH_4, a fossil fuel) in the presence of iron catalysts to produce NH_3. In addition, NO gas is formed in the internal combustion engines of vehicles, where N_2 combines with O_2 under conditions of high pressure and temperature. Large amounts of NO are emitted to the atmosphere in vehicle exhaust, contributing to air pollution (Chapter 16). Anthropogenic N_2 fixation now amounts to about 120 million tonnes per year, about 83% of which is the manufacturing of fertilizer. This is a globally important component of the modern nitrogen cycle and is comparable in magnitude with non-human N_2fixation (about 170 million tonnes per year).

Image 5.3. Most species in the pea family (Fabaceae), such as these soybeans, develop a mutualism with Rhizobium bacteria. The Rhizobium live in nodules on the roots and fix nitrogen gas (N_2) into ammonia (NH_3), which the plant can use as a nutrient. Source: D. Patriquin

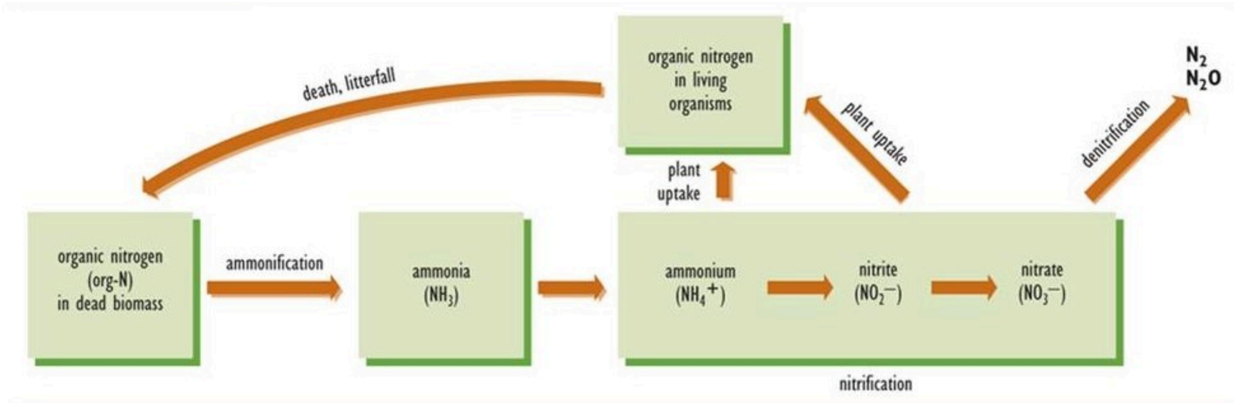
Ammonification and Nitrification

After an organism dies, its organically bound nitrogen must be converted to inorganic forms; otherwise, the recycling of its fixed nitrogen would not be possible (Figure 5.5). The initial stage of this process is ammonification, in which the organic nitrogen of dead biomass is transformed to ammonia, which acquires a hydrogen ion (H^+) to form ammonium (NH_4+). As such, ammonification is a component of the complex process of decay, but one that is specific to the nitrogen cycle. Ammonification is carried out by a variety of microorganisms. The resulting ammonium is a suitable source of nutrition for many species of plants, particularly those that live in environments with acidic soil. Most plants, however, cannot utilize NH_4+ effectively, and they require nitrate (NO_3-) as their main source of nitrogen nutrition.

Nitrification is the process by which nitrate is synthesized from ammonium. The initial step is the conversion of NH_4+ to nitrite (NO_2-), a function carried out by bacteria known as Nitrosomonas. Once the nitrite is formed, it is rapidly oxidized to nitrate by Nitrobacter bacteria. Because Nitrosomonas and Nitrobacter are sensitive to acidity, nitrification does not occur in acidic soil or water. This is why plants growing in acidic habitats must be able to use ammonium as their source of nitrogen.

Figure 5.5. Important Transformations of Fixed Nitrogen in Ecosystems. The diagram indicates the key transformations of nitrogen among its most important inorganic forms in soil and aquatic ecosystems. Source:

Modified from Freedman (1995).



Denitrification

In denitrification, also performed by a wide variety of microbial species, nitrate is converted to either of the gases N_2O or N_2, which are released to the atmosphere. Denitrification occurs under anaerobic conditions, and its rate is greatest when there is a large concentration of nitrate, for example in fertilized agricultural land that is temporarily flooded. In some respects, denitrification can be considered a counter-balancing process to nitrogen fixation. In fact, global rates of nitrogen fixation and denitrification are in a rough balance, so the total amount of fixed nitrogen in the biosphere is not changing much over time.

The Phosphorus Cycle

Phosphorus is a key constituent of many biochemicals, including fats and lipids, nucleic acids such as the genetic materials DNA and RNA, and energy-carrying molecules such as ATP. However, phosphorus is required by organisms in much smaller quantities than nitrogen or carbon. Nevertheless, phosphorus is often in short supply and so it is a critical nutrient in many ecosystems, particularly in freshwater and agriculture.

In contrast to the carbon and nitrogen cycles, that of phosphorus does not have a significant atmospheric phase. Although phosphorus compounds do occur in the atmosphere, as trace quantities in particulates, the resulting inputs to ecosystems are small compared with the amounts available from soil minerals or from the addition of fertilizer to agricultural land. Phosphorus tends to move from the terrestrial landscape into surface waters and then eventually to the oceans, where it deposits to sediment that acts as a long-term sink. Although some phosphorus minerals in oceanic sediment are eventually recycled to the land by geological uplift associated with mountain building, this is an extremely slow process and is not meaningful in ecological time scales. Therefore, aspects of the global phosphorus cycle represent a flow-through system.

Nevertheless, certain processes do return some marine phosphorus to portions of the continental landscape. For example, some kinds of fish spend most of their life at sea but migrate up rivers to breed. When they are abundant, fish such as salmon import substantial quantities of organic phosphorus to the higher reaches of rivers, where it is decomposed to phosphate after the fish spawn and die. Fish-eating marine birds are also locally important in returning oceanic phosphorus to land through their excrement.

Soil is the principal source of phosphorus uptake for terrestrial vegetation. The phosphate ion (PO_4^{3-}) is the most important form of plant-available phosphorus. Although phosphate ions typically occur in small concentrations in soil, they are constantly produced from slowly dissolving minerals such as calcium, magnesium, and iron phosphates

($Ca_3(PO_4)_2$, $Mg_3(PO_4)_2$, and $FePO_4$). Phosphate is also produced by the microbial oxidation of organic phosphorus, a component of the more general process of decay. Water-soluble phosphate is quickly absorbed by microorganisms and by plant roots and used in the synthesis of a wide range of biochemicals.

Aquatic autotrophs also use phosphate as their principal source of phosphorus nutrition. In fact, phosphate is commonly the most important limiting factor to the productivity of freshwater ecosystems. This means that the primary productivity will increase if the system is fertilized with phosphate, but not if treated with sources of nitrogen or carbon (unless they first have sufficient PO_4^{3-} added; see Chapter 20). Lakes and other aquatic ecosystems receive most of their phosphate supply through runoff from terrestrial parts of their watershed, and by the recycling of phosphorus from sediment and organic phosphorus suspended in the water column.

Humans are greatly affecting the global phosphorus cycle by mining it to manufacture fertilizer, and applying that material to agricultural land to increase its productivity. For some time, the major source of phosphorus fertilizers was guano, the dried excrement of marine birds. Guano is mined on islands, such as those off coastal Chile and Peru, where breeding colonies of seabirds are abundant and the climate is dry, allowing the guano to accumulate. During the twentieth century, however, deposits of sedimentary phosphate minerals were discovered in several places, such as southern Florida. Phosphorus had become geologically concentrated in sedimentary deposits in these places through the deposition of marine organisms over millions of years. These deposits are now being mined to supply mineral phosphorus used to manufacture agricultural fertilizer. However, when these easily exploitable mineral deposits become exhausted, phosphorus may turn out to be a limiting factor for agricultural production in the not-so-distant future.

About 50 million tonnes of phosphorus fertilizer are manufactured each year. This is a highly significant input to the global phosphorus cycle, in view of the estimate that about 200 million tonnes of phosphorus per year are absorbed naturally from soil by vegetation.

Image 5.4. Where colonial seabirds are abundant, their excrement (guano) can be mined as a source of phosphorus-rich fertilizer. This is a view of a large colony of fish-eating guanay cormorants (Phalacrocorax bougancillii) near Paracas off the coast of Peru. The dried guano is periodically scraped from the rocks and used for agricultural purposes. Source: B. Freedman.

Enviromental Issues 5.1. Too Much of a Good Thing – Pollution by Nutrients
Nutrients are essential to the healthy metabolism of organisms and to the proper functioning of ecosystems. Often, an increase in the supply of certain nutrients will enhance the productivity of wild and cultivated plants – this is the principle behind the use of fertilizer in agriculture. However, there are also cases in which an excessive supply of nutrients has caused important environmental problems.

Because the supply of available forms of nitrogen (particularly NO_3– and NH_4+) is often a limiting factor to agricultural productivity, these are generally the most abundant nutrients in fertilizer. However, the use of agricultural fertilizer can result in concentrations of NO_3– in drinking water that are high enough to be toxic to humans, especially to infants (see Chapter 24). We also know that plants can take up gaseous NO and N_2O from the atmosphere and use them as nutrients, along with NO_3– and NH_4+ from precipitation and soil water. Yet gaseous NO and N_2O are air pollutants if they occur in high concentrations, especially in sunny environments where they are involved in the photochemical production of toxic ozone (see Chapter 16). Furthermore, large amounts of NO_3– and NH_4+ in rain and snow may contribute to acid rain (see Chapter 19).

There are other examples of environmental problems caused by excessive nutrients. For instance, CO_2 is one of the most important plant nutrients because carbon comprises about half of plant biomass. But this critical nutrient occurs in a relatively small atmospheric concentration – only about 0.04%. However, the concentration of CO_2 in the atmosphere has increased by about 45% during the past two centuries and it continues to amplify. This well-documented change is contributing to global warming, an important environmental problem (see Chapter 17).

Eutrophication, or an excessive productivity of waterbodies, is another environmental problem related to an excessive supply of nutrients. It is most often caused by an excess of PO_4^{3-}, usually because of sewage dumping or runoff from fertilized agricultural land (see Chapter 20). Highly eutrophic lakes are degraded ecologically and may no longer be useful as a source of drinking water or for recreation.

Clearly, these examples show that there is a fine balance between chemicals serving as beneficial nutrients, or as damaging pollutants.

The Sulphur Cycle

Sulphur is a key constituent of certain amino acids, proteins, and other biochemicals. Sulphur is abundant in some minerals and rocks and has a significant presence in soil, water, and the atmosphere.

Atmospheric sulphur occurs in various compounds, some of which are important air pollutants (see Chapter 16). Sulphur dioxide (SO_2), a gas, is emitted by volcanic eruptions and is also released by coal-fired power plants and metal smelters. SO_2 is toxic to many plants at concentrations lower than 1 ppm. In some places, such as the Sudbury area, important ecological damage has been caused by this gas (Chapter 16).

In the atmosphere, SO_2 becomes oxidized to the anion (negatively charged ion) sulphate (SO_4^{2-}), which occurs as tiny particulates or is dissolved in suspended droplets of moisture. In this form, the negative charge of sulphate must be balanced by the positive charge of cations such as ammonium (NH_4+), calcium (Ca_2+), or hydrogen ion (H^+, a key element of "acid rain"; see Chapter 19).

Hydrogen sulphide (H_2S), which has a smell of rotten eggs, is emitted naturally from volcanoes and deep-sea vents. It is also released from habitats where organic sulphur compounds are being decomposed under anaerobic conditions, and from oxygen-poor aquatic systems where SO_4^{2-} is being reduced to H_2S. Dimethyl sulphide is another reduced-sulphur gas that is produced in the oceans and emitted to the atmosphere. In oxygen-rich environments, such as the atmosphere, H_2S is oxidized to sulphate, as is dimethyl sulphide, but more slowly.

Most emissions of SO_2 to the atmosphere are associated with human activities, but almost all H_2S emissions are natural. An important exception is the emission of H_2S from sour-gas wells and processing facilities, for example, in Alberta. Overall, the global emission of all sulphur-containing gases is equivalent to about 251 million tonnes of sulphur per year. About 41% of this emission is anthropogenic and the rest is natural (see Chapter 16).

Sulphur occurs in rocks and soils in a variety of mineral forms, the most important of which are sulphides, which occur as compounds with metals. Iron sulphides (such as FeS_2, called pyrite when it occurs as cubic crystals) are the most common sulphide minerals, but all of the heavy metals (such as copper, lead, and nickel) can exist in this mineral form. Wherever metal sulphides become exposed to an oxygen-rich environment, the bacterium Thiobacillus thiooxidans oxidizes the mineral, generating sulphate as a product. This autotrophic bacterium uses energy from this chemical transformation to sustain its growth and reproduction. This kind of primary productivity is called chemosynthesis (in parallel with the photosynthesis of plants). In places where large amounts of sulphide are oxidized, high levels of acidity are associated with the sulphate product, a phenomenon referred to as acid-mine drainage (see Chapter 19).

Sulphur also occurs in a variety of organically bound forms in soil and water. These compounds include proteins and other sulphur-containing substances in dead organic matter. Soil microorganisms oxidize organic sulphur to sulphate, an ion that plants can use in their nutrition.

Plants satisfy their nutritional requirements for sulphur by assimilating its simple mineral compounds from the environment, mostly by absorbing sulphate dissolved in soil water, which is taken up by roots. In environments where the atmosphere is contaminated by SO_2, plants can also absorb this gas through their foliage. However, too much absorption can be toxic to plants – there is a fine line between SO_2 as a plant nutrient and as a poison.

Human activities have greatly influenced certain fluxes of the sulphur cycle. Important environmental damage has been caused by SO_2 toxicity, acid rain, acid-mine drainage, and other sulphur-related problems. However, sulphur is also an important mineral commodity, with many industrial uses in manufacturing and as an agricultural fertilizer. Most commercial sulphur is obtained by cleaning "sour" natural gas (methane, CH_4) of its H_2S content and by removing SO_2 from waste gases at metal smelters.

Conclusions

Nutrients are chemicals that are essential for the metabolism of organisms and ecosystems. If they are insufficient in quantity, then ecological productivity is less than it potentially could be. Nutrients can also be present in excess, in which case environmental damage may be caused by toxicity and other problems. Nutrients routinely cycle among inorganic and organic forms within ecosystems. Key aspects of nutrient cycles are illustrated by the carbon, nitrogen, phosphorus, and sulphur cycles.

Questions for Review

1. What are the basic aspects of a nutrient cycle? In your answer, describe the roles of compartments and fluxes.
2. How is soil formed from a parent material? Include the influences of physical and biological processes in your answer.
3. What are the major kinds of soil? How do they differ?
4. What are the key chemical transformations in the nitrogen cycle, and which ones are affected by human influences?

Questions for Discussion

1. Compare and contrast key aspects of the cycling of carbon, nitrogen, phosphorus, and sulphur.
2. The use of nitrogen and phosphorus fertilizers is crucial to modern agriculture, yet these materials are manufactured from non-renewable resources and may not be so readily available in the future. What would be the consequences for agricultural production if these fertilizers were to become more expensive and less available?
3. How do your daily activities affect aspects of the carbon cycle?
4. If soil becomes acidic, the process of nitrification may no longer occur. What are consequences of this change for the nutrition of plants?

Exploring Issues

1. A sewage-treatment plant has applied for permission to dispose its nutrient-rich sludge onto nearby agricultural land. You have been asked to design a study that would examine the effects of the sludge on the cycling of nitrogen and phosphorus in the agroecosystem. What key response variables should be measured during the study? What experiments would you recommend for examining the potential effects of the sludge on nutrient cycling and crop productivity?

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Chapter 6 ~ Evolution

Key Concepts

After completing this chapter, you will be able to

1. Explain differences in environmental conditions before and after the natural genesis of life.
2. Discuss the differences between creationism and evolution as explanations of the origin of life and species.
3. Describe the theory of evolution by natural selection.
4. Explain the role of genetics in understanding evolution and biodiversity.

In the Beginning ...

Based on geological and astronomical data, the Earth is believed to have originated by the condensation of interstellar dust about 4.5 billion years ago. The pre-life environments of the planet were vastly different from what exists today. The initial atmosphere likely resulted from volcanic out-gassing and its chemistry was dominated by hydrogen sulphide (H_2S), methane (CH_4), ammonia (NH_3), carbon dioxide (CO_2), and other gases that today exist only in trace concentrations. In contrast, the modern atmosphere has large concentrations of oxygen (O_2) and nitrogen (N_2).

One reason for a profound change in atmospheric chemistry was the evolution of photosynthetic organisms, which release O_2 as a waste product of their autotrophic metabolism. As the concentration of O_2 increased, the atmosphere changed from an environment that favoured reducing reactions (in which the reaction products have a net gain in electrons) to one in which oxidizing reactions were predominant. Hydrogen sulphide, methane, and ammonia are all reduced compounds, but in an O_2-rich atmosphere, they become oxidized to sulphate (SO_4^{2-}), carbon dioxide, and nitrate (NO3−), respectively. In addition, O2 can participate in photochemical reactions that produce small amounts of ozone (O3). When present in the upper atmosphere, ozone absorbs solar ultraviolet radiation and thereby shields organisms from many of the damaging effects of this kind of electromagnetic energy.

The genesis of life on Earth is thought to have occurred in a primordial aquatic environment at least 3.5 billion years ago. It is not known exactly how life first began from inanimate matter, although many biologists believe that the process was a spontaneous occurrence. In other words, the origin of life happened naturally, as a consequence of the existence of appropriate conditions of chemistry, temperature, pressure, energy, and other environmental factors.

As such, the origin of life could have happened as a series of random events occurring under suitable conditions. Some biologists, however, believe that genesis could have taken place in a more purposeful manner, under the influence of autocatalytic (self-catalyzed) reactions that favoured the synthesis and persistence of particular organic chemicals. Under those selective influences, molecules and their interrelationships became increasingly more complex and eventually developed the qualities that define the simplest forms of life: metabolism, growth, and reproduction.

The appropriate environmental conditions for the genesis of life probably included the presence of many simple organic compounds in primordial waters. It is believed that the simple organic compounds were naturally synthesized by inorganic (i.e., non-living) reactions among the ammonia, methane, hydrogen sulphide, and other compounds that were abundant in the pre-life atmosphere. These reactions were favoured because the atmosphere at that time was a high-energy environment associated with ultraviolet radiation and lightning strikes. The resulting organic compounds were deposited into the primordial ocean by rainfall, where they became progressively concentrated, especially in shallow pools on oceanic shores, where the rate of evaporation would have been high.

Modern scientists have performed simple laboratory experiments that are thought to simulate those primordial conditions. In airtight flasks, mixtures of water and gaseous CH_4, NH_3, and H_2S are sparked by electric arcs. These experiments yield various types of hydrocarbons, amino acids (precursors of proteins), nitrogenous bases (precursors of nucleic acids), and other organic chemicals. Scientists think that something similar happened prior to the origin of life on Earth.

However, it is an enormous step from the occurrence of appropriate environmental conditions to the spontaneous genesis of living microorganisms. Scientists do not yet understand how this momentous event—the origin of the first organisms—occurred. In fact, the boundary between complex chemical systems and living organisms is somewhat arbitrary (for example, viruses exist at this boundary). Nevertheless, there is a broad consensus among scientists that microorganisms did appear in the oceans about 3.5 billion years ago (Table 6.1). Those first microorganisms were heterotrophic consumers of the rich soup of organic compounds that had accumulated in pre-biological oceans over hundreds of millions of years. The first chemoautotrophic microorganisms evolved several hundred million years later, and the first photosynthetic ones about 2.5 billion years ago.

Table 6.1. Estimated Dates of the Origins of Important Life Forms. The data represent the time of first appearance of each type of organism in the fossil record. Source: Modified from Raven and Johnson (2004).

Evolutionary Event	**Millions of Years Ago**
Formation of planet Earth	4,500
First life: anaerobic microorganisms	3,500
Chemoautotrophic microorganisms	3,100
Photosynthetic microorganisms	2,500
First eukaryotes	1,200
First multicellular organisms	600
Animals with an external skeleton	570
Lampreys	550
Crustaceans and mollusks	500
Plants	435
Jawed fish	415
Land plants	410
Amphibians	355
Insects	310
Reptiles	300
Conifers	270
Dinosaurs	223
Mammals	214
Birds	150
Angiosperm plants	135
Anthropoid primates	43
Hominids	5.5
Genus *Homo*	2
Homo sapiens	0.5

The earliest life forms were prokaryotes, which are single-celled organisms that lack an organized nucleus containing the genetic material, which was likely DNA or RNA (see In Detail 6.1). Eventually, eukaryotes (which have a nucleus bounded by a membrane) evolved from simpler prokaryotic predecessors.

More complex microorganisms, containing subcellular organelles such as mitochondria, plastids, and cilia, are thought to have evolved as a result of symbiotic associations occurring among different species. According to this theory, smaller microorganisms became encapsulated within larger ones in a mutually beneficial symbiosis (a mutualism; see Chapter 9). For example, certain smaller microorganisms may have evolved into specialized energy-processing organelles known as mitochondria. Other encapsulated microbes became specialized to capture light and to use that energy in photosynthesis–they became chloroplasts. Mitochondria and chloroplasts contain small quantities of DNA that is distinctive in character and believed to be residual from ancient times when these organelles were independent microorganisms.

Multicellular organisms were the next major category of life form to appear, in late Precambrian times (see Tables 3.1 and 6.1). The evolution and radiation of these complex organisms was driven by physiological and ecological adaptations associated with interactions of specialized cells and, eventually, organs. The first multicellular organisms were small and simple, but these eventually evolved into the larger, more complex organisms that are now prominent on Earth, including vertebrates, the phylum of animals to which humans belong.

"Progression" of Life

All species, from the smallest and simplest, such as bacteria tinier than 1 µm, to enormous blue whales exceeding 30 m in length, represent well-adapted and marvellous examples of the diversity of organisms. Moreover, in a sense modern biologists believe that all living species are similarly "advanced." The two reasons for thinking this are: (1) all living species have had the same amount of time to evolve since the first organisms appeared, and (2) they are all exquisitely adapted to coping with the opportunities and constraints presented by the environments in which they live.

Of course, species also vary enormously in their complexity. We should, however, be careful when we use the terms "simple" and "complex" in an evolutionary context, because these concepts are difficult to precisely define. In fact, all organisms display a mixture of traits, some of which evolved in ancient times, while others are more recent adaptations. For example, almost all organisms (except some viruses) have DNA as their genetic material, so this is an ancient trait. In contrast, flight in bats and intelligence in humans represent specific adaptations that occurred relatively late in only a few evolutionary lineages.

The fossil record clearly demonstrates that, over time, there has been a progression of life forms on Earth. The first prokaryotic organisms were tiny and simple, but through evolution these led to the development of more complex eukaryotic microorganisms, and so on until large, exceedingly complex animals and plants evolved. This evolutionary pattern implies a clear temporal sequence. Nevertheless, it is important to understand that relatively complex, more recent species (including humans) do not represent the acme of evolution, nor have they inherited the Earth and its opportunities. Rather, all living species share this bountiful planet and its biosphere – the only place in the universe known to sustain life.

> Image 6.1. Dinosaurs (order Dinosauria) were dominant animals on Earth for about 160 million years, but the last species became extinct 65 million years ago. We know that dinosaurs used to exist because their fossilized bones have been discovered on all continents. Modern reptiles are relatives of dinosaurs, and birds are their surviving descendants. This model of Troodon formosus, a predatory dinosaur, is located in the Museum of

Nature in Ottawa. Source: B. Freedman.

In Detail 6.1. A Primer on Genetics

Every organism has an individual complement of genetic information contained in the specific arrangement of nucleotides in its DNA or RNA. The following is a brief outline of the storage and translation of genetic information.

DNA (deoxyribonucleic acid) carries the genetic information in almost all species. In some viruses, however, the genetic information is contained in RNA (see below). DNA, a nucleic acid, consists of linear sequences of only four nucleotides: adenine, cytosine, guanine, and thymine. The sequences are arranged as two strands, which coil as a double helix (spiral) and are held together by hydrogen bonds between complementary nucleotides: adenine with thymine, and cytosine with guanine. The genetic information is embedded in the precise sequence of the nucleotides.

RNA (ribonucleic acid) is composed of a single strand of nucleotides. In RNA, uracil substitutes for the thymine of DNA. The nucleotide sequences of RNA guide the translation of the genetic information of DNA into the structure of proteins (see below).

Chromosomes are composed of DNA and protein and they contain the genetic information of the cell. Chromosomes are self-duplicating—they create exact copies of themselves through the process of replication (see below). An exact copy is passed to each daughter cell when a cell divides. Chromosomes in body (somatic) cells of plants and animals occur as complementary pairs (homologous pairs). The number of pairs of chromosomes varies greatly among species, from one to hundreds.

Genes are specific regions of a chromosome that determine the development of a particular trait by coding for a specific protein during transcription (see below). Because chromosomes occur in pairs, the genes also are paired. Genes commonly occur in more than one form, each of which is called an allele. Often, one allele is dominant (D) and the other recessive (r). The dominant one is expressed when both alleles in a gene pair are of this type (DD), and also when both dominant and recessive alleles occur (rD or Dr). Recessive alleles are expressed only if both are of this type (rr). The condition in which both alleles are the same (DD or rr) is referred to as homozygous, while the mixed condition (rD or Dr) is heterozygous.

Replication is the biochemical process during which the nucleotide sequence of each strand of DNA is copied. Replication is necessary for cellular division to occur, because each new cell requires an identical copy of the DNA. During replication, the double helix of DNA "unzips," which allows free nucleotides to hydrogen-bond with those in each strand, producing new but identical DNA molecules. If an error occurs during replication, the result in a change in the genetic information, which is called a mutation.

Transcription involves DNA unzipping and a complementary strand of RNA being made on one of the DNA strands, in a manner similar to replication. Then the RNA floats free and the DNA zips up again. Three types of RNA can be made: (a) ribosomal RNA (rRNA), which forms small bodies in the cytoplasm called ribosomes; (b) messenger RNA (mRNA), which transports information from DNA to the ribosome; and (c) transfer RNA (tRNA), which is described below.

Translation occurs when the mRNA, which contains information from a portion of a DNA strand, attaches to a ribosome in the cytoplasm (outside of the nucleus). There, tRNA molecules bind to specific amino acids and transport them to the mRNA in the correct sequence for the synthesis of a particular protein. (Amino acids are the building blocks of proteins. Only 20 amino acids are common, but they make up the extraordinary diversity of proteins that are found in organisms. Proteins are extremely important, mainly as structural chemicals and metabolism-regulating enzymes.) The information on the mRNA, copied from the DNA, determines the exact sequence of amino acids in a protein, and therefore determines its function.

Meiosis is important in sexual reproduction, in which two "sex" cells, one from each parent, combine to start a new life. If those cells were somatic cells, each would have the same number of chromosomes as the parent (the diploid number), and the progeny would then have double the number of the parent. However, this does not occur because sex cells are not diploid. Instead, through meiosis, the number of chromosomes in sex cells is halved (to haploid), so the progeny has the same number of chromosomes as the parent.

During meiosis, the paired chromosomes separate, with one of each pair going randomly to each daughter "sex" cell. Just before they separate, exchanges of genetic material may occur between the paired chromosomes—a phenomenon known as crossing-over. Both of these processes increase the variability of genetic information in sex cells. When the haploid sex cells (one from each parent) combine, the result is a diploid progeny. Having chromosomes from each parent, the progeny is genetically different from them, but also similar. This is how parents pass their genetic information to their offspring.

Genotype refers to the unique genetic information of individual organisms, as embodied in the nucleotide sequences of their DNA. The unique genotype of an individual is fixed (except for rare mutations). However, the collective genotypes of populations and species are quite variable, although this is restricted by the range of genetic variation among the constituent individuals.

Phenotype refers to the actual expression of an individual's genotype in terms of its anatomical development, behaviour, and biochemistry. For example, recessive alleles, unless in a homozygous condition, are not expressed, even though they appear in the genotype.

More importantly, the expression of genetic potential is also affected by environmental conditions and other circumstances. For instance, a geranium plant, with a fixed complement of genetic information, may be relatively tall and robust if it is grown under well-watered, fertile, uncrowded conditions. However, if that same individual were grown under drier, less fertile, more competitive conditions, its productivity and appearance would be quite different. Such varying growth patterns of the same genotype represent a phenotypically "plastic" response to environmental conditions. In contrast, the flower colour of individual geraniums (which can be white, red, or pink) is fixed genetically and is not affected by their environmental conditions.

The ability of an individual to exhibit phenotypically plastic responses to environmental variations is itself genetically determined to some extent. Therefore, phenotypic plasticity reflects both genetic capability and varying expression of that capability, depending on the circumstances met during the life of an individual.

Evolution

Evolution may be simply defined as genetically based changes in populations of organisms, occurring over successive generations. Evolution is a critically important theory because it accounts for the development of existing species from progenitors that may have been unlike their descendants in form and function. The reality of evolution is widely accepted by scientists, as much so as the theory of gravity, which explains how the Earth revolves around the Sun as well as many other aspects of the organization of the universe.

Natural selection is believed to be an especially important cause of evolutionary change. In essence, natural selection predicts that individual organisms that are better adapted to coping with the opportunities or limitations of their environment will have an increased likelihood of leaving descendants. If the adaptive advantages are genetically determined, they will be passed to some of the progeny, then to subsequent generations, and so on. This process will result in evolutionary change.

Evolution can also occur in response to catastrophic influences on populations of organisms, such as a forest fire or flood. This may result in more haphazard (random) changes in the genetic structure of a population. Small populations are particularly subject to such non-selective evolutionary influences. Evolution may also occur in response to choices made by humans of desirable traits in certain species—this is known as cultural selection (or artificial selection).

It is important to understand that individual organisms do not evolve. Evolution is a process of genetic change from generation to generation, occurring in populations or higher-order groupings of organisms (such as species). This is not to say that individual organisms cannot display variable responses to environmental conditions. These responses are, however, constrained by the degree of biochemical, developmental, and behavioural flexibility that is allowed by the genetic complement of each individual (its genotype). The variable expression of the genetic information of an individual is called phenotypic plasticity, but this response to variations in environmental conditions is not evolutionary change. For evolution to occur there must be a change in the collective genetic information of a population or species.

Evolution can occur at various scales. Evolutionary biologists use the term microevolution to refer to relatively subtle changes occurring within a population or species, often within only a few generations. This may lead to the evolution of a variety, race, or subspecies. In contrast, macroevolution describes the evolution of new species or higher taxonomic groups, such as a genus, family, or class. Evolutionary biologists continue to debate and discuss the linkages of these scales of evolution. Are patterns of macroevolutionary change simply the cumulative effects of many microevolutionary changes over long periods of time? Or is macroevolution actually a result of large changes occurring over a short time, each representing a great step (or saltation) of evolution? Or does macroevolution happen in both ways?

Despite debates regarding many of its details, the theory of evolution is a unifying theme in biology. This is because evolution can be used to understand so many phenomena in nature. Evolution is used by scientists to explain both the origin of life, as well as the extraordinary changes that have occurred in organisms over the billions of years of biotic history on Earth.

Relatedness and Descent

A biological definition of species is "a group of organisms that is reproductively isolated from other such groups." Within a species, individual organisms tend to resemble each other, but more importantly, they can breed with each other and produce fertile offspring. An inability to successfully interbreed implies reproductive isolation.

That species have evolved from earlier progenitors is a well-established theory, richly supported by evidence. Some of the most compelling lines of argument, showing evolutionary patterns of relatedness and descent, are explained in the following sections.

Patterns in the Fossil Record

A well-known example of evolution that is supported by evidence in the fossil record is that of the horse lineage. One of the earliest horse-like progenitors was Eohippus, a dog-sized creature that lived about 50 million years ago. Its foot had two fused and three separate toes. Comparison of the morphology (structure) of fossil bones suggests that Eohippus was an ancestor of Mesohippus, a larger animal that lived 35 million years ago. Its foot had three fused central toes and two free outer ones. Further evolution led to Merychippus, a somewhat larger animal living 20 million years ago that also had three fused and two free toes. Next came Pliohippus, a pony-sized animal living 10 million years ago, that had all five toes fused into a hoof. Modern horses evolved several million years ago and have a hoof like that of Pliohippus. They include the horse (Equus caballus), donkey (E. asinus), Mongolian wild horse (E. przewalskii), and zebra (E. burchelli).

Inferences from Modern Species

Modern species display many obvious similarities and dissimilarities that can be used to group them on the basis of inferred relatedness. Early studies of this sort mostly involved comparative anatomy. Research on animals relied mostly on the characteristics of bones, shells, skins, and other enduring structures, while studies of plants largely involved the anatomy of flowers and fruits. More recent studies gather a much wider range of comparative information to examine relatedness among groups of species, including information about their behaviour, ecology, proteins, and—most recently—specific base sequences of DNA. For example, studies involving DNA and blood proteins have clearly shown that humans are closely related to other great apes, such as the chimpanzee, orangutan, and gorilla. Of these, humans are most closely related to chimpanzees – in fact, the two species share about 99% of the information encoded in their DNA. These observations do not suggest that humans evolved from modern apes. Rather, the appropriate interpretation is that humans and living apes share common, ape-like ancestors.

Evolution Observed

As was just described, patterns of relatedness and descent can be inferred from comparative studies of the fossil record and of the attributes of modern species. However, it is important to understand that the evolution of a new species has never been directly observed. This is because it takes a very long time for populations of related organisms to diverge enough to become new species – perhaps thousands to hundreds of thousands of years. In spite of this, biologists have no doubt that new species have been evolving for billions of years—in fact, throughout the history of life.

Although speciation has not been observed in nature, clear examples of microevolution are known. These cases provide key evidence in support of the theory of evolution.

Industrial Melanism

One example of microevolution is that of the peppered moth (Biston betularia) of western Europe. The normal coloration of this moth is a mottled, whitish tan. During the day, the moth often rests on lichen-covered trees, where it is difficult to see against the bark. This camouflage is important to the moth's survival because its most important predators, such as birds, hunt using vision.

About a century ago in England, it was observed that some populations of peppered moths had developed a black coloration, known as melanism. This had apparently occurred in response to changes in local tree bark, which had lost its lichen cover because of air pollution and had become blackened by the deposition of soot. In these habitat conditions the normal light-coloured moths were highly visible to predators and were at a selective disadvantage compared to darker moths. Studies showed that melanism is genetically based, and that melanistic moths occurred, but were rare, in unpolluted habitats. However, melanistic individuals became dominant in populations living in polluted habitats, representing a population-level genetic change. This famous example of microevolution, which has also been demonstrated in other species of moths, is known as "industrial melanism".

Interestingly, air quality has greatly improved over most of western Europe in recent decades, largely due to clean-air legislation that has reduced the use of coal as a source of energy. As a result, lichens are again growing on trees and bark surfaces have less soot. These recoveries have been accompanied by the reappearance of light-coloured peppered moths in places where their populations had been dominated by melanistic ones—another evolutionary response to changing environmental conditions.

Metal-Tolerant Ecotypes

In another example of observed evolution, several plant species were found growing on sites in England and Wales that were polluted by metal-rich mine waste. Although the soil was toxic to most plants, populations of a few species were thriving. The most common species were grasses, such as bent-grass (Agrostis tenuis). Research showed that these local populations had a genetically based, physiological tolerance of the toxic metals, and that they differed in this respect from other populations of the same species growing on non-polluted sites. The locally adapted populations, referred to as "metal-tolerant ecotypes," were found to have evolved in as few as several years after their first exposure to the toxic soil. (This example was the first one to be documented and is famous for that reason. Canadian examples of metal-tolerant ecotypes, discovered later, are described in Chapter 18.)

Image 6.2. These are metal-tolerant ecotypes of the grass Deschampsia caespitosa, growing in metal-polluted soil close to a smelter near Sudbury, Ontario. Source: B. Freedman.

Religion and Evolution

The Book of Genesis is the first book of The Bible, an ancient text that provides the written foundation for many of the beliefs of the Abrahamic religions (Judaism, Christianity, and Islam). The description of divine creation in Genesis is the oldest written explanation of the origin of life on Earth, the existence of species, and the roles and responsibilities of humans in their interactions with the natural world. However, there are some profound disagreements between fundamentalist interpretations of Genesis and aspects of the theory of evolution. As a result, some religious interests have long attacked the theory of evolution, a circumstance that greatly intensified after the publication of Charles Darwin's ideas about the role of natural selection in evolution (see the next section).

Nevertheless, science and religion are not irreconcilable. Indeed, for many people, physical concerns belong to the domain of science, whereas spiritual ones belong to the domain of religion.

In any event, some religious groups continue to insist upon a literal interpretation of the Bible as the ultimate authority for all knowledge. In particular, creationists reject the theory of evolution in favour of a literal interpretation of Genesis. They assert that the account given in Genesis means that God created the universe and all living organisms during a six-day period, culminating with the creation of humans. Humans were created in the physical image of God and were given authority and power to freely use the resources of Earth: "And God said, let us make Man in our image, after our likeness; and let them have dominion over the fish of the sea, and over the fowl of the air, and over the cattle, and over all the Earth and over every creeping thing that creepeth over the Earth."

Moreover, humans were instructed to increase their populations and to exploit nature: "Be fruitful, and multiply, and replenish the Earth, and subdue it."

Note, however, that there is some controversy about the meaning of the word "replenish" in this biblical passage. Some people have interpreted it in the sense of conservation, as in to refill or restore resources as they are used. Others, however, maintain that the original meaning was "to fill up," and, in this sense, it referred to filling the Earth with humans and their economic activities. The latter interpretation is the one that is usually accepted in modern environmental writings that examine the relationship between humans, their economy, and the natural world.

Based on their literal interpretation of Genesis and other passages in the Bible, creationists have drawn the following conclusions relevant to evolution:

- Earth and its species are not ancient because creation occurred only a few thousand years ago.
- Species are essentially immutable, having been created as entities that have not changed since their creation.
- Because species were individually created, existing species did not descend from earlier ones through evolution.
- Humans are particularly special, having been created in the Creator's image—they are not related to or descended from any other species.

But these ideas do not accord with scientific findings, as were described on the preceding pages. In particular:

- The geological record clearly demonstrates that Earth and the solar system are extremely old, having begun to develop at least 4.5 billion years ago. Life is also ancient, having originated about 3.5 billion years ago. Earth and organisms date back much further than a few thousand years.
- The fossil record provides many examples of large changes in the characteristics of species over time, as do studies of some living species. Clearly, species are not immutable. Moreover, the existing complement of species on Earth represents only a small sample of all those that have ever lived. The fossil record demonstrates that most species that evolved during the long biological history of our planet are now extinct. Many of the extinct species, families, and even phyla have no living descendants—their entire lineage is extinct (see Chapter 7).
- The fossil record presents clear evidence of lineages among groups of organisms, indicating that living species have descended from earlier ones. In almost all cases, the progenitor species are now extinct. There are even a few examples in the fossil record of links between major groups. Perhaps the most famous of these is Archaeopteryx, a metre-long creature that lived about 150 million years ago. It had teeth and other dinosaurian characters, but it also had a feathered body and could fly. Archaeopteryx is considered to be a link between extinct dinosaurs and living birds.
- Fossil and genetic information indicate that humans are descended from earlier, now-extinct species and genera. Fossil records show that the human species (Homo sapiens) is derived from an evolutionary lineage of anthropoid apes. There are a few other surviving species in that lineage, with chimpanzees, and to a lesser degree gorillas and orangutans, being the closest living relatives of humans. All surviving members of the ape family are descended from now-extinct progenitors.

People known as scientific creationists also insist that their interpretation of Genesis is the most reliable source of knowledge about the origin and evolution of life. Scientific creationists have attempted to explain some of the discrepancies between their beliefs and current scientific understanding of evolution. For example, some of them acknowledge that geological and fossil evidence suggests that Earth and life are ancient phenomena and that most species have become extinct. Most scientific creationists also acknowledge that species have changed over time, but only through microevolution—they do not agree that macroevolution has led to the development of new species from earlier ones. By extension, scientific creationists also do not believe that humans are descended from previous species of hominids or are related to other ape-like creatures or other primates. Moreover, the theory of scientific creationism does not abandon the notion that, at one particular time in the past, God created all species that have ever lived on Earth.

Science proceeds by careful observation and hypothesis testing. But scientific creationism rests on a belief, not a testable hypothesis, concerning a literal interpretation of the Bible as representing "truth" and "knowledge". Most predictions of scientific creationists cannot be tested by rigorous methodology, but when they can be, they are refuted by the evidence. In short, despite its name, scientific creationism is not science.

Evolution by Natural Selection

Because organisms vary in their genetics and phenotypes, they also differ in their abilities to deal successfully with stresses and opportunities in their environment. Under certain conditions, an individual with a particular phenotype (which is substantially determined by its genotype) may be relatively successful compared with others having different genotypes and phenotypes.

In the sense meant here, the "success" of an individual means successful reproduction – having progeny that themselves go on to reproduce successfully. This is also referred to as fitness, or the proportionate genetic contribution made by an individual to all of the progeny in its population. A central tenet of evolutionary theory is that individuals maximize their fitness by optimizing the degree to which their own genetic attributes will influence future generations of their species.

Biologists believe that evolution proceeds mainly by natural selection, which operates when genetically based variation exists among individuals within a population, so that some of them are better adapted to deal with the prevailing environmental conditions. On average, the more-fit organisms have greater success in reproduction, and so have a disproportionate influence on the evolution of subsequent generations.

The theory of evolution by natural selection is perhaps the greatest unifying concept in modern biology, as it gives context to virtually all aspects of the study of life. This theory was co-announced publicly in 1858 by two English naturalists: Charles Darwin (1809–1882) and Alfred Russel Wallace (1823–1913). Darwin, however, had been working on aspects of the theory for about 20 years prior to its publication, and he had collected detailed evidence in support of natural selection as a mechanism of evolution. Darwin's copious evidence was marshalled in the famous book, On the Origin of Species by Means of Natural Selection, published in 1859. Because of this book, Darwin has become more closely linked than Wallace to the theory of evolution by natural selection. Darwin is also the more famous of the two scientists, largely because of his great contributions toward understanding the mechanisms of evolution. Perhaps the most influential biologist of all time, Darwin undertook an astonishingly broad range of research projects on a great variety of species and biological topics.

In his Origin of Species, Darwin summarized natural selection in the following way: "Can we doubt … that individuals having any advantage, however slight, over others, would have the best chance of surviving and of procreating their kind? On the other hand, we may feel sure that any variation in the least degree injurious would be rigidly destroyed. This preservation of favourable variations, I call Natural Selection."

In an unpublished essay that Wallace sent to Darwin for review in 1858, natural selection was expressed in a rather similar fashion: "The life of wild animals is a struggle for existence … in which the weakest … must always succumb … giving rise to successive variations departing further and further from the original type."

The theory of Darwin and Wallace was based on the following line of reasoning:

- It is known that the fecundity of all species is high enough that they could easily overpopulate their habitats, yet this does not generally happen.
- It is also known that the resources that species need to sustain themselves are limited, particularly in relatively stable habitats.
- Therefore, in view of potential population growth and limited resources, there must be intense competition among individuals of each species for access to the necessities of life. Only some individuals manage to survive this struggle for existence and reproduce.
- Because individuals within a species are different from each other, and much of this variation is heritable, it is reasonable to suggest that survival in the struggle for existence is partly influenced by genetically determined differences in abilities.
- Individuals that are more capable will have a better chance of surviving and reproducing, and their genetically based attributes will be disproportionately represented in future generations.
- Over long periods of time, this process of natural selection will lead to evolutionary changes within populations, and eventually to the evolution of new species.

When it was first presented publicly in 1858, the theory of evolution by natural selection created a sensation among scientists and also within society. The excitement and controversy occurred largely because the theory provided the first convincing body of evidence in support of the following three notions: (a) evolution occurs, (b) it proceeds under natural influences, and (c) it has resulted in the great diversity of living species.

This was a radically different view from that of creationism, which was the prevailing explanation of the origin of life and species in the mid-nineteenth century. Interestingly, Darwin's writings did not directly challenge the existence of a divine Creator. He mostly discussed the causes of change in species over time, and did not directly suggest that the initial ancestors had not been created by God. Modern theories about the spontaneous genesis of life on Earth are based on relatively sophisticated science that was unknown to Darwin. Nor did he know of the mechanisms of genetics and the inheritance of traits.

Modern extensions of the theory of evolution by natural selection suggest that new species evolve from progenitors (a process known as speciation). This is thought to happen when populations become isolated by intervening barriers such as a mountain range, extensive glaciers, or other inhospitable discontinuities. Isolation is important in speciation because it reduces or eliminates genetic interchanges, and thereby allows differentiation to proceed more effectively. Isolated populations that experience different environmental conditions are subject to differing selection pressures and can evolve in dissimilar ways. Eventually, there may be enough evolutionary change that the populations can no longer successfully interbreed, even if they become spatially reunited. At that point, the populations have achieved reproductive isolation, and so have become closely related but different species.

Speciation is also thought to occur in a more linear fashion, as when progenitor species gradually evolve over time in response to changes in environmental conditions. Eventually, the ancestral species may become extinct, but new ones evolved from the progenitor lineage may survive to continue the evolutionary chain.

The Importance of Genetics

Knowledge of genetics in Darwin's time was based on a highly incomplete understanding of how an organism's traits are passed to its offspring. One popular theory, the "inheritance of acquired traits", was based on the observation that the morphology, behaviour, and/or biochemistry of individual organisms could vary in response to environmental change. According to the theory, these plastic responses to environmental conditions could be passed along to an individual's progeny. For example, during periods of drought or intense competition for food, individual short-necked ancestors of giraffes might have stretched their necks as far as they could to reach scarce foliage higher up in trees, resulting in the development of a longer neck. The long-neckedness would have been passed to the giraffe's progeny, who developed it still further. Eventually, populations developed the familiar long neck of modern giraffes.

However, natural selection suggests a different mechanism of this evolutionary change: within populations of short-necked giraffes there existed a genetically determined variation in neck length among individuals. Because long-necked giraffes were better able to find food, they were more likely to survive and reproduce. This meant that more of the next generation had the long-necked trait, and this anatomical feature became increasingly prominent in the evolving population.

Modern observations and experiments have shown that "acquired traits" are just a manifestation of phenotypic plasticity. There is no evidence that they can become genetically fixed in an individual and passed along to its offspring. In contrast, the science of genetics has provided convincing evidence in support of the theory of evolution by natural selection. The biochemical mechanisms that determine the genotype of an individual organism and how some of its characteristics are passed to progeny have been discovered. The subject matter is rather complicated and cannot be dealt with in much depth here. It is, however, useful to examine the key experiments that first suggested the existence of genes.

This research was conducted by Gregor Mendel (1822–1884), an Austrian scientist (and monk) who developed important ideas about inheritance through breeding experiments with the garden pea (Pisum sativum). Mendel was interested in producing pea hybrids, which involves crossing two parent plants, each having distinctive traits. Prior research had shown that certain traits were fixed in cultivated varieties of peas, including flower colour (white or purple) and whether the seeds have a wrinkled or smooth coat. In total, Mendel worked with 32 traits of this sort. Pea flowers are bisexual, containing both female (pistil, containing the ovules) and male (anthers, containing pollen) parts. These are compatible within the same individual, so self-fertilization can occur. However, Mendel experimented by cross-fertilizing selected parents, producing known hybridizations.

In each experiment, Mendel cross-bred two inbred varieties in which certain traits "bred true" (they were homozygous, such as for a white or purple flower colour). The progeny (first generation) were all the same: they all had purple flowers. However, crosses between the first-generation plants yielded a ratio of about three purple flowers to one white flower in the second generation. This fits the prediction for two-generation crosses between two homozygous lines, as follows:

1. Represent the original purple variety as AA. This trait is dominant over the white flower trait (called recessive).
2. Represent the original white variety as aa.
3. When the two plants are crossed, the first-generation progeny all have purple flowers but are heterozygous (Aa).
4. A cross between the first-generation plants yields four possible outcomes: AA, Aa, aA, and aa. Each is equally probable. Because A is dominant to a, the AA, Aa, and aA progeny all have purple flowers. Only aa has white flowers. Therefore, the expected ratio of purple to white among the second-generation progeny is 3:1.

The most important conclusion to emerge from Mendel's work was that the inheritance of genetic information occurs in a "particulate" form (which we now refer to as genes), often involving dominant and recessive alleles. Inheritance is not a blended condition—in the example just described, a cross of purple- and white-flowered pea plants does not yield progeny of an intermediate colour. Therefore, flower colour and many other traits are discrete units that remain intact during inheritance and either are, or are not, expressed in progeny.

Mendel first published his results in 1865 in a relatively obscure journal. As a result, the work was unknown to the mainstream of science for many years. However, Mendel's work was re-discovered and republished in 1900 and it quickly became the basis of modern theories of genetic inheritance.

Mendel's work and the subsequent flourishing of the science of genetics have been extremely important in biology and in the development of the modern theory of evolution. This is because genetics allows a rational explanation of inheritance as a mechanism by which genetically fixed traits can be passed along to offspring. Subsequent research has found that new genotypes can arise through various mechanisms, such as hybridization, polyploidism (a spontaneous increase in the number of chromosomes), and mutations. Genetic variation is, of course, the menu of possibilities from which natural selection can choose so that adaptive evolution can occur.

It is important to recognize that much genetic information in an individual does not appear to code for functional enzymes or other proteins, and so does not code for traits that could be selected for or against. Because of its neutrality with respect to natural selection, this type of genetic material is sometimes referred to as "junk DNA". However, we may be ignorant of other roles that so-called junk DNA may play in the functioning of the genome.

Environmental Issues 6.1. Genetically Modified Organisms

Genetically modified organisms (GMOs) are a highly controversial topic. But what, exactly, is meant by the term?

Strictly speaking, GMOs are organisms whose genotype has been influenced by human intervention. But people have been doing this for an extremely long time. As early as about 10,000 years ago, when people first began to cultivate other species as crops, they selectively bred individual plants and animals that had favourable traits (see Chapter 10 for an explanation of socio-cultural evolution, including the early development of agriculture). This "artificial selection" rapidly led to the evolution of crop varieties that were more responsive to management and had greater yields than their wild progenitors. In this sense, almost all domesticated species of plants, animals, and microorganisms that are cultivated as sources of food, material, or energy are "genetically modified organisms." They were produced using conventional methods of selective breeding, a process that is not very controversial.

More recently, however, new techniques in biotechnology, specifically in molecular biology, have been used to create novel genetic modifications of organisms. These techniques allow biologists to selectively insert portions of the DNA of one species into the genome of another species. This is a fundamentally different kind of genetic modification than selective breeding, and it should more properly be referred to as transgenic modification, or as recombinant bioengineering. There are potential benefits to this kind of genetic modification of crop species, including the development of varieties that are resistant to diseases or pests and that require less fertilizer or pesticide. In spite of these seeming benefits, there is controversy over transgenic biotechnology and the commercial use of GMOs, largely because of the following issues:

- Should scientists be interfering with the very foundation of life—the genetics of species—by using methods of genetic "engineering" that do not normally exist in nature?
- Do novel, transgenic organisms represent "new" varieties of designed and manufactured life that are appropriate for patenting and use for commercial gain? (In fact, various legal rulings have stated that this can be done, and some transgenic crops have become extremely profitable to owners of the patents.)
- Are important ecological risks associated with the cultivation of transgenic organisms? Because many biological and ecological unknowns are associated with this practice, "surprises" may follow from the release of these organisms into the environment, including unanticipated damage to crops, wild species, and natural ecosystems.

These are contentious and precautionary issues, and the controversy is not resolved. In some cases, illegal releases of GMO products have been made by private interests, a circumstance that reflects weakness in the regulatory control mechanisms (Clapp, 2008). Nevertheless, some GMO products have been widely commercialized and are now routinely used. For instance, transgenic GMO varieties of soybean and canola have been developed to be resistant to glyphosate, which allows this herbicide to be used on those crops. This practice results in benefits to farmers from reduced costs of energy and machinery needed to control weeds. In a similar vein, transgenic varieties of maize (corn) have been developed that contain modified DNA of the insecticidal bacterium Bacillus thuringiensis. This provides resistance to important insect pests and allows farmers to use less insecticide. These and other transgenic crops are now widely cultivated in North America (although they are banned in other countries, including most of Europe and Brazil), but relatively little is known about the biological and ecological risks that may arise when their transgenic factors escape to wild plants.

Additional Mechanisms of Evolution

Although natural selection is the most important mechanism of evolution, it is not the only one. For example, artificial selection involves the deliberate breeding of plants, animals, and microorganisms to enhance certain traits that humans view as desirable. Artificial selection has obvious parallels to natural selection in that individual organisms with particular, genetically based traits experience greater success in breeding, so they become over-represented in subsequent generations. However, traits that are favoured in artificial selection may not be adaptive in the natural world. In addition, because the breeding of desired genotypes can be controlled, evolutionary change occurs much more rapidly under artificial selection than under natural selection.

For example, maize (or corn, Zea mays) is an important crop that, through artificial selection, now differs enormously from its closest wild progenitor, a Mexican grass known as teosinte (Euchlaena mexicana). Artificial selection has caused many evolutionary changes in maize. For example, the fruiting head (consisting of the cob and seeds) is much larger than in wild ancestors of maize; the seeds have different coloration; the seeds implant securely onto the cob so they do not scatter before harvesting; the ripe fruit is tightly wrapped within enclosing leaves known as bracts, again to prevent pre-harvest losses; and there are vigorous growth responses to fertilizer application, weed control, and other cultivation practices. Moreover, without the intervention of humans through cultivation, maize would likely become extinct within only a few generations. This is partly because artificial selection has rendered its seeds virtually incapable of detaching from the cob, which in any event is tightly bound in leafy bracts. Therefore, unaided seed dispersal is almost impossible.

All domesticated plant, animal, and microbial species have undergone artificial selection for desirable traits. Sometimes, however, artificial selection proceeds in bizarre directions, with the fostering of genetic traits that are viewed as desirable for aesthetic rather than practical reasons. For example, oriental breeders of pet fish have produced some amazing varieties of goldfish (Carassius auratus) and koi (a golden-coloured variety of carp, Cyprinus carpio). These varieties, often with grotesque shapes and behaviours, would be rapidly eliminated in a wild population but are prized as unusual and valuable specimens by aficionados of these aquatic pets. Similar comments could be made about curious varieties of cats, dogs, pigeons, and many kinds of horticultural plants.

Evolution can also occur through a process known as genetic drift, or random changes in the frequencies of genes occurring in small and isolated populations. Such populations often exist on islands, or they may be created through a catastrophic reduction of a larger population because of disease, disturbance, or some other factor. The relatively small genetic base of small populations is sometimes called a “bottleneck.” Subsequent evolution is based on the restricted genetic variation of only a few individuals, which may become further reduced through the effects of inbreeding (reproduction between closely related individuals, such as siblings). Given the restricted amount of genetic variation, the evolution of a small population may proceed very differently from that of a larger population.

Image 6.3. The many varieties of dog are a result of cultural selection for desired traits, but all are the same species, Canis lupus familiaris. Source: B. Freedman.

Conclusions

Earth is the only place in the universe that is definitely known to sustain life and ecosystems. It is thought that life spontaneously arose at least 3.5 billion years ago, because of the existence of environmental conditions appropriate for its genesis. Since that origin, profound changes have occurred in the morphology and functionality of organisms through a process known as evolution. Evolution may be simply defined as changes in the genetic makeup of populations and species over time (individual organisms do not evolve). Although evolution has influenced life on Earth ever since it began, there is controversy over the mechanisms of the process. Almost all biologists believe that natural selection has been the most important cause of evolutionary change, but some think that geological catastrophes (such as meteorite strikes of the planet or intense volcanic eruptions) have also had a large influence.

Questions for Review

1. How has the evolution of organisms, especially those capable of photosynthesis, resulted in important changes in chemistry of the environment?
2. What evidence supports the theory of evolution?

3. How is natural selection a mechanism of evolution? What are other means by which evolution can occur?
4. How does artificial selection result in the evolution of domesticated species?

Questions for Discussion

1. Why are many biologists reluctant to describe certain species as being "more advanced" or "more highly evolved" than others?
2. How might environmental conditions experienced during your lifetime have affected your own development? Relate your answer to the phenomenon of phenotypic plasticity.
3. Why is knowledge of genetics important to understanding evolutionary processes?
4. Do you think there is enough scientific evidence in support of the idea of spontaneous generation of life for it to replace faith-based notions of divine creation?

Exploring Issues

1. You have been asked to participate in a debate about the genesis and evolution of life. What kinds of evidence would you use to support the theory that life began from inanimate matter billions of years ago? What evidence supports the theory that humans evolved from earlier ancestors that are now extinct?

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Chapter 7 ~ Biodiversity

Key Concepts

After completing this chapter, you will be able to

1. Outline the concept of biodiversity and explain its constituent elements.
2. Explain the reasons why biodiversity is important and should be preserved.
3. Define the classification of life in terms of species, genus, family, order, class, phylum, and kingdom.
4. Describe the five kingdoms of life.

Biodiversity

Biodiversity is the richness of biological variation. It is often considered to have three levels of organization:

1. genetic variation within populations and species
2. numbers of species (also known as species richness)
3. and the variety and dynamics of ecological communities on larger scales, such as landscapes and seascapes

Genetic Variation

In almost all species, individuals differ genetically – that is, in terms of information encoded in their DNA. This variation constitutes genetic biodiversity at the level of populations, and ultimately of the species.

However, there are exceptions to this generalization. Some plants, for example, have little or no genetic variability, usually because the species relies on asexual (vegetative) means of propagation. In such species, genetically uniform clones can develop, which consist of plants that, although discrete, nevertheless constitute the same genetic "individual." For example, clones of trembling aspen (Populus tremuloides) can develop through vegetative propagation, in some cases covering more than 40 ha and consisting of thousands of trees. Such aspen clones may be the world's largest "individual" organisms (in terms of total biomass). Similarly, the tiny plant known as duckweed (Lemna minor), which grows on the surface of fertile waterbodies, propagates by developing small vegetative buds on the edge of its single leaf. These break off to produce "new" plants, resulting in a genetically uniform population. These interesting cases are exceptions, however, and most populations and species contain a great deal of genetic variation.

> Image 7.1. Species are a familiar element of biodiversity. The jaguar (Panthera onca) is a widespread large predator in South and Central America. This one was photographed in Tambopata National Park, Peru. Source: B. Freedman.

A high level of genetic diversity in a population is generally considered a desirable attribute. With greater genetic diversity, populations are more likely to have resistance to new diseases and to be more adaptable to changes in environmental conditions. In general, small populations with little genetic diversity are thought to be at risk because of inbreeding and low adaptability. Examples of such populations-at-risk include the several hundred beluga whales (Delphinapterus leucas) living in the estuary of the St. Lawrence River and the population of only about 150 panthers (Felis concolor coryi) in Florida.

Richness of Species

Species richness is the number of species in a particular ecological community or in another specified area, such as a park, province, country, or, ultimately, the biosphere. Species richness is the aspect of biodiversity that people can most easily relate to and understand.

It is well known that many tropical countries support a greater species richness than do temperate countries (such as Canada). In fact, tropical rainforest supports more species than any other kind of ecosystem. Unfortunately, species-rich rainforest in tropical countries is being rapidly destroyed, mostly by conversion into agricultural land-uses and other disturbances. These changes are causing the endangerment or extinction of many species and are the overwhelming cause of the modern-day biodiversity crisis (see Chapter 26). The magnitude of this crisis is much smaller in Canada. Nevertheless, many of our native species have become extinct or otherwise at risk because of over-harvesting or habitat loss (Chapter 26).

A total of about 1.9 million species have been identified and given a scientific name. About 35% of these “known” species live in the tropics, 59% in the temperate zones, and 6% in boreal or polar latitudes. However, it is important to recognize that the identification of species is very incomplete. This is especially true of tropical ecosystems, which have not yet been thoroughly explored and characterized. According to some estimates, the global richness of species could range as high as 30–50 million, with 90% of them living in the tropics, particularly in rainforests.

Most of the species that biologists have named are invertebrates, with insects making up the bulk of that total, and beetles (order Coleoptera) comprising most of the insects (Table 7.1). The scientist J.B.S. Haldane (1892–1964) was once asked by a theologian to succinctly tell, based on his deep knowledge of biology, what he could discern of God's purpose. Haldane reputedly said that God has "an inordinate fondness of beetles." This reflects the fact that, in any random sampling of all the known species on Earth, there is a strong likelihood that a beetle would be the chosen specimen.

Table 7.1. Numbers of Species in Various Groups of Organisms. The numbers of identified species are based on recent tallies, while the estimated numbers are based on the opinions of biologists about how many species will eventually be discovered in the major groups of organisms.

Group	**WORLD**		**CANADA**	
	Identified	**Estimated**	**Identified**	**Estimated**
Viruses	2,085	400,000	200	150,000
Bacteria	7,643	1,000,000	2,400	23,200
Fungi	98,998	1,500.00	11,800	15,600
Protozoans	40,000	100,000	1,000	2,000
Algae	40,000	350,000	5,303	7,300
Lichens	14,000	18,000	2,500	2,800
Bryophytes	16,236	22,750	1,100	1,060
Vascular plants	281,621	368,621	3,834	3,909
Molluscs	85,000	200,000	1,500	1,635
Arachnids	102,248	600,000	3,275	7,730
Crustaceans	47,000	150,000	3,139	4,539
Insects	1,000,000	5,000,000*	18,530	30,330
Fishes	31,153	40,000	1,100	1,600
Amphibians	6,515	15,000	42	44
Reptiles	8,734	10,000	42	42
Birds	9,990	10,000	426	426
Mammals	5,487	5,500	194	194
Total	1,900,000	9,000,000*	56,385	252,409

*This is a conservative number. Some estimates suggest more than 30 million species of insects living in tropical forests alone (see text). Sources: Modified from Groombridge (1992), Heywood (1995), Environment Canada, (1997), Chapman (2009), and United Nations Environment Program (2001), and Bernhardt (n.d.).

Furthermore, it is believed that many tropical insects have not yet been described by biologists – perhaps more than another 30 million species, with many of them being small beetles. This remarkable conclusion initially emerged from research by T.L. Erwin, an entomologist who was studying tropical rainforest in South America. Erwin treated small areas of forest canopy with a fog of insecticide, which resulted in a “rain” of dead arthropods that was collected in sampling trays laid on the ground. In the trays were large numbers of unknown species of insects, most of which had a highly localized distribution, being limited to only a single type of forest or even to a particular species of tree.

Clearly, biologists know remarkably little about the huge numbers of relatively small, unobtrusive species that occur in poorly explored habitats in the tropics and elsewhere, such as the deep ocean. However, even in a relatively well-prospected country like Canada, many species of invertebrates, lichens, microbes, and other small organisms have not yet been discovered. Of course, larger plants and animals are relatively well known, partly because, for most people (including scientists), these have greater “charisma” than small beetles, microbes, and the like. Still, even in Canada and other relatively well-studies countries, new species of vascular plants and vertebrate animals are being discovered.

Compared with invertebrates and microbes, the species richness of other groups of tropical-forest organisms is better known. For example, a survey of rainforest in Sumatra, Indonesia, found 80 species of tree-sized plants (with a diameter greater than 20 cm) in an area of only 0.5 hectare. A study in Sarawak, Malaysia, found 742 woody species in a 3-ha plot of rainforest, with half of the species being represented by only a single individual. A similar study in Amazonian Peru found 283 tree species in a 1 ha plot, with 63% represented by only one individual and 15% by only two. In marked contrast, temperate forest in North America typically has fewer than 9-12 tree species in plots of this size. The richest temperate forest in the world, in the Great Smokies of the eastern United States, contains 30–35 tree species, far fewer than occur in tropical forest. More northern boreal forest, which covers much of Canada, has only 1-4 species of trees present.

A few studies have been made of the richness of bird species in tropical rainforest. A study of Amazonian forest in Peru found 245 resident bird species, plus another 74 migrants, in a 97-ha plot. Another study found 239 species of birds in a rainforest in French Guiana. In contrast, temperate forest in North America typically supports 30-40 species of birds. Not many comprehensive studies have been made of other kinds of biota in tropical ecosystems. In one study, a 108 km_2 area of dry tropical forest in Costa Rica was found to contain about 700 species of plants, 400 vertebrate species, and 13,000 species of insects, including 3,140 kinds of moths and butterflies.

Image 7.2. Community-level biodiversity. This intertidal community in Pacific Rim National Park on the west coast of Vancouver Island sustains various algae, barnacles, mussels, starfish, and other species that vary in their tolerance of environmental stress associated with tidal cycles. Source: B. Freedman.

Richness of Communities

Biodiversity at the level of landscape (or seascape; collectively these are referred to as ecoscapes) is associated with the number of different communities that occur within a specified region, as well as their relative abundance, size, shape, connections, and spatial distribution. An area that is uniformly covered with a single kind of community would be judged as having little biodiversity at the level, compared with an ecoscape having a rich and dynamic mosaic of different communities.

Because natural ecoscapes contain many species and communities that have evolved together, it is as important to conserve this level of biodiversity as it is to protect genetic and species diversity. Natural communities, landscapes, and seascapes are being lost in all parts of the world, with the worst damages involving the destruction of tropical forest and coral reefs. However, dramatic losses of this level of biodiversity are also occurring in Canada:

- Only about 0.2% of the original area of tall-grass prairie remains, the rest having been converted to agricultural use.
- Almost all of the Carolinian forest of southern Ontario has been destroyed, mostly by conversion to agricultural and urbanized landscapes.
- The survival of old-growth forest in coastal British Columbia is at risk, with the dry coastal Douglas-fir type being especially depleted. The loss of old-growth forest is mostly due to timber harvesting, which converts the ecosystem into a younger, second-growth forest (see Chapter 23).
- Throughout southern Canada, wetlands of all kinds have been destroyed or degraded by pollution, in-filling, and other disturbances.
- Natural fish populations have been widely decimated, including mixed-species communities in the Great Lakes, populations of salmonids (salmon and trout) in western Canada, and cod and redfish off the Atlantic Provinces.

- The habitats of various bottom types have been obliterated by the extensive practice of bottom-dragging in fisheries on the continental shelves, with great consequences for dependent types of ecological communities.

In all of these Canadian examples, only remnant patches of endangered natural communities and ecoscapes remain. These are at great risk because they are no longer components of robust, extensive, naturally organizing ecosystems.

The Value of Biodiversity

Biodiversity is important for many reasons. The value of biodiversity provides credence for its conservation. The reasons why biodiversity is important can be categorized into several groups.

Utilitarian Value

Humans are not isolated from the rest of the biosphere, in part because our survival depends upon having access to products of certain elements of biodiversity. Because of this requirement, humans must exploit species and ecosystems as sources of food, biomaterials, and energy—in other words, for their utilitarian value (also known as instrumental value).

For instance, all foods that we eat are ultimately derived from biodiversity. Moreover, about one-quarter of the prescription drugs dispensed in North America contain active ingredients extracted from plants. In addition, there is a wealth of additional, as yet undiscovered products of biodiversity that are potentially useful to people. Research on wild species of plants, animals, and microorganisms has discovered many new bio-products that are useful as food, medicines, materials, or other purposes. Like many of the species already known to be useful, some of the newly discovered ones have a potentially large economic value.

To illustrate the importance of medicinal plants, consider the case of the rosy periwinkle (Catharantus roseus), a small herbaceous plant that is native to Madagascar, a large island off northeastern Africa. One method used in the search for anti-cancer drugs involves screening large numbers of wild plants for the presence of chemicals that have an ability to slow the growth of tumours. During one study of that kind, an extract of rosy periwinkle was found to counteract the reproduction of cancer cells. Further research identified the active chemicals to be several alkaloids, which are probably synthesized by the rosy periwinkle to deter herbivores. These natural biochemicals are now used to prepare the drugs vincristine and vinblastine, which have proved to be extremely useful in chemotherapy to treat childhood leukemia, a cancer of the lymph system known as Hodgkin's disease, and several other malignancies.

The exploitation of wild biodiversity can be conducted in ways that allow the renewal of harvestable stocks. Unfortunately, many potentially renewable biodiversity resources are overharvested, which means they are managed as if they were non-renewable resources (they are being "mined"; see Chapters 12 and 14). This results in biological resources becoming degraded in quantity and quality.

Sometimes, over-exploited species become locally extirpated or are even rendered globally extinct, and when this happens their unique values are no longer available for use by humans. The great auk and passenger pigeon are examples of Canadian species that were made extinct by over-harvesting. Local and regional extirpations have been more numerous and include the cougar, grizzly bear, timber wolf, and wild ginseng over most of their former ranges (see Chapters 14 and 26).

Image 7.3. Many elements of biodiversity provide products useful to people as food, materials, and medicines. In the 1990s, a chemical called taxol extracted from species of yews was found to be helpful in treating certain malignancies, particularly ovarian cancer. Commercial harvests were made of two yews native to Canada to supply biomass from which taxol can be extracted. These are the Pacific yew (Taxus brevifolia) of British Columbia and the Canada yew (Taxus canadensis) of eastern Canada. The wild harvest is less now, because the taxol can be synthesized in laboratories. This image is of Canada yew growing in Prince Edward Island. Source: B. Freedman.

Canadian Focus 7.1. Medicinal Plants

Plants and products derived from them have always been vital to human survival, being used as sources of food, medicine, material, and energy. For instance, most foods eaten by people are the biomass of plants; the rest is animal or microbial products, but even these are produced indirectly from plants. Moreover, useful products are derived from a great richness of plant species—about 1,800 medicinal plants are commercially available in North America, and perhaps 20,000 worldwide. All of these bio-products are potentially renewable resources that can be harvested and managed on a sustainable basis (see Chapter 12).

Studies by anthropologists have repeatedly shown that Aboriginal peoples are intimately aware of useful medicinal plants that grow within their local ecosystems. This “traditional ecological knowledge” is helpful in identifying useful plants for further investigation by scientists. Nevertheless, only a small fraction of the enormous richness of biodiversity has been investigated by scientists for its potential to supply us with useful products. Because of the likelihood of discovering new bio-products, it is imperative that we continue to engage in “bio-prospecting” research. Work of this sort is ongoing in many countries, including Canada. Canada supports about 3,200 species of native plants, of which as many as 1,000 have been used for medicinal purposes, mostly by Aboriginal peoples. Of this relatively large number, several tens of species have become widely enough used that they are of significant commercial value. Some of them are being cultivated to supply the emerging herbal medicine markets, while others are still harvested from the wild. A few examples of Canadian species that are of interest as medicinal plants include the following:

- Yarrow (Achillea millefolium) is a widespread perennial herb of disturbed habitats and meadows that can be taken (often in capsule form) to treat the common cold, diarrhea, fever, and some other maladies, or used as a poultice to stanch the flow of blood from wounds. It is easily cultivated or may be gathered from the wild.
- Purple coneflower (Echinacea pallida var. angustifolia) is a perennial herb of prairie habitats that is widely drunk as a root extract. The root may also be chewed or taken in other forms to prevent or treat the common cold, sore throat, bacterial infections, and other ills. It is easily cultivated and is one of the most widely used herbal medicines in North America.
- Evening primrose (Oenothera biennis) is a widespread biennial herb of disturbed habitats and meadows that may be taken as a whole-plant infusion to treat asthma and gastrointestinal disorders, or as a pressed-oil product as a nutritional supplement. It is easily cultivated or can be gathered from the wild.
- Ginseng (Panax quinquefolius) is a perennial understorey plant of eastern hardwood forest that may be taken as a root infusion as a general tonic or to treat headache, cramps, fever, rheumatism, and other maladies. It is cultivated on a five- to seven-year rotation, and may be the most widely used herbal medicine in the world. It should not be gathered from the wild because past over-harvesting has rendered it endangered.
- Pacific yew (Taxus brevifolia) is a tree-sized plant of the humid of the west coast, and Canada yew (T. canadensis) a shrub of eastern forest. An extract of bark or leaves containing the chemical taxol has proven useful in the treatment of certain malignancies, particularly ovarian and breast cancers. Biomass for processing is gathered from wild plants, but local over-harvesting has been an issue in some areas. Plantations of Pacific yew and other yews are being established to relieve the pressure on slow-growing populations of wild plants.
- Cranberry (Vaccinium macrocarpon) is a widespread trailing shrub of bog wetlands that may be taken as a pressed juice as a source of vitamin C, to treat urinary tract infections and kidney ailments, and for other purposes for which its diuretic properties are useful. The species is extensively cultivated and is also gathered from wild habitats.

Reference and Additional Information

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Provision of Ecological Services

Biodiversity provides many ecological services that are critical to the stability and integrity of ecosystems as well as the welfare of humans. They include nutrient cycling, biological productivity, control of erosion, provision of oxygen, and removal of carbon dioxide and its storage as organic carbon. All of these services are critical to the welfare of people and other species, but they are not usually assigned economic value. In part, this is because we do not yet have sufficient understanding and appreciation of the "importance" of ecological services and of the particular species and communities that provide them. According to Peter Raven, a famous botanist and advocate of biodiversity, "In the aggregate, biodiversity keeps the planet habitable and ecosystems functional."

Intrinsic Value

Biodiversity has its own intrinsic value (or inherent value), regardless of any direct or indirect worth in terms of the needs or welfare of humans. This value is fundamental to all elements of biodiversity, and is irreplaceable. This intrinsic value raises certain ethical questions about actions that threaten biodiversity. Do humans have the "right" to impoverish or exterminate unique and irretrievable elements of biodiversity, even if our species is technologically able to do so? Is the human existence somehow impoverished by extinctions caused by our actions? These are philosophical issues, and they cannot be resolved by science alone. However, enlightened people or societies would not facilitate the endangerment or extinction of species or natural communities.

Biodiversity Is Worthwhile

Many people firmly believe that wild biodiversity and natural ecosystems are worthwhile and important. They cite the utilitarian and intrinsic values of biodiversity, but may also mention less tangible opinions, such as the charisma of many species (such as wolves, pandas, and baby harp seals) and the spirituality of natural places (such as towering old-growth forest and other kinds of wilderness). Because this belief is becoming increasingly widespread and popularized, it is having a major influence on politicians, who are including biodiversity issues in their agendas for action—threats to biodiversity have become politically important.

Undoubtedly, there is an undiscovered wealth of products of biodiversity that are potentially useful to humans. Many of these bio-products will be found in tropical species that have not yet been "discovered" by biologists. Clearly, the most important argument in favour of preserving biodiversity is the need to maintain natural ecosystems so they can continue to provide their vast inventory of useful products and their valuable ecological services. In addition, biodiversity must also be preserved for its intrinsic value.

Image 7.4. Landscapes and seascapes are spatial mosaics of various communities occurring at a large scale. This landscape in Nova Scotia is characterized by a mosaic of conifer-dominated (dark green) and hardwood (bright colours) stands of forest, plus lakes, streams, and wetlands. Source: B. Freedman.

Classification of Organisms

Biologists classify species into higher-order groupings on the basis of their relatedness and similarities. Similarity is judged using information about anatomy, development, biochemistry, behaviour, and habitat selection. These classifications are made by systematists (biologists who study the evolutionary relationships among groups of organisms) and taxonomists (who focus on naming groups of organisms).

The systematics of life is organized hierarchically, with levels ranging through subspecies, species, genus, family, order, class, phylum, and kingdom. This system is illustrated in Table 7.2.

Table 7.2. Biological Classification. The hierarchical, systematic classification of organisms is illustrated by three representative species.

Grouping	**Douglas Fir**	**Monarch Butterfly**	**Humans**
Kingdom	Plantae	Animalia	Animalia
Phylum	Coniferophyta	Arthropoda	Chordata
Class	Gymnospermae	Insecta	Mammalia
Order	Coniferales	Lepidoptera	Primates
Family	Pinaceae	Danaidae	Hominidae
Genus	*Pseudotsuga*	*Danaus*	*Homo*
Species	*menziesii*	*plexippus*	*sapiens*
Scientific name	*Pseudotsuga menziesii*	*Danaus plexippus*	*Homo sapiens*

A species is described using two Latinized words, known as a binomial. If a subspecies is also recognized, the name has three Latin words (such as Pseudotsuga menziesii glauca, the interior form of the Douglas-fir).

Many species also have a scientifically recognized "common name," and they may also have informal common names. For example, the scientifically recognized common name of the widespread tree Populus tremuloides is trembling aspen, but this species is also known as aspen, golden aspen, mountain aspen, poplar, quaking asp, quaking aspen, trembling poplar, and that old-time favourite, "popple." Some of the common names have only a local use and are unknown in other parts of the range of the species. Common names may also overlap among species—for instance, both the balsam poplar (Populus balsamifera) and large-toothed aspen (P. grandidentata) are often called "poplar."

To avoid the ambiguities associated with common names, species are assigned a globally recognized binomial and sometimes a "proper" common name. Because of this system, biologists working in Canada, the United States, Germany, Turkey, Russia, China, and other countries where the animal Ursus arctos occurs all know it by its binomial. In English, this animal is known as the grizzly or brown bear, and in other languages by other common names. But no one is confused by its scientific binomial name.

The Organization of Life

Most biologists divide all of Earth's species into five major groups, known as kingdoms. Although somewhat controversial and subject to ongoing refinement, this systematic organization is believed to reflect the evolutionary relationships among groups of organisms. The kingdoms and their major characteristics are briefly described below.

Monera

Monerans are the simplest of single-celled microorganisms and include bacteria and blue-green bacteria, the latter being photosynthetic. They are prokaryotes, because their genetic material is not contained within a membrane-bounded organelle called a nucleus. Organisms in the other kingdoms have nuclei within their cells and are called eukaryotes. Prokaryotes also do not have other kinds of organelles, such as chloroplasts, flagella, or mitochondria. They were the first organisms to evolve, about 3.5 million years ago. It was not until 1.5 billion years ago that the first eukaryotes appeared.

At least 7,643 species of bacteria have been named (Table 7.1), but there are many additional species that have not yet been described by microbiologists. The diversity of bacteria includes species capable of exploiting a phenomenal range of ecological and metabolic opportunities. Many are decomposers, found in "rotting" biomass. Some species are photosynthetic, others are chemosynthetic, and still others can utilize virtually any organic substrate for their nutrition, either in the presence or absence of oxygen. Some bacteria can tolerate extreme environments, living in hot springs as torrid as 78°C, while others are active as deep as 400 m in glacial ice.

Many bacterial species live in mutually beneficial symbioses (mutualisms) with more-complex organisms. For example, some live as a community in the rumens of cows and sheep, and others live in the human gut, in both cases aiding in the digestion of food. Other bacteria, known as Rhizobium, live in the roots of leguminous plants (such as peas and clovers), where they fix atmospheric nitrogen gas into a form (ammonia) that plants can use as a nutrient (see Chapter 5).

Many bacteria are parasites of other species, causing various diseases. For example, Bacillus thuringiensis is a pathogen of moths, butterflies, and blackflies and has been used as a biological insecticide against certain pests in agriculture and forestry. Species of bacteria also cause important diseases of humans, including cholera, diphtheria, gonorrhea, Legionnaire's disease, leprosy, pneumonia, scarlet fever, syphilis, tetanus, tooth decay, tuberculosis, whooping cough, most types of food poisoning, and the "flesh-eating disease" caused by a virulent strain of Streptococcus.

Protista

Protists include a wide range of simple, eukaryotic organisms, comprising both unicellular and multicellular species. Protists include foraminifera, protozoans, slime moulds, and single-celled and multicellular algae. The latter group includes the large seaweeds known as kelps, some of which are over 10 m long. The kingdom Protista consists of 14 phyla and about 60,000 named species, which vary enormously in their genetics, morphology, and function. Many biologists believe that the Protista is a catch-all group of not-so-closely related groups. It is likely that the protists will eventually be divided into several kingdoms because of accumulating evidence of key differences among groups and recognition that the other, more-complex eukaryotic kingdoms (fungi, plants, and animals) evolved from different protistan ancestors.

Several phyla of protists, broadly known as algae, are photosynthetic. These groups include the diatoms (Bacillariophyta), green algae (Chlorophyta), dinoflagellates (Dinoflagellata), euglenoids (Euglenophyta), red algae (Rhodophyta), and brown algae such as kelps (Phaeophyta). Algae are important primary producers in marine and freshwater ecosystems. Some seaweeds are harvested to extract chemicals known as alginates, which are important additives to many foods and cosmetics. Uncommon marine phenomena known as "red tides" are blooms of certain dinoflagellates that produce extremely toxic metabolites.

Other phyla of protists are heterotrophic in their nutrition. These groups include the ciliates (Ciliophora), forams (Foraminifera), slime moulds (Myxomycota), amoebae (Rhizopoda), and unicellular flagellates (Zoomastigina). Forams are unicellular microorganisms that form an architecturally complex shell of calcium carbonate, the remains of which may accumulate over geological time to form a mineral known as chalk- the white cliffs of Dover in southern England are made of foram remains. Trypanosomes are unicellular flagellates that are responsible for sleeping sickness, a disease of humans and other vertebrate animals. Certain species of amoebae are parasites of animals, including amoebic dysentery in humans. The ciliate Giardia causes a water-borne disease known as hiker's diarrhea (or beaver fever), the risk of which is a reason why even the cleanest-looking natural water should be boiled or otherwise disinfected before drinking.

Fungi

This kingdom consists of yeasts, which are single-celled microorganisms, and fungi, which are multicellular and filamentous. Fungi evolved at least 400 million years ago, but they may be much older than that because their remains do not fossilize well. Fungal cells excrete enzymes into their surroundings, which then externally digest complex organic materials. The fungus then ingests the resulting simple organic compounds. All fungi are heterotrophic—most are decomposers of dead organic matter, while others are parasitic on plants or animals. There are three major divisions (phyla) of fungi, distinguished mainly by their means of sexual reproduction. Asexual reproduction is also common.

The zygomycetes (division Zygomycota) achieve sexual reproduction by the direct fusion of hyphae (the thread-like tissues of fungi), which form resting spores known as zygospores. There are about 600 named species, the most familiar of which are the bread moulds, such as Rhizopus, with their fluffy mycelium (a loosely organized mass of hyphae).

The ascomycetes (division Ascomycota) include about 30,000 named species, some of which are commonly known as a cup fungus or morel. During sexual reproduction, ascomycetes form numerous microscopic, cup-shaped bodies known as asci, which are located in specialized fleshy structures called ascocarps. Familiar species include yeasts, morels, and truffles, as well as the pathogens that cause chestnut blight and Dutch elm disease (see below).

The basidiomycetes (division Basiodiomycota) include about 16,000 named species. Sexual reproduction involves a relatively complex spore-producing structure known as a basidium, which depending on its shape may be called a mushroom, puffball, toadstool, or shelf fungus. In Canada, the largest of these structures is developed by the giant puffball (Calvatia spp.), which has a ball-like basidium with a diameter up to 50 cm.

Lichens are mutualisms between a fungus and either an alga or a blue-green bacterium. Most of the lichen biomass is fungal tissue, which provides habitat and inorganic nutrients for the photosynthetic partner, which in turn provides organic nutrition to the fungus. Another type of mutualism, known as a mycorrhiza, involves a relationship between plant roots and certain fungi. This relationship is beneficial to the plant because it allows more efficient absorption of inorganic nutrients from the soil, especially phosphate. About 80% of plant species develop mycorrhizae.

Fungi are ecologically important because they are excellent decomposers, allowing nutrients to be recycled and reducing the accumulation of dead biomass.

Various kinds of fungi are economically important because they spoil stored grain and other foods, are parasites of agricultural or forestry plants, or cause diseases in humans and other animals. Ringworm is a disease of the skin, usually the scalp, which is caused by various fungi. The chestnut blight fungus (Endothia parasitica) was accidentally introduced to North America and wiped out the native chestnut (Castanea dentata), which used to be a prominent and valuable tree in eastern forests. The Dutch elm disease fungus (Ceratocystis ulmi) is another introduced pathogen that is killing elm trees (especially white elm, Ulmus americana).

Economically useful fungi include a few species of yeast that can ferment sugars under anaerobic (O_2-deficient) conditions, yielding gaseous CO_2 and ethanol. The CO_2 raises bread dough prior to baking, while brewers take advantage of the alcohol production to make beer and wine. Other fungi are used to manufacture cheese, soy sauce, tofu, food additives such as citric acid, and antibiotics such as penicillin.

Some mushroom-forming fungi are cultivated as a food, while other edible species are collected from natural habitats. The most commonly cultivated species is the meadow mushroom (Agaricus campestris), while the most prized wild mushroom is the extremely flavourful truffle (Tuber melanosporum). Some wild mushrooms contain chemicals that induce hallucinations, feelings of well-being, or other pleasurable mental states, and are sought by people for religious or recreational use. These include the fly agaric (Amanita muscaria), a species widespread in Canada and elsewhere, and psilocybin (Psilocybe spp.) of more southern regions of North America and Central America. Some wild mushrooms are deadly poisonous even when eaten in tiny quantities. The most toxic species in Canada are the destroying angel (Amanita virosa) and deathcap (A. phalloides).

Plantae

Plants are photosynthetic organisms that manufacture their food by using the energy of sunlight to synthesize organic molecules from inorganic ones. Plants evolved from multicellular green algae about 430 million years ago, and the first tree-sized ones appeared 300 million years ago. Plants are different from algae in that they are always multicellular, have cell walls rich in cellulose, synthesize a variety of photosynthetic pigments (including chlorophylls and carotenoids), and use starch as their principal means of storing energy. Plants are extremely important as photosynthetic fixers of CO_2 into organic carbon, and they are dominant in terrestrial ecosystems, where algae and blue-green bacteria are sparse. Plants can be separated into 12 divisions, which are aggregated into two functional groups.

Bryophytes are relatively simple plants that lack vascular tissue and do not have a waxy cuticle covering their foliage, a characteristic that restricts these plants to moist habitats. The bryophytes consist of the following:

- liverworts (division Hepaticophyta), of which there are about 6,500 species
- mosses (Bryophyta), including about 10,000 species, which are prominent in some wetlands, especially in bogs, where the dead biomass of peat mosses (species of Sphagnum) accumulates as a partially decayed material known as peat, which is mined as a soil conditioner and a source of energy
- hornworts (Anthocerophyta), with 100 species

Vascular plants are relatively complex and have specialized, tube-like, vascular tissues in their stems for conducting water and nutrients. There are nine divisions of vascular plants:

- whisk ferns (division Psilophyta), containing several species
- club mosses and quillworts (Lycophyta), about 1,000 species
- horsetails or scouring rushes (Sphenophyta), 15 species
- ferns (Pterophyta), 12,000 species
- cycads or sago palms (Cycadophyta), 100 species
- gnetums (Gnetophyta), 70 species
- ginkgo (Ginkgophyta), with one relict species (Ginkgo biloba)
- conifers (Coniferophyta), including about 550 species of firs, hemlocks, pines, redwoods, spruces, yews, and others
- flowering plants (Anthophyta), containing a diverse assemblage of about 235,000 species

The flowering plants are also known as angiosperms, because their ovules are enclosed within a specialized membrane, and their seeds within a seedcoat. The conifers, ginkgo, and gnetums lack these structures and are referred to as gymnosperms. Together, the angiosperms and gymnosperms are known as seed plants. Their seeds develop from a fusion between specialized haploid cells known as pollen and ovules, in a process called pollination.

The seed plants are extremely diverse in their form and function. The tallest species are redwood trees (Sequoia sempervirens), which can exceed 100 m in height. The smallest is an aquatic plant known as watermeal (Wolffia spp.), only the size of a pinhead. Many seed plants live for less than one year (these are "annual" plants), while the age of others can exceed 4,500 years—for example, the oldest bristlecone pines (Pinus aristata).

Many flowering plants grow as shrubs or trees. Rigid, woody tissues in their stems provide mechanical strength that allows these plants to grow tall against the forces of gravity and wind. Other angiosperms lack rigid stem tissues and grow as herbaceous plants that die back to the ground at the end of the growing season.

Species of angiosperms are important crops in agriculture, while both conifer and angiosperm trees are prominent in forestry. Plants are also economically important as sources of biochemicals in industry and medicine, and because they provide the food and habitat required by so many other organisms, including many animals that are used by people as food.

Animalia

Animals are multicellular organisms, and most are mobile during at least some stage of their life history, having the ability to move about to search for food, to disperse, or to reproduce. Animals are heterotrophs: they must ingest their food, ultimately consuming the photosynthetic products of plants or algae.

Most animals (except the sponges) have their cells organized into specialized tissues that are further organized into organs. Almost all animals reproduce sexually, a process that involves the joining of haploid gametes from a male and female to produce a fertilized egg. Animals comprise the bulk of identified species of organisms, with insects being the most diverse group. Apart from these broad generalizations, animals are extremely diverse in their form and function. They range in size from the largest blue whales (Balaenoptera musculus), which can reach 32 m in length and 136 tonnes of weight, to the smallest beetles and soil mites, which are less than 1 mm long and weigh a few milligrams.

The animal kingdom includes about 35 phyla. The majority occur in marine habitats, with a smaller number in freshwater and on land. All animals in all the phyla except one are considered to be invertebrates (with no backbone), while the phylum Chordata includes the vertebrates – animals with a backbone. The most prominent phyla are described below.

- **Sponges** (phylum Porifera) include a marine group of about 5,000 species plus 150 freshwater ones. Sponges are simple animals, sessile (non-mobile) as adults, with no differentiation of tissues into organs. They filter-feed on organic matter suspended in their watery habitat. The slow flow of water through sponges is driven by surface cells that use flagella, tiny whip-like structures, to move water over their surface.

- **Cnidarians** (phylum Cnidaria) include about 9,000 species, almost all of which are marine. Familiar groups include corals, hydroids, jellyfish, and sea anemones. Cnidarians have a simple, gelatinous body structure. They display radial symmetry, meaning a cross-section in any direction through their central axis yields two parts that are mirror images. Jellyfish are weakly swimming or floating animals, with a body form known as a medusa. Most other cnidarians are sessile as adults, being attached to a bottom substrate. Cnidarians are carnivores that use tentacles ringing their mouth opening to capture prey, often after subduing the victim by stinging it with specialized cells. Corals develop a protective casement of calcium carbonate and are important reef-building organisms.

- **Flatworms and tapeworms** (phylum Platyhelminthes) include about 12,000 species of soft-bodied, ribbon-shaped animals. Many flatworms are free-living scavengers or predators of small animals, while tapeworms and flukes are internal parasites of larger animals, including humans.

- **Nematodes** (phylum Nematoda) include 12,000 species of small, worm-like creatures. These animals are round in cross-section and are abundant in almost all habitats that contain other forms of life, ranging from aquatic habitats to desert. Many species are parasites, living in or on their hosts. Virtually all plants and animals are parasitized by one or more species of nematodes, which are often specialized to a particular host. Species of hookworms, pinworms, and roundworms are important parasites of humans. The Trichinella roundworm causes a painful disease known as trichinosis, while Filaria causes filariasis, a tropical disease.

- **True worms** (phylum Annelida) include about 12,000 species of tubular, segmented, soft-bodied animals. Most worms are marine, but others occur in freshwater and moist terrestrial habitats. Worms are divided into three major groups: bristleworms or polychaetes, typical worms or oligochaetes (including earthworms), and leeches or hirudineans. Most feed on dead organic matter, but leeches are blood-sucking parasites of larger animals. Earthworms provide an important service by helping to recycle dead biomass in many terrestrial habitats.
- **Molluscs** (phylum Mollusca) comprise about 85,000 species of clams, cuttlefish, octopuses, oysters, scallops, slugs, snails, and squids. Many have a hard shell of calcium carbonate that protects the soft body parts. Other molluscs, such as squid and octopus, lack this hard shell. Molluscs are most abundant in marine and freshwater habitats, with relatively few terrestrial species. Most are herbivores or scavengers, but some are predators. Various species are used by humans as food, and several produce pearls, used for making jewellery. Some slugs and snails are pests in agriculture, while others are alternative hosts for certain parasites, such as the tropical fluke that causes schistosomiasis in humans.
- **Arthropods** (phylum Arthropoda) comprise the largest group of organisms. There are more than a million named species and likely millions of others that have not yet been described. Arthropods have an exterior skeleton (exoskeleton) made of a polysaccharide known as chitin, with their body parts segmented to allow movement. They have at least three pairs of legs. The most abundant groups are the spiders and mites (class Arachnida), crustaceans (Crustacea), centipedes (Chilopoda), millipedes (Diplopoda), and insects (Insecta). Insects alone make up more than half of all named species. Arthropods are of great economic importance, with some species being used by people as food (such as lobster), and others used to produce food (such as the honey of certain bees). Termites damage buildings by eating wood, while various insects are pests in agriculture. Species of mosquitoes, blackflies, fleas, and ticks spread diseases of humans and other animals, including malaria, yellow fever, encephalitis, and plague.
- **Echinoderms** (phylum Echinodermata) include about 6,000 species of marine animals, such as brittle stars, sand dollars, sea stars, sea cucumbers, and sea urchins. Echinoderms have radial symmetry as adults. Most have an exoskeleton of calcium carbonate, some are covered with spiny projections, and some move about using large numbers of small, tube-feet. Sea urchins and sea cucumbers are harvested as a minor source of food, popular in some Asian countries.
- **Chordates** (phylum Chordata) are the most familiar group of animals. Distinctive characters (in at least the embryonic phase) include a hollow nerve cord that runs along the dorsal (top) surface and a flexible, rod-like dorsal structure (the notochord), which is replaced by the vertebral column in adults. There are about 63,000 species of chordates, divided among three subphyla. The tunicates (Urochordata) are composed of about 1,000 species of marine animals, including sea grapes and sea peaches. Tunicates have a small notochord and adults are sessile filter-feeders. The lancets (Cephalochordata) consist of 23 species of filter-feeding marine animals, which have a long, laterally compressed body. The vertebrates (Vertebrata) comprise almost all species in the group, most of which have a vertebral column as adults. The major classes of living vertebrates are the following.
    - **The jawless fishes** (class Agnatha) include 63 species of lampreys and hagfishes, which first evolved 470 million years ago. These marine or freshwater animals have a notochord and a skeleton of cartilage.

- **The cartilaginous jawed fishes** (class Chondrichthyes) consist of 850 species of dogfish, rays, sharks, and skates, all of which occur in marine habitats. Cartilaginous fishes evolved more than 410 million years ago.
- **The bony fishes** (class Osteichthyes) include about 30,500 species of typical fish, such as cod, salmon, tuna, and guppies. The first bony fishes evolved about 390 million years ago.
- **The amphibians** (class Amphibia) consist of 6,515 species of frogs, salamanders, toads, and legless caecilians. The first amphibians evolved about 330 million years ago. Early stages in the life history (egg and larva) are aquatic, but adult stages of many species can live in terrestrial habitats.
- **The reptiles** (class Reptilia) include 8,734 species of crocodilians, lizards, snakes, and turtles. Reptiles first evolved about 300 million years ago. Extinct groups include the dinosaurs, plesiosaurs, and pterosaurs, the last of which became extinct about 65-million years ago. Reptiles were the first fully terrestrial animals, capable of completing all stages of their life history on land (although some species, such as turtles, are highly aquatic as adults). Reptiles have a dry skin and lay eggs on land. Their young are miniature versions of the adults.
- **The birds** (class Aves) consist of 9.990 species, which first evolved about 225 million years ago from small, dinosaurian ancestors. Birds are homeothermic (warm-blooded), are covered in feathers, lay hard-shelled eggs, and have a horny covering of the jaws known as a beak. Most species can fly, the exceptions being the largest birds, penguins, and many species that evolved on islands lacking predators.
- **The mammals** (class Mammalia) consist of 5,487 species, which first evolved about 220 million years ago (the earliest fossil mammals are difficult to distinguish from reptiles). Mammals became prominent after the extinction of the last dinosaurs, about 65 million years ago. Mammals are homeotherms, have at least some hair on their body, feed their young with milk, and have a double circulation of the blood (i.e., a four-chambered heart and fully separate circulatory systems for oxygen-poor and oxygen-rich blood). There are three major groups of mammals: **Monotremes** are a few species of egg-laying mammals that live in Australia and New Guinea—the platypus and several species of echidnas. **Marsupials** bear live young that at birth are at an extremely early stage of development. After birth, the tiny young migrate to a special pouch (the marsupium) on the mother's belly where they develop further while feeding on milk. Examples of marsupials include kangaroos, koala, and wallabies, which live only in Australia, New Guinea, and nearby islands, and the opossum of the Americas. **Placental mammals**include many familiar species of the Americas, Africa, and Eurasia. Placental mammals give birth to live young that are suckled by the mother. Humans are a species of placental mammal.

Image 7.5. Humans and dogs are species of mammals. Humans (Homo sapiens), along with other great apes, are in the family Hominidae. Dogs (Canis lupus familiaris) are a domesticated subspecies of the wolf and are in the family Canidae. Source: B. Freedman.

Conclusions

Biodiversity is the richness of biological variation—it exists at the levels of genetics, species richness, and community diversity on landscapes and seascapes. Biodiversity is important to the survival of humans and their economy, and also to all other species. Biodiversity also has inherent value. Human activities have resulted in the extinction of many elements of biodiversity, and the survival of many others is being placed at grave risk (Chapter 26). Damage to biodiversity is a principal aspect of the environmental crisis.

Questions for Review

1. What are the major components of biodiversity? Provide an example of each.
2. Pick any species in which you are interested. Illustrate the hierarchical classification of life by giving the scientific names of its species, genus, family, order, class, phylum, and kingdom.
3. What are the five kingdoms of life? Identify several groups within each of the kingdoms.

Questions for Discussion

1. Why is biodiversity important? Outline several reasons.

2. Discuss the notion that all species are similarly "advanced" in the evolutionary sense but may vary greatly in their complexity.
3. All elements of biodiversity are considered to have intrinsic value. What does this mean? Can it be fully justified in a strictly scientific context?
4. Choose an economically important "pest," such as the house mouse (Mus musculus), a disease-carrying mosquito (such as an Anopheles species), or the groups A and B Streptococcus bacteria that cause deadly infections. Now suppose that a new method has been discovered to eradicate that pest, which would cause its global extinction. Based on ideas about intrinsic value and other considerations, could you mount a logical defence of the pest to argue against its extinction?

Exploring Issues

1. You are a biodiversity specialist, and a group of politicians has asked why it should spend public money to protect an endangered species occurring within their jurisdiction. You know that these people are sceptical, and that if you do not convince them to preserve the species and its habitat, it may become extinct. What information and arguments would you include in your presentation to the politicians?
2. Make a comprehensive list of products of biodiversity that you use in a typical day. The list can include raw and processed foods, medicines, materials, and sources of energy.

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Chapter 8 ~ Biomes and Ecozones

Key Concepts

After completing this chapter, you will be able to

1. Identify the major biomes and outline their characteristics.
2. Identify Canada's ecozones.
3. Describe the differences between natural and anthropogenic ecosystems.

Biomes: Global Ecosystems

A biome is a geographically extensive type of ecosystem. A particular biome occurs wherever environmental conditions are suitable for its development, anywhere in the world. Biomes are characterized by the life forms of their dominant organisms, but not necessarily by their particular species. On land, biomes are generally identified by their mature or older-growth vegetation. In contrast, aquatic biomes are usually distinguished by their dominant animals. Biomes are classified using a system that is used at an international level—that is, by ecologists working in many countries.

Figure 8.1 shows a map of the distribution of the most extensive terrestrial biomes. The distribution of biomes is determined by environmental conditions, which must be appropriate to support the dominant species. Moisture and temperature are usually the most important environmental influences on the distribution of terrestrial biomes (Figure 8.2). The distribution of various types of wetlands within terrestrial biomes is mostly influenced by the amount and permanence of surface water and the availability of nutrients. Marine biomes are most strongly influenced by water depth and upwellings, which affect the amounts of light and nutrients that are available to support primary productivity.

Figure 8.1. Distribution of the Major Terrestrial Biomes. Note that the spatial complexity is greatest in regions with mountainous terrain, such as the western Americas and southern Asia. Source: Modified from Odum

(1993).

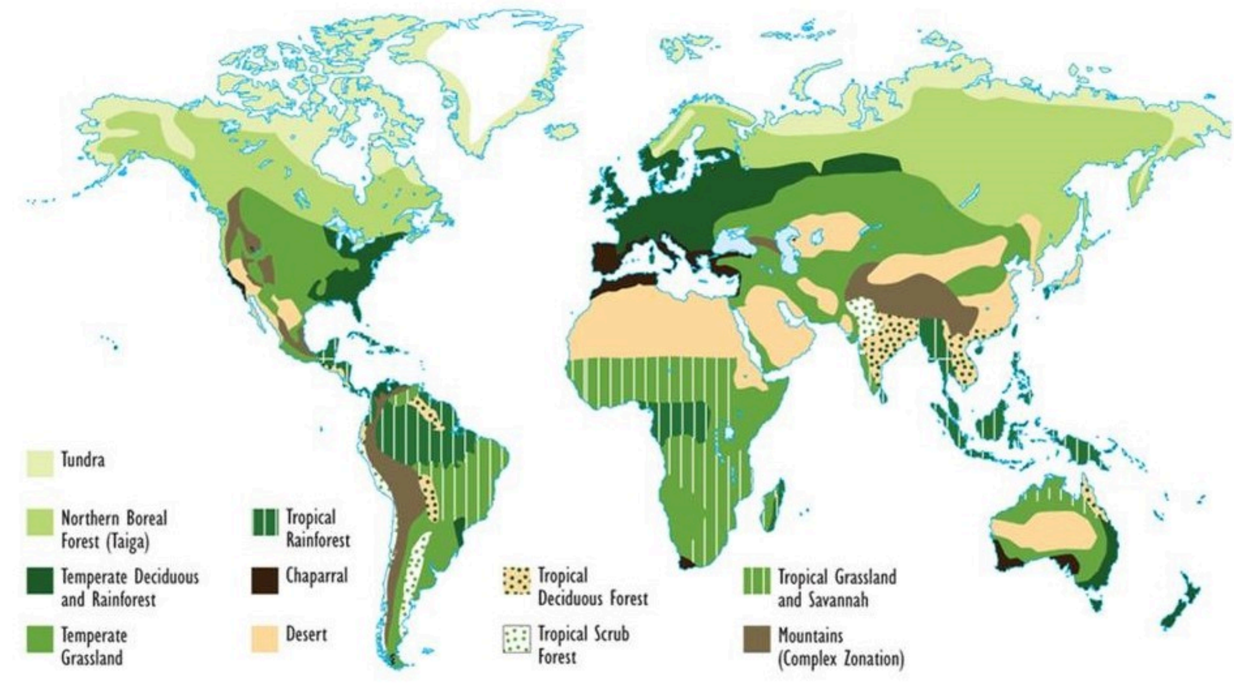
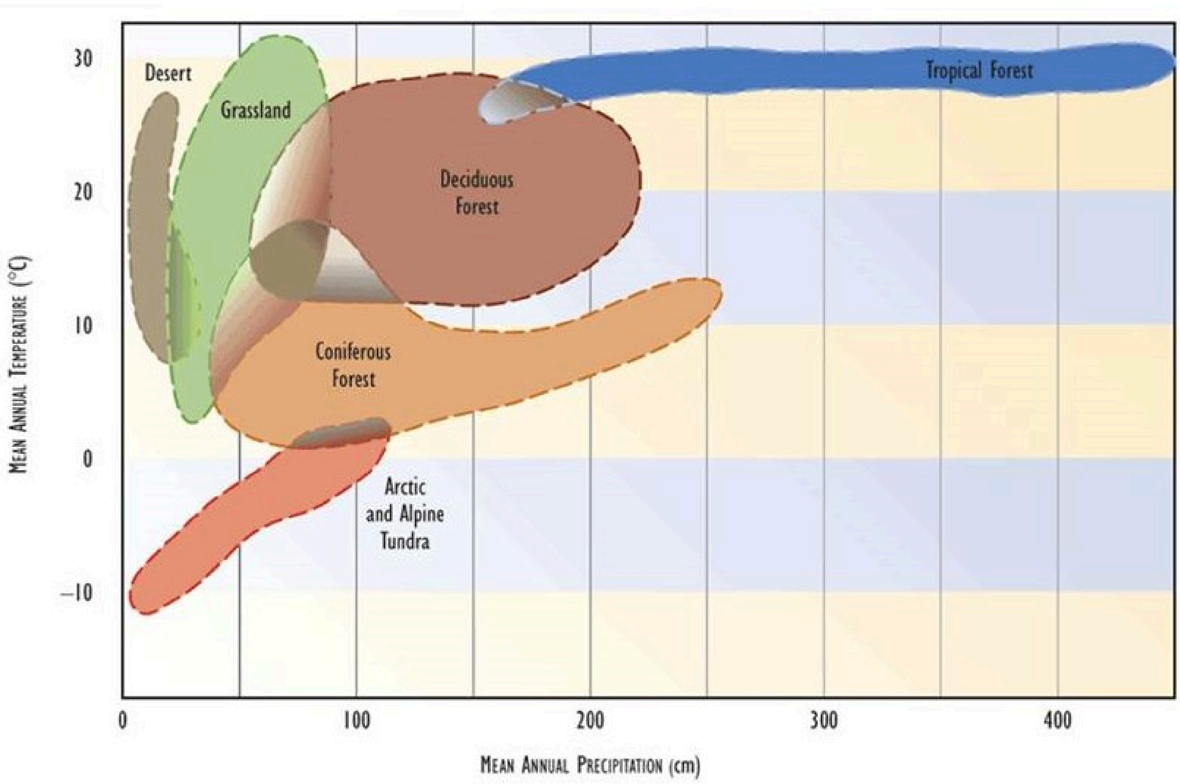


Figure 8.2. Environmental Influences on the Distribution of Terrestrial Biomes. This diagram suggests the reasons why temperature and moisture are believed to be the most important environmental factors affecting the distributions of terrestrial biomes. Source: Modified from Odum (1993).



As long as environmental conditions are suitable for its development, a particular biomes may occur in widely divergent regions, even on different continents. Although widely separate regions of a biome may be dominated by different species, their life forms are typically convergent. In other words, the different species are comparable in their form and function, because the regimes of natural selection occurring in similar environments result in parallel (or convergent) evolutionary responses. Therefore, biomes are defined primarily by the structure and function of their ecosystem, but not necessarily their species composition.

This context is illustrated by the boreal forest, an extensive biome that occurs in northern regions of Canada, Alaska, and Eurasia. The boreal forest occurs in regions with a cold and long winter, short but warm summer, and generally moist soil. This biome is situated between the more northern tundra, and temperate forest or prairie to the south. The dominant vegetation of boreal forest is typically coniferous trees, especially species of fir, larch, pine, or spruce. However, the particular species vary from region to region, and angiosperm (hardwood) trees may also be present.

Over much of northern Canada the boreal coniferous forest is dominated by stands of black spruce (Picea mariana). However, in some regions, stands of white spruce (Picea glauca), jack pine (Pinus banksiana), balsam fir (Abies balsamea), or tamarack (Larix laricina) are dominant. In the boreal forest of northern Europe, Siberia, and northern parts of Japan, Korea, and China, there are other species of coniferous trees. In some cases, there may be stands dominated by hardwood trees, such as trembling aspen (Populus tremuloides) in parts of northern Canada. However, all of these different forest types occurring on several continents are structurally and functionally convergent ecosystems within the same biome—the coniferous forest.

We should also note that any particular biome is described on the basis of its dominant, most extensive kind of ecological communities. For the boreal forest, this is usually stands of coniferous trees. However, biomes are not homogeneous, and they contain other kinds of less-widespread communities. For instance, parts of the boreal forest are dominated by persistent areas of shrubs such as species of alder, dwarf birch, and willow, and there may also be wetlands such as bogs and fens as well as distinctive communities associated with streams and rivers.

In addition, local areas may be subjected to occasional catastrophic disturbances, which may result in a landscape being composed of a mosaic of stands of various stages (and ages) of ecological recovery, called succession. In the case of boreal forest, disturbances are typically caused by wildfire or by epidemics of insects that kill trees (see Chapter 22).

The Major Biomes

Natural biomes are characterized by their dominant ecological communities, which are composed of particular assemblages of plants, animals, and microorganisms. There are also anthropogenic ecosystems that are strongly influenced by humans and their activities, such as cities and agricultural land. In fact, all of the modern biomes have been influenced by people to some degree—at the very least, all organisms in even the most remote places now contain trace contaminations of organochlorine chemicals (such as DDT and PCBs) that humans have manufactured and dispersed into the environment (see Chapter 22).

Ecologists have used a number of systems to divide the biosphere into major biomes, one of which is illustrated in Figure 8.1. The classification of global biomes described here is modified from a system proposed by the ecologist E.P. Odum. In the following sections, the world's biomes are examined within global and ecoregional contexts. This is appropriate because biomes are widespread ecological units whose boundaries and species do not respect political boundaries.

Terrestrial Biomes

Tundra is a treeless biome that occurs in environments with a long, cold winter and a short, cool growing season. There are two types of tundra: alpine and arctic. Alpine tundra occurs at higher elevations in mountainous regions, even in tropical countries. Arctic tundra occurs at high latitudes—that is, in northern regions of the Northern Hemisphere and southern parts of the Southern Hemisphere. Most tundras are a meteorological desert because they receive sparse precipitation. Nevertheless, the soil may be moist or wet because the cold environment restricts the amount of evaporation that occurs, and frozen soil may prevent deep drainage of water. The coldest, most northerly, high-Arctic tundra is extremely unproductive and dominated by short, long-lived plants, generally growing less than 5-10 cm above the surface. In the less-cold environments of the lower Arctic, well-drained tundra may be dominated by shrubs growing as tall as 1-2 m, while wetter habitats support productive meadows of sedge, cottongrass, and grass.

Image 8.1. Tundra is a biome of short vegetation growing in climatically stressed environments of the Arctic and Antarctic and on mountaintops. This is a view of arctic tundra on northeastern Somerset Island. The rock was marked by James Ross, who from 1848 to 1849 commanded the first search for John Franklin's expedition, and overwintered at the site. The initials E. I. refer to his ships, the Enterprise and Investigator. Source: B. Freedman.

Boreal coniferous forest, or taiga, is an extensive biome of environments with a cold winter, short but warm growing season, and moist soil. It is most extensive in the Northern Hemisphere. The boreal forest is dominated by coniferous trees, especially species of fir, larch, pine, and spruce. Some angiosperm trees may also be prominent, particularly aspen, birch, and poplar. Stands of boreal forest are poor in tree species, and may be dominated by only one or a few kinds. Most regions of boreal forest are subject to periodic disturbances, usually by wildfire, but sometimes by windstorms or insect epidemics.

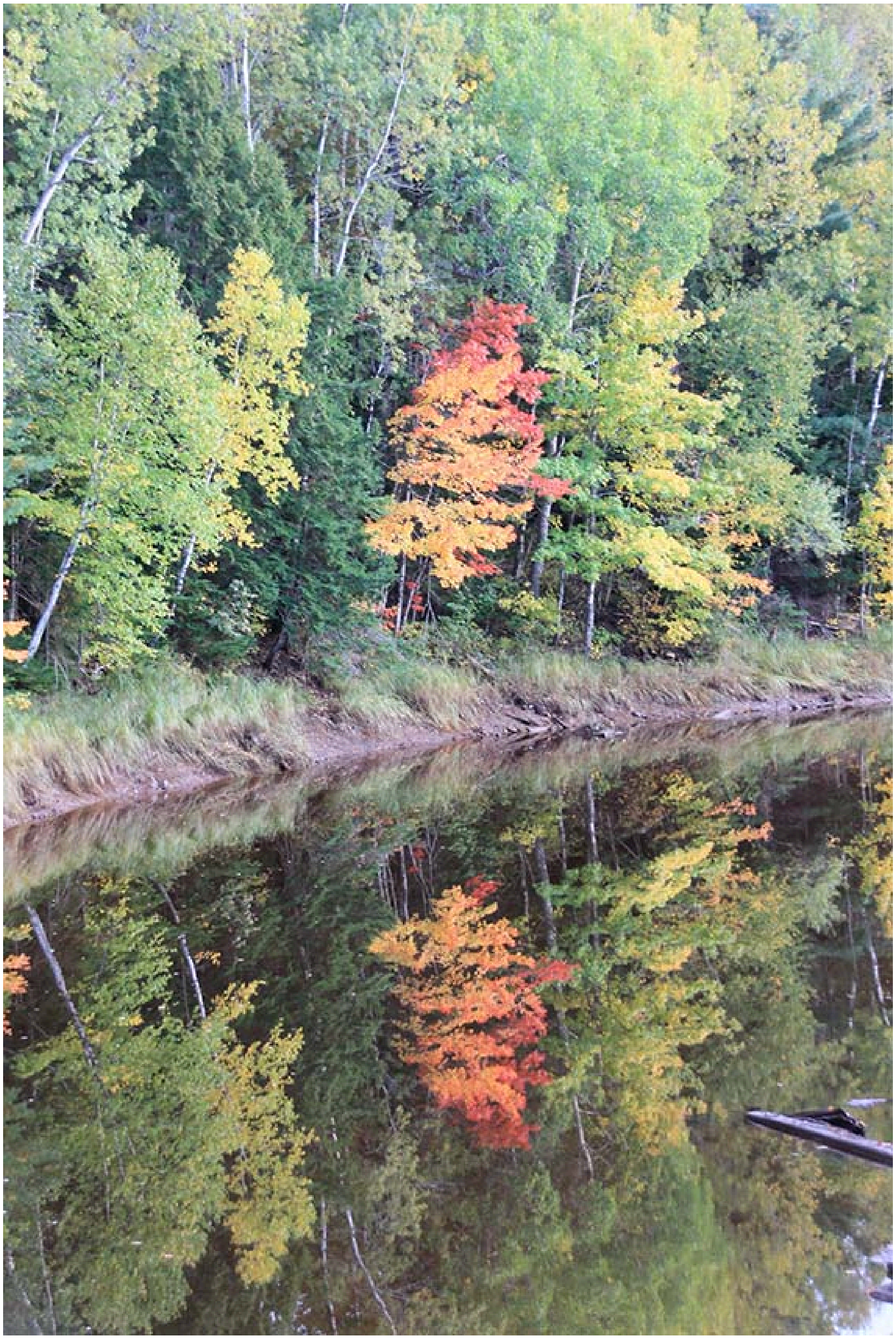
Image 8.2. The boreal coniferous forest (taiga) is extensive in northern regions of Canada, Alaska, and Eurasia. This photo shows a stand of black spruce with a carpet of feather mosses, in central Labrador. Source: B. Freedman.

Montane forest occurs at sub-alpine altitudes on mountains in temperate latitudes. It is similar in structure to high-latitude boreal forest and is also dominated by conifers.

Temperate deciduous forest occurs in relatively moist, temperate climates with a short, moderately cold winter and warm summer. This biome is dominated by a mixture of hardwood tree species. Most of the trees have seasonally deciduous foliage, meaning their leaves are shed each autumn and then regrown in the springtime. This is an adaptation to surviving the drought and other stresses of winter. Common trees of temperate deciduous forest in North America are species of ash, basswood, birch, cherry, chestnut, dogwood, elm, hickory, magnolia, maple, oak, sassafras, tulip-tree, and walnut. These trees occur in distinctive communities based on their preferences for particular qualities of soil moisture and fertility, soil and air temperature, and other environmental factors.

Image 8.3. The temperate deciduous forest contains species of angiosperm trees, which drop their leaves in the autumn, plus some coniferous trees. This biome is widespread south of the boreal forest. This stand in Nova

Scotia is dominated by birches, maples, and white spruce. Source: B. Freedman.



Temperate rainforest develops in a climate in which the winter is mild and precipitation abundant year-round. Because this climate is too moist to allow frequent wildfires, old-growth forest often develops. The old-growth forest is dominated by coniferous trees of mixed age and species composition, but some individual trees are extremely large and can be centuries old, sometimes even exceeding a thousand years. Prominent tree species in temperate rainforest of the humid west coast of North America are Douglas-fir, hemlock, red cedar, redwood, Sitka spruce, and yellow cypress.

Temperate grassland occurs in temperate regions where the annual precipitation is 25-60 cm/y. Under these conditions, soil moisture is adequate to prevent desert from developing, but insufficient to support forest. Temperate grassland is called prairie in North America and steppe in Eurasia, and this biome occupies vast regions in the interiors of both continents. Prairie is commonly divided into three types according to the height of the dominant vegetation: tall-grass, mixed-grass, and short-grass. Tall-grass prairie is dominated by various grasses and herbaceous angiosperm plants, such as blazing stars and sunflowers, some as tall as 2-3 m. Fire is an important factor that prevents tall-grass prairie from developing into an open forest. Tall-grass prairie is a critically endangered ecosystem because almost all of it has been converted into agricultural land. Mixed-grass prairie occurs where there is less rainfall and the habitat is characterized by shorter species of grasses and herbaceous angiosperms. Short-grass prairie develops where precipitation is even less, and it can be subject to unpredictable, severe drought.

Image 8.4. Temperate grassland is widespread in the dry interior of North America and other continents, and is dominated by species of grasses and other herbaceous plants. This view is of shortgrass prairie in Grasslands National Park in southern Saskatchewan. Source: B. Freedman.

Chaparral develops in south-temperate environments with a so-called Mediterranean climate, with winter rains and summer drought. Typical chaparral is characterized by dwarfed trees and shrubs with interspersed herbaceous vegetation. Periodic fires are characteristic. In North America, chaparral is best developed in coastal southern California.

Desert can be temperate or tropical, and it most commonly occurs in continental interiors or in the rain shadow of mountains. The distribution of desert is determined by the amount of soil moisture, which in the temperate zones is generally associated with an annual precipitation of less than about 25 cm. The driest desert supports almost no plant productivity, but less-dry conditions may support communities of herbaceous and succulent plants, both annual and perennial. Occasional moist places with springs of groundwater develop a relatively lush vegetation of shrubs or trees and are known as oases.

Image 8.5. Desert is a sparsely vegetated biome of extremely dry environments. This view is of arid habitat in Peru, in a region where there is no detectable precipitation in some years. Source: B. Freedman.

Tropical grassland and savannah occur in regions with as much as 120 cm of annual rainfall, but a pronounced dry season. Savannah is dominated by grasses and herbaceous angiosperms, with scattered shrubs and tree-sized plants that provide an open canopy. Some tropical grasslands and savannahs support large populations of big animals, including migratory ones. This is particularly true of Africa, where this biome supports a diverse community of large mammals, such as elephant, gazelle and other antelopes, hippopotamus, rhinoceros, water buffalo, and predators of these herbivores, such as cheetah, hyena, leopard, lion, and wild dog.

Semi-evergreen tropical forest develops in a warm climate with pronounced wet and dry seasons. Most trees and shrubs are seasonally deciduous, shedding their foliage in anticipation of the dry season. This biome supports a great richness of biodiversity, though less than tropical rainforest.

Evergreen tropical rainforest occurs in tropical climates with copious precipitation throughout the year. Tropical rainforest often develops into an old-growth condition because wildfire and other catastrophes are uncommon. Old-growth tropical rainforest supports a tremendous richness of tree species of many sizes and ages, most of which retain their foliage throughout the year. This forest also sustains an extraordinary diversity of other plants, animals, and microorganisms. Tropical rainforest represents the peak of development of terrestrial ecosystems because the biome supports huge biomass, high productivity, and rich biodiversity under relatively benign climatic conditions.

Image 8.6. Evergreen tropical forest occurs in warm regions where rainfall is abundant throughout the year.

Tropical rainforest, such as this one in Peru, sustains more species than any other ecosystem. Source: B. Freedman.

Freshwater Biomes

Lentic ecosystems contain standing or very slowly flowing water, as occurs in lakes and ponds. The ecological character of lentic systems is most strongly influenced by water chemistry, particularly its transparency and nutrient concentration. Waters that are well supplied with nutrients are highly productive (eutrophic), while infertile waters are unproductive (oligotrophic). In general, shallow waterbodies are much more productive than deeper ones of a comparable surface area. However, waterbodies with poor transparency are much less productive than might be predicted on the basis of their nutrient supply. Waters that are brown-coloured because of dissolved organic matter have poor transparency, as do turbid waters with fine suspended particulates. Lentic ecosystems are characterized by zonation in two dimensions. Horizontal zonation is due to changes in water depth and is usually related to the slope and length of the shore. Vertical zonation occurs in deeper water and is related to the amount of light, water temperature, and nutrient and oxygen concentrations. Lentic ecosystems often develop distinct communities along their shore (known as the littoral zone), in their deeper open water (the pelagic zone), and on their sediment (the benthic zone).

Lotic ecosystems are characterized by flowing water and include rivers and streams. The quantity, velocity, and seasonal variation of water flow are important environmental factors. Within streams or rivers, silt-sized particles are deposited in places with relatively calm water, leaving a fine-grained or muddy substrate. In contrast, the substrate of places with vigorous water flow is rocky because fine particles have been eroded away. For similar reasons, the turbidity is greatest during times of high water flow. Turbidity is an important factor because it interferes with light penetration and thereby restricts primary productivity. Lotic ecosystems sustain some productivity of algae and aquatic plants, but usually their primary production is not large. Most of the productivity of aquatic invertebrates and fish in lotic ecosystems is sustained by inputs of organic matter from upstream lakes and from the terrestrial watershed in the form of plant debris.

Wetlands occur in shallow, flooded places on land. There are four major types: marsh, swamp, bog, and fen. Marshes are the most productive; they are dominated by plants that are rooted in sediment but grow as tall as several metres above the water surface, such as reed, cattail, and bulrush. Open-water areas of marshes have floating-leaved plants, such as water lily and lotus. Swamps are forested wetlands that may be flooded seasonally or permanently. Swamps are often dominated by such trees as silver maple (Acer saccharinum), white elm (Ulmus americana), or bald cypress (Taxodium distichum). Bogs are acidic, relatively unproductive wetlands that develop in a cool, wet climate. Their supply of nutrients is sparse because bogs are fertilized only by atmospheric inputs of dust and chemicals dissolved in precipitation. Bogs are typically dominated by species of Sphagnum moss (also known as peat moss). Fens also develop in a cool and wet climate, but since they have a better nutrient supply than bogs, they are less acidic and more productive.

Image 8.7. A marsh is a fertile wetland dominated by taller herbaceous plants, such as bulrush and cattail. This images shows a lakeside marsh dominated by cattail (Typha latifolia) in Point Pelee National Park in southern Ontario. Source: B. Freedman.

Image 8.8. A swamp is a forested wetland. This example is dominated by silver maple (Acer saccharinum) in

Point Pelee National Park. Source: B. Freedman.

Marine Biomes

The open ocean consists of pelagic and benthic ecosystems. The pelagic (open-water) ecosystem is strongly influenced by physical and chemical factors, particularly waves, tides, currents, salinity, temperature, light intensity, and nutrient concentration. The rate of productivity is small, and comparable to that of terrestrial desert. The primary production is associated with phytoplankton, which range in size from extremely small photosynthetic bacteria to larger (but still microscopic) unicellular and colonial algae. The phytoplankton are grazed by tiny animals known as zooplankton (most of which are crustaceans), which are eaten in turn by larger zooplankton and small fish. Large predators such as bluefin tuna, sharks, squid, and whales are at the top of the pelagic food web. The benthic ecosystem of the open ocean biome is supported by a sparse rain of dead biomass from the surface. The benthic ecosystem of the deep oceans is not yet well described, but it appears to be somewhat rich in species, low in productivity, and extremely stable over time. Some large regions of the open ocean have an enormous rotating surface current known as a gyre, which is caused by the Coriolis effect associated with the rotation of Earth. Gyres in the Northern Hemisphere rotate in a clockwise direction, while those in the Southern Hemisphere are counter-clockwise. Gyres collect floating material, such as floating seaweeds like Sargassum, as well as garbage from coastal dumping and debris from fishing fleets. One example is the North Pacific gyre, which covers most of that oceanic basin, and another is the North Atlantic gyre, also known as the Sargasso Sea.

Continental shelf waters occur near the shores of continents and are relatively shallow because they overlie an underwater projection of the landmass (a continental shelf). Compared with the open ocean, these nearshore waters are relatively warm and well supplied with nutrients. The nutrients come from inputs of rivers and from deeper, relatively fertile oceanic water that is occasionally stirred from the bottom by currents or turbulence caused by windstorms. Because the nutrient supply of coastal waters is relatively high, phytoplankton are productive and support a higher biomass of animals than occurs in the open ocean. Some of the world's most important fisheries are supported by the continental shelf biome – for example, those on the Grand Banks and other shallow waters of northeastern North America, in the nearshore waters of western North and South America, and in the Gulf of Mexico.

Image 8.9. The Pacific continental shelf waters are rich in marine life. Pictured here is a “forest” of large seaweeds known as kelps (Nereocystis spp.), which provide critical habitat for many animals, such as black rockfish (Sebastes melanops). Source: C. Harvey-Clark.

Regions with persistent upwelling occur where local oceanographic conditions favour the upwelling of relatively deep, nutrient-rich water to the surface. The increased nutrient supply allows these areas to sustain high rates of primary productivity. This ecological foundation supports large populations of animals, including big fish, sharks, marine mammals, and seabirds. Some of the most productive fisheries occur in upwelling areas, such as those off the west coast of South America and extensive regions of the Antarctic Ocean.

Estuaries are a complex group of coastal ecosystems that are open to the sea but are semi-enclosed in an embayment. Estuaries are transitional between marine and freshwater biomes, typically having large fluctuations of salinity associated with inflows of fresh water from the nearby land, twice-daily tidal cycles, and marine storm surges. Estuaries typically occur as coastal bays, river mouths, salt marsh, and tropical mangrove forest. They are highly productive ecosystems, largely because their semi-enclosed circulation tends to retain much of the water-borne input of terrestrial nutrients. Estuaries provide critical habitat for juvenile stages of commercially important fishes, shellfish, and crustaceans.

Seashores are an interface of terrestrial and oceanic biomes and they support a complex of coastal ecosystems. The seashore biome is locally influenced by physical environmental factors, especially bottom type, the intensity of wave action, and the frequency of major disturbances such as storms. Hard-rock and cobblestone bottoms in temperate regions usually develop communities dominated by large species of seaweeds or kelp. These are productive ecosystems and can maintain large amounts of algal biomass. Areas with softer bottoms of sand or mud develop communities supported by the productivity of benthic algae and inputs of organic detritus from elsewhere. These soft-bottom ecosystems are usually dominated by invertebrates, especially molluscs, echinoderms, crustaceans, and marine worms.

Coral reefs are a tropical marine biome that develops in shallow, relatively infertile places close to land. The physical structure of coral reefs is composed of the calcium carbonate shells of dead corals and molluscs. Coral reefs support a highly biodiverse veneer of crustose algae, living corals, other invertebrates, and fish. The biome is dominated by corals, which are colonial animals that live in a mutualism with unicellular algae. Because this symbiosis is efficient in acquiring nutrients from water, corals can sustain a high rate of productivity even though they occur in infertile water.

Global Focus 8.1. Transnational Species and Ecosystems

Because biomes are defined as "geographically extensive ecosystems, occurring throughout the world wherever environmental conditions are suitable," they have a global context. Temperate forest, for instance, occurs in all countries in which environmental conditions are favourable for its development. In comparison, ecozones are more specifically defined on the basis of their landforms, climate, species, and ecological communities. Because ecozones are identified on the basis of their natural biophysical features, which are not related to the political boundaries of countries, the southerly ecozones of Canada extend into the neighbouring United States.

Species may also have a transnational context. For example, the western red cedar (Thuja plicata) occurs in humid coastal forest throughout western North America, as does white pine (Pinus strobus) in the east. The grizzly (or brown) bear (Ursus arctos) is even more widespread—its original range encompassed much of Eurasia and North America, in the latter extending from Arctic regions of northwestern Canada, through much of the western United States, to northern Mexico.

Many animals are migratory, undertaking long-distance movements between their summer and winter ranges. Because great distances may be involved, many migratory animals use habitats in various countries at different times of the year. This pattern is well known for the millions of migratory birds that venture to Canada to breed in the summer, but spend the winter in warmer climes, and it is also true of some other kinds of animals.

For instance, the monarch butterfly (Danaus plexippus) is one of the most wide-ranging insects in the world, being native to North and South America, the Caribbean, Australia, New Zealand, and other Pacific islands, and also being introduced to Western Europe. The monarch is highly migratory in its North American range. At the end of the growing season, during September and October, adult monarchs undertake along migration to the south, where they spend the winter in one of two small areas. Most venture to central Mexico, where they winter in dense, multi-million populations at only about 12 mountain roosts in the states of Michoacán and Mexico. A much smaller population of western monarchs undertakes a migration to roosts in coastal southern California. The longest migrations are made by monarchs that were born in eastern Canada—these intrepid butterflies travel thousands of kilometres to reach their wintering roosts in Mexico.

When spring comes, the overwintering monarchs begin a northward migration. When they find a sufficient abundance of milkweed plants (Asclepias spp.), the only food eaten by the larvae, the females lay about 400 eggs and die soon afterward. The larvae hatch, feed voraciously, metamorphose into adults after 20-45 days, and then continue the northward migration. After a breeding relay of three to five generations, adult monarchs reach the northernmost parts of their range in Canada, where they breed wherever milkweed is abundant. The last generation of the year, which transforms into adults in September, is the one that undertakes the astonishing southward migration to the wintering roosts in Mexico or California.

The conservation of the monarch butterfly is greatly complicated by its migratory habit, the use of various kinds of ecosystems at different times of the year, and the fact that all of its habitats must be conserved if the species is to survive. However, the greatest conservation risk is the survival of its only 12 winter roosts in

Mexico. These critical habitats are in natural forest of oyamel fir (Abies religiosa) that is threatened by deforestation, illegal logging, and tourism development. Although the monarch is an abundant and familiar species, it could quickly become lost from most of its North American range if its winter roosts are not conserved. In addition, the species requires an abundance of milkweeds in its breeding range, and these native plants are being widely depleted by the extensive use of herbicide in agricultural management. As is the case for all transnational species and ecosystems, conservation of the monarch butterfly requires the co-operation of various countries, levels of government, and economic interests.

Image 8.10. Monarch butterflies wintering in Michoacán, Mexico. Source: B. Freedman.

Human-Dominated Ecosystems

Immense areas that were once occupied by natural habitats have been converted into land-uses that serve the human economy in various ways. These human-dominated ecosystems are anthropogenic in the sense that their characteristics are a consequence of environmental conditions associated with the activities of people. The character of these ecosystems may be an intended result of management practices, as is the case of agroecosystems in which crops are grown, or horticultural ecosystems where the intent is more aesthetic. Less-deliberate anthropogenic influences, such as pollution and disturbance, also affect the character of human-dominated ecosystems, often by causing ecological damage.

Of course, human-dominated ecosystems are prevalent wherever people are living in dense populations, such as in cities and towns. But they are also widely prevalent in the countryside where resource-extraction industries such as forestry and mining are important, and in transportation corridors associated with highways and electricity-transmission lines. Because anthropogenic ecosystems are becoming so widespread, and they support relatively few native species, they are the leading cause of the biodiversity crisis, which is characterized by the extinction and endangerment of native species and even of kinds of natural ecosystems (see Chapter 26). There is a great diversity of human-dominated ecosystems, but they can be aggregated into three major categories: urban-industrial techno-ecosystems, rural techno-ecosystems, and agroecosystems.

Urban-industrial techno-ecosystems are typical of urbanized areas and are dominated by the dwellings, businesses, factories, and other infrastructure of society (see Chapter 25). This anthropogenic biome supports many species in addition to humans, but they are mostly alien plants and animals that have been introduced from other regions. Typically, the non-native species cannot live locally outside this biome (other than the foreign biome to which they are indigenous).

Rural techno-ecosystems occur outside of urbanized areas and consist of the extensive technological infrastructure of civilization. These ecosystems include rural transportation corridors (highways, railways, and electricity-transmission corridors) as well as small towns supporting industries involved in the extraction and processing of natural resources. Rural techno-ecosystems support a blend of introduced species, plus those native species that are tolerant of stresses associated with human activities.

Agroecosystems are a complex of habitats that are managed to grow crops for use by humans. The most intensively managed kinds involve monocultures (single-species crops) of plants or animals that are cultivated in agriculture, aquaculture, or forestry. These valuable and necessary crops are grown under conditions that enhance their productivity, although intensive management systems may cause many ecological problems (see Chapter 24). Less-intensively managed agroecosystems may involve the cultivation of mixtures of species (polycultures), and they may provide habitat for some native species. Semi-natural habitats used for the grazing of livestock also support some indigenous biodiversity. When a agroecosystem is abandoned, it slowly reverts to a more natural condition, although it can take many decades before there are ecological communities that are similar to what was originally present, especially in forested regions.

Image 8.11. Urban-industrial techno-ecosystems are dominated by the dwellings, businesses, factories, and other infrastructure of human society. These areas support the economic activities of large numbers of people, and are sustained by enormous flows of resources from the surrounding landscape, and even from other countries. This aerial view of Halifax shows an area used entirely for roads, hospitals, homes, and schools.

Source: Nova Scotia Department of Natural Resources.

Ecoregions and Ecozones

As we have learned, biomes are geographically extensive ecosystems that occur anywhere in the world where environmental conditions are suitable for their development, and they are characterized by the life forms of their dominant organisms rather than by their particular species. Learning about biomes is important because it provides insight into the character and environmental influences on major kinds of ecosystems.

Nevertheless, in the practical context of identifying and conserving the species and natural ecosystems of the world, there are limitations to the concept of biomes, mostly because of the non-specificity of their biotic assemblages. If the biodiversity of the world is to be conserved, we need to understand how species are naturally aggregated into communities and larger ecosystems, and how these biotic assemblages are distributed over space and time—there must be enough biogeographic resolution (identification of distinct communities) to conserve the intricate fabric of life on Earth, and biomes do not provide this kind of information.

This problem is dealt with by identifying and mapping extensive units known as ecozones (or as ecoregions). These units are large landscapes or seascapes (ecoscapes) that contain distinct groupings of naturally assembled species and their communities. Like biomes, their spatial boundaries reflect conditions that existed prior to major changes in land-use caused by anthropogenic influences. The distribution of terrestrial ecoregions of the world has been mapped by Olson et al. (2001) and is presented in Figure 8.3. Note that the identity and distribution of the freshwater and marine ecoregions of the world must also be known for the purposes of conservation, but this work has not yet been done.

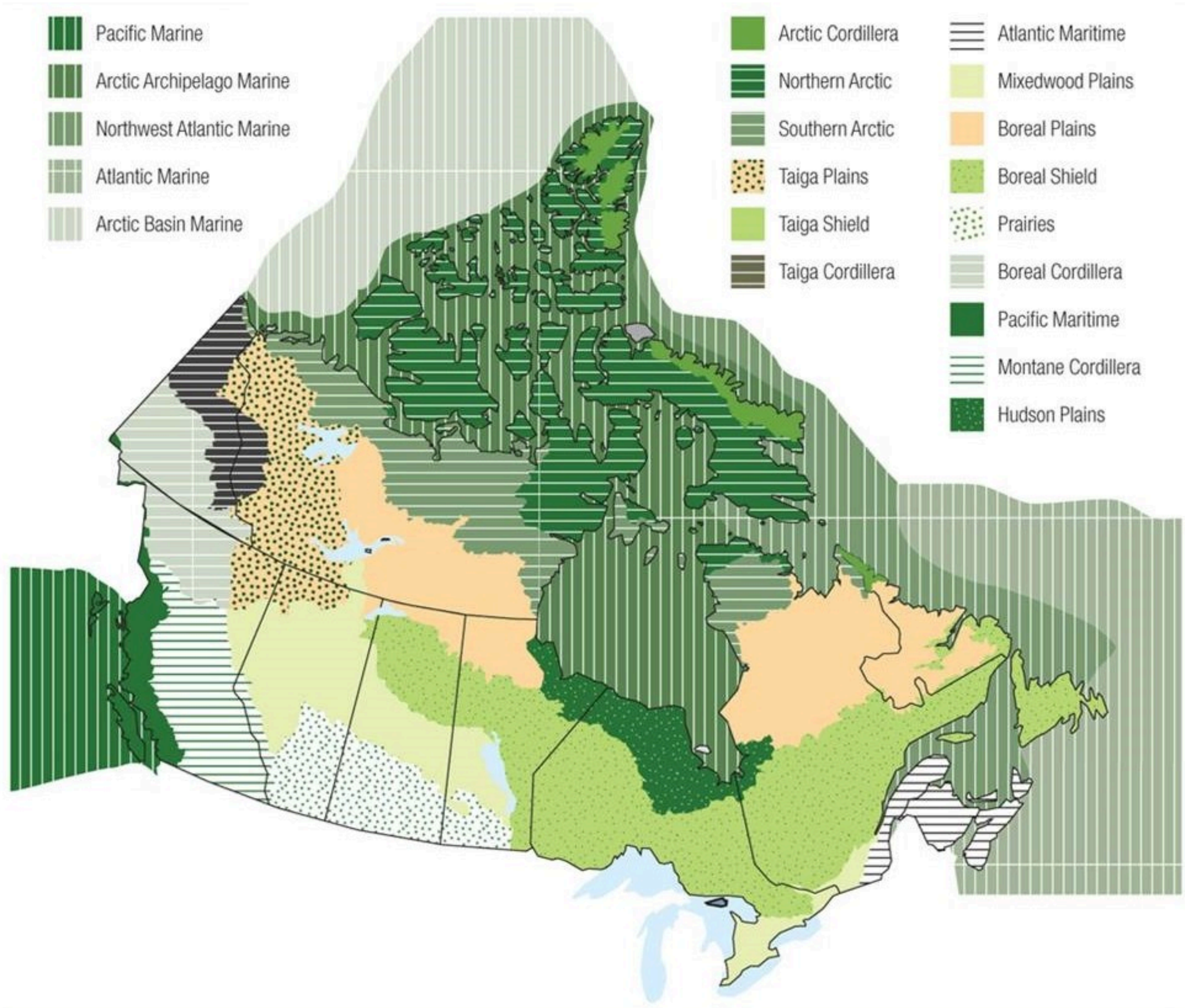
Figure 8.3. Terrestrial Ecoregions of the World. This map recognizes 867 terrestrial ecoregions, with the greatest amount of diversity occurring in humid tropical realms. Note that this map only covers terrestrial

environments—comparable results for freshwater and marine ecoregions are also needed for effective conservation planning, but are not yet available. Source: Modified from Olson et al. (2001).

Terrestrial Ecozones of Canada

The ecosystems found in Canada have been described in various ways, including a hierarchical classification of distinctive types. The largest ecological zones in the national classification are referred to as ecozones. There are 15 terrestrial and 5 marine ecozones in Canada (Figure 8.4). Each of these natural ecozones is characterized by key aspects of the physical environment, such as the climate and dominant landforms, as well as by their natural ecosystems and prominent species. Because so much of the Canadian landscape has been intensively modified through human activities, three anthropogenic ecosystems also occur: urban, agricultural, and industrial.

Figure 8.4. Ecozones of Canada. Canada's ecozones are described by the nature of their dominant biota and aspects of the physical environment, particularly climate, soil, geology, and other landscape-scale geographic features for terrestrial ecozones, and climate and ice cover for marine ecozones. Source: Modified from Ecological Stratification Working Group (1995).



Each of the Canadian ecozones represents a hierarchical agglomeration of distinct ecosystems of more local character. Ecoregions are sub-ecozone units, and are characterized by regional factors related to climate and landform and, to some degree, by soil, vegetation, fauna, and land-use. There are 194 terrestrial ecoregions in Canada. Canada's marine ecozones have not yet been divided into ecoregions.

Of course, the boundaries of biomes and ecozones rarely align with political borders. Consequently, all of the southern ecozones of Canada also extend into the United States. Figure 8.5 shows the results of a collaborative ecosystem-mapping study that involved scientists from Canada, Mexico, and the United States (CEC, 1997). This map shows the distribution of the 15 Level-1 ecological regions of North America (these are equivalent in scale and qualities to biomes). In addition, there are 52 Level-2 ecological regions (equivalent to Canadian ecozones). Because countries share ecozones, they also have a mutual responsibility to steward their ecological values. Sometimes, this can lead to conflict if one country believes the other is damaging shared resources or natural ecosystems. For example, Canada and the United States (or particular provinces or states) have ongoing arguments related to such binational issues as the following:

- The effects of raw sewage discharged by the city of Victoria, BC, may be damaging water quality in nearby U.S. waters in Juan de Fuca Strait.

- During seasonal times of high water levels, some of the volume of Devil's Lake, North Dakota, is released into the Sheyenne River, a tributary of the Red River that runs north into Manitoba. This is done to reduce the risks of flooding on shoreline properties on Devil's Lake. However, the Government of Manitoba is concerned about down-river flooding as well as the release of alien invasive species into the ecosystem of the Red River.
- There are many environmental issues associated with the jointly managed ecosystems of the Great Lakes, including those related to the diversion of water out of the system to serve U.S. purposes to the south, the release of alien invasive species, and pollution by sewage, agricultural fertilizer and pesticides, and industrial chemicals.

Binational considerations are also relevant to the many species that migrate between their breeding and wintering grounds, which may involve the use of different ecoregions in separate countries. For example, many of the songbirds that breed in Canada spend much of the year in habitats in the United States or in Central or South America. Migratory species of economic value are also an issue, such as species of Pacific salmon that may breed in particular rivers in Canada or the United States, but could be fished in waters of either country, or even in international waters of the high seas. Global Focus 8.1. examines one such example concerning the monarch butterfly, some of which may breed in southern Canada, and then migrate through the United States to reach their hibernating sites in central Mexico.

Figure 8.5. Distribution of the 15 Terrestrial Ecological Regions (Level-1) for North America. These regions are roughly comparable to global biomes. Source: Commission for Environmental Cooperation (1997).

It is beyond the scope of this book to describe the ecozones of Canada in detail. Detailed information is available in Ecological Stratification Working Group (1995) and on the website of the Canadian Council on Ecological Areas (https://web.archive.org/web/20090224235638/http://www.ccea.org/ecozones/index.html). For more details on the Level-1 and -2 ecoregions of North America, see CEC (1997).

Canadian Focus 8.1. Alexandra Fiord: A High-Arctic Oasis

An important field of research in ecology involves undertaking integrated studies of particular ecosystems. Such work is carried out by teams of ecologists, geologists, meteorologists, and other environmental scientists. This sort of work allows scientists to understand the physical, chemical, and biological factors that govern the structure and function of ecosystems and sustain their species.

One such project began in 1980, when a team of Canadian scientists working in the tundra biome began to study a place with a relatively moderate climate, known as a high-Arctic oasis. This one in particular is located on a lowland adjacent to the coast of Alexandra Fiord on eastern Ellesmere Island. Their objectives were to describe the plant and animal communities of the oasis and to determine the environmental factors that influence its biodiversity and productivity. Specific research topics included work on the local and regional climate, geology, soils, distribution and species composition of plant communities, ecological productivity, the life histories of prominent plant species, responses of vegetation to experimental manipulations of environmental conditions, and animal populations and their habitat relationships.

This was a multidisciplinary research program, but because all the component studies were carried out in the same place, their results could be integrated to develop a larger picture of the structure and function of the oasis. This kind of understanding is of scientific importance because ecosystems in the Arctic biome have not yet been well studied. The research also contributes to the knowledge required to assess the many kinds of ecological damage that are potentially associated with increasing resource exploitation, ecotourism, and climate change in the Arctic.

The team at Alexandra Fiord found that the climate of the lowland is indeed more moderate than that of the larger landscape. In general, the air and surface temperatures are warmer, soil moisture is greater, and there is less wind. It appears that dark-coloured cliffs on nearby uplands absorb solar radiation and then re-radiate infrared energy that helps to warm the oasis, in a similar manner to how an oven is heated by its hot, enclosing walls. The lowland is also relatively sheltered, so heat-dispersing winds are less vigorous. In addition, snow meltwater from surrounding uplands helps to keep local soils moist, so wet meadows and other communities that depend on abundant moisture can develop.

The moderate environmental conditions allow the lowland to support abundant vegetation, including lush wet meadows dominated by sedge and cottongrass. The communities in drier places are dominated by dwarf shrubs and cushion plants, which are long-lived woody plants that grow no taller than 5 cm above the soil surface. These include avens, bilberry, white heather, arctic willow, and purple saxifrage. Disturbed habitats beside rivers and streams or near human habitations (the lowland contains an abandoned post of the Royal Canadian Mounted Police) support profuse flowerings of herbaceous plants, such as arctic poppy and willow-herb. These plant communities are much more productive than those on the prevailing polar desert that surrounds the lowland, and consequently the oasis supports relatively large populations of animals. The abundant birds include snow bunting, Baird’s sandpiper, hoary redpoll, arctic tern, oldsquaw duck, greater snow goose, rock ptarmigan, parasitic jaeger, and another 19 species. Studies of the Arctic skipper butterfly discovered that its slow-growing larvae take 14 years to accumulate enough energy to undergo metamorphosis to the adult stage, resulting in a remarkably long life cycle.

Because of its relatively small area (only 8 km2), this lowland oasis is not able to support a population of muskox, the most important large herbivore in the larger ecozone. However, small numbers of this impressive animal occasionally feed in the oasis while passing through on their way to larger oases nearby. **Sources** Henry, G.H.R. 1998. Environmental influences on the structure of sedge meadows in the Canadian Arctic. Plant Ecology, 134: 119–129. Svoboda, J. and B. Freedman (editors). 1994. Ecology of a Polar Oasis. Alexandra Fiord, Ellesmere Island, Canada. Toronto, ON: Captus Press.

Conclusions

Biomes are geographically extensive ecosystems that occur throughout the world wherever environmental conditions are suitable for their development. The same biome may occur in far-flung places, even on different continents, and in such cases it will be similar in structure and function but will usually be dominated by different species. Temperature and moisture availability are the most critical environmental factors affecting the distribution of terrestrial biomes. Marine biomes are most influenced by depth, nutrient availability, and temperature.

The natural landscapes of Canada are divided into biophysical regions known as ecozones—15 terrestrial and five marine. In turn, the ecozones are divided into smaller units known as ecoregions. Ecozones and ecoregions are characterized by their natural landforms, climate, species, and ecological communities. The natural biomes of the world, and the ecozones of Canada, are being rapidly modified by human activities, and many of their inherent biodiversity values are becoming increasingly at risk. These damaging changes are most intensive in regions where people live and work in high population densities, such as in the southern regions of Canada.

Questions for Review

1. List five biomes. What are the essential characteristics of each of them?
2. What are the characteristics of the ecozones that occur in the province where you live? For detailed information, visit http://canadianbiodiversity.mcgill.ca/english/ecozones/ecozones.htm .
3. Select any Canadian ecozone. What are the most important environmental factors affecting the species and ecological communities of that ecozone? Have these factors changed much over the past century or during the past decade? For detailed information on the ecozone, visit the website noted in the previous question.

Questions for Discussion

1. Why is it useful to know about the species of plants and animals that live in some defined area, such as a park, county, or province? Is it useful to know about the ecological communities? How does this kind of information assist in planning for conservation and sustainable development?
2. Ecologists usually consider native species to have greater "value" than non-native ones. Why do they think this way? Is the rationalization only scientific, or does it include an element of non-objectivity?
3. Select any one of the more southerly Canadian ecozones, where human activities have become dominant influences affecting species and ecological communities. Describe any damage that you think human activities might have caused to the native species and natural ecosystems of that ecozone, and consider whether it might be possible to repair any of those effects. For detailed information on the ecozone, visit http://canadianbiodiversity.mcgill.ca/english/ecozones/ecozones.htm.

Exploring Issues

1. You have been asked to characterize and map the various ecosystems occurring in a national park (choose one near where you live). How would you determine the distribution and characteristics of the various kinds of terrestrial, wetland, and aquatic ecosystems present in the park?

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Chapter 9 ~ Ecology: From Individuals to the Biosphere

Key Concepts

After completing this chapter, you will be able to

1. Describe how species are adapted to different levels of stress and disturbance in their habitat.
2. Explain how population growth occurs, as well as constraints on population size.
3. List major environmental factors that influence ecological communities.
4. Describe what is meant by a landscape (and seascape) and how environmental influences affect their spatial and temporal dynamics.
5. Outline the Gaia hypothesis and discuss its applicability to the functioning of the biosphere.

Introduction

Ecology is the study of the relationships between organisms and their environment. In the sense meant here, "environment" includes both (a) non-living factors, such as temperature, moisture, nutrients, and physical disturbances, as well as (b) living organisms, which exert influences through competition, herbivory, predation, and disease, and by providing elements of habitat (as when trees provide habitat for species living in a forest). Because all organisms and ecosystems are subjected to a multiplicity of influences, it can be difficult to predict the ecological effects of changes in environmental conditions.

Some environmental influences are resources that organisms can exploit as opportunities, which allows them to gain the necessities of life and livelihood. Other environmental influences are stressors, or constraints on productivity and reproductive success. Many stressors operate in a continuous (chronic) fashion, as is often the case for climatic factors, soil and water pollution, and many biological interactions. Other stressors affect organisms and ecosystems as events of disturbance, which cause severe damage in a short period of time. A disturbance is followed by an extended period of ecological recovery called succession. Disturbance may be caused by natural forces such as a wildfire or windstorm, or by anthropogenic influences such as the clear-cutting of a forest or ploughing of a field.

Image 9.1. An individual organism is genetically unique and is different from other individuals of its species. This green heron (Butorides virescens) was photographed in southern Florida, but it also occurs in southern Canada.

Source: B. Freedman.

Image 9.2. This population of northern gannets (Morus bassanus) breeds at Cape St. Mary's in Newfoundland. Source: B. Freedman.

Ecology considers the structure and function of the web of life at a hierarchy of levels:

1. An **individual organism** is defined, in an evolutionary context, as a genetically unique entity. However, some species propagate by asexual mechanisms, and they may develop clones of genetically identical "individuals".
2. A **population** is a group of individuals of the same species that are co-occurring in time and space and can potentially interbreed with each other.
3. A **species** consists of one or more populations in which individuals can potentially interbreed, and are reproductively isolated from other such groups.
4. A **community** is an assembly of populations of various species that co-exist and interact as a distinctive grouping.
5. An **ecoscape** is a spatial integration of various kinds of communities over a large area. Each community is a spatial "patch" and the ecsoscape comprises a dynamic mosaic, which is referred to as a landscape in terrestrial environments and as a seascape in marine ones.
6. The **biosphere** consists of all of life and ecosystems on Earth and the environments where they occur.

Each of these levels of ecology is meaningful, and all are relevant to environmental science. However, these various tiers of ecology are not totally discrete–they are all interconnected and each level influences every other. This chapter examines issues that are relevant to the various hierarchical levels of ecology.

Image 9.3. Coral reefs are shallow-water ecosystems in tropical seas, and they are extremely rich in species, as is illustrated by this community near Puerto Morelos, Mexico. Source: A. Pinder

Individuals and Species

Autecology is the field within ecology that deals with the study of individuals, populations, and species. Important topics in autecology include the following:

- differences among species in life-history characteristics and in adaptations to various kinds of environmental conditions
- influences of the environment on individual organisms, including effects on their development and behaviour
- the causes of changes in the size and makeup of populations

Life-History Characteristics

Each species is unique and can be described by its anatomical, behavioural, biochemical, and ecological attributes. These characteristics are ultimately determined by the collective genetic variation that exists among the individuals that comprise the species.

Each species is unique. Nevertheless, species can be aggregated into groups based on similarities of their attributes. These affinities may be due to ancestral relatedness, due to related species sharing aspects of their evolutionary history. For example, all maple trees (genus Acer) look rather alike and occur in habitats of temperate forest. Similarly, all members of the cat family (Felidae) bear a certain resemblance and are ecologically comparable in that all are predators, although of different prey and in different kinds of habitat. However, unrelated species may also display similar attributes, usually because they have had a history of analogous changes through a phenomenon known as evolutionary convergence (or parallel evolution). Convergence suggests that, through natural selection, unrelated species living in comparable environments may evolve to resemble each other and to play similar functional roles in their ecosystem.

There are many examples of evolutionary convergence among unrelated groups of organisms. For instance, all perennial (long-lived) plants growing in arid environments have a need to conserve moisture. This critical function is enhanced by a growth form that includes adaptations to reduce water loss, such as a cylindrical trunk and branches, tissues protected by a waxy cuticle, and no leaves. Thorniness is another useful trait in an arid environment because spines deter herbivores from consuming biomass and stores of water. Many desert-inhabiting plants have developed one or more of these adaptations, including species of cacti (family Cactaceae), euphorbs (Euphorbiaceae), and succulents (Crassulaceae). Although species in these families are not closely related in an evolutionary sense, they may resemble each other because of evolutionary convergence.

There are also examples of convergence among species of animal. One is the similarities of the timber wolf (Canis lupus) of Eurasia and North America and the marsupial wolf (thylacine, Thylacinus cynocephalus) of Australia. Another example is the groundhog (Marmota monax) of North America and the marsupial wombat (Vombatus ursinus) of Australia. Also, the penguins (family Spheniscidae) of the Southern Hemisphere are similar to the guillemots, murres, puffins, and related auks (family Alcidae) of the Northern Hemisphere.

Ecologists often categorize plant species on the basis of their autecology. One system is based on the adaptations of plants for coping with certain kinds of habitat conditions. The ecologist Philip Grime has suggested that plant strategies can be divided into three basic categories, which are determined by life history and its relationship to habitat. This system proposes that two groups of environmental factors – disturbance and stress – have a strong influence on the evolution of plant life-history strategies. Disturbance may be a frequent or uncommon occurrence, and severe or mild in its intensity. Stress is a longer-term site condition, and it can be intense if associated with an extreme shortage of moisture, light, or nutrients, or innocuous if these vital factors are well available. Any particular environment can be characterized by the importance of these two groups of factors, which results in four basic kinds of habitat conditions:

1. low stress and rare disturbance
2. low stress but frequent disturbance
3. intense stress but rare disturbance
4. intense stress and frequent disturbance

However, Grime suggests that plants exhibit only three primary life-history strategies, because they cannot cope with an environment that is both stressful and frequently disturbed (4 above). The three primary life-history strategies are:

- **Competitor** plants are dominant in habitats in which disturbance is rare and environmental stresses are relatively unimportant. Under such conditions, competition is the major selective influence on plant evolution and on the organization of their communities. Competitive plants are effective at acquiring resources and using them to achieve a dominant position in their community by interfering with the productivity of other plants. Useful adaptations in competitors include rapid tall growth, a spreading canopy, and a widely spreading root system—these characters help to occupy space and take advantage of resources. In addition, seedlings of many competitive plants can establish themselves beneath a closed canopy.
- **Ruderals** occur in frequently disturbed environments with abundant resources, so stress is not great. Ruderal plants are therefore well adapted to utilizing rich but temporary habitats. They are typically short-lived and intolerant of stress and competition. Ruderals produce large numbers of seeds, which usually have mechanisms for long-distance dispersal so that newly disturbed habitats can be colonized.
- **Stress-tolerators** are adapted to environments that are marginal in terms of climate, moisture, or nutrient supply, but are infrequently disturbed and therefore stable. They are typical of arctic, desert, and other stressful environments, and are generally short, slow-growing, and intolerant of competition.

Another system of categorizing organisms, more commonly applied to animals, involves two groups of life-history characteristics. One consists of longer-lived organisms that produce relatively few progeny, but invest a lot of resources in each to improve their chance of survival. These are known as K-selected species. The other group, referred to as r-selected, includes short-lived species that produce large numbers of small offspring, each of which has a relatively small chance of survival, but due to the enormous numbers it is likely that some will persist. K-selected species are dominant in relatively stable, mature habitats in which competition is the controlling influence on community structure, while r-selected species occur in younger, recently disturbed habitats in which resources are freely available and rapid population growth is possible. (The source of the “K” and “r” labels comes from the logistic equation, a fundamental element of population ecology that, for simplicity, is not examined here.)

Species can also be considered in terms of other aspects of their reproductive strategy, such as how often they reproduce. Some species have only one reproductive event during their lifetime, usually dying afterward. This type of reproduction, known as semelparous, is seen in annual and biennial plants, many insects and other invertebrates, and Pacific salmon. Most semelparous species are short-lived, but some can live for many years, gradually accumulating enough energy to sustain a massive, “big-bang” reproductive effort. Semelparous reproduction is favoured in rich habitats that are frequently disturbed, and it is common among ruderal and r-selected species.

Species that reproduce a number of times during their lives are known as iteroparous. These are typically long-lived species that live in stable habitats. Iteroparous species may produce large numbers of small offspring (r-selected), or they may produce fewer, larger young, each of which receives a substantial investment of parental resources (K-selected).

Individuals and Environment

Autecology also deals with the lives of individual organisms and how they are influenced by their physical and biological environments.

As we examined in Chapter 6, all individual organisms have a fixed complement of genetic information, known as their genotype. However, the expression of genetic information (the phenotype) is influenced by environmental conditions, a phenomenon known as phenotypic plasticity. If individuals experience difficult environmental conditions, the phenotypic expression of their genetic potential may include a suboptimal growth rate and the production of few or no progeny. In contrast, other individuals that live in a more benign environment can achieve higher productivity and have many offspring. The latter, more prolific circumstance is highly desirable in terms of an individual achieving evolutionary "success." By definition, successful individuals have managed to maximize their fitness—their genetic contribution to future generations.

The success of an individual organism is also affected by unpredictable disturbances, which may result in injury or premature death. Even if living in a benign environment, with good access to the necessities of life, an unlucky individual may just happen to be scorched by a wildfire, devoured by a predator, debilitated by a disease, or hit by a truck.

Population Ecology

The study of populations is another aspect of autecology. The abundance of all species changes over time in response to environmental factors that affect four population-related (or demographic) variables: birth rate (BR), immigration rate (IR), death rate (DR), and emigration rate (ER). The change in population size (ΔP) during a unit of time (say, a year) is described using the following equation:

$$\Delta P = BR - DR + IR - ER$$

This demographic relationship is true of all species, including humans. In some cases, isolated (or closed) populations do not receive any immigration of new individuals and do not lose any to emigration. Under such conditions, ΔP is calculated as BR – DR, a value known as the natural rate of population change.

Often, ΔP is expressed as a percentage change by dividing its value by the initial population size – for instance, a population of 100 individuals that increases by 10 in one year has a 10% annual growth rate. If the percentage change in a population is constant over time, there will be an accelerating rate of increase or decrease, called exponential change.

Imagine a circumstance in which a fertile pair of individuals manages to discover a new suitable habitat—one that has not been previously occupied by their species. Under such conditions, the founder individuals will breed and the population will grow over time. Initially, resources are abundant and do not constrain growth of the population. During that period the percentage rate of increase will be constant, being limited only by how quickly progeny can be produced (the birth rate) and themselves become fertile (the maturation rate), and countered only by any deaths that might occur. This is the maximum rate of population growth, which is limited only by the biology of the species and not by competition for resources, and it is referred to as the intrinsic rate of population increase. Any population that is growing at the intrinsic rate of increase (or indeed at any fixed percentage rate) will quickly explode in abundance (see In Detail 9.1).

Eventually, however, the population will approach the carrying capacity of the available habitat, or the population that can be supported without causing resources to become limiting, or other environmental damages. At or beyond the carrying capacity, opportunities are constrained by the limited availability of resources, and so individuals in the population must compete with each other. Intense competition results in physiological stress, which may cause a decrease to occur in the birth rate and an increase in the death rate. In some cases, the rate of population increase may then decrease to zero, which occurs when the birth rate equals the death rate. This condition is referred to as zero population growth (ZPG). If ZPG is maintained, the population size will eventually level off, perhaps at a level appropriate to the carrying capacity of the habitat. A population curve of this type is referred to as "S-shaped."

However, the earlier exponential growth may have resulted in an abundance that exceeded what the habitat could support. Such an overpopulation would degrade the environment, resulting in a decrease in its carrying capacity. If this happens, the population size will decrease through an increase in the mortality rate, or perhaps by a surge of emigration in search of new habitats. These may result in an oscillation of abundance around the carrying capacity, or in a rapid crash in the numbers of individuals in the population. Usually, a crash takes the population to a level below the carrying capacity, creating a circumstance for renewed population growth. In small habitats, however, the crash can be massive enough to extirpate a local population.

Population ecologists have developed mathematical models of population dynamics that account for the influences of such factors as the intrinsic rate of population increase, the carrying capacity of habitats, the effects of predation and disease, and even the effects of unpredictable disturbances. These models are described in introductory textbooks of ecology and are not dealt with here in any detail. For the present purposes, there are several important points to understand about population ecology:

- Populations of all species are dynamic. They change over time due to varying rates of birth, death, immigration, and emigration.
- Populations of all species can, potentially, increase rapidly under conditions in which resource availability and other factors are not constraining. Examples of rapid population growth are illustrated in Figure 9.1. However, unlimited growth cannot be sustained – in all of the cases in Figure 9.1, the population sizes eventually levelled off, decreased, or crashed.
- Ultimately, the sustainable abundance of a species is limited by the carrying capacity of the available habitat. Examples of population growth that level off at the carrying capacity of the habitat are illustrated in Figure 9.2.
- Some populations are relatively stable. Usually they exist in environments in which resource availability is predictable so that a balance can be achieved with the carrying capacity. For example, relatively little change occurs in the year-to-year populations of trees growing in old-growth forest, unless a rare, catastrophic disturbance occurs.
- Other populations are relatively dynamic, changing greatly over time and rarely achieving even a short-term balance with the carrying capacity of their habitat. This is commonly true of species living in habitats that are disturbed frequently or are in an early, relatively dynamic stage of succession. Some populations are cyclic, achieving great abundances at regular intervals, interspersed by longer periods of lower abundance. Cyclic populations are obviously unstable over the short term, but they may be stable over the long term.
- Populations that exceed the carrying capacity of their habitat are never sustainable at that high level, because of the environmental damage is caused. Unsustainable populations eventually crash to a smaller abundance and sometimes to extinction. Figure 9.3 shows an example of rapid population growth that resulted in habitat degradation and a subsequent population crash. Populations can also crash for other reasons, such as the sudden occurrence of a deadly disease. This is happening with the native white elm (Ulmus americana) of North America, which is being decimated by an introduced pathogen (the Dutch elm disease fungus, Ceratocystis ulmi) to which this tree has little immunity. Other causes of population crashes include unsustainable levels of predation and extensive disturbances such as wildfire or clear-cutting.

Figure 9.1. Rapid Growth of Some Natural Populations. (a) The population of mourning doves (Zenaida macroura) wintering in southern Ontario over 48 years. This used to be a rare bird, but it has apparently benefited from a warming climate, suburban habitat, and winter feeding. (b) The population of mallards (Anas platyrhynchos) wintering in southern Ontario over 35 years, illustrated with two independent sets of data. This

duck has expanded its breeding and wintering ranges into eastern Canada, likely in response to habitat made available by the clearing of forest. (c) The population of lodgepole pine (Pinus contorta) near Snowshoe Lake, British Columbia, during natural afforestation following deglaciation 7000-9000 years ago. In this case, tree populations are indicated by the amount of pollen in dated layers of lake sediment. Sources: Modified from (a) Freedman and Riley (1980); (b) Goodwin et al. (1977); (c) MacDonald and Cwynar (1991).

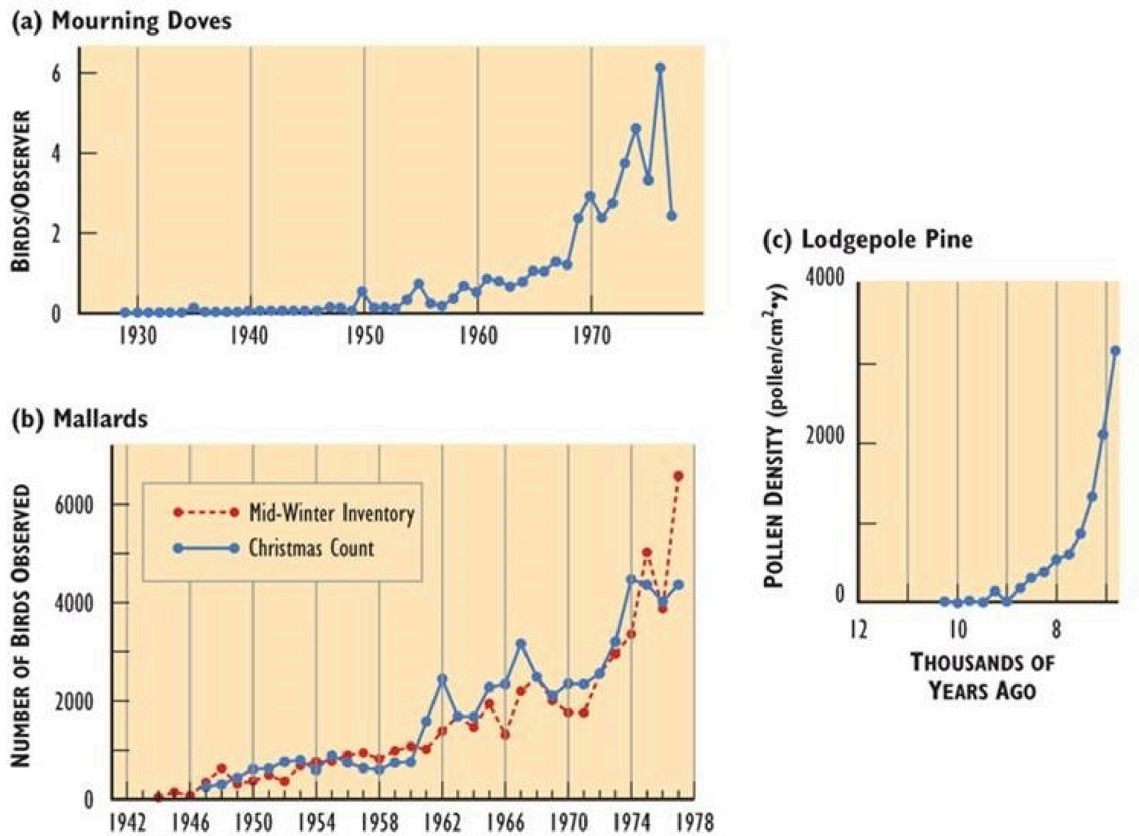


Figure 9.2. Population Growth Stopping at Carrying Capacity. (a) The population growth of yeast cells grown in a flask is initially exponential but then levels off at the carrying capacity of the habitat. Carrying capacity is determined by the volume of the flask, the quantity of nutrients available, and the increasing concentrations of toxic metabolites, including ethyl alcohol. (b) The population of a moss colonizing a suitable, but initially bare, rock substrate in Iceland. The carrying capacity is limited by the amount of two-dimensional space. Sources: Modified from (a) Krebs (1985); (b) Silverton (1987).

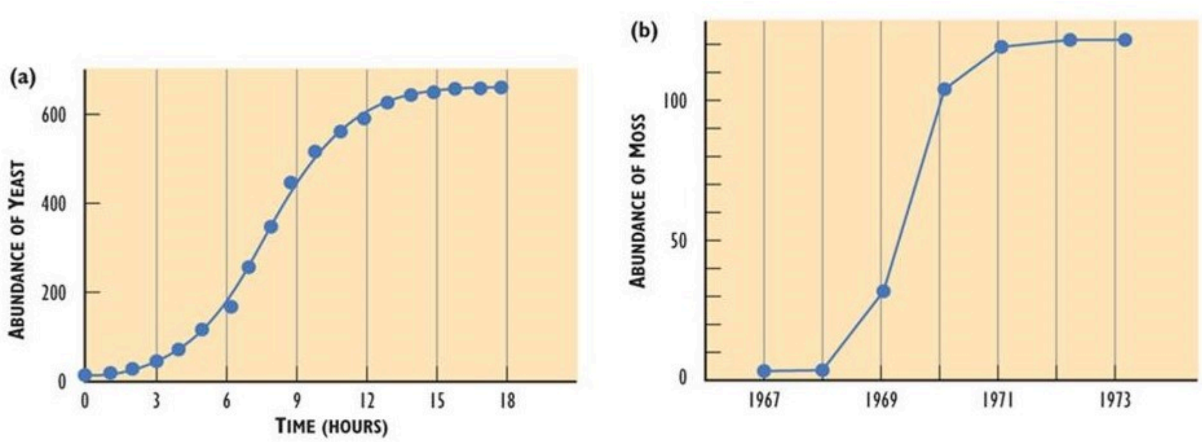
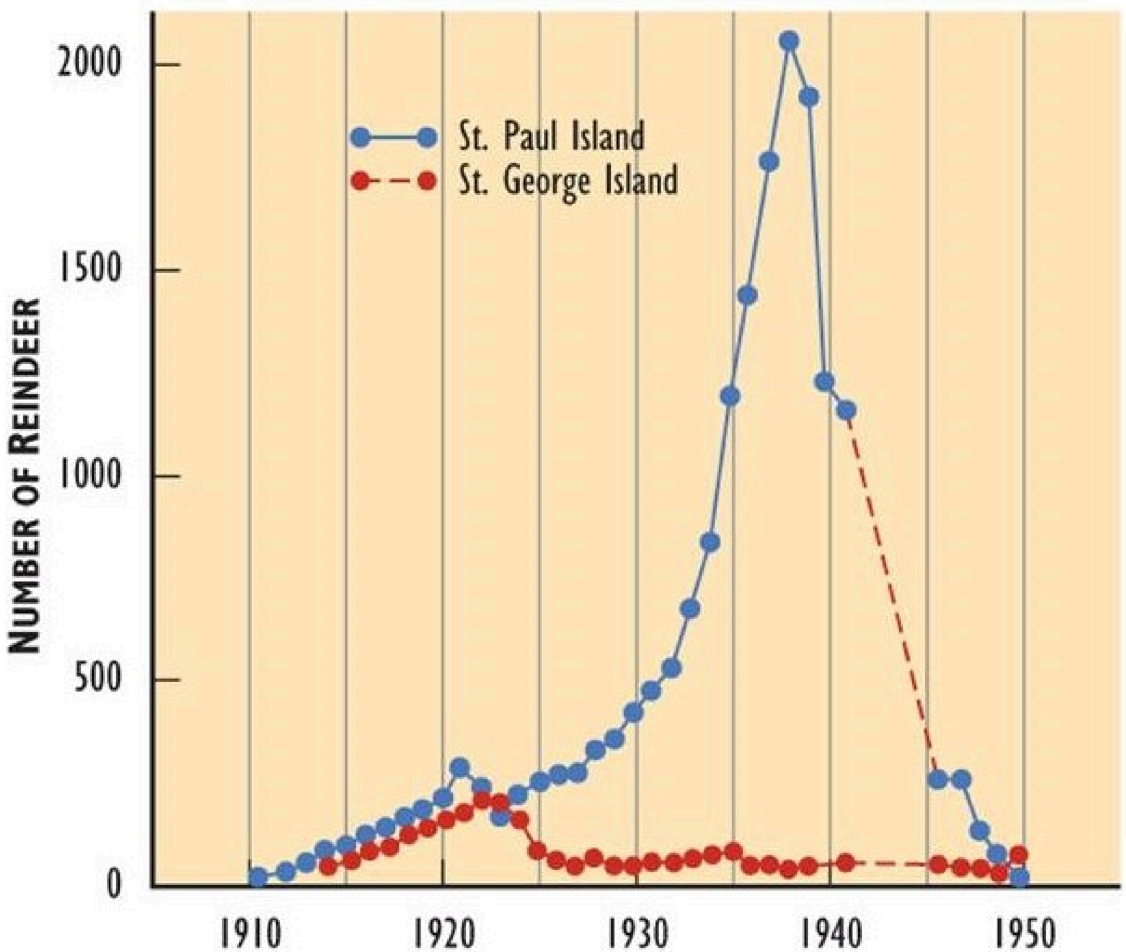


Figure 9.3. Population Growth and Crash. In 1910, reindeer (Rangifer tarandus tarandus; the Eurasian subspecies of caribou) were introduced to two islands in the Aleutian chain off Alaska in an attempt to establish a new food resource for local use. On both islands, the reindeer population increased rapidly. However, they exceeded the carrying capacity of the habitat and caused severe damage through overgrazing. The populations then crashed. Source: Modified from Krebs (1985).



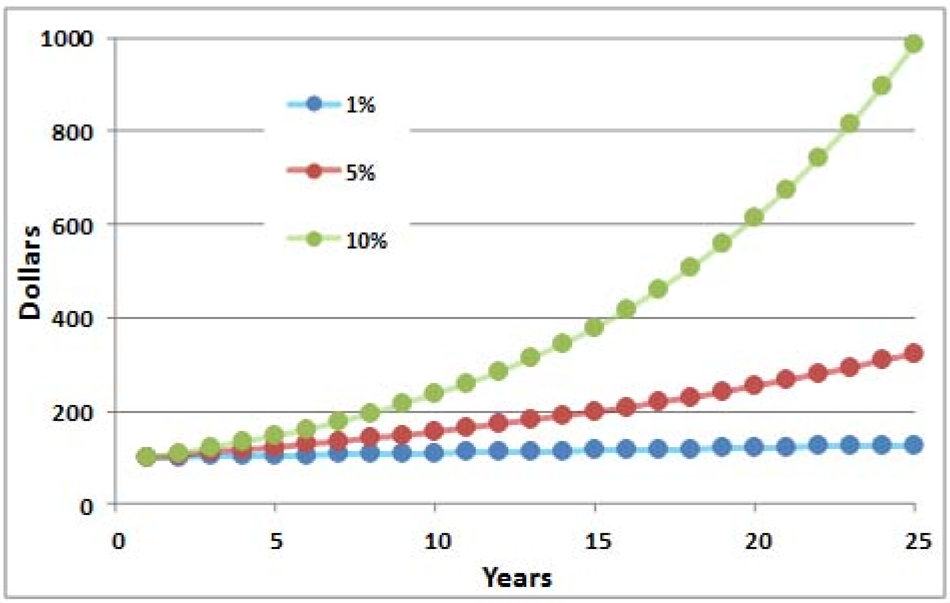
In Detail 9.1. Exponential Growth
A constant rate of increase leads to rapid growth in the size of a population. This happens for the same reason that money invested at a fixed rate of interest will quickly increase in quantity. This phenomenon, known in finance as compound interest, is illustrated below.

Consider, for example, an investment of $100 made at a fixed interest rate of 10% per year, locked in for a 10-year period. After Year 1, the initial deposit grows to $110, which represents the initial investment plus accumulated interest. In Year 2, the 10% interest rate is applied to the $110, so the earned interest is larger ($11) than in Year 1 ($10). In Year 3, the 10% interest is applied to the accumulated $121, so the earned interest is larger yet ($12.10), and the accrued value of the investment is $133.10. At the end of Year 4, the initial investment of $100 is worth $146.41. It is then $161.05 at the end of Year 5 … and $259.37 at the end of Year 10, representing an impressive 159% return on the initial investment. Clearly, a compounded rate of interest leads to a rapid increase in capital.

Exponential growth refers to the accelerating growth of an initial quantity due to a constant rate of increase. Sometimes an important parameter known as the doubling time is calculated—it is the time required for a twofold increase in capital. The doubling time can be roughly calculated as 70 divided by the constant rate of increase. In the example above, 70 divided by 10% per year yields seven. Therefore, the initial $100 would double in amount in only seven years, and the accumulated $200 would again double (to $400) in another seven years, and so on as long as the investment conditions do not change.

The mathematics of compounded interest can also be applied to the exponential growth of populations of organisms. One example will suffice: In 2015, the global human population was about 7.3 billion people, growing at about 1.3% per year. Therefore, in only 54 years (i.e., 70 divided by 1.3% per year), the human population could double to more than 14 billion, if the growth rate were not to change. The environmental implications of such a population increase are immense (see Chapter 10).

Figure 9.4. Exponential Growth. This curve shows the growth of an initial deposit of $100 invested at a compound interest rate of 1, 5, or 10% per year. Biological populations also grow in an exponential fashion if their rate of increase is constant. However, when resources become limiting, the rate of increase decreases, and the population may crash.



Community Ecology

An ecological community is an aggregation of populations that occur in the same time and place as a distinctive grouping, and that interact physically, chemically, and/or behaviourally. The study of relationships among species within communities is known as synecology. Strictly speaking, a community consists of all plant, animal, and microbial populations occurring together on a site.

The Niche

Each species within a community exploits the environment and interacts with other species in a particular manner. Ecologists use the word niche to describe the role of a species in its community, which can also be viewed as its "occupation" or livelihood. Some niches are relatively narrow and specialized, as is the niche of bats that feed only on flying insects of a certain size, or wasps that pollinate only one or a few species of plants. Other niches, however, are much broader, such as those of bears and humans, both of which forage over an extremely broad range and affect their ecosystem in diverse ways.

The so-called fundamental niche is determined by the range of a species' tolerance of environmental conditions. These tolerances are reflected in the ways that a species obtains its nutrition and how it interacts with other species, and they are mediated by aspects of behaviour, morphology, and physiology. In comparison, the realized niche reflects the range of environmental conditions that a species actually manages to exploit in nature. The realized niche is smaller than the fundamental niche because all species are to some degree constrained by biological interactions such as competition, predation, and disease.

Functional Communities

Because of their complexity, entire communities are rarely examined by ecologists. Ecological studies are usually limited by the amounts of funding and breadth of expertise available. Instead, community-level research usually involves the examination of selected groups of similar organisms, such as "communities" of insects, fish, birds, plants, or microbes. Although the scope of such work is limited, it does allow ecologists to investigate important aspects of community ecology.

Forest communities, for example, contain a wide range of organisms of various species and sizes, including plants, animals, and microorganisms. The populations of the diverse species interact in myriad ways. Trees, for instance, provide the physical structure of the habitat, make food available for herbivores, and drop leaf litter that is decomposed by species of the detrital food web. Other interactions within a forest community include predation, parasitism, and disease, as well as symbioses such as pollination, seed dispersal, and root mycorrhizae. Because of the inherent complexity of forest communities, most ecological studies only investigate selected components.

This pragmatic approach to community-level research can be illustrated by studies of the ecological effects of forestry conducted in the Maritimes by the author and a number of students. To do this work we divided the larger community into the following functional groups:

- trees, which we defined as woody plants with a diameter greater than 10 cm
- shrubs, with a diameter less than 10 cm but taller than 1 m, including shrub-sized young individuals of tree species as well as "true" shrubs
- ground vegetation, including all plants, mosses, and lichens, growing within 1 m of the ground
- epiphytes growing on other plants, such as lichens and mosses on the bark-covered surfaces of trees
- small mammals such as mice, shrews, voles, and squirrels
- large mammals such as deer, bear, and coyote
- birds
- reptiles and amphibians
- insects
- fungi and other microorganisms in the soil

During some of the studies of birds, specific work was done with species that nest in cavities in trees. These comprise a "cavity-requiring" element of the larger avian community. Similarly, work on insects and other invertebrates has involved functional groups that live in soil, in rotting deadwood, or on foliage. But even with all of these (and other) functional groups, we did not manage to examine all of the elements of the forest communities that we were studying.

Factors Influencing Communities Ecological communities are affected by various environmental factors, particularly those described below.

Species Present – Obviously, only those species that are present in a habitat, or are capable of dispersing into it, can play a role in the community that develops. The ability of a species to colonize an available habitat is influenced by its biology, intervening barriers such as a mountain range or ocean, the disturbance regime, and other factors. Increasingly, humans are influencing the species composition of communities, often by introducing non-indigenous species beyond their natural range.

Appropriate Habitat – If a habitat is unsuitable, then a particular species will not be able to use it even if it is capable of dispersing to the site. There are many aspects of habitat suitability, and all of them must be satisfied within the limits of tolerance of a species if it is to become a component of a community.

Biological Interactions – Species interact through herbivory, predation, competition, disease, and symbiosis, the latter including mutualism, commensalism, and parasitism. All of these interactions can influence the presence and abundance of species within communities. The following examples illustrate these influences.

Herbivory – occurs when animals feed on plant biomass. Larvae of the hemlock looper (Lambdina fiscellaria) are voracious feeders on the foliage of spruce, fir, and other coniferous trees. When conditions are suitable, this moth can proliferate rapidly, causing damage over a large area of forest, as periodically happens in eastern Canada. Stands defoliated for several years have many dead trees, representing an important element of community change. The loss of much of the forest canopy has indirect effects, such as allowing understorey plants to grow more vigorously. The changes in vegetation affect the habitat available for species of insects, birds, and other animals. Microorganisms and other detritivores are also affected because large quantities of dead tree biomass are available to be decomposed.

Predation – involves an animal killing and eating another animal. Predators can greatly reduce the abundance of their prey, thereby changing the structure of the community. For instance, during the summer, most forest birds feed on insects, spiders, and other invertebrates, which are nutritious food for both adults and their rapidly growing nestlings. Avian predation can change the invertebrate community, as has been demonstrated by studies in which small areas of forest were enclosed with netting. This excluded avian predators, but invertebrates could move in or out. Under these conditions, the abundance of many insects and spiders increased, with species vulnerable to avian predation benefiting the most.

Image 9.4. Species interact with each other in various ways, such as herbivory, predation, competition, disease, and symbiosis. This photo shows caribou (Rangifer tarandus) grazing in a tundra meadow in the Nunavik region of northern Quebec. Source: B. Freedman.

Competition – occurs when the biological demand for an ecological resource exceeds the supply, causing organisms to interfere with each other. Plants, for example, often compete for access to limited supplies of sunlight, water, nutrients, and space. Animals may compete for food, nesting sites, mates, and other resources. Intraspecific competition occurs when individuals of the same species vie for access to resources, while interspecific competition occurs between species. If a species is particularly effective at co-opting resources to its own benefit, it may displace other species, a phenomenon known as competitive displacement (or in extreme cases, competitive exclusion). This affects the presence and relative abundance of species in the community. For example, sugar maple (Acer saccharum) is a highly competitive tree in hardwood forests of eastern Canada. Where environmental conditions are well suited for this species, it can dominate mature stands. If large sugar maple trees are removed from a stand, perhaps by a selective timber harvest, other tree species (as well as small sugar maples) will benefit from the reduced competition and will grow more vigorously.

Disease – is a pathological relationship in which the health of plants or animals suffers from an infestation of another species, usually a microbe. Virulent diseases can cause enormous changes in the composition of ecological communities. In the early 1900s, the American chestnut (Castanea dentata) was afflicted by chestnut blight (Endothia parasitica), an introduced fungal pathogen. Because chestnuts have little immunity to this disease, the species was virtually eliminated from the forests of eastern North America by the 1950s. This change released other tree species from competition with the previously dominant chestnut, and they quickly filled gaps in the canopy created by its demise.

Symbiosis – refers to intimate relationships that may occur among species. This may involve an obligate relationship in which the symbionts cannot live apart, but more commonly the association is somewhat flexible. Symbioses can greatly influence the performance of species in particular environments by improving their competitive ability and decreasing their vulnerability to predation, disease, or other stresses.

The main types of symbiosis are mutualism, in which both partners benefit; parasitism, in which one organism benefits and the other is harmed; and commensalism, in which one organism benefits without harming the other. While symbioses are critical to one or both partners, they can also indirectly affect the habitat and the resources available to other members of the community.

Lichens are a familiar example of a mutualism. They are an obligate association between a fungus and either an alga or a blue-green bacterium. The fungus benefits from the productivity of the photosynthetic partner, while the latter gains a relatively moist microhabitat and improved access to inorganic nutrients.

Another mutualism, called a mycorrhiza, is an intimate association between fungi and the roots of vascular plants. The plant benefits through enhanced access to nutrients, especially phosphate, while the fungus receives nutritious exudates from the roots. This mutualism also provides a broad, community-level benefit through increased primary productivity. Many species of legumes live in a mutualism with the bacterium Rhizobium japonicum, which fixes nitrogen gas (N_2) into ammonia, a critical nutrient.

Another mutualism involves species of dinoflagellates (single-celled algae) that live within corals (small, colonial animals), where they receive protection and access to nutrients. The corals benefit through access to the photosynthetic productivity of the algae.

Many animals eat plant biomass, but few are able, on their own, to digest complex polymeric biochemicals such as cellulose and lignin. Consequently, many herbivores live in a mutualism with microorganisms, which inhabit their gut and secrete enzymes that digest cellulose and lignin, making those abundant sources of nutrition available to the animal. Cows, deer, and sheep host their digestion-aiding microorganisms in a specialized pouch of their fore-stomach, called the rumen. Humans also harbour a diverse community of microorganisms in their gut, many of which are important to our nutrition.

Other mutualisms include the many species of flowers that are pollinated by particular kinds of insects. Pollination is crucial to the reproductive success of plants, while the insects benefit from an abundant food source of nectar or pollen. In addition, herbivores in the community benefit from the fruits that are produced because of pollination, and in turn they may help to disperse the plant seeds.

An example of commensalism is the epiphyte community of plants, lichens, and mosses that often grow on large trees. The epiphytes gain an benefit from the relationship through increased access to sunlight, but the host trees are not affected to any meaningful degree. There are many familiar examples of parasitism, including fleas on a dog and tapeworms in humans. The parasite benefits by taking nutrition from the host, but the host usually suffers, and may even die from a severe infestation.

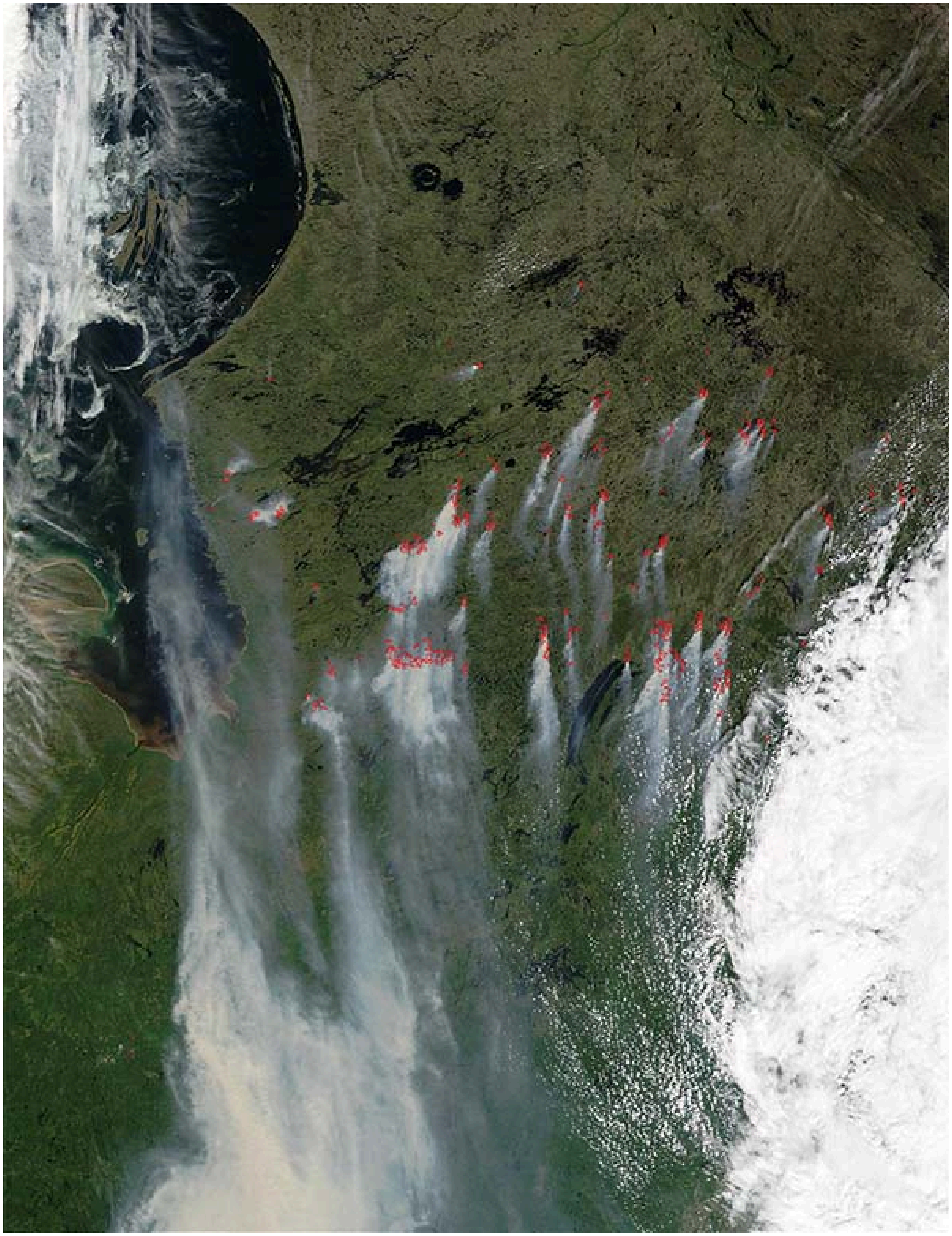
Image 9.5. A mutualism is an intimate symbiosis in which both partners benefit from the relationship. Lichens, such as the light-coloured Parmelia saxatilis in the photo, are an obligate mutualism between a fungus and an alga, meaning the two species cannot live apart in nature. Thus, taxonomists treat them as a single “species.”

Source: B. Freedman.

Disturbance is an event of destruction of some part of a community, an occurrence that is followed by a sometimes pronged period of ecological recovery called succession. All communities are dynamic, changing over time in their species composition and functional attributes (such as productivity, decomposition, and nutrient cycling). However, the rate of change depends on the stability of environmental conditions, which is greatest in communities that are close to the end-point of a succession. In contrast, the most dynamic communities are associated with the younger stages of succession. Disturbances can occur on two spatial scales.

- **Stand-replacing disturbances** are caused by wildfire, a disease epidemic, clear-cutting, and other cataclysmic events. This kind of disturbance is extensive and results in the immediate replacement of a community with a different one, followed by a period of successional recovery. Over time, succession may regenerate a community similar to what existed before the disruption, or a different one may result. The younger stages of a sere (successional sequence) are especially dynamic in terms of community change. During the initial years of recovery, competition is not intense, and ruderal, r-selected species dominate. Later stages of succession are much less dynamic, and K-selected species dominate.
- **Microdisturbances** are local disruptions that affect small areas within an otherwise intact community. A microdisturbance may, for instance, be associated with the death of an individual large tree, which results in a gap in the canopy, below which community change is relatively dynamic as species compete to take advantage of the additional sunlight. Similarly, the death of an individual coral head represents a microdisturbance within a tropical reef community. Although ecological changes are dynamic within a gap created by a recent microdisturbance, at the stand level the community is relatively stable. Gap-phase community dynamics occur in all ecosystems but are especially important during later stages of succession, such as in older-growth forests.

Image 9.6. Ecosystems are occasionally subjected to catastrophic disturbances, such as these forest fires in 2002 in the boreal forest of northern Quebec. The individual fires are marked with a red dot, and their smoke plumes are blowing to the south. The large white mass at the bottom right is cloud cover. Source: NASA photo ID 751339; https://www.dvidshub.net/image/751339/fires-quebec-canada-send-smoke-us-natural-hazards#.VOS_vXUtHIU



Spatial variation of the environment reflects the fact that conditions are always changing from place to place, and sometimes extremely so. These spatial variations influence the character of ecological communities, in ways that may be gradual or more rapid:

- Gradual changes environmental conditions are associated with varying altitude on a mountain, differences of climate over large distances across continents, and other relatively continuous gradients. This type of spatial change is reflected in gradual variations of communities because individual species have different but overlapping tolerances and requirements of environmental conditions. These biological differences result in overlaps of the distributions of species, which can make it difficult for ecologists to determine the locations of boundaries (ecotones) between types of communities.
- Rapid changes in environmental conditions occur at sharp boundaries between different kinds of soil or bedrock, at interfaces between aquatic and terrestrial habitats, and in places affected by disturbance. The latter influence can occur, for instance, between a burned and unburned tract of forest, or between an ecological reserve and its surrounding area, which may be affected by agriculture or forestry. Relatively discrete changes in environmental conditions favour large differences in community types, with distinct boundaries between them.

Landscape Ecology

Landscapes (or seascapes in the marine context) are a mosaic of "patches", each of which represents an ecological community. A landscape may contain various kinds of communities for the following reasons:

- each community reflects particular environmental conditions, such as different soil or bedrock types or variations of standing water (as in lakes, streams, or wetlands)
- the communities represent various stages in succession, such as patches of different age after wildfire or insect damage
- the communities may be related to land-use, as when parts of landscapes are affected by urbanization, agriculture, forestry, roads, or other human influences.

Over time, the spatial patterns of communities on landscapes are highly dynamic. This largely reflects the influence of disturbances and successional recovery. A patch that today is a pasture, a recent clear-cut, or a burn may be a mature forest after 50 years of succession. Similarly, a pond may in-fill over the centuries and become a wetland, which with further time may succeed into a forest. Ecologists use the term "shifting mosaic" to integrate the spatial and temporal variations of communities on landscapes. The following factors affect the shifting mosaic of communities.

- Patch size relates to the area of particular stands of communities (a stand is a community in a specific place). All species need some minimal area of habitat to support their populations, and small patches may not be adequate for that purpose. Relatively small patches may, however, help to support a population living in several stands on the landscape (an extensive population of this sort is known as a metapopulation). This can happen if the patches are connected by corridors to other suitable habitat, or if the species is capable of dispersing through surrounding inhospitable habitat (for this to occur, the landscape matrix must be permeable to movements of the species).
- The amount of edge is important because it influences the length of ecotone (transitional) habitat associated with a patch. A circular patch has the smallest ratio of edge to area, and smaller patches have higher ratios than larger ones of the same shape. An ecotone between patch types is a particular kind of habitat, and it may be selectively used by "edge species." However, the greater the ratio of edge to area, the less "interior" habitat there is (this is uninfluenced by ecological conditions associated with an ecotone). Ecologists have identified "interior species" that are less successful if they try to use habitat close to an edge. Certain forest birds, for example, experience

greater rates of predation and nest parasitism in small remnants of mature forest (see Chapter 26).

- Connectedness refers to the presence of links between otherwise discrete patches of similar habitat. These links may be used by a species as corridors to move among patches, allowing their metapopulation to function on the landscape. As was noted previously, connectedness is also related to the ability of a species to disperse among habitable patches through the surrounding habitat.
- Age-class adjacency is important in a landscape in which patches represent different stages of a successional sequence. This commonly occurs in landscapes affected by disturbances such as wildfire, insect epidemics, or clear-cutting. In general, patches of a similar post-disturbance age will be comparable in many aspects of habitat, while those of different age will be less similar. This can be an important consideration for movements of species among isolated patches that are suitable as habitat.
- Complex habitat requirements are characteristic of some larger animals, such as deer, bear, and wolf. These species need different kinds of habitat patches for specific purposes at various times of year. Because these animals participate in various kinds of communities, all of the habitat patches they need must be present on the landscape if a viable metapopulation is to be sustained.
- Landscape-level biodiversity is related to the richness of community types over a large area (see Chapter 7). A landscape that is uniformly covered by a single community has less biodiversity at this scale than one composed of a rich and dynamic mosaic of different kinds of communities.
- Landscape-level functions operate over extensive areas, and they may integrate the influences of many kinds of communities. A watershed, for example, is the expanse of terrain from which water drains into a stream, lake, or some other waterbody. Most watersheds contain various kinds of habitat patches, each with particular influences on hydrology and water chemistry. In general, watersheds covered with mature forest yield the cleanest flows of water. Other environmental services provided by well-vegetated landscapes include evapotranspiration, control of erosion, moderation of climatic extremes, and absorption of atmospheric carbon dioxide and release of oxygen.

Landscape ecology is an important subject area in environmental science. Humans commonly affect individual stands of particular kinds of communities, but many of the ecological effects must be managed at the scale of landscapes and seascapes.

Image 9.7. A landscape is a mosaic of various kinds of communities, each stand of which represent a patch. In addition, landscapes are subjected to patch dynamics associated with natural disturbances, such as wildfire, windstorms, and insect outbreaks. However, the patch dynamics of many forested landscapes are being increasingly structured by forestry. In this aerial view of an area in New Brunswick, the natural forest is being harvested by clear-cutting (the lighter patches are snow in clear-cuts), which initiates a succession that restores a forest for another harvest in 60-80 years. Unless some areas are set aside for protection, this entire landscape may become used in this way. Source: M. Sullivan.

The Biosphere

The biosphere consists of all life and ecosystems on Earth. It is bounded by the presence of living organisms, and it is the only place in the universe definitely known to support life. Ecological processes at the level of the biosphere include global climatic, oceanic, and atmospheric regimes (Chapter 3), the planetary energy budget (Chapter 4), and global nutrient cycles (Chapter 5). These biospheric processes influence all life and ecosystems. At the same time, life and ecosystems also influence biosphere-level processes.

In fact, some scientists have suggested that there may be a degree of homeostatic control, or feedback, between the reciprocal influences of global ecosystems and their environment. A notion describing these biosphere-environment relationships is known as the Gaia hypothesis, a controversial idea popularized by the scientist James Lovelock. He suggests that organisms and ecosystems have caused large changes to occur in certain physical and chemical attributes of the global environment, and they have resulted in improvements in living conditions on the planet. The hypothesis envisions all of Earth's species and ecosystems as being a sort of "superorganism," which is called Gaia. According to Lovelock, Gaia attempts to optimize environmental conditions toward enhancing its own health and continuity, and it uses feedback mechanisms to help maintain conditions within a range that life can tolerate. The ancient Greeks believed that Gaia (or Gaea) was the prolific ancestor of many of their most important gods. The Romans, who adopted many Greek gods and ideas, knew Gaia as Terra. More recently, the Gaian myth has been personified as "mother Earth."

The Gaian idea is attractive and interesting, largely because it integrates many ideas and large-scale observations into a consolidated belief and world view. However, Earth is the only planet in the universe that is known to support life and ecosystems, and so it is the only known replicate in the great experiment of life. Consequently, the Gaia hypothesis cannot be tested by rigorous experimentation, and for this reason many scientists reject its inferences. Except in the broadest of terms, Gaian ideas may not be useful in helping humans to manage the detrimental impacts of their increasing population and industrial activities on the biosphere. Nevertheless, some intriguing lines of evidence can be marshalled in support of the Gaian notion. Two examples follow.

Atmospheric Oxygen

Earth's primordial atmosphere did not contain oxygen (O_2). This gas appeared only after the first photosynthetic organisms, blue-green bacteria, evolved. These, and the somewhat later evolved green algae, give off O_2 as a waste product of photosynthesis. The modern concentration of O_2 in the atmosphere, about 21%, has resulted entirely from photosynthesis and is a critical environmental factor for most species and many key ecological processes. It appears that the concentration of atmospheric O_2has been fairly stable for several billions of years. This suggests a long-term equilibrium between O_2production by photoautotrophs and its consumption by respiration, including decomposition. Interestingly, if the concentration of oxygen were much higher than 21%, say 25%, then biomass would be much more combustible. This condition would lead to more frequent and extensive wildfires, which would severely damage terrestrial ecosystems. These observations can be interpreted as suggesting the existence of a homeostatic control of the concentration of atmospheric O_2, operating at the biospheric scale. This control may achieve a balance between the need to have sufficient O_2 to sustain the most abundant organisms (which have an aerobic metabolism), and larger O_2 concentrations that would result in destructive conflagrations.

The Greenhouse Effect

The concentration of carbon dioxide (CO_2) in the atmosphere is regulated by a complex of physical and biological processes by which this gas is emitted and absorbed. Atmospheric CO_2 is important in Earth's greenhouse effect, which maintains the surface temperature within a range that organisms can tolerate (Chapters 4 and 17). The greenhouse effect helps maintain an average surface temperature of about 15°C, compared with the -18°C that would otherwise occur and would be too cold for organisms to tolerate. Advocates of the Gaia hypothesis suggest that these observations imply a homeostatic control of atmospheric CO_2 and an indirect control of the greenhouse effect and climate.

There is clear evidence that organisms and ecosystems cause substantial changes to occur in their environment, and also that they are affected by those conditions. The scientific community does not, however, widely support the notion that Earth's species and ecosystems have somehow integrated into a mutually benevolent symbiosis aimed at maintaining a comfortable range of environmental conditions.

The Gaia hypothesis is nevertheless quite useful in environmental science. Gaian ideas emphasize the diverse connections that exist within and among ecosystems, as well as the damaging consequences of human actions that are increasingly causing large environmental and ecological changes to occur. If these changes were to exceed the biospheric limits of homeostatic tolerance and repair, the consequences for the planet's geophysiology and ecology could be catastrophic.

Evolutionary Ecology

Evolutionary ecology is a fusion of ecology and evolution – it involves the interpretation of ecological relationships in terms of evolution, natural selection, and related themes. Moreover, it acknowledges that species and their ecology have an evolutionary history that involves change over time, usually occurring as adaptive responses to environmental influences. Natural selection is a particularly significant influence on evolutionary change, and it is evident in the regimes of environmental stressors and disturbances that affect the survival and reproductive success of organisms. Core subject areas in evolutionary ecology are the evolution of life-history traits, of relations between species (such as mutualism, parasitism, pollination, and predator and prey), and of communities and biodiversity in general. Examples of the interpretation of nature in terms of evolutionary ecology include convergence and coevolution:

- Convergence occurs when unrelated species occupy similar niches in distant but comparable environments. As a result they are subjected to parallel regimes of natural selection, and evolve to be similar in morphology and behaviour. An example noted earlier is the placental wolf (Canis lupus) of Eurasia and North America and the thylacine or marsupial wolf (Thylacinus cynocephalus) of Tasmania.
- Coevolution occurs when species interact in ways that affect the survival or reproductive success, so that they are subject to regimes of natural selection that result in integrated evolutionary change. The intensity of coevolution can, however, vary greatly. In extreme cases, it may lead to the evolution of an obligate mutualism, meaning that neither partner can survive without the other. Lichens are one example—these are mutualisms between a fungus and an alga, neither of which can survive on its own.

Coevolution also affects the feeding relationships of organisms. For example, milkweed plants (such as the common milkweed, Asclepias syriaca) have evolved to produce high concentrations of cardiac glycosides, which are distasteful and poisonous to most animals and help to protect the plants from being eaten. However, the monarch butterfly (Danaus plexippus) has evolved a tolerance to those biochemicals and so can eat milkweed tissues (in fact, their larvae eat nothing else). When this happens, the cardiac glycosides are incorporated into tissues of the monarchs, giving a measure of protection from being eaten by birds and other predators. The defence is so effective that the unrelated viceroy butterfly (Limenitis archippus) has evolved a colouration and flight pattern that mimic those of the monarch, which helps deter its own predators.

Coevolutionary interactions have also been studied between many plants and their pollinating insects. One example is the bee orchid (Ophrys apifera), whose flower structure has evolved to resemble the abdomen shape of the solitary bee Eucera. This induces male bees to try to copulate with the orchid, which becomes pollinated in the process (although it is also capable of self-pollination).

Image 9.8. Convergent evolution can be illustrated by comparison of the skulls of two unrelated mammalian predators – the timber wolf (Canis lupus), a placental mammal, and the thylacine or Tasmanian wolf (Thylacinus cynocephalus), a marsupial. Source: B. Fenton.

Some ecologists have even speculated about the possibility of natural selection operating at levels higher than populations or species (this is known as group selection). For instance, there has been speculation that certain boreal-forest assemblages have evolved to be highly flammable, and that this characteristic has promoted stand-replacing wildfires, a disturbance that can rejuvenate the ecosystem. It is true that mature boreal forest dominated by black spruce or white birch can easily ignite and burn rapidly, but there is not yet a supporting theory of the adaptive evolution of communities, as opposed to their constituent species.

As is true for all of biology, evolutionary theory provides a key element of the conceptual background of ecology. Knowledge and insights from evolution and ecology are also central to understanding the environmental effects of the human economy.

Applied Ecology

The application of ecological principles to dealing with economic and environmental problems is known as applied ecology (or as environmental ecology). There are three major subject areas:

1. the management of renewable resources, such as those important in agriculture, fisheries, and forestry

2. the prevention or repair of ecological damages, such as those related to endangered biodiversity, and the restoration of degraded land or water
3. the management of ecological processes, such as productivity, carbon storage, nutrient cycling, hydrology, and erosion

Later chapters in this textbook contain many examples of the use of applied ecology to deal with problems of resource management, pollution, and disturbance. Although the subject is not dealt with here in detail, it can be briefly illustrated by the following examples:

- Setting Harvest Limits: The rate of forest productivity in a region can be estimated by measuring trees in plots that are re-sampled over the years, or by coring populations of trees and examining the annual ring-width of the recently grown wood. This information can be used to set limits on the amount of timber that can be harvested without degrading the resource. Analogous methods of measuring productivity can be used to manage the sustainable harvesting of populations of mammals, birds, and fish.
- Increasing Biological Productivity: Applied ecological research can determine whether the productivity of biological resources can be increased—for example, if forest growth could be enhanced by applying fertilizer, thinning dense stands, or establishing plantations. Research can also predict other implications of these management practices, including effects on biodiversity and water quality.
- Remediation, Reclamation, and Restoration: Ecologists can provide research-based advice for improving conditions in areas that have been degraded by pollution or disturbance. Various kinds of schemes can be used to deal with ecological damage:
- Remediation involves actions that are undertaken to deal with a particular problem, such as liming lakes and rivers to decrease their acidity, planting tolerant plants in polluted environments, or undertaking captive breeding and release to increase the abundance of an endangered species.
- Reclamation involves more comprehensive actions to establish a productive ecosystem on degraded land. For example, an old landfill or a disused industrial site may be reclaimed to a permanent cover of vegetation, such as a pasture.
- Restoration has a loftier goal of attempting to establish a self-maintaining facsimile of a natural ecosystem on degraded land. For instance, the techniques of restoration ecology might be used to convert abandoned farmland back to a native prairie or forest.
- Offsets for Greenhouse Gases: Ecologists can predict the amount of forest that must be grown and protected in order to offset industrial emissions of greenhouse gases. This can allow companies and nations to reduce their net emissions of CO_2 and to make progress toward meeting international agreements to deal with climate change.
- Reducing Erosion: Some areas have been badly degraded by erosion caused by deforestation and other land-use changes. Ecologists can find ways to deal with this problem—for example, by planting forests, using terraced agricultural fields, or managing local hydrology to reduce overland or subsurface water flows.

Conclusions

Ecology is the study of the relationships of organisms with the environmental factors that provide the requirements of life and livelihood. These factors include resources such as nutrients and food, the influences of other organisms through competition and predation, as well as stressors such as disturbance and pollution. Knowledge of ecology is central to understanding many of the most important damages that the human economy is wreaking to the biosphere. Applied ecological knowledge is essential to managing renewable resources on a sustainable basis, to conserving biodiversity, and to avoiding and repairing damage caused by pollution and other destructive influences of humans.

Questions for Review

1. Distinguish between autecology and synecology. Give examples to illustrate each.
2. What are birth rate, death rate, immigration rate, and emigration rate? How do these demographic factors influence changes in a population?
3. What environmental and biological influences affect the structure and function of a kind of ecological community with which you are familiar?
4. What are the attributes of an ecological landscape (or seascape)? Illustrate your answer with an example in the region where you live.
5. In a general sense, what are the goals and methods of a project in restoration ecology?

Questions for Discussion

1. Use the principles of autecology to discuss the resource needs and environmental tolerances of humans.
2. How is the human economy integrated into the biosphere?
3. How are ideas and knowledge about population ecology relevant to people?
4. What are the core elements of the Gaia hypothesis? What evidence exists to support this hypothesis? How are Gaian ideas relevant to environmental science?
5. It is difficult and expensive to implement a large-scale project in restoration ecology. Under what sorts of conditions do you think such a project might be worthwhile?

Exploring Issues

1. The niche has sometimes been described as the "occupation" of a species—what it does for a living, the resources it uses, and its habitat. You have been asked to make a presentation to a group of non-ecologists, in which you must describe the niche of humans. What information would you include in your presentation?

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PART III: THE HUMAN POPULATION

Chapter 10 ~ Global Populations

Key Concepts

After completing this chapter, you will be able to

1. Outline the process of cultural evolution and explain how it has increased the carrying capacity for the human population.
2. Describe the growth of the human population during the past 10,000 years.
3. Explain why population growth has been especially rapid during the past several centuries.
4. Discuss why there are large differences in population growth rates between developed and less-developed countries.
5. Explain the demographic transition and how it affects age-class structure and population growth.
6. List the major methods of birth control, and discuss why they are controversial.
7. Explain what a population policy is, and how it can affect future human population.
8. Outline possible causes of a population crash.

Introduction

About ten-thousand years ago, only a few million humans were alive. Since then our population has grown enormously – in 2015, there were more than 7.3 billion, and the number is climbing steadily (by about 86.6 million, or 1.2% per year). In terms of consequences for the biosphere, the enormous growth of the human population is the most important event to have occurred since the end of the most recent continental-scale glaciation, which ended about 12,000 years ago.

Although the global population of humans has been increasing for millennia, the growth rate been particularly rapid during the past few centuries. Moreover, there is every indication that the present, extremely large population will continue to increase for at least another 50-100 years. Several possible scenarios of future population growth will be examined later in this chapter.

The environmental consequences of any human population are a function of a number of interacting factors, but two are especially important: the number of people and their per-capita environmental impact. The per-capita impact is related to both the lifestyles of individual people and the level of technological development of their society. These both affect the use of natural resources, the production of wastes, and the degradation of ecosystems (see also Chapter 1).

The growth of the human population during the past several millennia is a remarkable phenomenon, and its scale may be unprecedented during the history of life on Earth. This inference is based on the following observations:

- the population growth has been sustained over a long period of time
- an extraordinarily large abundance has already been achieved
- there has been a similarly impressive population growth of species that live in a close, mutualist relationship with humans, such as cows, pigs, chickens, and agricultural plants, which have their own cumulative environmental impacts
- a remarkable variety of species and ecosystems is being exploited as natural resources to support the human enterprise

Image 10.1. The human population is growing rapidly and now numbers more than 7 billion. This scene shows an urban market in Hong Kong. Source: B. Freedman.

In large part, these phenomenal achievements of Homo sapiens have been realized through the profound benefits of cultural evolution (or socio-cultural evolution). This term refers to the progression, throughout human history, of a series of adaptive discoveries of increasingly sophisticated tools and social systems. The capacity of people to learn from the experience of others, including the transmission of knowledge from one generation to the next, has allowed cultural evolution to proceed. In turn, this adaptive process has allowed people to become increasingly more efficient in the capture of natural resources by exploiting other species, ecosystems, and non-renewable materials (Chapter 12). Cultural evolution has allowed humans to achieve an unparalleled success in their domestication of planet Earth.

Unfortunately, the remarkable growth of the human economy (which represents increases in both population and per-capita environmental impact) has also caused terrible damage to the biosphere. Much of this damage has resulted in a large reduction in the carrying capacity for people and their enterprise. Moreover, natural ecosystems have been severely reduced in area, a change that is causing a massive loss of innumerable other species (see Chapter 26). In its totality, this damage already represents a global environmental crisis, and it is still worsening. Regrettably, the impressive growth of the human enterprise through cultural evolution has largely been achieved by reducing the ability of the biosphere to support most other species and natural ecosystems.

It is important to understand that the increasing size of the human population is not, on its own, the root cause of the environmental crisis. The rapid escalation of per-capita resource use and waste production is at least as important. Nevertheless, However, a sustainable resolution of the environmental crisis cannot be achieved if the explosive growth of the human population is not dealt with.

In this chapter we examine the remarkable changes that have occurred in the abundance of people during the past 10,000 or so years, and how cultural evolution has further increased the intensity of resource use. We also look at predictions of population change into the near future. Global patterns of change are emphasized in this chapter; we will examine the population of Canada in Chapter 11.

Cultural Evolution and Carrying Capacity

The biological history of hominids, including Australopithecus africanus, extends to perhaps 4 million years. The genus Homo goes back about 2 million years; Homo sapiens, the only surviving species, is about 200,000 years old.

For almost all of the evolutionary history of our species, relatively small numbers of people were engaged in subsistence lifestyles – they foraged over large areas while hunting wild animals and gathering edible plants. These people roamed the landscape in small family groups, searching for food and other necessities and using simple weapons and tools made of bone, stone, wood, and other natural materials. The hunter–gatherer lifestyle characterized the first 95% or so of human history, and during that lengthy time the population of our species was probably fewer than 1 million individuals.

By some 12-15-thousand years ago, people had discovered all of the major habitable landmasses, including the Americas. The latter were colonized relatively late, when small groups roved eastward across a broad (up to 1000 km wide) but temporary land bridge that connected Siberia and Alaska, through a region that is now the Aleutian Islands. That bridge was still present as recently as 11,000 years ago, and it existed because so much of global water was tied up in glaciers on land that sea level was about 110 m lower than it is now. (Note, however, that some archaeologists believe there may have been an earlier colonization of the Americas, occurring up to 60,000 years ago.) The wandering Siberians discovered a landscape with bountiful resources that had never before been exploited by people. Descendants of those first colonists of the Americas spread quickly, in the manner of an expanding wave, to occupy and exploit all habitable regions of North, Central, and South America. Occurring at the same time as the colonizing surge of people was a mass extinction of many species of large mammals and birds. It is likely that these unfortunate animals were naive to the lethal prowess of the novel two-legged predators that hunted in well-coordinated packs, and they were unable to adapt to the onslaught (Chapters 12 and 26).

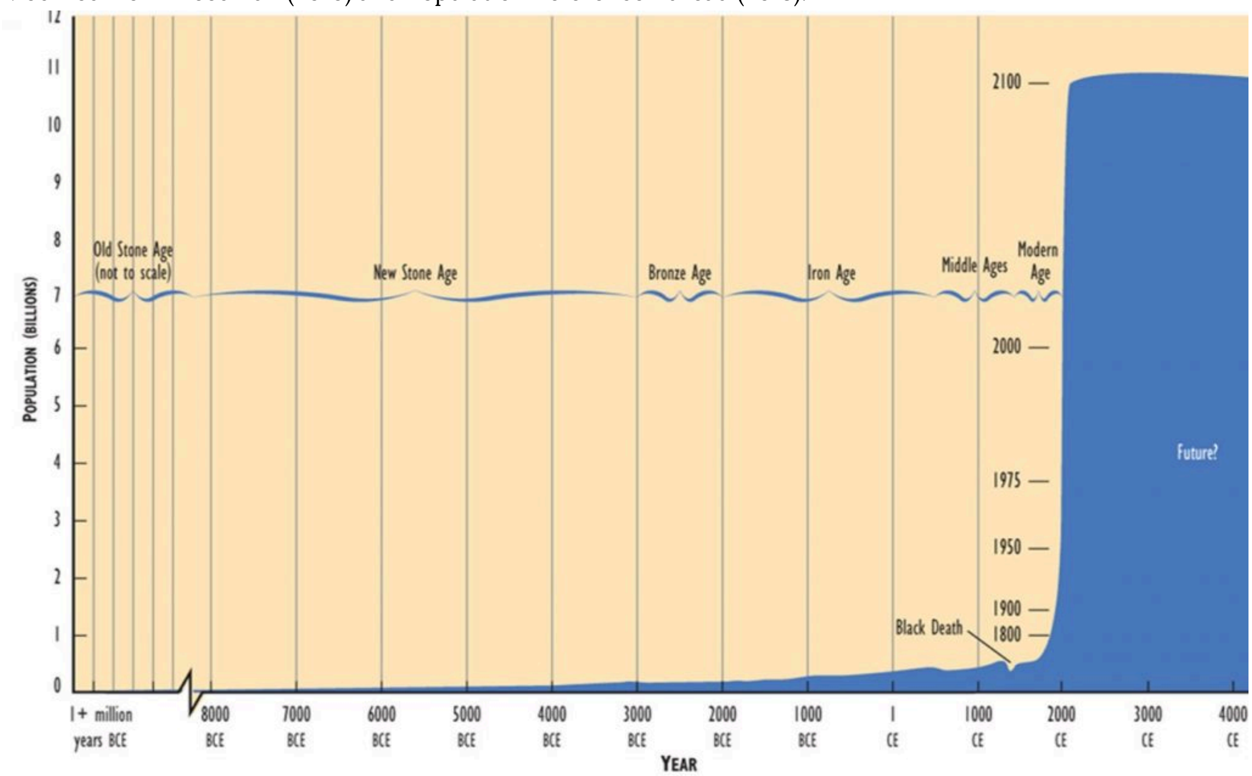
Cultural evolution has been a pervasive characteristic of our species, and there were many adaptive innovations of society and technology during the long-lasting prehistoric phase of foraging societies. These were cumulative advancements, meaning that each innovation built upon earlier ones and so the tools, practices, and social organizations got better and better. The innovations allowed natural resources to be exploited more efficiently, and economies of increasing size and complexity to be supported. The key advances of these prehistoric times, which because of their immense influence are sometimes referred to as “revolutions” (or great forward steps) of cultural evolution, include the following:

- the invention and improvement of tools and weapons
- discoveries of edible and medicinal species
- the elaboration of language and other means of communication
- the development of improved social organizations
- the mastery of fire
- the domestication of the dog, which allowed hunting to be more efficient, provided a pack animal, and helped keep encampments clean

Each of these breakthroughs enhanced the ability of people to exploit natural resources. This increased the effective carrying capacity of the ecosystems they were utilizing and allowed the population to increase and the overall economy to grow. By the end of this period (9-10-thousand years ago), when most people still engaged in foraging lifestyles, the global population was likely 1 to 5 million individuals.

At about that time, the first significant developments of primitive agriculture began, marking the beginning of a period known as the neolithic revolution (or the new stone age; see Figure 10.1). The first agricultural innovations included the beginning stages of domestication of a few edible plants and animals, such as barley and sheep, and the discovery of simple ways to cultivate them to achieve greater yields. Because crops must be tended and protected, the adoption of agricultural practices meant that lifestyles had to be much more sedentary. The eventual achievement of predictable food surpluses allowed some people to be supported as non-agricultural workers living in villages. This social and economic change eventually fostered the development of city-states and then nation-states, along with their relatively sophisticated cultures and technologies.

Figure 10.1. History of Population Growth.
For most of the history of Homo sapiens, the global population was several millions or less. However, adaptive and cumulative innovations through cultural evolution allowed increasingly more efficient exploitation of natural resources to occur, so the effective carrying capacity for humans was increased. This process intensified greatly during the past several millennia, and especially in the past two centuries. The human population is now showing extremely rapid growth, of a magnitude that is probably unprecedented for any large animal in the history of the biosphere. The future levelling off of the population is conjecture. Source: Modified from Freedman (2010) and Population Reference Bureau (2015).



The development of agriculture and its associated socio-cultural systems was one of the great forward leaps of human cultural evolution. The neolithic revolution provided an enormous increase in the carrying capacity of the environment for people and their domesticated species. Steady population growth was a result of this change, because even the primitive agricultural systems of those early times could support many more people than could subsistence lifestyles based on foraging for wild plants and animals.

The initial development of agriculture was followed by further innovations that increased the yield of crops. These improvements included the domestication of additional species of useful plants and animals, their genetic improvement through selective breeding (or artificial selection), and the discovery of better ways of managing the environment to increase crop productivity. There were also many non-agricultural enhancements of the carrying capacity, including the discoveries of the useful properties of metals and their alloys, which allowed the manufacturing of tools and weapons that were far superior to those made of bone, stone, or wood. In addition, the domestication of beasts of burden and the invention of boats and wheeled vehicles made it easier to transport large quantities of valuable commodities, which greatly stimulated trade.

This brief outline suggests that the cultural evolution of human socio-technological systems has involved a long and cumulative series of adaptive discoveries and innovations. Each of them increased the ability of people to exploit the resources of their environment, which increased the effective carrying capacity and thereby fostered growth of the populations of people and their mutualist species, and of the overall human economy.

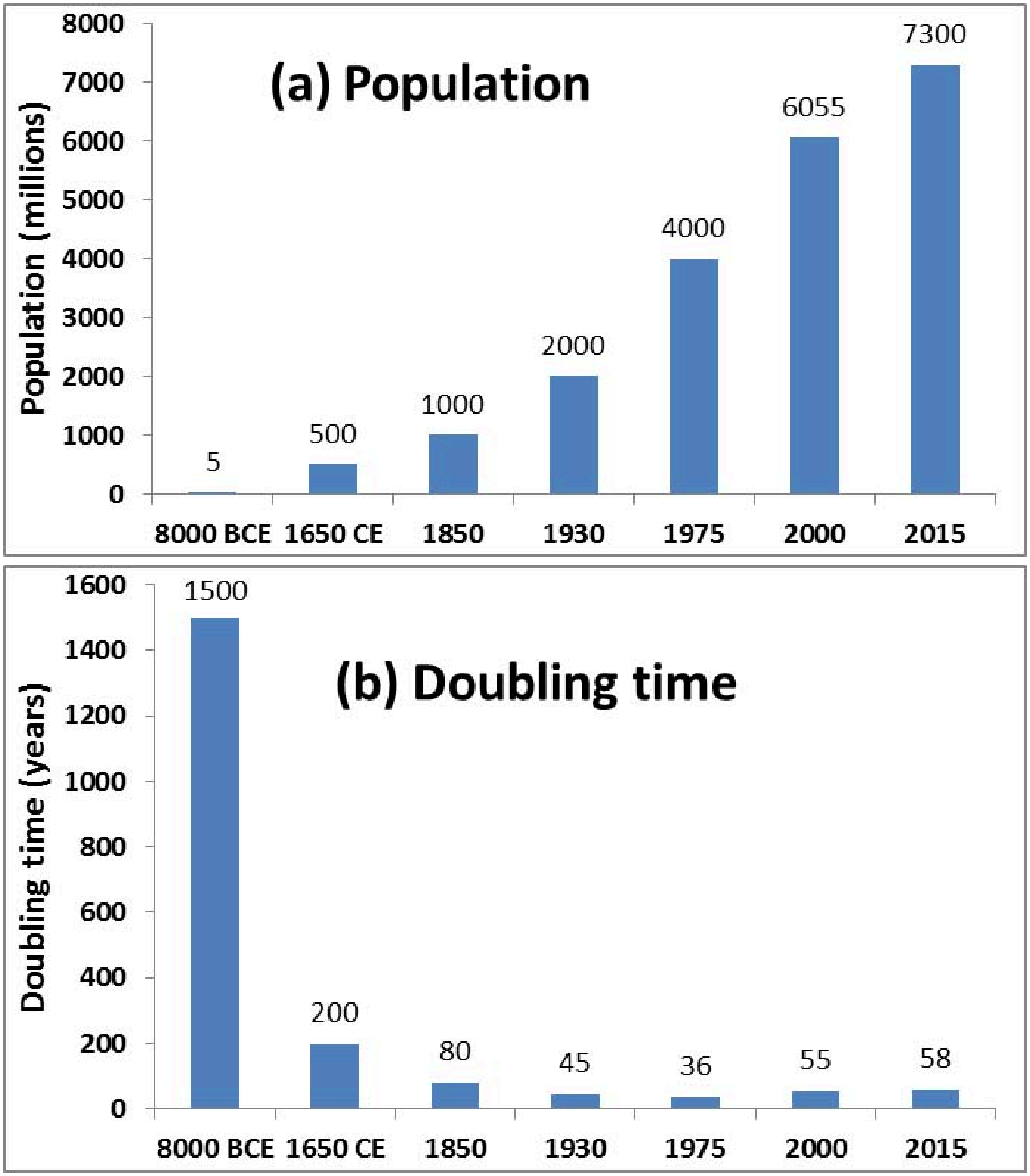
As a result of this adaptive progression, there were about 1-5 million people alive at the dawn of agriculture about 10-thousand years ago, 200–300 million at the beginning of the Common Era 2000 years ago (0 CE), and 500 million in 1650.

The rate of population growth then began to increase markedly, a trend that has been maintained to present times. These recent, extremely rapid increases in the human population have occurred for several reasons. Of primary importance have been the discoveries of increasingly effective processes and tools in sanitation and medicine, which resulted in great decreases in death rates. Ways of preventing lethal communicable diseases have been especially important in this respect.

In addition, recently discovered technologies have allowed for an increasingly effective harvesting of natural resources, the manufacturing of improved products, and greatly improved methods and infrastructure for transportation and communications. These have been achieved as a result of the industrial revolution, which began in the mid-eighteenth century. Agricultural systems have also been greatly improved through the development of improved crop varieties and better methods of cultivation, which have resulted in substantial increases of yield. Again, all of these progressions of cultural evolution have further increased the carrying capacity of the environment for people.

Between 8000 BCE and 1650 CE, the human population increased from about 5 million to 500 million, with an average doubling time of 1500 years and a growth rate of 0.01% per year (Figure 10.2). Since then the population has increased greatly and the doubling times have become less. The global population reached 1 billion in 1850, 2 billion in 1930, 4 billion in 1975, and 7.3 billion in 2015.

Figure 10.2. Growth and Doubling Times of the Human Population. Sources: Data from Ehrlich et al. (1977) and Population Reference Bureau (2015).



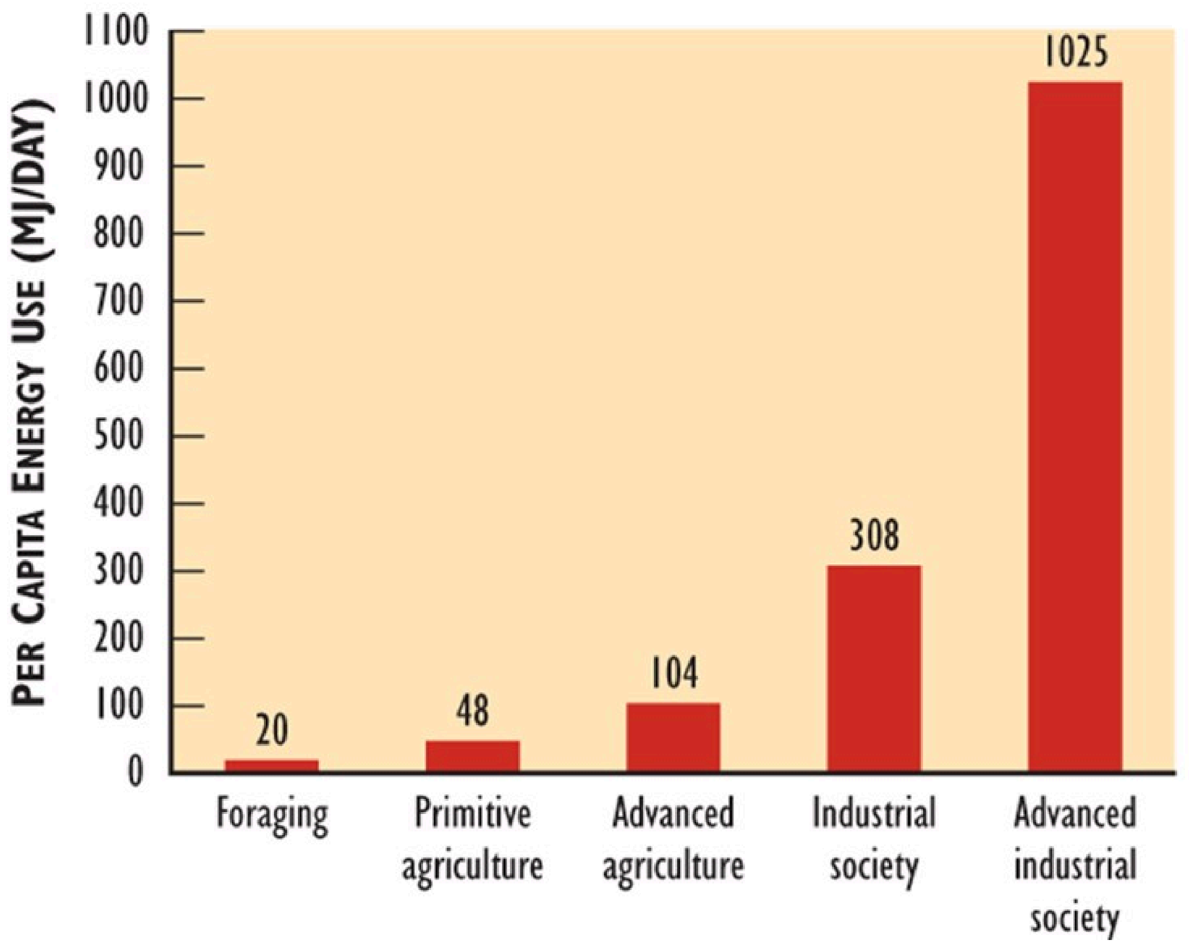
The population growth rate was at a historical maximum of about 2.1% per year during the late 1960s. At this rate of increase, the population is capable of doubling in only 33 years. Since then, the growth rates have slowed somewhat, to about 1.2% in 2015. If maintained, however, even that rate of increase would double the population in only 58 years. In fact, there is now an annual net addition of about 79 million people to the global population. For context, this annual increase is equivalent to about 2.3 times the population of Canada.

The cultural evolution of social, technological, and economic systems has allowed many people to enjoy great improvements of lifestyle. The main advancements have been in food and health security, which are a result of better access to sanitation, health care, food, shelter, and other elements of subsistence. (In the sense meant here, "security" is related to having access to the necessities and amenities of life, which enhances the likelihood of living to old age and raising healthy children.) The quality of life has also been improved through improved access to aesthetic resources and amenities, such as culture and recreation. Of course, these betterments of lifestyle are not shared equally among all people – they are largely unavailable to enormous numbers of poor people.

This is not to say that hunter-gatherers did not enjoy aspects of their lifestyle. These people undoubtedly had a rich cultural life, and many were able to satisfy their subsistence needs by “working” only a few hours each day, leaving much time for relaxing and socializing. In fact, the transitions to agricultural and then industrial societies have involved considerably greater workloads for average people and less time for relaxation. The additional work has, however, reaped benefits of the sort noted above, and for much larger numbers of people.

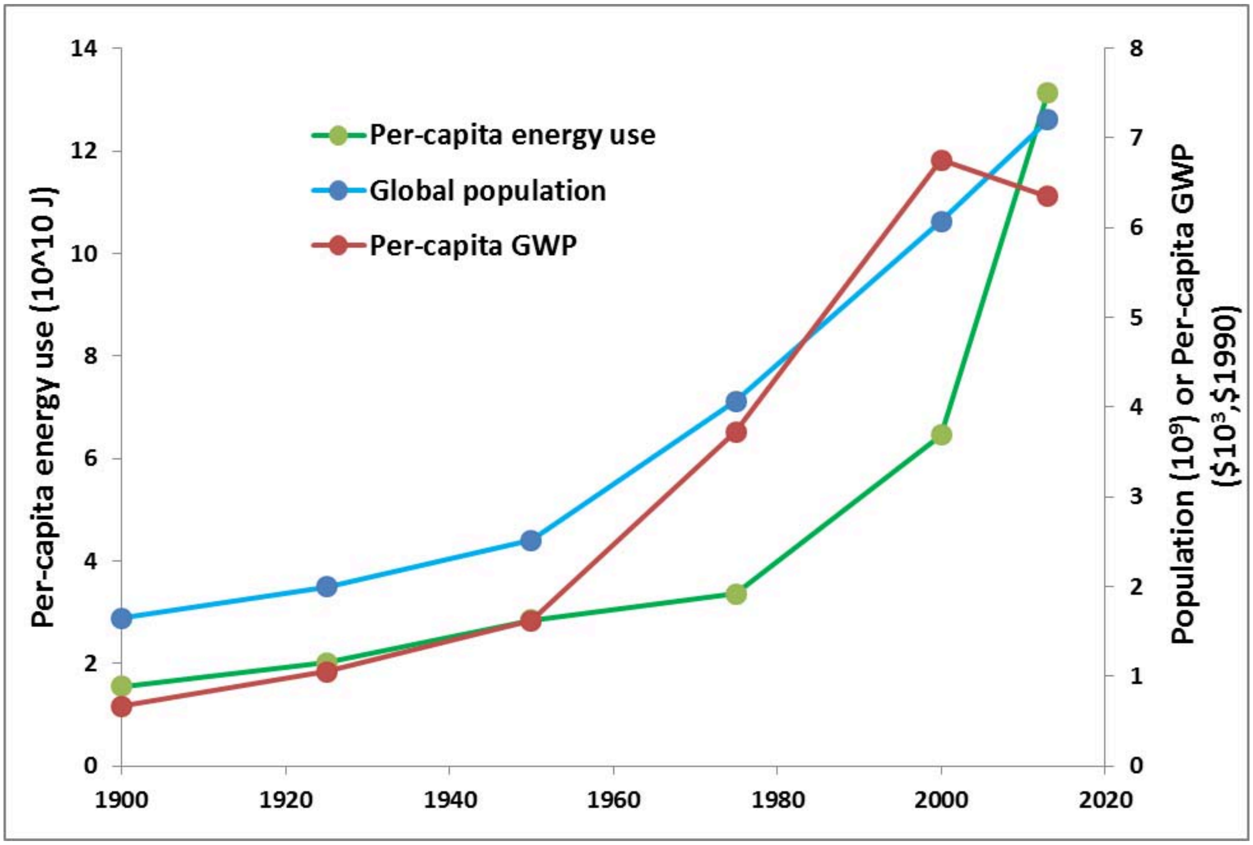
It is important to understand that the many improvements in human security and lifestyle have involved a great intensification of the per-capita environmental impact. We can easily understand this important change by examining patterns of energy usage, which is a simple indicator of per-capita impact (Figure 10.3; see also Chapter 1). Compared with hunter-gatherers, people living in an advanced technological society use at least 50 times more energy, and their environmental impact is greater by a similar degree.

Figure 10.3. Cultural Evolution and Energy Use. These data are estimates of the per-capita use of energy by people engaged in various kinds of lifestyles. Energy use is presented here as a simple indicator of environmental impact. Source: Modified from Goldemberg (1992).



The intensification of the per-capita use of energy has been especially great during the past century of accelerating technological development. In fact, during the past century, the global per-capita economic output and energy use have both increased at similar or greater rates as the human population (Figure 10.4). These per-capita increases have, of course, been especially rapid in developed countries such as Canada, and much less so in poorer countries (see Chapters 13 and 14). For instance, the per capita consumption of energy in developed countries averages about 194 gigajoules/year (GJ/y), compared with 38 GJ/y in less-developed ones (WRI, 2008). Although developed countries account for about 20% of the human population, they are responsible for 59% of the global consumption of energy.

Figure 10.4. A Century of Change in Global Population and Per-capita Environmental Effect. Global-scale economic activity and energy use are being used here as simple indicators of the environmental impact of a human population. Economic activity is given in constant US$ (year 1990), so inflation does not account for the increase over time. Sources of data: DeLong (1998), Population Reference Bureau (2015), and BP (2014).



It is important to remember that the rapid increases of population and per-capita environmental influence multiply together to determine their total effect. For example, population is multiplied by the per-capita economic activity to calculate the gross world product (GWP), or the sum of the economic activities of all people in the world. Using this calculation, the data in Figure 10.4 suggest that the GWP in 2013 was about 42 times larger than in 1900 ($\$41.7 \times 10^{12}$ versus $\$1.1 \times 10^{12}$; note that to account for inflation, both of these values are in constant year-1990 US$; note the 2013 data, if expressed in year-2013 dollars, would be $\$71.8 \times 10^{12}$; note also that 10^{12} is a trillion, or a thousand billion). This is much larger than the growth of population during that same period (4.3 times larger), and also that of per-capita economic activity (9.5 times larger).

A similar calculation can be made for global energy consumption, again using data from Figure 10.4. If we do this, we determine that global energy use was about 40 times larger in 2013 than in 1900. Because of the multiplication effect, this is much larger than the growth of population during that period (4.3 times larger) or of per-capita energy use (8.5 times larger).

Global Focus 10.1. Population in Context

The abundance of humans in 2015 was more than 7.3 billion individuals. That enormous population was growing by about 1.2% per year, equivalent to an additional 87 million people each year. Although the rate of growth is slowing, it is projected that 9-12 billion people might live on Earth when the population eventually levels off. These are gigantic numbers, and to put them into perspective it is useful to consider the abundance of other species of “large” animals (defined as weighing more than 44 kg, or 100 pounds).

Some large animals have been domesticated and live in a mutualism with humans. The most populous of these are cows (Bos taurus and B. indica) with a population of about 1.5 billion, sheep (Ovis aries) with 1.2 billion, goats (Capra hircus) with 1.0 billion, and pigs (Sus scrofa) with 1.0 billion (FAO, 2015). Some smaller mutualists are even more abundant, including an estimated 22 billion chickens (Gallus gallus).

It is doubtful that any wild, large animals ever had such enormous populations as do humans and our domesticated animals (Freedman, 2010). Within historical times, the most populous wild, large animal was the American bison (Bison bison), which prior to its near extermination by over-hunting, may have numbered 60 million individuals. At the present time, the most populous large animals in the wild are the white-tailed deer (Odocoileus virginianus) of the Americas with 40-60 million individuals, large kangaroos in Australia (Macropus gigantea and M. rufus) with up to 50-60 million, and the crabeater seal (Lobodon carcinophagus) of the Antarctic with 15 million. The populations of these wild animals are only 1% or less of that of humans.

A few other wild species of large animals maintain populations in the millions, including as many as 7 million ringed seals (Phoca hispida) in the Arctic, 7-8 million harp seals (Phoca groenlandica) in the North Atlantic, and 3 million caribou (reindeer, Rangifer tarandus) in the Arctic and Subarctic.

Clearly, humans and their large-animal mutualists are unusually abundant, and even unnaturally so. The huge populations of domesticated animals (humans included) can be maintained only by using an extremely large fraction of the productivity of Earth’s ecosystems. Some ecologists have estimated that fraction to be as large as one-quarter (Vitousek et al., 1986; Haberl et al., 2013).

Regional Variations

It is important to recognize that population growth varies enormously among regions and countries. In recent decades, some countries have achieved a natural rate of growth (birth rate minus death rate) as high as 4% per year, which if maintained could double their population in only 18 years.

Populations are growing most quickly in Africa, with a rate of increase of about 2.4% per year (Table 10.1). Although African countries vary considerably, as a whole, the continent is the world’s poorest region. Its socioeconomic condition is partly due to legacies of its colonial history, including national boundaries that often make little sense in view of the distributions of tribal and language groups. In some countries, other factors also detract from development, particularly endemic corruption in government and business and strife between tribes. In addition to those important problems, the increasing populations of African countries are also making it extremely difficult to deal with chronic poverty. The population of continental Africa was about 224 million in 1950, 1,136 million in 2014, and an anticipated 2,428 million (or 2.43 billion) in 2060. With human populations increasing so quickly, and the amounts of agricultural land and other resources remaining static or even declining because of over-exploitation, it will be a formidable challenge to avert social and ecological catastrophes in many African countries. Resolving these problems will require both national fortitude and generous international assistance.

Table 10.1. Regional Population Growth. Data for 2025 and 2050 are estimated from recent demographic trends (i.e., in rates of birth, immigration, death, and emigration). The natural rate of population increase (in 2014, data

in percent) is calculated as births minus deaths, while the total rate also accounts for net migration. Data are from World Resources Institute (2008) and Population Reference Bureau (2015).

	Population (millions)				Rate of increase	
Region	**1950**	**2014**	**2030**	**2060**	**Natural**	**Total**
World	2,520	7,238	8,444	9,683	1.2	1.2
Africa + Middle East	293	1,391	1,959	2,815	2.4	2.4
Asia	1,328	4,096	4,585	4,865	1.1	1.1
North America	172	353	396	444	0.4	0.7
Latin America + Caribbean	167	618	710	773	1.2	1.1
Europe	547	741	746	726	0	0.2
Oceania	13	39	48	60	1.1	1.7
More Developed	861	1,,249	1,292	1,309	0.1	0.3
Less Developed	1,666	5,989	7,152	8,375	1.4	1.4

Populations are growing least quickly in Europe, where the present change is about 0.2% per year, a rate that is expected to hold for several decades (the rate of natural change is 0.0%/y, while net immigration is 0.2%/y). Populations are growing somewhat more quickly in North America, currently at 0.7% per year (the natural increase is 0.4%/y, while net immigration is 0.3%/y).

Much of the population growth in Canada and the United States is due to relatively open levels of immigration from other countries rather than to natural population change (see Chapter 11). The major source regions of the immigration are Asia, Central and South America, and Africa, mostly from countries with growing populations and few prospects for poor people to improve their lifestyle. Immigration is also coming from parts of eastern Europe where there is little population growth but much unemployment and economic hardship.

Populations of Particular Countries

Data for recent population growth in selected countries are listed in Table 10.2. Countries with the fastest increases in population are in Africa and Asia, and to a lesser degree, in Central and South America. Populations are increasing rapidly in almost all countries in those regions.

Table 10.2. Population Growth in Selected Countries. Data are from World Resources Institute (2008) and

Population Reference Bureau (2015).

	Population (millions)				Rate of increase (2014; %/y)		
Country	**1950**	**2014**	**2030**	**2060**	**Natural**	**Migration**	**Total**
Rapidly Growing Population							
Afghanistan	8	31	44	57	2.7	-0.3	2.4
Bolivia	3	10	13	16	1.9	0	1.9
Iran	17	77	90	99	1.4	0	1.4
Madagascar	4	22	34	53	2.7	0	2.7
Nigeria	33	178	262	397	2.5	0	2.5
Pakistan	37	194	255	348	2	-0.3	1.7
Tanzania	8	51	79	129	3.1	-0.1	3
Declining Rate of Growth							
Canada	14	36	42	48	0.4	0.8	1.2
China	555	1364	1400	1312	0.5	0	0.5
India	358	1296	1510	1657	1.5	0	1.5
United States	158	318	354	395	0.4	0.3	0.7
Slow or No Growth							
France	42	64	68	72	0.3	0.1	0.4
Germany	68	81	80	76	-0.2	0.5	0.3
Japan	84	127	117	97	-0.2	0	-0.2
Russia	103	144	144	134	0	0.2	0.2

There are, however, some anomalous situations whose dynamics are largely driven by the movements of large numbers of refugees. For instance, Afghanistan had a population decrease of 1.8% per year during the period 1980 to 1985 (WRI, 2008). This was mostly because a devastating civil war killed many people, while even larger numbers fled to neighbouring Pakistan and Iran. In contrast, the population of Afghanistan increased by an extraordinary 6.9% per year during 1990–1995, largely because many refugees migrated back after a sporadic ceasefire restored relative peace. Overall, the intrinsic rate of increase of the Afghani population has been 2.7-3.5% per year. In 1950, the population of Afghanistan was 8 million. By 2014 it had increased four-fold to 31 million, and it is projected to reach 44 million by 2030 and 57 million by 2060.

Some countries have had recent population growth even more rapid than Afghanistan. In Nigeria, for example, the population was 33 million in 1950 and is projected to reach 262 million in 2030 (about an 8-fold increase) and 397 million in 2060 (12-fold). (Note, however, that such predictions for Nigeria and some other countries could prove inaccurate because of mortality from the AIDS epidemic or some other disaster; see the last section of this chapter and Global Focus 10.2). In Iran, the population increase between 1950 and 2030 is projected to be about 5-fold. Try to imagine the ecological and resource stresses associated with population explosions like these! Contemplate being a politician or governmental bureaucrat who is charged with the responsibility of ensuring livelihoods and an acceptable quality of life for so many citizens, while also protecting the environmental quality and ecological heritage of the country! The challenges are daunting.

The countries with the most stable populations are mainly in Europe. The populations of most European countries are growing at less than 0.5% per year, and the doubling times are longer than 100 years. As was previously noted, the intrinsic rates of population increase in Canada and the United States are similar to these values, although because of substantial immigration, their populations are still growing at about 1% per year.

Fortunately, many countries are showing rapid decreases in their rate of population increase. China, for example, had population growth rates exceeding 3% per year in the 1960s and 1970s, but this decreased to 0.5% per year in 2014. The slowdown is occurring because the government of China has recognized the acute problems associated with population growth, and so has developed policies to slow the increases and is implementing them in an effective manner. However, China's government has imposed its population policy with a determination that has sparked debates about human rights. Controversial measures have included coerced sterilization and the enforcement of a one-child-per-family guideline, particularly in urban areas. Nonetheless, China appears to be firmly on the road to rapidly decreasing its rate of population growth. We can only hope this necessary action has occurred in time. China's population in 2050 was 555 million, but this had more than doubled in 2014 to 1.4 billion, and even with its aggressive population policy this could still increase further. These are immense numbers of people to accommodate within the bounds of the landmass and natural resources of China, which are not increasing in area or quantity.

The situations in Brazil, India, Indonesia, Korea, Mexico, and Thailand are similar, although none of these countries is experiencing declining rates of population growth as rapid as that of China. India, the world's second-most populous country, had 1.3 billion people in 2014, and may somehow have to support 1.5 billion in 2030. Although all of these countries have started to develop population policies aimed at reducing growth rates, they are not being implemented as effectively as in China.

In general, countries that are experiencing the most rapid population growth are relatively undeveloped and poor, and they are tropical or subtropical in distribution. However, not all poor countries have high population growth rates. The population growth rates of Cuba, for example, have been consistently less than 1% per year since the 1950s. Although Cuba is relatively poor, almost all of its citizens are literate and its social system provides ready access to housing, food, social security, and health care, including effective means of birth control.

It can be broadly generalized that the wealth and state of development of nations correlate inversely with their population growth rate. Nevertheless, any country with an appropriate and effectively delivered population policy can achieve a strong measure of control of the rate at which its population is increasing. The case of Cuba demonstrates this fact.

The explosive rates of population increase in so many poor countries are straining the ecosystems that must somehow sustain the burgeoning numbers of people and their livelihoods. This can be illustrated by the case of Sudan, in northeastern Africa. The population of Sudan was 2.9 million in 1917, but it had irrupted to 38 million by 2006, an increase of 6.4 times (Olsson and Rapp, 1991; WRI, 2008) (an irruption is a rapid increase). Because most Sudanis are engaged in agricultural livelihoods, the populations of livestock also increased tremendously during that period. The number of cattle increased 51-fold (to 41 million); camels, 17-fold (to 3.9 million); sheep, 39-fold (to 50 million); and goats, 35-fold (to 43 million). These enormous amounts of growth in the populations of people and livestock have degraded the carrying capacity of rangelands in Sudan and other regions of Africa. At the same time, terrible damage has been caused to natural ecosystems.

It must be remembered, however, that comparable rates of growth occurred in Europe and North America in previous centuries. In Britain, for example, extensive deforestation and other habitat losses resulted in the extirpation of many species of native plants and animals. In addition, deforestation and the grazing of hillsides in Scotland virtually eliminated the native forest that once covered that landscape, although there has since been some replacement by conifer plantations. These ecologically destructive activities have largely been forgotten, and most inhabitants of Britain now regard the transformed landscape of their country as being "natural." Comparable stories can be told of regions of southern Canada that were once extensively forested, but are now covered by urban and agricultural land-uses, with only small areas of degraded "natural" habitat.

Birth and Death Rates

Societies living in relatively primitive, undeveloped conditions have always tended to have high rates of births and deaths, typically about 40-50 per thousand. (Birth and death rates are commonly expressed as the average number per thousand individuals in the population per year.) These were the usual rates of natality (births) and mortality (deaths) throughout almost all of human history. As long as the rates of births and deaths remained high and similar to each other, the population growth was small or zero. It is only during the past several centuries that rapid growth has occurred.

This has occurred largely because death rates have decreased substantially in all countries. The large reductions of death rate are due to the benefits of improved sanitation, medicine, immunization, and social welfare, along with widespread access to education (which, among other things, provides a widespread awareness of the benefits of sanitation and medicine).

The life-saving benefits of sanitation, immunization, and medicine are particularly consequential for younger people, especially those less than five years old. This group tends to have the highest death rates under "primitive" conditions. Other relatively vulnerable groups that have benefited include the elderly and women in childbirth. As well, large reductions in mortality from infectious diseases, such as bubonic plague, diphtheria, influenza, malaria, plague, smallpox, tuberculosis, and yellow fever, have been important in reducing mortality during the past several centuries.

However, these medical and social benefits have not been shared equally among countries, or among income groups within nations. For this reason, people living in less-developed countries, and poorer income groups within countries, typically have considerably higher death rates than do more-developed or wealthier ones. This trend is readily apparent if data for death rates in poorer countries with increasing populations are compared with those of wealthier countries having more stable populations (Table 10.4).

Compared with the relatively large decreases of death rates in all of countries and cultures, decreases in birth rates have been much slower (Table 10.3). In general, the wealthiest, most developed countries have relatively low birth rates, with rates typically about 10 per thousand. Moreover, these are almost in balance with death rates, so the natural population increase in those countries is low or zero. In large part, the relatively low birth rates of the wealthier countries have resulted from the emergence of a cultural inclination to have small families, which can be achieved because there is ready access to safe and effective methods of birth control.

Table 10.3. Demographic Information for Selected Countries. Note that the intrinsic rate of population change is calculated as the birth rate minus the death rate. A difference of +10 units is equal to a 1% increase per year. The fertility rate is the number of children born to an average woman over her lifetime. Life expectancy is the number of years lived from birth. Data are from World Resources Institute (2008) and Population Reference

Bureau (2015).

	Birth Rate (births/1000)		Death Rate (deaths/1000)		Fertility Rate (births/woman)		Life Expectancy (years)	
Country	**1970–75**	**2014**	**1970–75**	**2014**	**1970–75**	**2014**	**1970–75**	**2014**
Rapidly Growing Population								
Afghanistan	51	35	25	8	7.7	5.1	40	61
Bolivia	45	26	19	7	6.5	3.2	47	67
Iran	45	19	13	5	6.4	1.8	55	74
Niger	48	50	26	11	7.1	7.6	37	58
Nigeria	47	39	22	13	6.9	5.6	43	52
Tanzania	48	40	16	9	6.8	5.3	50	61
Relatively Slow or No Population Growth								
Canada	16	11	7	7	2	1.6	73	81
China	29	12	6	7	4.9	1.6	63	75
Germany	11	8	12	11	1.6	1.4	71	80
Japan	20	8	7	10	2.1	1.4	73	83
Russia	15	13	9	13	2	1.7	70	71
UK	16	12	12	7	2.3	1.9	71	81
USA	16	13	9	8	2.9	1.9	72	79
World	31	20	12	8	4.5	2.5	58	71

Changes in cultural attitudes about family size appear to be a natural outcome of increasing affluence and health as societies develop and become wealthier. Such cultural changes are critically important for dealing with the potentially explosive population growth of modern times. In a sociological sense, however, it is not exactly known how these changes in attitude come about. In less-developed societies, children are often viewed as a source of inexpensive labour and providers of material comfort for their parents in old age. In contrast, in wealthier societies, children are considered to be substantial economic and social responsibilities for their parents – they are expensive consumers of space, education, energy, food, clothing, and other necessities. This context provides a strong incentive for having a smaller family.

Although birth rates have recently been decreasing, they are nevertheless quite high in most less-developed countries. Because death rates have fallen considerably, their populations are growing rapidly (see Table 10.4). In general, birth rates have remained high because of cultural preferences for larger families – this factor is strongly influenced by high death rates in recent history, particularly of young children. Fifty years ago, a family might have had six birthed children, with only three surviving because of a high rate of infant mortality. Today, however, all six might survive. In addition, some religions influence birth rates because they promote large families or strongly disapprove of modern methods of birth control. The social factors result in a lag in the cultural adjustment of birth rate to offset the rapid declines in mortality. The ensuing imbalance has resulted in the rapid population growth that is occurring in almost all less-developed countries.

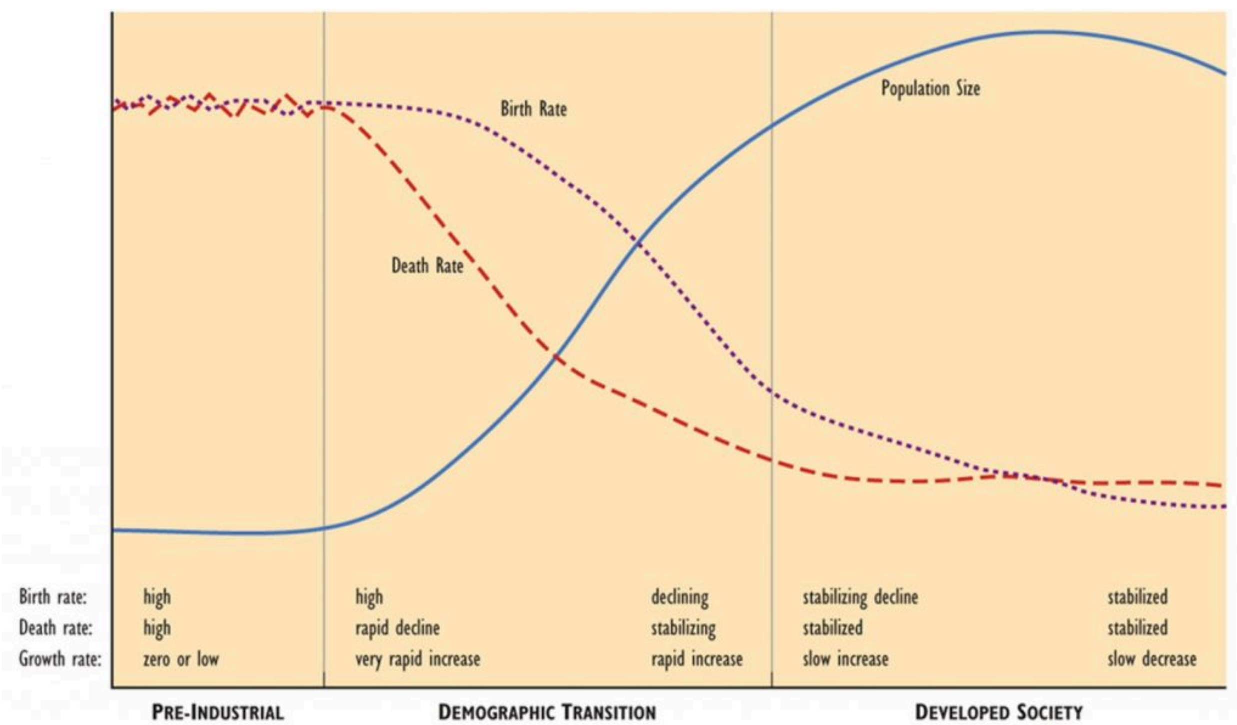
However, the situation is not quite as simple as this. In many countries, the fertility rate is maintained at a considerably higher level than many people, particularly women of childbearing age, might freely choose. This happens because many women do not have sufficient access to safe and effective means of birth control. Exceptions are countries such as China and Cuba, and to a lesser degree Brazil, India, Indonesia, Korea, Sri Lanka, and Thailand, all of which are substantially reducing their population growth rates, mainly by ensuring that their citizens have access to effective means of controlling their fertility.

The Demographic Transition

Almost all of human history has been characterized by relatively primitive living conditions, and during that time there was low or zero population growth (ZPG) because high death rates were balanced by high birth rates. During the past several centuries, however, many countries have had rapid population growth because the rate of births exceeded that of deaths. More recently, during the past five decades or so, a condition of ZPG has occurred in relatively "developed" nations and cultures, in which low death rates are balanced by low birth rates.

The so-called demographic transition refers to the transition of a population from a condition of high birth and death rates to another of low birth and death rates (Figure 10.5). It typically takes a rather long time, usually several generations, for a society to make it through this transition, and while that is happening the population increases at a high rate. The imbalance occurs because modern sanitation, immunization, and medicine contribute to a rapid decrease of mortality, but that occurs without a simultaneous off-setting decrease in birth rates. If, for example, the annual birth rate remained at 45 per thousand while the death rate declined to 11 per thousand, the population would grow at 3.4% per year. If that situation continued, the population would double in only 20 years. These numbers are, by the way, actual demographic parameters for Zambia in 2014, one of the least-developed countries in the world.

Figure 10.5. The Demographic Transition. This illustration models the transition from a condition of high birth and death rates to one of low birth and death rates. Typically, the death rates decrease faster than birth rates, and the corresponding imbalance has an explosive influence on population growth. Zero population growth occurs when birth and death rates offset each other. If the birth rate falls below the death rate, the population will decrease in size.



No cultures prefer high death rates, but some do have a preference for larger families. Recent history has shown that it takes one or two generations to overcome cultural inclinations toward having large families, and for birth rates to decline to a level that is in balance with modern death rates.

Many of the developed countries of today had the great fortune of passing through their demographic transition during times when their populations were relatively small, and under circumstances in which their "surplus" people were able to migrate to other places. At the time, many European countries had a surfeit of labourers because of mechanization associated with the beginning of the Industrial Revolution, as well as the consolidation of small farms into larger ones, which also deprived large numbers of people from employment. To escape their poverty and dim prospects, many people chose to emigrate to colonial "frontiers" in the Americas, Australia, and elsewhere. Many countries, such as Argentina, Australia, Brazil, Canada, Chile, Mexico, New Zealand, South Africa, the United States, and Venezuela, were then colonies of European nations. At the time, these were considered to be "underpopulated" places with bountiful resources, capable of assimilating a large amount of immigration.

In actual fact, however, at the time of their European "discovery" these regions were already occupied by indigenous peoples. Nevertheless, in the socio-political context of the time (16th to 19th centuries), European powers seized ownership of many foreign regions, displaced or subjugated the original inhabitants, and colonized the freed-up land through an immigration of poor or otherwise mobile citizens from the home countries. To a substantial degree, the notion of under-population lingers today, particularly in Canada, the United States, and Australia, which still allow relatively high rates of immigration of people from other countries. As a result, the population growth rates in those countries substantially exceed what would be expected based on birth and death rates, which are almost in balance and reflect passage through the demographic transition.

In recent centuries, immigrants from a great many countries have swelled the populations of Canada and the United States. For example, at the time of the first United States census, in 1790, that country had a population of 4 million. Sixty years later, in 1850, the population had increased to 23 million. That growth was largely achieved through immigration of many people from Britain and other European countries. (The natural increase in population during that period was also vigorous, adding 4-8 million people.) Changes of a similar degree occurred in Canada (see Chapter 11). The ability of many European countries to export so much of their surplus population was critical to their relatively smooth passage through the demographic transition.

Today, only a few countries still allow a substantial rate of immigration, most notably Canada, the United States, and Australia. However, the actual numbers of people involved in transnational immigration to developed countries, several million per year, is small in comparison with the global population growth (about 87 million per year in 2014). Moreover, there is no reason to expect that these and other host nations will continue to be willing, or able, to absorb population surpluses from other countries.

One of the bitter truths of modern times is that the relatively poor, less-developed countries of the world, which have the fastest population growth, have no significant outlets for their burgeoning surpluses of people. All nations today have access to the mortality-reducing benefits of modern sanitation and medicine, but in most countries these are not yet balanced by a control of birth rates. Consequently, many less-developed countries are faced with a pressing need to bridge their demographic transition much more quickly than today's developed countries ever had to do. Moreover, this daunting feat must be accomplished without much emigration. There are no underpopulated frontiers left on Earth – local population crises can no longer be exported somewhere else.

Future Populations

All trends in demographic indicators indicate that the human population will continue to grow rapidly into the foreseeable future. However, there are convincing signals of decreasing rates of population growth in almost all countries. This is encouraging, but it does not negate the fact that the global population is still growing rapidly (although not as quickly as several decades ago).

It is never possible to accurately foretell how complex phenomena, such as changes in human populations, will unfold in the future. Nevertheless, by extrapolating from recent trends it is possible to infer the likely values of birth and death rates and other demographic variables in coming decades. Such predictions can then be modified according to anticipated changes in social policies that may influence birth or death rates.

There is also, of course, the possibility that some catastrophic event or environmental deterioration could cause a massive increase in human death rates, resulting in a population crash. Such a calamity might be caused by a newly emerged virulent disease, a collapse in the availability of vital resources, a nuclear holocaust, or some other global emergency. However, events such as these are unpredictable and can never be forecast with accuracy – the most that can be suggested is that they may occur at some time in the future.

Population scientists have developed sophisticated mathematical models to predict the future abundances of humans. These models can be run using various demographic scenarios, for example, by changing the values of birth rate, death rate, population structure, or other variables. These models are not catastrophist – rather, they assume that future population size will be determined by relatively small changes in birth and death rates and not by a huge increase in death rates (i.e., a population crash).

Figure 10.6 shows world population growth from 1800 to 2010, and three models of future growth to 2100. The models are low-, medium-, and high-level projections based on studies by the United Nations. The low-level model uses optimistic demographic predictions, such as assuming that effective population policies will be implemented rapidly and will allow stable populations to be achieved as quickly as can be hoped. This model suggests that the population will increase to about 8 billion around 2050 and then decline to 6 billion by 2100. The high-level model uses relatively conservative parameters, such as effective policies not being implemented until considerable time has passed, so that the necessary demographic transitions will take a long time to occur in rapidly growing populations. This model forecasts a continuing increase of population to about 16 billion in 2100.

The medium-level prediction is perhaps most realistic because it uses more likely scenarios of political and economic factors that affect population policies and their influence on demographic parameters. This model suggests that the population will level off around 2100 at an abundance of 10 billion people.

Therefore, it appears that the global population will increase greatly from its present level before it (hopefully) stabilizes. This assumes, of course, that there is no intervening catastrophe such as a collapse of the environmental carrying capacity for our species, an unprecedented pandemic, or a global war.

Figure 10.6. The human population from 1800 to 2100. The data in black and blue are estimates to 2110, with those in blue being relatively accurate. Future populations are based on three population scenarios, ranging from low-level to high-level in terms of the assumptions of demographic parameters. The low-level model makes optimistic and probably unrealistic assumptions about population policies. The high-level model is more conservative and assumes that the imbalance between birth and death rates will be addressed more slowly. The medium-level model may be the most likely outcome, although there is considerable uncertainty. Source: Cobb

(2012).

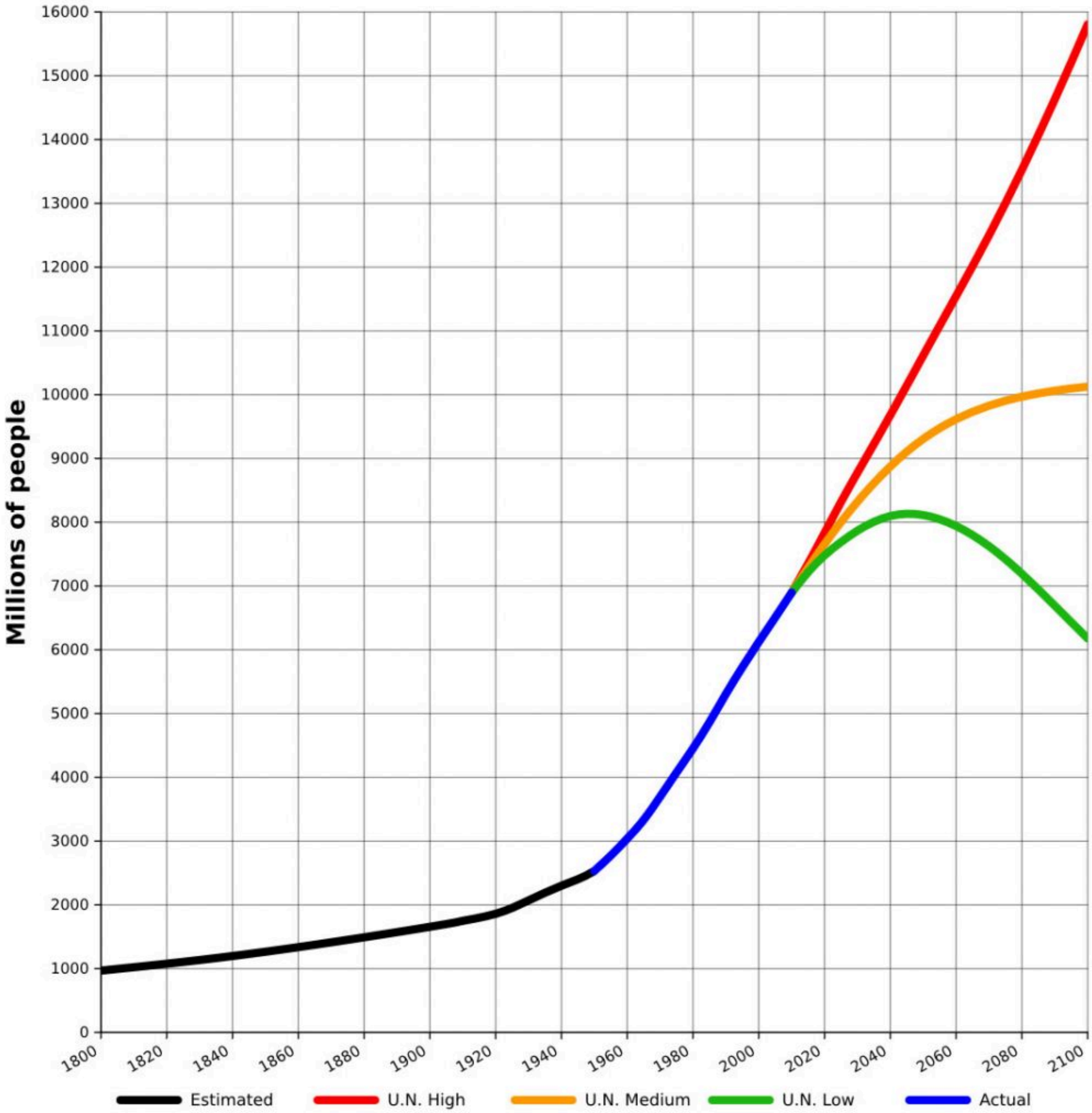


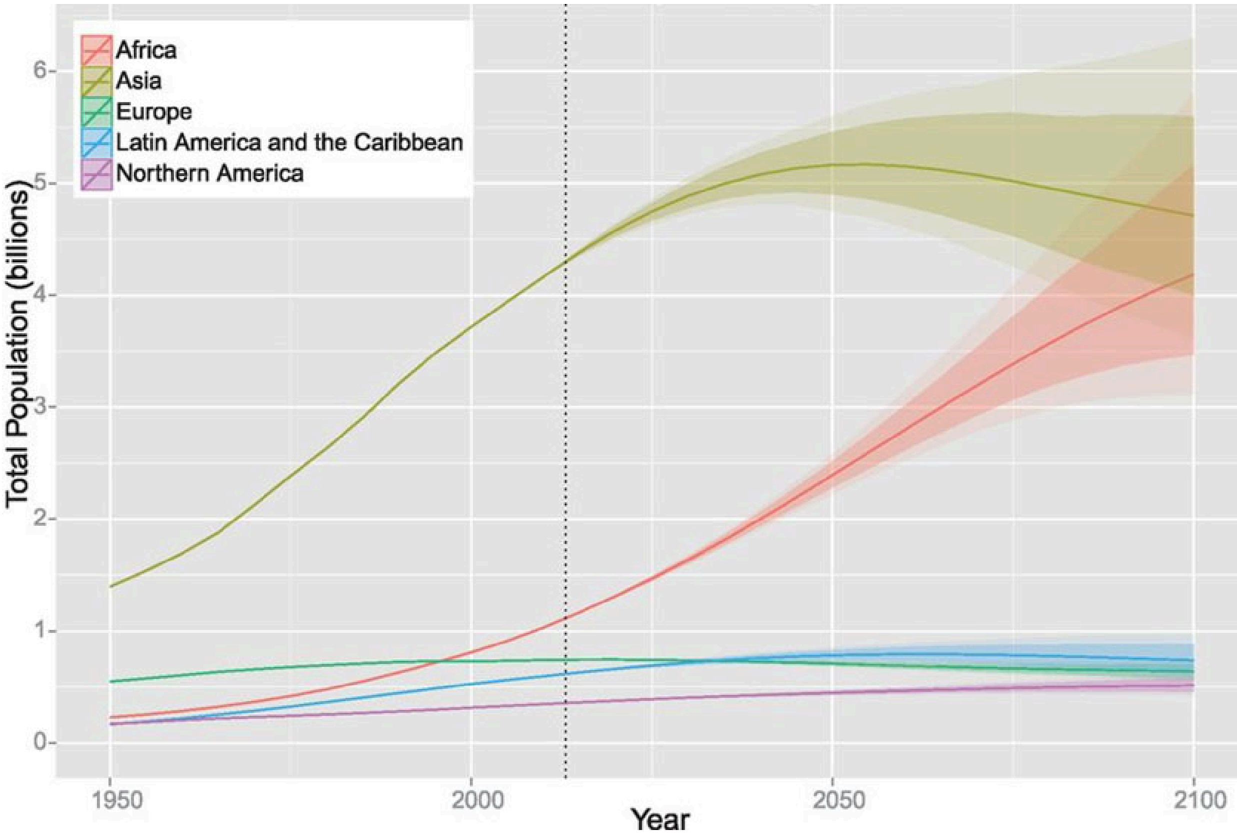
Image 10.2. In less-developed countries, governments will have to find livelihoods for increasingly larger numbers of young people, even as space, resources, and environmental quality are rapidly diminishing. These

students live in Padung Pajung, Sumatra, Indonesia. Source: B. Freedman.

Moreover, it appears that the populations of almost all countries will increase. However, the population growth will not be equitably shared between the less-developed and more-developed regions of the world. In 1950, about 34% of the world's population of 2.5 billion lived in developed countries. However, recent population growth has been much more rapid in less-developed countries, so that in 2014, only about 17% of the world's 7.3 billion people lived in developed regions. This disparate trend will intensify in the near future, and by 2050, perhaps less than 10% of the world's 10-12 billion people may be living in developed regions (Figure 10.7).

Figure 10.7. Predicted Populations by Major Regions. The predictions are based on medium-level projections, with the cones indicating probability intervals of 80% (darker shading) or 95% (lighter shading). Source:

Modified from Gerland et al. (2014).



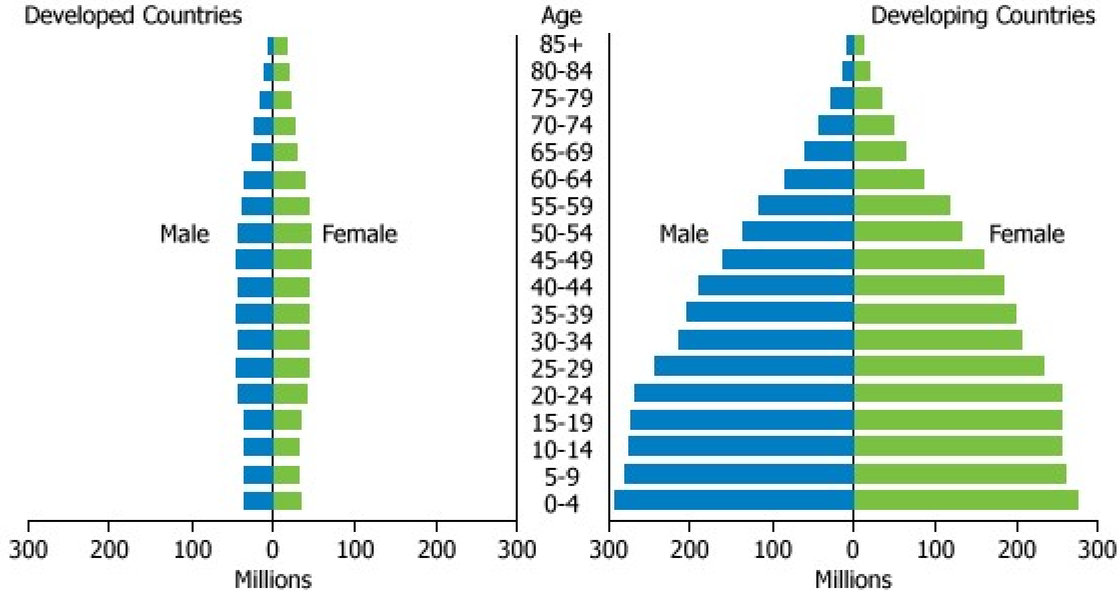
Age-Class Structure

A population structure describes the relative abundances of specified groups of people. This includes the age-class structure, or the proportions of individuals in various age groups. This aspect of population structure differs greatly between populations that are growing or stable, and there are important implications for their future growth.

Populations that have been stable for some time have similar proportions of people in various age classes (Figure 10.8). In other words, there are roughly comparable numbers of people aged 5-10, 10-15, 15-20, 20-25 years, and so on. This equitable distribution holds for most age-classes, except for the elderly, who always have a higher risk of mortality. This kind of age-class distribution is typical of relatively developed countries that have made it through their demographic transition.

Figure 10.8. Age-Class Structure of the Global Population. Compare the age-class structures of a relatively young, rapidly growing population (the less-developed world, in 2010) with a stable population (developed

countries). Source: Modified from Population Reference Bureau (2011).



In marked contrast, the age-class distribution of a rapidly growing population reflects the fact that there are larger numbers of younger individuals than older ones. Consequently, growing populations have a triangular age-class structure – it is much wider at the bottom than at the top. In fact, almost half of the people in a rapidly growing population are typically less than 15 years old (Table 10.5). This kind of population structure suggests an enormous potential for future growth as increasingly larger numbers of young people mature to reproductive age. This kind of age-class distribution is typical of less-developed countries that have not passed through a demographic transition.

Table 10.5. Age Structure of the Populations of Selected Countries in 2014. Data from Population Reference Bureau (2015).

Country	**Percentage of Population**		
	<15	**15–65**	**>65**
Rapidly Growing Population			
Afghanistan	46	52	2
Bolivia	35	62	3
Iraq	40	57	3
Niger	50	47	3
Tanzania	45	52	3
Relatively Slow or No Population Growth			
Canada	16	69	15
Germany	13	66	21
Japan	13	61	26
United States	19	67	14
World	26	66	8

The growth potential of populations with a triangular age structure is an important demographic fact. It is difficult for populations to stop growing quickly because of this age-class inertia, and it usually takes several generations to pass through the demographic transition. For example, a "young" population (having a triangular age-class structure) might rapidly achieve a replacement fertility rate, at which the number of progeny would only replace their parents (this is equivalent to about 2.1 children per family, which is slightly more than 2 per family to account for the fact that some people are infertile). Nevertheless, a population with a triangular age-class structure would continue to grow for some time, although at a progressively slowing rate of increase. This happens because, for several decades, increasingly larger numbers of people mature to a reproductive age, a circumstance that is related to the initial, triangular age-class structure of the population. Eventually, however, the replacement fertility rate would bring about a stable age-class structure, the demographic transition would be achieved, and there would be zero population growth.

Since 1979, the government of China has enforced a "one-child policy" for most families in the country, which is a fertility rate that is considerably smaller than that which would replace the numbers of parents (about 2.1). This policy is mostly enforced in urban areas, and ethnic minorities are exempt from it. Families that are subjected to the one-child policy may experience intense social pressure to not have more than one child and there are also substantial economic disincentives such as fines and poor educational opportunities for second children. Many parents have been sterilized against their will.

In addition, there is a cultural preference in China for male children because of the prevailing system of inheritance of family lineage and property by the first-born son. This attitude has led many people to give up girl newborns for adoption, and even the abortion of female fetuses and infanticide. These are all disagreeable choices, but many parents have chosen them in order to make another attempt to ensure that the single allowed child is male. Because of female abortion and infanticide, an imbalance has developed in the female to male ratio in the population, which is already having important social implications because many men are having difficulty finding a spouse and starting a family. Already, in 2014, there were 16% more males younger than 20 years in China than females in the same age group.

Some of the population-control measures that occur in China are controversial, and from some points of view they abuse human rights. However, the Chinese government considers such measures to be necessary in view of the enormous population of their country and the further growth that is inherent in its relatively young age-class structure. In other words, in countries where population growth is causing a desperate situation, a vigorous implementation of aggressive population policies seems appropriate.

Distribution of Populations

Another important element of population structure is the spatial distribution of people and this has changed over time. This is a complex topic because the distribution of people varies enormously among countries in different stages of development, and also within countries (for example, there are dense urban populations and much sparser rural ones).

As we previously examined, most of the world's people live in relatively poor, less-developed countries, almost all of which are located in tropical and subtropical regions. Because populations are growing most quickly in those less-developed countries, this pattern of the global distribution of people will become even more pronounced over time (see Figure 10.7). The rapidly growing populations in those countries present enormous challenges to their governments, international agencies (such as the United Nations as well as non-governmental organizations), and more broadly, the sustainability of the global human society and economy. Even today, many of the great masses of poor people in less-developed countries do not have access to equitable livelihoods, or even to acceptable standards of food, shelter, education, health care, and other necessities, not to mention the cultural and entertainment amenities that help to make life a worthwhile experience. Faced with rapidly increasing populations, will these poor countries be able to do better in the future? Will wealthier countries be willing to help them to the degree that is necessary?

Urbanization (the development of cities and towns) is a critical aspect of population distribution. All countries are urbanizing rapidly, and in fact, urbanization is occurring more rapidly than population growth. Increasing urbanization is being driven by a number of interacting factors, the most important of which is the migration of poor rural people to towns and cities in search of employment, services, and cultural amenities. On average, about three-quarters of the population of developed countries are now living in urban environments, compared with one-third of people in the less-developed parts of the world. By 2025, it is expected that the urban population will double to more than 5 billion and 90% of that increase will be in developing countries. Global urbanization represents an extraordinary change in the distribution of people, compared with the essentially agrarian societies of only one century ago, when more than 95% of people lived in rural areas.

The greatest metropolitan areas in the world are known as megacities (having >10 million inhabitants) or as urban agglomerations (large contiguous urban areas). Most of the largest ones are located in developing countries (Table 10.6), a trend that will increase in the future. Note that in the year 1950, the only megacity in the world was New York. This fact highlights the fact that urbanization of the global population during the past several centuries is an extremely important aspect of human history.

Table 10.6. Megacities. These are the largest urban agglomerations in the world, of which 33 existed in 2014. Data are for 2014 (Demographia, 2014).

Urban agglomeration	Country	Population (millions)
Tokyo-Yokohama	Japan	37.6
Jakarta (Jabotabek)	Indonesia	30
Delhi	India	24.2
Seoul-Incheon	South Korea	23
Manila	Philippines	22.7
Shanghai	China	22.7
Karachi	Pakistan	21.6
New York	United States	20.7
Mexico City	Mexico	20.3
Sao Paulo	Brazil	20.3
Beijing	China	19.3
Guangzhou-Foshan	China	18.3
Mumbai	India	17.6
Osaka-Kobe-Kyoto	Japan	17.2
Moscow	Russia	15.9
Los Angeles	United States	15.3
Cairo	Egypt	15.2
Bangkok	Thailand	14.9
Kolkota (Calcutta)	India	14.9
Dhaka	Bangladesh	14.8

Of course, urban people live under densely crowded conditions, and their livelihoods tend to involve work in manufacturing, government, financial institutions, commerce, education, and services (see also Chapter 25). In addition, many urban people depend on social assistance. No cities are self-sufficient in food, energy, or raw materials for building and manufacturing, and few have enough potable water. Urban areas depend on trade with the surrounding countryside and with foreign nations to provide these necessities of life and economy. Urban areas also generate enormous quantities of waste materials, much of which is disposed of in nearby rural areas. The development and maintenance of the complex economic, physical, and social infrastructures required to care for enormous numbers of urban people is an extraordinary challenge for governments, especially in relatively poor countries.

Birth Control

Many individual people and families make conscious choices about their reproduction, including how many children to have. Historically, the available methods of controlling pregnancy were few, unreliable, and sometimes unsafe.

One of the most effective methods of birth control is the avoidance of sexual intercourse before marriage (or before a non-married spousal partnership). This is because society generally accepts that matrimony is a social institution involving a commitment by both parents to care for their children. Avoidance of sexual intercourse affects population-level birth rates by delaying and spacing reproduction. A complementary effect is gained by delaying marriage until relatively late in life, which if accompanied by pre-marital chastity, also delays reproduction and decreases birth rates. Coitus interruptus, or withdrawal of the penis prior to ejaculation, likewise contributes to lower rates of impregnation associated with copulation. This practice has been widely used throughout history. In addition, breast-feeding mothers have a lower probability of conceiving another child, so delaying the weaning of children also helps to space births.

Some birth control practices have long been used, even by hunter-gatherer and early agricultural cultures, particularly when they had to deal with resource crises such as insufficient food. These practices include the following:

- the use of traditional medicines to prevent conception or to induce abortion
- infibulation, or the insertion of pebbles or other objects into the uterus, where they may be retained for years, and prevent the implantation of fertilized ova
- the use of mechanical means of inducing abortion
- infanticide, or the killing of newborn infants
- use of means to raise the temperature within the scrotum, such as wearing a warming pouch, which inhibits sperm production and reduces fertility of the male

The Polynesian culture inhabits islands in the southwestern Pacific Ocean. Perhaps because of the obvious resource constraints associated with living on islands, they were aware of the problems of overpopulation and carrying capacity and practiced several methods of birth control. Prior to the modern era, Polynesians engaged in a subsistence economy, cultivating various crops (notably coconut, sweet potato, taro, and yam), raising pigs and chickens, and hunting fish, marine mammals, and mollusks in shallow waters. Their populations were closed to varying degrees, with no or little immigration or emigration, depending on the isolation of their island homes. On some islands, such as Easter Island, there was likely no exchange of people after the initial colonization.

The methods of population control practiced by the Polynesians included polyandry (in which one woman has several husbands at the same time), non-marriage of men who did not own land, abstention from sex for some time after birth of a child, coitus interruptus, abortion, and infanticide. However, these methods were not always sufficient to prevent population growth. Consequently, the Polynesians are well known for their voyages of colonization, undertaken during times of population pressure. They constructed sea-going outrigger sailing canoes and provisioned them with stores of water, crop plants, pigs, and chickens. Family units then embarked and headed toward the vast Pacific horizon in search of habitable but unpopulated islands. These courageous, extremely risky dispersals allowed some of the population surplus to discover new ecological opportunities, although many unfortunate people must have perished at sea.

Today, people have access to a diversity of methods of birth control that are safer and more effective than most of those available in the past (see In Detail 10.1). Consequently, individuals and families in many countries can now choose from a range of safe and readily available methods of birth control to control their reproduction.

However, the use of birth control raises questions beyond issues that are purely medical and scientific, including many related to religion, ethics, and philosophy. For example, because of beliefs regarding the sanctity of human procreation, the Catholic Church opposes almost all methods of control of conception and birth. So do most fundamentalist Christian, Jewish, and Muslim denominations.

In Canada and the United States, the most contentious method of birth control is abortion. On the one hand, anti-abortionists (also known as "pro-life" activists) contend that abortion violates the sanctity of life and should never be permitted. On the other hand, pro-abortion activists (also known as "pro-choice") argue that a fetus is not a viable life and that each woman living in a free and democratic society should have the right to make decisions regarding her own body and reproduction. The acrimonious debate over abortion has erupted in both legal and illegal demonstrations, including the picketing of clinics and hospitals. Unlawful acts have been committed by radical fringe elements from both sides of the issue, including a few cases of extremists who oppose abortion committing arson and even the murder of physicians and other medical personnel.

> In Detail 10.1. Methods of Birth Control
> The methods listed below vary in their effectiveness in achieving birth control, and all have physiological and psychological drawbacks.
>
> A contraceptive works by preventing ovulation, implantation of ova, or entry of sperm into the cervical canal. Oral contraceptives are most common and have a typical failure rate of less than 1% if properly used (the failure rate is the number of pregnancies per year while using the method, compared with no birth control). Depo-Provera, an injectable hormone, prevents ovulation for three months. The morning-after pill (RU486) is taken within 72 hours of intercourse and is 75-95% effective. These methods are reversible, so conception is possible soon after stopping use.
>
> A spermicide is a chemical that kills sperm and is applied by women by inserting a sponge, foam, jelly, or cream into the vagina. The failure rate is 3-20% (the higher failures are associated with improper use of the method; this also applies to ranges cited for other methods).
>
> An intrauterine device (IUD) is inserted into the uterus, where it prevents the implantation of ova, probably by stimulating an inflammatory response. IUDs have a failure rate of 1-5%. This method is now being used less often because of risks of pelvic inflammation and infertility.
>
> A cervical cap is a mechanical block, inserted by a woman to block access of sperm to the cervix. The failure rate is 3-10%.
>
> A contraceptive diaphragm blocks entrance to the cervix and is used with spermicidal jelly and/or foam. The failure rate is 3-14%.
>
> A condom provides a mechanical barrier that contains the sperm after ejaculation, thereby preventing entry into the vagina. The failure rate is 2-10%.
>
> Douching involves flushing the vaginal area with water (often containing a spermicide) after intercourse. Douching is not very effective because it does not completely remove sperm, so the failure rate is about 40%.

Coitus interruptus (withdrawal) involves the male withdrawing his penis from the woman's vagina prior to ejaculation. This method is not reliable because it runs contrary to powerful sexual urges and because sperm are present in pre-ejaculation fluids emitted from the penis. The failure rate is 9-20%.

Natural family planning includes several methods approved by the Catholic Church that are based on abstinence or on the timing of intercourse according to periods when women have a relatively low fertility. One of these is the rhythm method, which involves the timing of sexual intercourse to avoid days during which the woman is fertile. This method has a high failure rate (13-20%), largely because it is difficult to accurately determine the fertile period.

Vasectomy is a method of sterilization for males. It involves cutting and/or tying the vas deferens, the tube that carries the sperm from the testis before mixing with seminal fluids. This method has a failure rate of less than 0.2%.

Tubal ligation is a method of sterilization for women, in which the oviduct (fallopian tube) connecting the ovary and the uterus is tied, preventing the passage of ova. This method has a failure rate of less than 0.1%.

Abortion involves the use of medication or surgery to terminate a pregnancy before the fetus is viable (meaning before it is capable of living unassisted outside the womb). In much rarer cases, a late-term abortions may occur, even in the third trimester of pregnancy. Abortion is an effective method of birth control and is relatively safe if carried out by qualified medical personnel (although the procedure is not without medical risk).

Abstinence is avoiding heterosexual intercourse.

No birth control – on average, heterosexual intercourse without the use of birth control will result in fertilization and pregnancy about 10% of the time. If pregnancy is not desired, this would correspond to a failure rate of 90%.

Sources: Kane (1983), Solomon et al. (1990), and Leisinger and Schmitt (1994), and Speroff and Darney (2010).

Population Policies

A population policy refers to a larger social strategy that is designed and implemented by a government. Whether or not a country has an official population policy, it does have a population issue. From the perspective of environmental studies, the population problems of less-developed and developed countries are quite different in terms of their characteristics and prospects for effective action through the implementation of a policy.

Less-Developed Countries

As was previously examined, less-developed countries are relatively poor and have not progressed far in terms of industrial and socio-economic development. In addition, their populations are growing rapidly because of a large excess of births over deaths. Under such conditions, unfettered population growth is a huge barrier to the development process – it is an enormous undertaking just to provide the minimal requirements of life to rapidly increasing numbers of people, let alone to achieve the improved standards of living that are expected from socio-economic development.

Although many people migrate from less-developed countries to wealthier ones, there are not enough of those emigrants to make much of a difference in their overpopulated home countries. This is because wealthy countries have tight controls over the numbers of immigrants they are willing to receive, and compared with global population growth, those numbers are relatively small. When they were going through their own demographic transition some 100-200 years ago, the presently developed countries exported much of their surplus population to colonies in the Americas and elsewhere. This option is not available to less-developed countries today. National population policies in less-developed countries must focus on reducing birth rates as quickly as possible so that population growth can be arrested and hopefully even reversed (this is negative population growth, or NPG). Ideally, this would be achieved by educating the populace about the social and economic benefits of smaller families, so that individuals and families would make appropriate choices about reproductive planning and the number of children to have. Also, ideally, there would be ready access to safe and effective means of birth control in support of this kind of enlightened population-level initiative.

In addition, because people who are better off are more inclined to have smaller families, a more equitable distribution of wealth in less-developed countries would contribute greatly to achieving the necessary population goals. For a similar reason, many people and agencies (such as the United Nations Population Fund) support the idea of a transfer of some wealth from developed to less-developed countries. This could include both direct transfers of wealth and relief of much of the foreign-held debt loads of poorer countries.

An effective but less desirable alternative to these sorts of population policies involves coercive initiatives in family planning, such as social and/or economic disincentives to having more than one or two children per family. Forcing people to use family-planning practices infringes on their human rights, even if there are long-term social and environmental benefits. Consequently, coercion presents a social and ethical dilemma for governments. Such actions may, however, prove to be necessary if free choices do not result in sufficient reductions of population growth.

There is also, of course, another alternative, which is easily implemented by all societies and governments. Instead of designing and adopting effective population policies, governments could do little to reduce birth rates, thereby allowing populations to continue to rapidly grow. This would intensify the severe environmental damage already being caused in most less-developed countries, which would further decrease the carrying capacity for people, their economy, and other species. The population and resource crises would then eventually resolve themselves in a natural, biological fashion, as would happen for any species. There would be a catastrophic increase in the death rate – a crash of the population.

Image 10.3. Compared with people living in wealthy countries, the inhabitants of less-developed countries use much smaller amounts of material and energy resources. Therefore, on a per-capita basis, the environmental impacts of poorer people are relatively small. This family is engaged in subsistence agriculture in West Papua

(Western New Guinea), Indonesia. Image: Bill Freedman.

Developed Countries

Developed countries are relatively wealthy, and their average citizens have access to desirable lifestyles compared to the typical conditions in less-developed countries. Moreover, most developed countries have passed through their demographic transition or have substantially done so. Consequently, their natural rate of population growth is relatively slow.

Progress through the demographic transition requires the maturation of new cultural attitudes about appropriate family size and access to effective means of controlling reproduction. As such, population policies in developed countries tend to ensure that people are sympathetic to small-family goals and that they have easy access to means of birth control.

A major issue concerning the population policies of developed countries is the rate of immigration to allow. There are huge numbers of poor people living in less-developed countries who would happily migrate to wealthier ones in search of better economic, lifestyle, and social opportunities. In fact, many economists and politicians believe that this kind of immigration should be encouraged. They believe that it is desirable for developed countries to have a growing population, which would be an increasing marketplace for saleable goods while providing an abundant source of inexpensive labour. In contrast, ecologically minded economists and environmental specialists argue that there are severe limits to this kind of population and economic growth. This is because the relatively intensive lifestyles of the growing numbers of people living in developed countries would require disproportionately increasing amounts of resources, while generating large amounts of wastes. This kind growth is not sustainable for very long.

The characteristically high per-capita environmental impact of people living in wealthier countries integrates closely with population issues. As was examined in Chapter 1, people who are living a resource-rich lifestyle cause a greater intensity of per-capita environmental damage than do typical people in poorer countries. This fact must be recognized in the development of population policies in wealthier countries – their governments must acknowledge that there are limits to the numbers of resource-intensive people that can be sustained within their national boundaries.

Potential Causes of a Population Crash

Environmental scientists have suggested that continued uncontrolled growth of the human population could eventually lead to a population crash. If such a catastrophe were to occur, it would probably be due to one of the following kinds of scenario.

A Pandemic

A population crash could be caused by the emergence of one or more new, deadly, communicable diseases to which humans have little or no immunity. There are historical precedents for such a disastrous pandemic. The best example is the bubonic plague (or black death), which was caused by the bacterium Pasteurella pestis. Bubonic plague is thought to have originally been an endemic disease of a species of wild rodent in Asia, later spreading to rats. Under unsanitary conditions, humans and rats may live in close proximity, which can allow rat-fleas to bite people and spread bubonic plague. The first outbreak of this disease occurred in the early fourteenth century, starting in central Asia and then spreading through Europe. This was an extremely virulent disease with no known cure at the time, and it killed as much as half of some human populations. Around 1320, the population of Europe was about 85 million, but this fell to 60 million by 1400 as a result of bubonic deaths. Today, bubonic plague can be effectively treated with antibiotics, and rat populations are controlled by routine sanitation measures.

Another killer pandemic swept the world in 1918-19, caused by an epidemic of a novel strain of influenza. As many as 20-40 million people died. Other virulent diseases will probably emerge in the future, probably transmitted to humans by close contact with other species, most likely from chickens or primates. A recent example is the Ebola virus, which causes a deadly hemorrhagic (bleeding) fever. It was probably spread to humans from a species of rainforest monkey in west-central Africa. Two other examples are a virulent strain of avian flu, which would likely jump to humans from domestic chickens or ducks, and severe acute respiratory syndrome (SARS), whose origin is believed to be wild carnivores killed as food for people. Some epidemiologists believe that acquired immunodeficiency syndrome (AIDS) also has the potential to cause catastrophic mortality in human populations. AIDS is a slowly developing syndrome that is almost always lethal unless there is access to the right kinds of drugs, which are rather expensive (see Global Focus 10.2). Finally, deadly antibiotic-resistant strains of Staphylococcus and other pathogenic bacteria may have to potential to cause a human pandemic.

So far, medical science has managed to deal with these new, lethal, communicable diseases. However, science may not be able to cope with all of the future pestilences that may arise. If this proves to be the case, there could be catastrophic results for dense, vulnerable populations of modern humans. Such an event could be caused by the emergence of a new virulent pathogen, but it could also be initiated by germ-warfare terrorism, for example, using the anthrax or smallpox germs.

> Global Focus 10.2. AIDS and Population
> AIDS (acquired immunodeficiency syndrome) is a relatively new disease that was first noticed in the late 1970s and was not reported in North America until 1981. Caused by a virus (HIV, human immunodeficiency virus), AIDS results in a syndrome of intensifying sickness and body-wasting that over a period of years can prove lethal in people who harbour the pathogen (who test positive in an antibody assay). AIDS may be transmitted by

transfusions of blood products, from mother to fetus, the sharing of hypodermic needles, and sexual relations (listed in order of decreasing per-incident risk).

In 2013, about 35 million people were living with HIV (Table 10.7). The highest rates of infection are in sub-Saharan Africa, where more than 24 million people are HIV-positive, equivalent to 5% of the adult population. The infection rate is lower in Asia, but is increasing. However, because of programs to reduce the risk of becoming infected, the annual rate of new infections has fallen by about 38% since 2001 (from as many as 3.6 in 2011 to 2.1 million in 2013; UNAIDS, 2014). The reduction of new HIV infections has declined especially in children, by about 52% over that period. The cumulative mortality since the epidemic began is more than 39 million. The number of deaths was as many as 1.7 million in 2013, down from 2.6 million in 2005.

Table 10.7 Numbers of People with HIV/AIDS in 2013 (UNAIDS, 2013, 2014)

Region	Numbers with HIV/AIDS (millions)	Prevalence (%)
GLOBAL	35.3	0.8
Sub-Saharan Africa	24.1	5
South & SE Asia	4.5	0.3
Latin America	1.7	0.4
Eastern Europe & Central Asia	1.7	0.9
North America	1.9	0.6
East Asia	1.1	0.1
Europe, West & Central	0.9	0.2

The death rate of HIV-positive people is relatively low in developed countries, where there is relatively good access to antiretroviral and other drugs that can slow the development of the disease or treat its consequences. Fewer people in less-developed countries have access to those treatments (nor do many poorer people in wealthier countries). In fact, many HIV-positive people in less-developed countries do not even know that they are HIV-positive. Fortunately, this situation in less-developed countries is improving due to assistance programs originating in more-developed ones. In total, about 13 million HIV-positive people had access to antiretroviral therapy in 2013, compared with 5 million in 2009.

Some countries in Africa have been hit especially hard by AIDS. Botswana is one of the worst-hit countries, with 23% of adults being HIV-positive in 2013. AIDS-related mortality will have an enormous effect on life expectancy in that country, which in 2012 was 47 years, compared with 65 years in the absence of AIDS. The huge increase in mortality has enormous implications for social and economic conditions in that country, as is the case of all heavily afflicted countries.

AIDS is a terrible illness that is devastating for afflicted people and their families, and it is already contributing to slowing the rate of increase of the human population. Nevertheless, this medical calamity does not mean that world governments no longer need to develop and implement rational population policies. The human population is still expected to grow substantially from its present huge size. Like population growth, the AIDS epidemic is only partially recognized by most governments, and like population growth, it can be dealt with if appropriate policies are developed and effective actions are taken.

Famine

The specter of famine has been present throughout human history. A famines can be caused by various factors, including an insect outbreak, insufficient rainfall causing drought, excessive precipitation causing flooding, and warfare and other socio-political upheavals. Ancient historical records are full of descriptions of deadly famines in many societies. Some of the most catastrophic famines of pre-twentieth-century Asia and Europe killed hundreds of thousands of people.

However, much greater famines have occurred since the beginning of the twentieth century. For example, as many as 5-10 million people may have starved in the Soviet Union during 1932-1934 as a combined result of drought and social upheaval associated with the forced collectivization of private farms by the communist government. Another famine in West Bengal in 1943 killed 2-4 million people. More recent famines have occurred in various parts of Africa and Asia, usually caused by a crop failure due to drought and other extremes of weather, and often aggravated by the chaos of war or revolution.

Overpopulation exacerbates most factors that contribute to famine. In general, a region or country is vulnerable to famine under the following conditions:

- the population is large and dense
- there are only small reserves of stored food
- the environmental conditions for agriculture are marginal, partly because population pressure has led to land being cultivated in semi-arid regions that are susceptible to drought
- there is little foreign exchange to purchase food from elsewhere during times of shortage, so people and governments must rely on goodwill and aid
- the economic and political systems do not foster the stable governments and social systems that are required for effectively dealing with crisis

Environmental Issues 10.1. Controversy over Population Policies, Family Planning, and Birth Control

Any objective consideration of national and global environmental problems would have to conclude that the rapidly increasing population of humans is a key issue – in general, more people means an accelerating depletion of natural resources, as well as more pollution and damage to biodiversity. Of course, it is not as simple as this because environmental damage is also greatly affected by the lifestyles that people lead, which influences their per-capita use of resources, generation of wastes, and effects on the natural world.

In spite of the obvious importance of actions to reduce the rate of population increase, there is much controversy over policies related to family planning and birth control. A population policy is a strategy that is designed and implemented by a government in order to influence growth of the numbers of people and other demographic factors, such as the age distribution. For example, here are some key elements of provincial or national population policies in Canada:

- encouraging immigration (which has more than double the influence on population growth in Canada than does natural increase; see Chapter 11)
- in particular, encouraging the immigration of younger persons, who have a relatively long lifespan within the working economy and so would help to offset the increased "aging" of the general population
- having more babies – various jurisdictions have enacted pro-natalist policies to encourage larger family sizes, such as financial subsidies and relief from income tax
- ensuring that Canadians have easy access to safe and effective measures of birth control, which allows people to make choices about their reproduction and family size

However, no Canadian government has ever indicated what it considers to be a "desirable" size of the population. In fact, there is a general apprehension among politicians that our regional and national populations must keep growing in order to increase the size of the labour force and the economy, which are viewed as being inherently "good" results from a societal perspective. Although this pro-growth view has not yet generated much controversy, it is arguable that the world does not need increasing numbers of people living such environmentally intensive lifestyles as those of typical Canadians.

In many other countries, however, national leaders view an increasing population as being a clear threat to the sustainability of their economy and to other environmental concerns. China is one such case – its population was 0.55 billion in 1950 and grew to 1.364 billion in 2014, the largest of any country (Table 10.3). Because the Government of China is acutely aware of the economic and environmental risks that are associated with rapidly increasing numbers of people, it has enacted a relatively strong population policy. That policy is substantially founded on allowing people to have easy access to a wide range of effective means of birth control, including abortion, as well as only allowing one child per family (the latter policy began in 1979). This strategy is showing signs of success, and the national population is expected to peak at around 1.4 billion in 2030, and to then have a moderate decline to 1.3 billion in 2060.

However, the one-child policy is intensely controversial because it denies the right of people to choose their family size. Moreover, those who have more than one child may be subjected to strong economic or social penalties, such as a fine or restricted access to schooling, and in early years of implementation of the policy there were cases of coerced abortion or sterilization – all of these consequences may be viewed as being contrary to basic human rights. The case of China's population policy presents a clear dilemma – it reflects the tension between a desire to maintain individual rights and a larger societal goal of a sustainable population.

To varying degrees, there is controversy in all countries over the rights of people to have easy access to effective means of birth control. In Canada, much of the argument is about access to abortion services (see Canadian Focus 11.3). In many other countries, however, other means of family planning are also controversial – in some cases, only abstinence is considered acceptable. This is particularly the case of countries or social communities in which fundamentalist religious views have a powerful influence on public attitudes and governmental policies, including nations in which the dominant religions are fundamentalist versions of Christianity, Hinduism, Islam, or Judaism. This social circumstance could also be regarded as disregarding certain basic rights, such as that of a woman to control her own body and fertility, and that of a family to plan its size. There are varying rationales for the restriction of access to means of birth control in these sorts of countries or communities. In essence, they involve ideas such as natural population increase being mandated by God, while birth control is not, and they are further complicated by the notion that a large population somehow transmutes into increased national power or influence.

It is clear that controversies over population policies, family planning, and birth control are not fully resolvable – they are a societal dilemma. From the environmental perspective, it is crucial that the human population be limited to a size that can be sustained by the capacity of the biosphere to provide resources and assimilate wastes, while also respecting the need to conserve a viable natural world. This goal of sustainability can only be achieved if people have easy access to effective means of controlling their reproduction, and in many cases, the existing policies and laws are in conflict with those sorts of free choices.

Decline of Carrying Capacity

Environmental catastrophists suggest that there could be a collapse in the ecological carrying capacity for the extremely large human population. If that were to happen, widespread starvation would follow. It is already clear that some potentially renewable resources have been exhausted by over-harvesting and that stocks of non-renewable ones are being rapidly depleted (Chapters 12, 13, and 14). Compelling evidence of this phenomenon comes from collapsing fish stocks, deforestation, desertification, depleted groundwater, degradation of agricultural soil, and diminishing stocks of fossil fuels and metals. Large declines of natural resources are a clear signal of a decrease in the carrying capacity of the biosphere for the human enterprise.

A Nuclear Holocaust

Enormous numbers of people have died prematurely through the direct and indirect consequences of warfare. The most lethal conflicts were the First World War, which killed as many as 20 million people, and the Second World War, during which at least 38 million died (Freedman, 1995). Potentially, however, modern humans are capable of killing enormously larger numbers of people through the unbridled use of nuclear weapons. Despite significant reductions since the "Cold War" ended in the early 1990s, the nuclear powers still have enormous arsenals of extremely powerful nuclear weaponry, particularly the United States and Russia. The explosive power of these weapons is immense and capable of causing such extreme damage to the human economy and the biosphere that any surviving people could be returned to a Stone Age existence. Conventional military theory holds that nuclear arsenals are most useful as deterrents against other nuclear-power nations, and recent treaties have resulted in large reductions in arsenals. Nevertheless, the remaining stockpiles are immense and in active service, and it is not difficult to imagine scenarios of political instability and conflict that could lead to a nuclear holocaust. Until all nuclear weapons are beaten into ploughshares, a global nuclear disaster cannot be ruled out.

A Natural Big Bang

Although extraordinarily unlikely, it is conceivable that Earth and its ecosystems could suffer a natural, unpredictable, environmental catastrophe such as a meteorite impact. There are precedents for such a rare event, with clear evidence from the geological record (Chapter 3). For instance, it appears that about 65 million years ago, Earth may have been struck by a meteorite, an accident that caused enormous environmental change and resulted in a mass-extinction event (Chapters 6 and 26). Fortunately, cosmic calamities of such a colossal intensity are exceedingly rare, occurring only every 25-30 million years or so. It is much more likely that any crash that might occur in the human population would be caused by a virulent disease or a collapse of carrying capacity, rather than by a big-bang cataclysm from a meteorite strike.

Conclusions

The human population has been growing exponentially in recent centuries. Additional growth will occur in the foreseeable future, but at decreasing rates. Demographic models suggest that the population will eventually stabilize, but this may happen at a level at least 50% larger than the more than 6 billion people alive today.

Accompanying the growth of the human population has been an even more rapid increase in per-capita environmental impact. In combination, these have changed the biosphere on a scale and intensity that is comparable to the effects of such enormous geological events as full-blown glaciation. The damage includes deforestation, depletion of all kinds of natural resources, pollution, and mass extinction. It is clearly apparent that the cumulative, anthropogenic impacts on the environment will escalate even further with increases in the abundance of people.

A key to decreasing the growth of the human population is to get less-developed countries through their demographic transition, which requires reducing birth rates to a level that balances already low death rates. If this is to happen, a widespread cultural change in favour of smaller families will have to occur, or else governments will have to coerce people to have fewer children. In either case, it will be necessary to provide widespread access to safe and effective means of birth control for all people, but particularly women.

The enormous growth of the human population must be kept in mind whenever environmental problems are considered. To some degree, the environmental effects of people and their economies can be avoided or repaired by technological strategies such as pollution control and the conservation of natural resources. However, the size of the human population remains a root cause of the ecological damage caused by our species.

Questions for Review

1. What are major stages of cultural evolution? How do they relate to changes in carrying capacity and growth of the human population?
2. Explain the demographic transition. Compare its dynamics in developed and less-developed countries.
3. Why is age-class structure so important in future growth of a population?
4. Describe possible reasons why the human population will eventually level off or decrease.

Questions for Discussion

1. What is the recent pattern of growth of the human population? Discuss possible scenarios for future growth.
2. Compare demographic parameters and population growth rates in developed and less-developed countries. What social and economic factors explain the differences?
3. What are the major means of birth control? Discuss controversies associated with their use.
4. What is the likelihood of a human population crash? What are the potential causes?
5. Why is HIV/AIDS more prevalent in poorer countries than in wealthier ones?

Exploring Issues

1. The government of a less-developed country has asked for your help in designing a population policy. You will visit the country for several months to get an appreciation of the socio-economic and environmental problems that exist and to help you understand cultural influences on the design of a population policy. What kinds of studies would you want to make during your visit? What key elements would you recommend for the population policy?
2. The personal choice to use birth control can be difficult and is further complicated by considerations about the various methods that are available. Make a list of the key ethical, social, and economic issues associated with any three methods of birth control (you can select them from In Detail 10.1). Consider both the personal dimensions of choice (personal ethics and views) as well as those relevant to society at large (such as group pressure, whether a particular method is legal, and the ease of access to particular methods).

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Chapter 11 ~ The Canadian Population

Key Concepts

After completing this chapter, you will be able to:

1. Outline changes in the Canadian population over time.
2. Describe the recent populations and demography of the provinces and territories of Canada.
3. Describe the urbanization of Canada.
4. Discuss the desirability of a population policy for Canada.

Introduction

In Chapter 10 we examined the dynamics of human populations in different countries as well as on a global scale. This information provides an international context for the examination of population issues in Canada. Canada ranks among the top 20% of nations in terms of its human population (about 36 million in 2015). Canada also ranks among the wealthiest of nations in terms of per-capita indicators of economic development, use of natural resources, and impacts on environmental quality (see Chapter 1). Because Canadians have an environmentally intensive lifestyle, our country has a much greater impact on Earth and its resources than would be predicted on the basis of its population alone.

Image 11.1. Although population densities are high in Canadian cities (illustrated by this crowd listening to musical buskers in Halifax), they are relatively low in the country as a whole. Most of Canada is not suitable for supporting a large population, mainly because of a difficult climate. Source: B. Freedman.

Because Canada has achieved a relatively high level of economic and social development, it has an opportunity to manage its environmental quality in a sustainable manner. Canada also has a responsibility to control its population growth within sustainable limits. Moreover, because of our privileged and wealthy status, Canada has an obligation to demonstrate a vision of sustainability to other nations, including less-developed countries that are hoping to emulate our achievements. A central element of sustainable development is the implementation of a sensible population policy.

It is important that Canadians become knowledgeable about national and global population issues. If Canadians understand these subjects, they will be sympathetic to population policies that are appropriate within Canada, as well as abroad.

Aboriginal Populations

Around 1000 CE, the Norse explorer Leif Ericsson made several landfalls along the northeast coast of North America. The Norse attempted a colonization, including a settlement at l'Anse aux Meadows in Newfoundland, but that quickly failed. About 500 years later, other European explorers encountered vast regions in the Americas that had previously been unknown to them. They did not, however, find unpopulated lands. In fact, all of the Americas were fully occupied by various indigenous or Aboriginal cultures (consisting of First Nations or Amerindians, plus the northern Inuit). At the end of the fifteenth century, at the time of the voyages of Christopher Columbus and John Cabot, the indigenous peoples of the Americas had an estimated population of about 35 million people. About 30 million of these people lived in South and Central America, and 5 million in North America.

Some of the First Nations had developed advanced cultures and economies, particularly the Aztecs and Maya of Central America and the Inca of South America. These people built elaborate cities that contained great pyramids and other impressive buildings. Their nations were supported by complex physical and social infrastructures. Like cities everywhere, those of the more advanced Amerindian societies relied on the surrounding agricultural landscape to supply food, water, and other resources. Furthermore, taxes were collected from people living in the producing regions to support the rulers, administrators, soldiers, and artisans who were living in the urbanized centers.

The First Nations cultures in what is now Canada were diverse, comprising 12 language groups, some of which had many dialects. Some of the cultures, such as the Huron and Iroquois of the eastern temperate woodlands, were essentially agrarian societies. These people supplemented their agricultural livelihood by foraging for useful wild plants and by hunting deer, birds, fish, and other animals. They lived in grand longhouses in stockaded villages, surrounded by well-tended fields in which they cultivated maize, beans, pumpkin, squash, sunflower, and other crops.

Other First Nations subsisted largely through hunting and foraging lifestyles. The Bella Coola, Haida, Nootka, Tlingit, and related nations of the humid Pacific coast exploited a relatively abundant and predictable resource base, and consequently, they lived in permanent settlements. These people were mostly fishers of salmon, molluscs, and additional coastal resources, supplemented by wild plants, deer, and other terrestrial resources.

Most of the First Nations of the western prairies, such as the Assiniboine, Blackfoot, and Piegan, were semi-nomadic hunters of the enormous herds of bison and other prairie animals that existed at the time. The more northern Athapaskans, Chipewyan, Cree, Dene, and Innu of the sweeping boreal forest hunted caribou, moose, beaver, and waterfowl, and fished for grayling, trout, whitefish, and pike. The Beothuk, Mi'kmaq, and Maliseet of the Atlantic region also hunted moose, deer, and caribou, fished in freshwaters, and gathered shellfish in shallow coastal waters. All of these peoples also gathered wild plant foods when they were abundant. The northernmost Inuit were the most recent Aboriginal migrants to Canada. They subsisted on marine mammals, such as ringed seal, walrus, beluga, narwhal, and even great bowhead whales. They also hunted caribou when those migratory animals were nearby.

Not much is known about the population sizes of these Aboriginal nations of what is now Canada. Estimates are based on assumptions about their lifestyle and the presumed carrying capacity of their habitats. At about the time when the first Europeans came to Canada, the total Aboriginal population may have been about 300,000.

European Contact

The European colonization of the Americas began in the early sixteenth century, following the "discovery" of these lands in 1492 by Christopher Columbus, who was a Genoan sailing on behalf of the Spanish Crown. Columbus was seeking an oceanic passage to the rich spices and silks of China, India, Japan, and Southeast Asia, but he blundered on the Americas, with his first landfalls occurring in what are now the Bahamas, Cuba, and Hispaniola. In 1497, John Cabot, also a Genoan but employed by the King of England, sighted Newfoundland and possibly Cape Breton.

Soon after the arrival of the Europeans, the numbers of Aboriginal people began to precipitously decline. By the end of the nineteenth century, the Amerindian population of North America was only about 20% of their initial 5 million. The most important causes of this calamitous mortality were infectious diseases, particularly measles, smallpox, tuberculosis, and influenzas. Europeans were relatively tolerant of these diseases that they brought to the Americas, but the indigenous peoples were extremely vulnerable. Epidemiologists refer to populations that are hypersensitive to infectious diseases as "virgin fields". Such populations can suffer intense mortality from introduced diseases (known as virgin-field epidemics).

In addition, huge numbers of Aboriginal peoples died as a direct and indirect result of conflicts associated with the European conquest. Others died during inter-tribal wars, some of which were precipitated when competing European nations upset previous balances of power among indigenous groups, in part by providing their Aboriginal allies with advanced weaponry. In addition, many people starved when they were dispossessed of their resources and livelihoods by European colonists and governments. For example, the rapacious 19th-century slaughter of the great bison herds was partly a stratagem to deprive the Plains First Nations of their crucial resource base.

In 1500, there were about 300,000 indigenous people in Canada, a population that subsequently collapsed to perhaps 60,000. The Aboriginal nations of Canada now number about 1.4 million people whose self-identified ancestry is First Nation (or Indian; 852-thousand), Métis (452-thousand), or Inuit (60-thousand) (2011 data; Statistics Canada, 2012).

Early European Immigration

The initial wave of Europeans coming to Canada were mostly French and British adventurers seeking furs, fish, timber, agricultural land, trade, and colonial lands. Compared with their European homelands, which even then were relatively densely populated, Canada represented a great frontier to these colonists, replete with boundless opportunities to develop livelihoods and make money. The fact that these lands were already occupied by Aboriginal cultures did not matter much to the European colonists because the dominant world views of the time were aggressive and imperialist. These beliefs served to legitimize the displacement of indigenous peoples by the technologically empowered Europeans.

Slowly over the first century or so, and then as a great flood of immigration, colonists came to Canada from France and Britain, and later from many other countries. Today, the population is an amalgam derived from a rich diversity of immigrants from virtually all parts of the world, plus descendants of the original Aboriginal cultures.

Between 1500 and 1700, the population of the North American continent increased to about 6 million people. This included about 1 million black slaves, who had been brought unwillingly from Africa to the southeastern colonies to work on plantations. Under laws of the time, slaves were the human property of their "owners," having no personal freedom and few rights. Although people in the northern colonies had few slaves, they did employ large numbers of indentured servants, mostly of European origin, who were bound to their employers by contracts and debts that in many cases were impossible to pay off. Those difficult obligations were not much removed from slavery.

Following this initial phase of colonization, the pace of immigration markedly quickened. Data are not available for the entire period, but between 1820 and 1930 at least 50 million persons of European birth migrated to colonies and former colonies around the world, but particularly to the Americas. This immense human dispersal involved about one-fifth of the population of Europe during the period. The mass migration was stimulated by a combination of factors: rapid population growth in Europe, a shortage of arable land there, famine in Ireland and other countries, and rivalries among the imperial powers to develop empires and dominate world trade. In addition, some religious and ethnic minorities were heavily persecuted in European countries, and this persuaded many of those oppressed peoples to emigrate to North America or elsewhere.

As was noted in Chapter 10, this great 19th and 20th-century dispersal was a critical factor in allowing European countries to have a relatively easy passage through their demographic transitions.

> Canadian Focus 11.1. The Legacy of Daniel LeBlanc and Françoise Gaudet
> In 1650, Daniel LeBlanc emigrated from France to Acadia. He married Françoise Gaudet, also an immigrant, and settled into subsistence farming near what is now Annapolis Royal in Nova Scotia. Many families during that time were large, which was considered a good thing because children helped with the onerous labour of clearing the forest, tending crops and livestock, and taking care of the home and extended family. In fact, fecundity remained high among French Canadians for more than three centuries until the 1950s and 1960s, when birth rates began to plummet.
>
> Daniel and Françoise had seven children – six sons and a daughter. Five of their sons married, presenting Daniel and Françoise with 35 grandchildren. Today, the LeBlanc family has an enormous legacy of descendants, estimated to number more than 300,000 in Canada and the United States (many have the anglicized surname White). The LeBlanc clan is the largest of the Acadian lineages. This extraordinary case demonstrates the awesome power of human population growth.

> Canadian Focus 11.2. A Remarkable Legacy of New France
> The best early demographic data for any area of Canada are for New France. This region encompassed the valley of the St. Lawrence River in southern Quebec, and the Acadian regions of what are now Nova Scotia, New Brunswick, and Prince Edward Island.
>
> The French effort of colonization began in 1604, when Samuel de Champlain led an expedition that settled near Annapolis Royal in the lower Bay of Fundy, followed by another mission that founded Quebec City in 1608. In the early 1600s, there were about 500 French colonists in the region known as New France. In 1663, after a half-century of tentative colonization, a census reported 3,215 people of French origin in Quebec, while another in 1671 found about 400 in Acadia. Most were single men who had journeyed to the Canadian frontier as soldiers, as priests hoping to convert indigenous people to Roman Catholicism, as government administrators, or as adventurers seeking their fortune through the fur trade.
>
> In the following decade, the pace of colonization quickened markedly because of renewed sponsorship by the French government. Many families of settlers arrived from France, intent on developing agriculture in the fertile lowlands of Acadia and along the St. Lawrence River. The immigration of single women was also encouraged to offset a substantial deficit of females in New France. Many of these young women were recruited from Parisian orphanages and were known as les filles du roi. In 1673, there were about 6700 Francophones in New France.
>
> Immigration then greatly slowed because royal sponsorship of emigrants ended and there were also dwindling prospects for finding work in the colonies. French immigration to Acadia ceased when that area was ceded to Britain in 1713, and it terminated to Isle Royale (Cape Breton Island) after the fortress of Louisbourg was lost to a British siege in 1758. Immigration to Quebec then also ended after the British victory at the Plains of Abraham in 1759, which effectively ended the colonization of eastern Canada by France. Population growth after this period was almost entirely due to natural increases, owing to the excess of births over deaths.
>
> Birth rates were high in New France (and elsewhere) during the 18th century, typically about 50-60 per 1000 people in the population. Anecdotal evidence suggests there was great fecundity in early colonial times – one soldier serving under the Marquis de Montcalm is said to have had 250 descendants when he died. Families of

15-20 children were not uncommon. Even though infant mortality was high, particularly from communicable diseases, the population grew quickly.

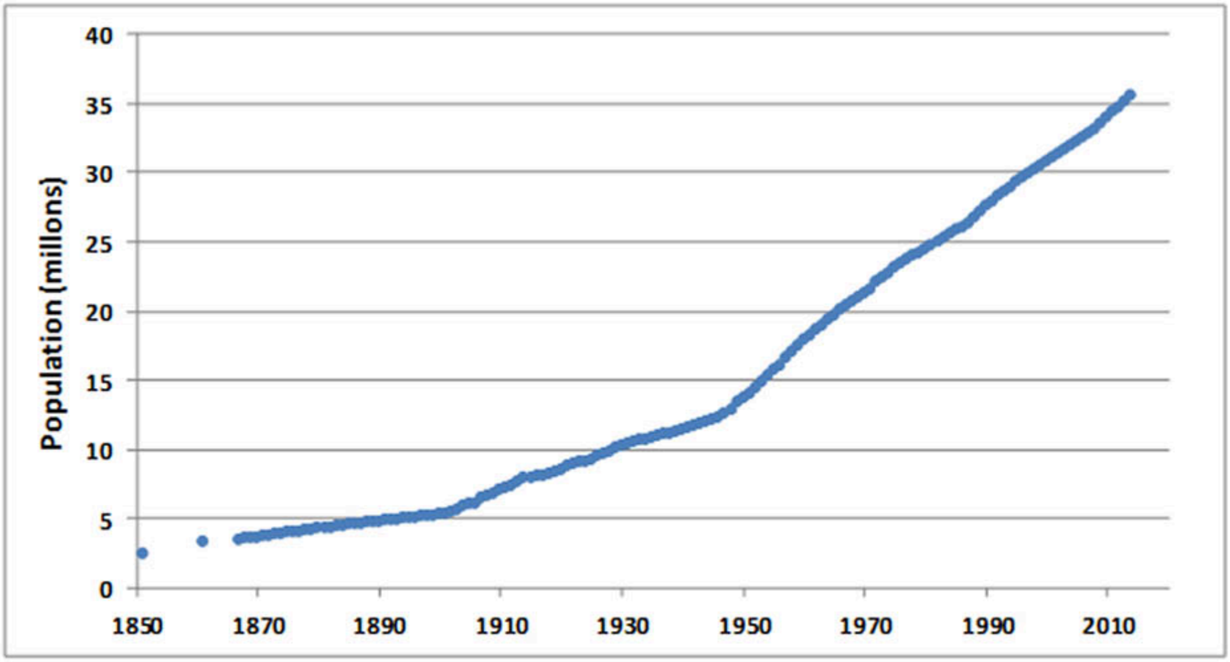
By 1770, the francophone population of Quebec had increased to 86,000. After 1759, all the growth of the French-Canadian population was due to the natural excess of births over mortality, while much of the growth of the non-francophone population was due to immigration. By 1815, the francophone population of Quebec was 269,000 (there were also about 60,000 British colonists), and in 1885, it was 1.18 million (plus 250,000 non-Francophones). During the nineteenth century, the average number of births in Catholic families in Quebec was about seven (this refers to all Catholics, but the great majority of them were French). This high fecundity is typical of populations at the beginning of their demographic transition. It should be pointed out, however, that high fecundity was not unique to Quebec – it was also typical of areas elsewhere in Canada, including Ontario.

In 1926, there were about 3 million Francophones in Quebec, elsewhere in Canada, and in the United States. Almost all of these people were descendants of the original few hundred emigrants from France. At the present time, there are about 6.8 million French Canadians. This includes about 5.9 million Francophones living in Quebec, 300-thousand Acadians, and smaller numbers in other provinces. There are also hundreds of thousands of Americans of French descent, many of whom live in Louisiana and New England.

Population Growth

Reliable information is available describing early population growth in some regions of what is now Canada, notably in the eastern tracts known as New France (see Canadian Focus 11.1 and 11.2). The first credible estimate of the population of all of Canada is for 1851, when there were about 2.4 million people (Figure 11.1). By 1867, the year of Confederation, the population was 3.3 million, and by the turn of the twentieth century it had increased to 5.4 million. Much of the population growth resulted from a natural rate of increase of 1.3-2.0% per year, with birth rates of 36-45 per 1000 people and death rates of 18-21 per 1000. In fact, because of a relatively depressed economy during the first several decades after Confederation, immigrants to Canada were fewer than emigrants.

Figure 11.1. The Population of Canada. In 1851, the Canadian population was about 2.4 million. This graph shows the steady growth of the population up to 2015, when it was 35 million. Data from Statistics Canada (1992, 2014a) and World Resources Institute (2008).

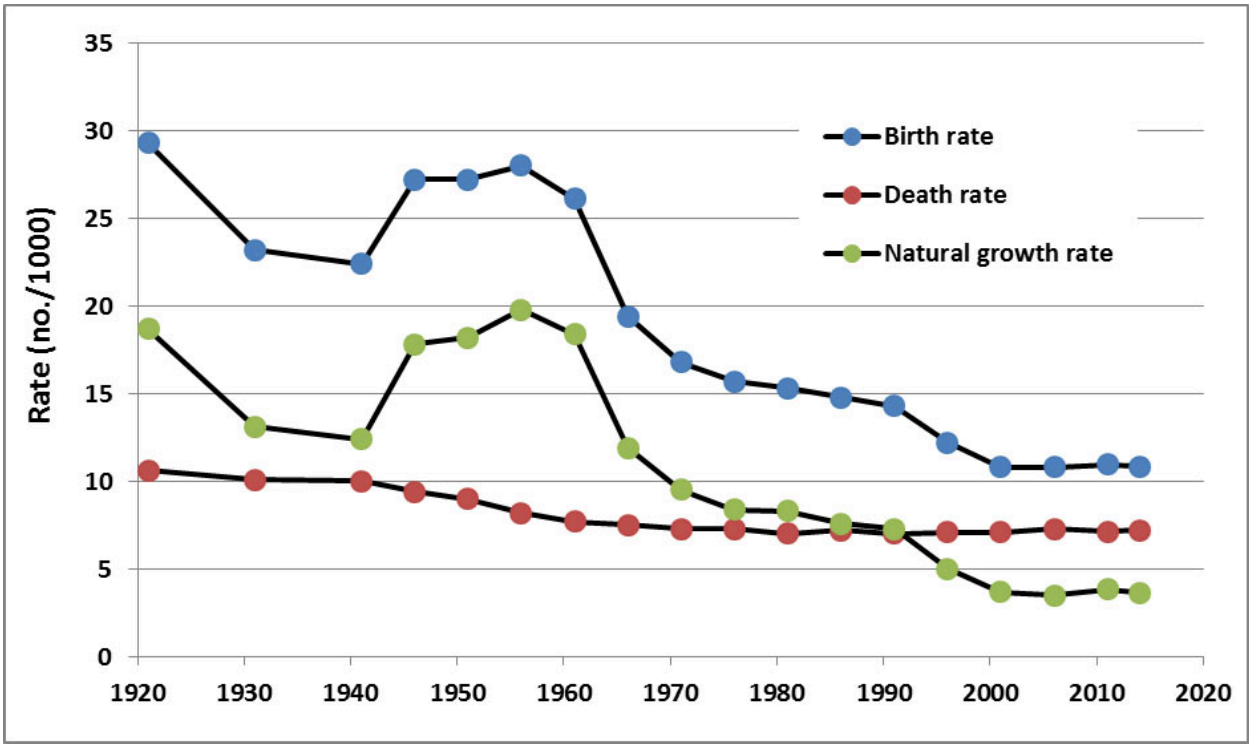


During the 20th century, birth and death rates both declined steadily, although the natural rate of population increase remained greater than 1% per year until the mid-1970s. This natural growth, coupled with vigorous immigration, led to continued rapid increases in the population of Canada. Population growth rates were as high as 3% per year and averaged about 1.6% per year overall. By 1950 there were about 14 million Canadians, and in 2015 more than 35 million.

The natural rate of growth of the Canadian population (birth rate minus death rate) has slowed markedly during the past century (Figures 11.2 and 11.3). This has happened mainly because of rapid decreases in the birth rates, which now almost counterbalance the death rates (which had declined earlier).

Figure 11.2. Components of Natural Growth of the Canadian Population. The data are standardized per 1000 people in the population and are annual rates. Note that an annual growth rate of 10/1000 is equivalent to 1%

per year. Data from Kalbach (1988), Dumas and Belanger (1998), and Statistics Canada (2014a).

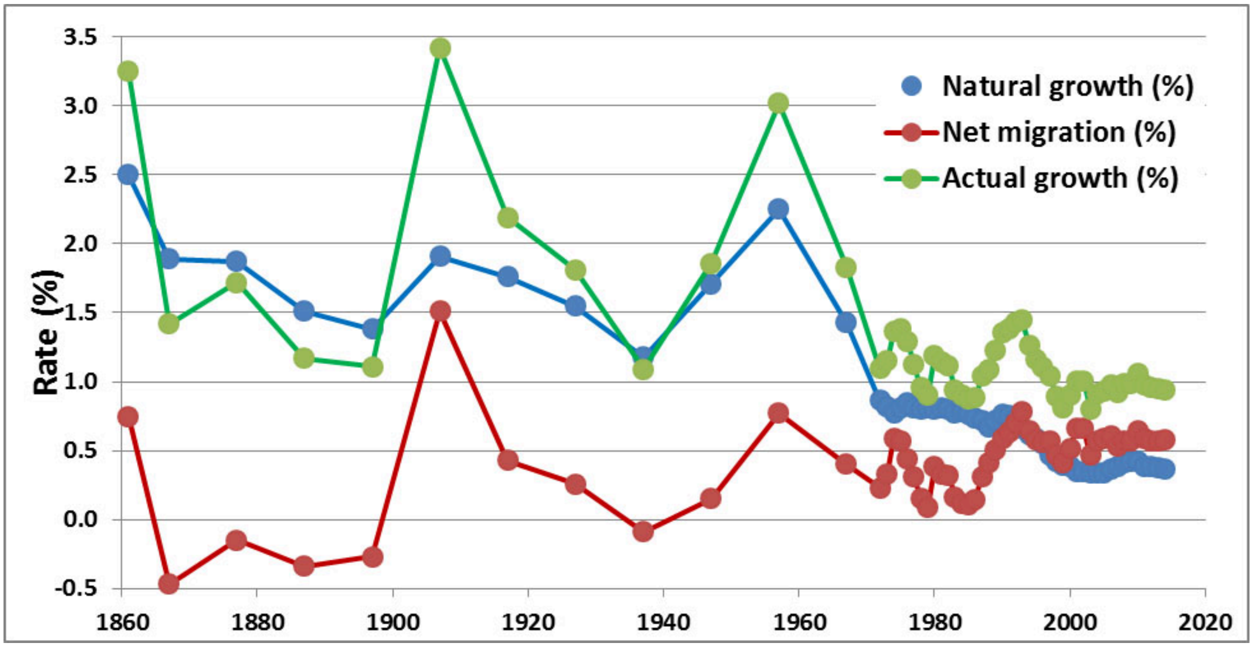


An exception to the general decline in birth rates is a demographic anomaly known as the baby boom, which occurred between the mid-1940s and late-1950s. This period of relatively high fecundity was due to social optimism following the end of the Second World War. In addition, during that War many couples delayed marriage and childbearing because so many young men went overseas to fight, while many women were employed in factories and other wartime occupations. After the war ended, people again turned their attention to having families. During the baby boom, the birth rate averaged about 27 per 1000, and the natural growth rate of the population was 1.9% per year.

An important reason for the end of the baby boom was the growing affluence and urbanization of many Canadians, which led to a general preference to have smaller families. Also important was the increasingly easy access to and social acceptance of methods of birth control. By the year 2014 the birth rate in Canada was 11 per 1000, and the natural rate of increase of the population was 0.36% per year.

Immigration has always been an important factor in the population growth of Canada, as can be appreciated by examining Figure 11.3. During most of Canada's history, considerably more migrants have moved to this country than away from it. The major exception was during the latter decades of the 19th century, when many people emigrated from Canada to the United States and there were brief episodes of negative migration. During the 20th century, however, Canada had consistently high rates of net migration.

Figure 11.3. Population Growth Rates in Canada. Natural growth rates are calculated as births minus deaths, while the actual growth rate also accounts for net migration (immigrants minus emigrants). The data are standardized to the size of the population and are average annual rates. Data from Kalbach (1988) and Statistics Canada (2007a, 2014a).



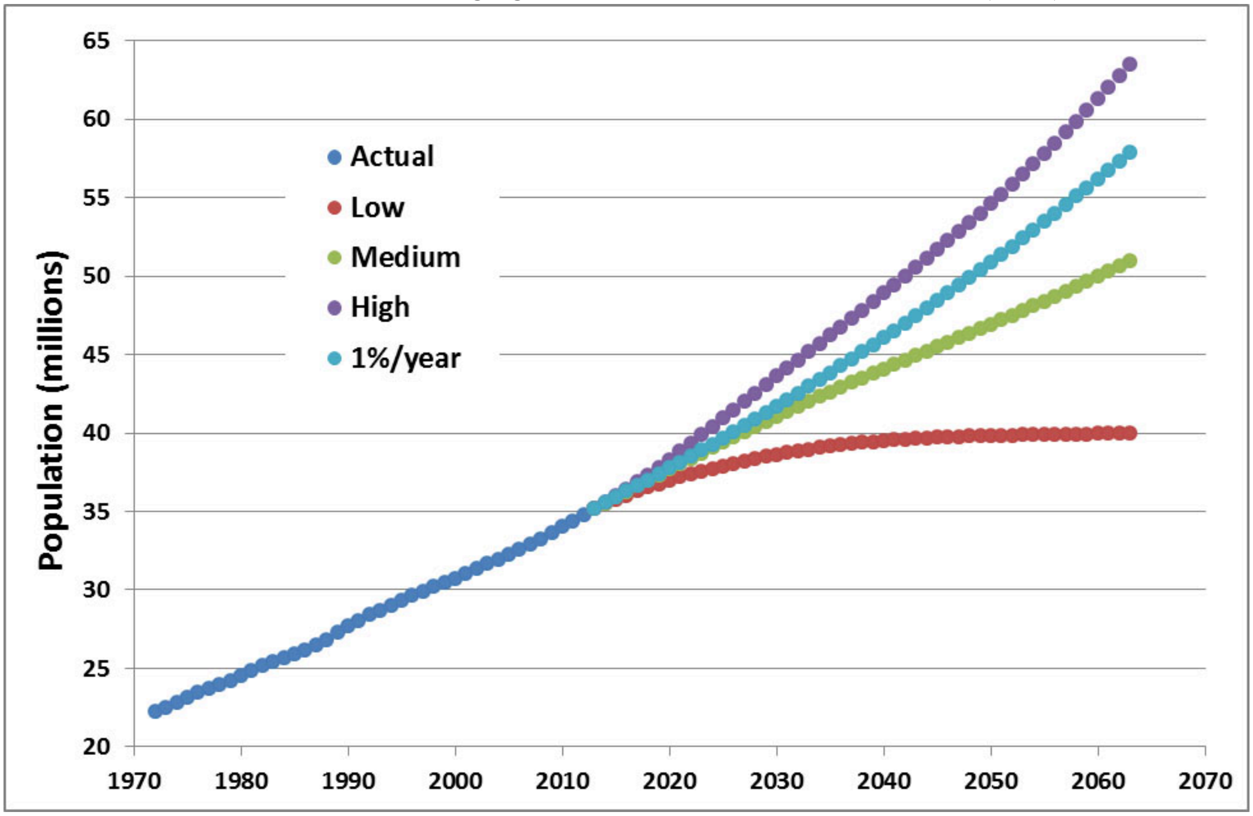
Immigration has been vigorous since the 1960s, when the Government of Canada loosened many restrictions associated with national and ethnic origins of immigrants. These were replaced with criteria based on education, occupational skills, and wealth. Since the early 1970s there has been a substantial increase in the numbers of immigrants. Between 1972 and 1991, an annual average of 144,000 people immigrated to Canada. This was followed by an increase to 243,000 per year during 1996–2001 and 250,000 during 2002-2014.

Since the mid-1980s, net immigration has contributed about half of Canada's population growth rate (the rest is due to natural growth; Figure 11.3). If sustained, the 0.98% per year rate of increase of 2010–2014 would result in the population doubling in only 72 years. This rate of population growth is similar to that of the United States and Australia, which are also relatively wealthy countries with small natural rates of population growth but substantial rates of immigration. These three countries are exceptional: most other developed nations, particularly those of Europe, have much smaller rates of population increase, in part because they do not permit much immigration (see Chapter 10). This can be attributed mainly to higher population densities of European countries in comparison with Canada, the United States, and Australia.

Future Growth

Results of four models of future Canadian populations are summarized in Figure 11.4. Actual population growth is shown from 1972 to 2013, and then four scenarios are presented to 2063. The low-, medium-, and high-growth models are from Statistics Canada (2014), and the fourth is a simple projected based on growth at 1% per year (which has been the rate over about the past decade). All of the scenarios are realistic to some degree because they involve plausible outcomes of either recent trends or reasonably anticipated changes in government policy regarding immigration and demographic issues, as well as reproductive choices made by families. Overall, the models predict that the population of Canada will grow substantially from its 2015 value of about 36 million. The slow-growth model project a population of about 40 million in 2062, compared with 51 million in the medium-growth, 64 million in the high-growth, and 58 million in the 1% per-year model. Clearly, the population of Canada is likely to experience a large amount of growth over the next half-century or so.

Figure 11.4. Recent and Projected Canadian Populations. The low-growth model is based on lower rates of fertility and immigration than occur at present. The high-growth model is based on higher rates of fertility and immigration, while the medium-growth model is between those two. The 1% per year model is based on a compounded calculation based on the typical rate of population increase that has occurred over the past decade. Data for the low-, medium, and high-growth models are from Statistics Canada (2014b).



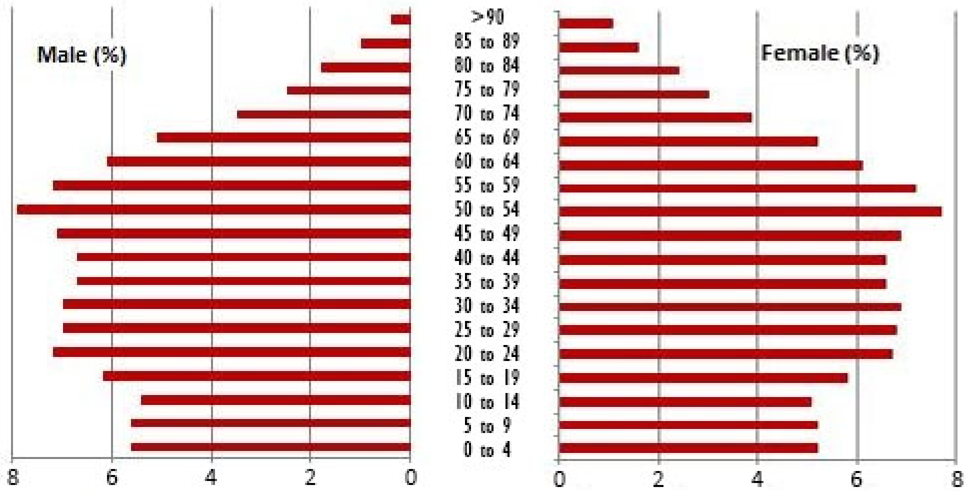
Population Structure

The age structure of the Canadian population is illustrated in Figure 11.5. In general, the pattern is typical of a population that has progressed most of the way through its demographic transition. Note, however, the anomalous bulge of numbers that corresponds to the baby boomers. Fecundity dropped in Canada after the baby boom, and once this bulge has worked its way through the population structure, the age distribution will assume a more uniformly vertical shape. As the baby boomers age and retire from work, they are expected to exert significant strain on Canada's capacity for providing social and medical care for its elderly citizens.

Although Canada has a population structure characteristic of a country that has almost completed its demographic transition, the growth rate remains relatively high, at about 1% per year. Much of the population growth is due to immigration. Although this factor is not related to age-class structure, it is notable that relatively young people of childbearing age are prominent among immigrants to Canada. This adds further momentum to population growth.

Figure 11.5. Age Structure of the Canadian Population in 2014. This diagram shows the relative numbers of people by age. The demographic "bump" of people peaking at about 55 years old corresponds to a period of

high birth rates that occurred in the post-war 1940s to early 1960s, known as the baby boom. Source: Data from Statistics Canada (2014c).



Regional Differences

All regions of Canada have experienced substantial population growth during the past century (Table 11.1). During the past several decades, however, the increases have been most rapid in Alberta, British Columbia, Ontario, and Saskatchewan. In 1867, the Atlantic Provinces accounted for 21% of the Canadian population, while Quebec was 32%, Ontario 44%, and the rest of the country 3%. At that time the western regions were largely unsettled, but tremendous population growth has since occurred there. The Atlantic Provinces now account for 7% of the Canadian population, Quebec 23%, Ontario 39%, the Prairie Provinces 18%; British Columbia 13%, and the three territories 0.3% (Table 11.2).

Table 11.1. Regional Distribution of the Canadian Population. These data show the growth of the population of Canada and its regions since Confederation in 1867. Note that data for the Prairie Provinces prior to 1901 include only Manitoba. Data for Alberta, Saskatchewan, and Yukon were combined with the Northwest Territories until 1901, when they became separate political units. In 1949, Newfoundland joined Canada. Data are in thousands of people. Data from Statistics Canada (1992, 2014d)

Year	Canada	Atlantic Provinces	Quebec	Ontario	Prairie Provinces	British Columbia	Territories
1867	3,466	726	1,123	1,525	15	32	45
1891	4,833	880	1,489	2,114	153	98	99
1911	7,207	938	2,006	2,527	1,327	393	16
1931	10,375	1,008	2,874	3,431	2,354	694	14
1951	14,001	1,618	4,056	4,598	2,549	1,165	25
1971	21,962	2,083	6,138	7,849	3,597	2,240	55
1991	28,031	2,370	7,065	10,428	4,705	3,373	90
2001	31,021	2,348	7,397	11,898	5,208	4,078	99
2011	34,342	2,369	8,001	13,264	6,090	4,499	113
2014	35,540	2,370	8,215	13,679	6,529	4,631	110

Table 11.2. Population by Province and Territory in 2014. Data are in thousands of people. Data from Statistics Canada (1992, 2014d).

Province	Population	% of Canada
Ontario	13,678	38.5
Quebec	8,215	23.1
British Columbia	4,631	13
Alberta	4,122	11.6
Manitoba	1,282	3.6
Saskatchewan	1,125	3.2
Nova Scotia	943	2.7
New Brunswick	754	2.1
Newfoundland & Labrador	527	1.5
Prince Edward Island	146	0.4
Northwest Territories	44.6	0.1
Yukon	36.5	0.1
Nunavut	36.5	0.1

The highest rates of natural population increase (births minus deaths) occur in Nunavut (1.9%/year), the Northwest Territories (1.4%/y) (Table 11.3). In those territories, the populations are dominated by persons of First Nations and Inuit communities, which tend to have relatively large families and a higher rate of population growth. Those territories also have the lowest mortality rates, largely because of their comparatively young populations. People younger than 15 years comprised 30% of the population of NU and 21% of NWT in 2014, compared with a national average of 16% (Statistics Canada, 2014g). Overall, the age structure and growth rates of these territories is comparable to regions that are only beginning to pass through their demographic transition, and in that sense, they are anomalous with the rest of Canada.

Table 11.3. Demographic Parameters by Province and Territory. Data are per 1,000 people in the population and are annual rates (for 2014; note that a value of 10 per thousand per year is the same as 1% per year). Data for total increase include net migration. Fertility rate is the average number of births per woman aged 15-49 (in 2011). Data from Statistics Canada (2014e,f).

Province	Birth Rate	Death Rate	Natural Increase	Net Migration	Total Increase	Fertility Rate
Canada	10.9	7.2	3.7	5.8	9.5	1.6
Ont.	10.4	7.1	3.3	5.5	8.8	1.5
Que.	10.7	7.4	3.3	5.2	8.5	1.7
B.C.	9.4	7.1	2.3	5.3	7.6	1.4
Alta.	13.7	5.6	8.1	8	16.1	1.8
Man.	12.7	8.2	4.5	10.9	15.3	1.9
Sask.	13.7	8.6	5	10.2	15.2	2
N.S.	9.1	9.5	-0.4	1.6	1.2	1.5
N.B.	9.1	9.1	0	2.5	2.5	1.5
N.L.	8.4	9.2	-0.8	1.7	0.9	1.5
P.E.I.	9.7	8.9	0.8	9.3	10.1	1.6
Y.T.	10	5	5	6.3	11.3	1.7
N.W.T.	19.1	5.4	13.7	3.4	17.1	2
Nunvt.	24.5	5	19.4	0.6	20	3

Alberta, Manitoba, and Saskatchewan have the fastest population growth rates among the provinces, averaging 1.6% per year (2014), which is equivalent to a doubling time of only 45 years. This rapid rate of population increase occurs in spite of a relatively small natural rate of population increase. Obviously, the populations of these provinces are growing because of high rates of immigration from other countries and from other regions of Canada.

The population of Canada is much denser in southern parts of the country, and especially in urbanized areas (Figure 11.6). This pronounced spatial pattern reflects the distribution of economic opportunities in Canada, most of which are related to urbanization, climate, and suitability of the land for agriculture.

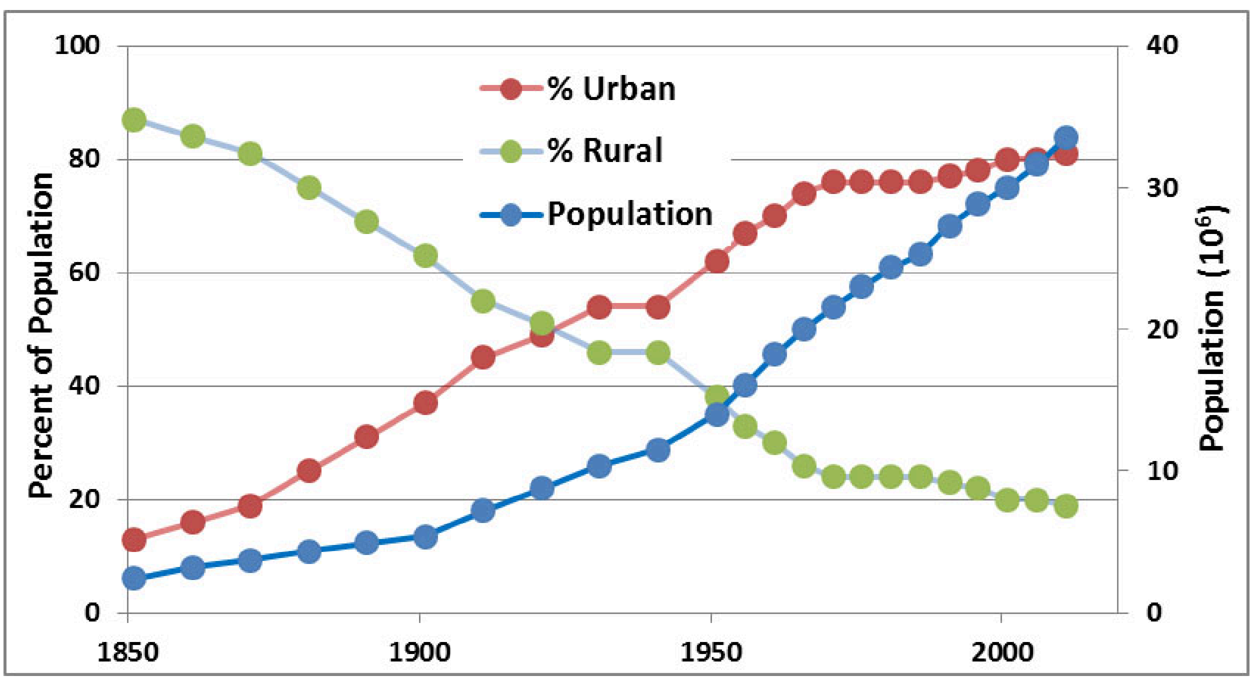
Figure 11.6. Population density in Canada. The areas marked in red account for 75% of the population, while those in light-orange account for almost 25%. The area in white, which accounts for about 99% of the area of

our country, holds less than 1% of the population. Map modified from Natural Resources Canada (2012).

Rural and Urban Populations

Until the latter half of the twentieth century, most Canadians lived in rural environments where they worked in agriculture and other country livelihoods. The proportion of Canadians living in the countryside has steadily decreased, from 87% in 1851 to 19% in 2011 (Figure 11.6).

Figure 11.7. Rural and Urban Populations in Canada. The total population (millions of people) and the percentage distribution of urban and rural Canadians are presented. The definitions of "rural" and "urban" have varies over time, but recently rural has meant people living outside populations centres smaller than 1,000 and outside areas with more than 400 persons/km^2. Data from Statistics Canada (2014h).



In large part, this mass migration of people to urban areas has been caused by the mechanization of much of the routine labour in agriculture, fishing, forestry, mining, and other rural industries. In earlier times, most of this work was performed by humans or draft animals, but their muscle power has largely been replaced by various kinds of machinery. As a result, many fewer Canadians are employed in the rural economy, even though the financial value of the outputs from these sectors has increased greatly over time. The displaced rural people have moved to the towns and cities of Canada, where they earn their livelihoods in manufacturing, financial and service industries, commerce, government, and education.

As time passes, urban Canadians are living in increasingly larger centres of population. In 1871, only 2.9% of Canadians lived in centres with a population greater than 100-thousand people. In 2011, 63% of Canadians lived in the 20 largest cities in the country (Table 11.4), even though these metropolitan areas account for only 0.6% of the country's landmass. In fact, 35% of Canadians live in the three largest cities.

Table 11.4. Cities of Canada. The populations of the 20 largest metropolitan areas of Canada, in decreasing order of population (in 2011). Percent increase refers to growth over the period 1971 to 2011. Data from Statistics Canada (1997, 2014i).

	Population (thousands)		Increase
City	**1971**	**2011**	**(%)**
Toronto, ON	2,628	5,583	112
Montreal, QC	2,743	3,824	39
Vancouver, BC	1,082	2,313	114
Ottawa-Gatineau, ON-QC	603	1,236	105
Calgary, AB	403	1,214	201
Edmonton, AB	496	1,160	134
Quebec, QC	481	766	59
Winnipeg, MB	540	730	35
Hamilton, ON	499	721	44
Kitchener-Cambridge-Waterloo, ON	227	477	101
London, ON	286	475	66
St. Catharines, ON	303	392	29
Halifax, NS	223	390	75
Oshawa, ON	120	356	197
Victoria, BC	196	345	76
Windsor, ON	259	319	23
Saskatoon, SK	126	261	107
Regina, SK	140	211	51
St. John's, NF	132	197	49
Sherbrooke, QC	–	191	-

Population Policy

Most government planners, politicians, and leaders in business do not consider Canada to be overpopulated. In fact, they more typically believe that Canada is underpopulated and capable of comfortably absorbing considerable growth of its population. This view is debatable in view of the relatively intensive lifestyles of Canadians (which is typical of people living in developed countries) and the correspondingly large per-capita environmental impact. Nevertheless, continuing the population-growth paradigm is the predominant way of thinking among decision makers in Canadian governments and businesses. Consequently, Canada and its regions do not have well-developed population policies, other than those that establish targets and guidelines for the numbers and types of immigrants that will be allowed into the country.

In addition, Canadian governments have not encouraged other countries to develop their own population policies, especially those that are less-developed and have rapidly growing populations. Canadian governments also do not provide significant aid to those poorer countries to help them increase the availability of birth control. By not becoming involved in the population problems of less-developed countries, our governments avoid potentially high-profile controversy. However, this attitude contributes little to dealing with the global increase of the human population.

Governments within Canada also lack policies to encourage their citizens to have smaller families as a means of slowing the growth of national or regional populations. In fact, Canadian governments more typically pursue policies that are pro-natalist. This has been true of the government of Quebec, which in recent times has provided cash payments to women based on the number of children they have, and had provided daycare at greatly subsidized costs to parents. In addition, all provinces and the federal government provide substantial income-tax breaks to parents based on the number of children they are supporting. These tax benefits are intended to help lower-income families with the costs of child-rearing, but they can be interpreted as a pro-natalist aspect of the income-tax system.

Image 11.2. People living in wealthy countries, such as Canada, use resources intensively and therefore have a high per capita environmental impact. This is a view of the Eaton Centre in Toronto. Source: B. Freedman.

However, governments in Canada do permit their citizens to choose freely among a wide range of safe and effective birth control options. But this is not to say that all birth control methods are freely available across the country. For example, the governments of Prince Edward Island and New Brunswick restrict access to abortion by not funding services provided by private clinics, and in Nunavut there are no hospitals or clinics providing abortion. Consequently, many women must travel to another province, or even to the U.S., to have access to this medical service. Similarly, reproductive and family-planning education in schools varies considerably across Canada, and is often lacking in the comprehensiveness of its curriculum.

As was discussed in Chapter 10, abortion is an extremely contentious issue in Canada and elsewhere. The controversy has resulted in many public demonstrations and confrontations between pro-life (anti-abortion) and pro-choice (pro-abortion) groups. In a few instances, the patrons and personnel of abortion clinics have been illegally harassed or assaulted, and clinics have even been firebombed. In the 1990s, there were three cases of doctors who had provided abortion services being shot (in Ancaster, Vancouver, and Winnipeg), and in 2000 another was stabbed at his clinic (Vancouver).

Nevertheless, although abortion and other means of birth control remain controversial issues, Canadians who desire to control the number and spacing of their children do have relatively easy and inexpensive access to safe and effective means of birth control. While most Canadians take responsible advantage of this opportunity, it is not comparably available to most people in the world. Consequently, the natural rate of population increase in Canada is relatively small, while it is high in almost all poorer countries.

Moreover, immigration is a key contributor to population growth in Canada. It is well known that, other than descendants of its original Aboriginal peoples, Canada is almost entirely populated by immigrants and their offspring (accounting for about 97% of the total population). Canada has always had a relatively open immigration policy, and this continues today. In 2013, Canada admitted 259-thousand immigrants (permanent residents) from more than 200 countries, including 24-thousand refugees, equivalent to about 0.8% of the national population (Citizenship and Immigration Canada, 2014). The top source countries of immigrants were the Philippines (14%), China (12%), and India (10%). The overall population growth of Canada is about 1% per year, and net immigration accounts for about 60% of that growth. If not for its rather vigorous immigration rate, Canada would be close to a ZPG (zero population growth) condition.

There has always been some controversy over the immigration and refugee policies of Canada, as is true of all countries. Newcomers have contributed enormously to the economic development and cultural diversity of Canada – they have helped to make the country an interesting and prosperous place to live. These benefits must, however, be balanced against some of the downsides of continuing to have relatively open immigration policies, because of their contribution to rapid population growth. It is obvious that any population policy to reduce the rate of population growth in Canada must deal with the numbers of immigrants that the country accepts.

> Canadian Focus 11.3. Birth Control and the Issue of Abortion.
> The key reason for the growth of the human population has been a precipitous reduction of mortality rates, due to great improvements in sanitation and medical science. The most desirable way to slow population growth is to reduce the birth rate – it would never be acceptable to increase the death rate! Various family-planning options are available (see Chapter 10), including abstinence, the use of ways to prevent conception (birth-control pills, condoms, diaphragms, intrauterine devices), sterilization (vasectomy of the male or tubal ligation of the female), and termination of a pregnancy by abortion. All of these methods can result in safe and effective birth control, allowing parents to plan the size of their family and the spacing of births. Such choices generally result in smaller family sizes, and so contribute to decreased population growth.
>
> However, all of these methods of birth control are controversial to varying degrees. As a result, powerful interest groups, including major religions, have steadfastly opposed the use of some of the most effective

methods of birth control. This dispute is a critical impediment to family planning, and to the implementation of effective population policies.

Abortion is, by far, the most contentious method of birth control. Many people view abortion as the taking of a human life, while others regard this medical procedure as a safe means by which a woman can choose to terminate an unwanted pregnancy. The situation is sometimes described as pitting the right to life of the fetus against the right of the mother to control her body and make decisions about her own life and lifestyle. Although both positions may share concerns about preventing unwanted pregnancies, the highly polarized views on abortion are essentially irreconcilable and so there is intense controversy. In Canada, the medical procedure of abortion is no longer a crime, but anti-abortion groups have continued to picket in public places, including hospitals and clinics where the service is provided. Most of the protest actions have been peaceful, but a few have not. There have been cases of violence in Canada and the United States, including arson and bombing of clinics, and physical attacks on doctors and other personnel involved with providing abortion as a medical service.

Henry Morgentaler is the most famous crusader for access to abortion services in Canada. He has been prosecuted several times under provisions of the Criminal Code that had effectively banned abortion services outside of a framework for access decisions in public hospitals. (The consent of a committee of doctors was required before an abortion could be provided, but some hospitals did not have such a committee, and some provinces did not allow them to be formed.) However, Morgentaler was never convicted by a jury of any of the charges laid against him (in four trials). Eventually, in 1988, ruling on an appeal by the Crown of a Morgentaler acquittal, the Supreme Court of Canada struck down the criminal code provisions as contravening the Charter of Rights and Freedoms, based on the lack of access for many women to abortion services in hospitals. That decision effectively legalized the availability of the medical procedure in Canada. In 2011, about 92.5-thousand abortions were reported in Canada (60% in private clinics; CIHI, 2014).

Although Henry Morgentaler has been a highly polarizing force within Canadian society, in July 2008 he was awarded the Order of Canada. This highest available and prestigious civilian honour was given in recognition of his notable contribution to Canadian society. Not surprisingly, the award was controversial.

An important context of the abortion debate is whether women, particularly those living in isolated regions and in poorer countries, should have reasonable access to alternative means of family planning (including birth-control drugs, condoms, and intrauterine devices). Many people believe that a successful population policy requires the education of women about health and reproductive issues, while ensuring that they have access to safe and effective means of birth control. The education of men to take responsibility for pregnancy is also crucial. However, in most cultures and circumstances, women have traditionally had the primary responsibility for pregnancy and childcare.

In addition to family planning, birth control, and abortion, some new issues related to human reproduction are also creating controversy. These include advances in reproductive technology leading to artificial insemination, test-tube babies, and cloning. Social changes, such as the acceptability of same-sex couples, are also altering the traditional allocation of childcare responsibilities.

Population issues are controversial, and they are uncomfortable for many people to examine and discuss in an objective manner. Yet they are too important to ignore, because sustainable economies will never be developed unless the population of humans is controlled.

Selected Web Resources Lifesite Canada, https://www.lifesitenews.com/ (a pro-life web site) Feminist Majority Foundation, https://feminist.org/ (a pro-choice web site) United Nations Population Fund, http://www.unfpa.org/

Conclusions

At the time of its "discovery" by European explorers, about 300-thousand Aboriginal people were living in what is now Canada. The Aboriginal population then collapsed due to the effects of introduced diseases, warfare, and social disruption, but it has now increased to more than 1 million. The colonization of New France began in 1604 but totaled only a few thousand immigrants; however, the descendants of these people today number more than 7 million. Immigration of English and other Europeans also began in the 17th century and continued to the present, to be joined in the 20th and 21st centuries by migrants from all parts of the world. Today, the population of Canada is more than 35 million and it continues to increase at about 1% per year, which is sufficient to double its size in another 70 years.

Questions for Review

1. How did the population size of Aboriginal people in Canada differ before and after the European colonization?
2. How have recent trends in population and growth rates differed among the provinces and territories of Canada?
3. What are the relative importance of birth rate, death rate, immigration, and emigration to the population growth in the province or territory where you live?

Questions for Discussion

1. How has the growth of the Canadian population changed over time? Discuss the factors influencing growth during the past several decades and those that will likely influence it into the near future.
2. Compare the age-class structure of the Canadian population with that of a less-developed country. Explain the differences.
3. What are the basic elements of the population policy of the government of Canada? Do you think they should be changed? If so, which aspects should be changed?
4. Do you consider Canada to be underpopulated or overpopulated? Explain your reasons.

Exploring Issues

1. Assume that the government of Canada is worried about the "aging" population and is thinking about implementing pro-natalist policies (such as giving money to parents who have additional children) as well as increasing the rate of immigration. You are a prominent environmental specialist and have been asked to make a presentation to a House of Commons committee that is considering these issues. What arguments would you use to convince the politicians that an increase in the rate of population growth is not desirable?
2. The decision whether to have children and how many is complex. Make a list of the "benefits and costs" of having a child and how these change with increasing family size. Consider the personal benefits and costs (such as the satisfaction of nurturing children, and the cost of purchasing clothing) as well as those shared with society (such as medical and education costs).

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PART IV: NATURAL RESOURCES

Chapter 12 ~ Resources and Sustainable Development

Key Concepts

After completing this chapter, you will be able to

1. Explain the differences between renewable and non-renewable natural resources.
2. Outline the ways that appropriate management practices can increase the harvest of biological resources.
3. Describe at least two case studies of the degradation of potentially renewable resources and explain why those damages occurred.
4. Distinguish between economic growth and economic development and outline the nature of a sustainable economy.

Introduction

For about five decades now, we have been able to examine photographs of Earth as viewed from space. Images from that perspective show that Earth is a spherical mass, with a blue oceanic surface, brownish-green landmasses, and a clear atmosphere except where visibility is obscured by whitish clouds. Such images also reveal that beyond Earth and its atmosphere is the immense, black void of space – an extremely dilute, universal matrix. If we divert our attention from this compelling image of spaceship Earth and focus instead on the unimaginably larger abyss of space, we cannot fail to be stirred by the utter isolation of our lonely planet, the only place in the cosmos that is known to sustain life and ecosystems.

With such a lucid image of Earth in mind, it is not difficult to understand that the resources necessary to sustain life are limited to those already contained on the planet. That is, with one critical exception – the electromagnetic radiation that is continuously emitted by the Sun. A tiny fraction of that solar energy irradiates Earth, warms the planet, and drives photosynthesis. With the exception of sunlight, however, Earth's resources are entirely self-contained and finite.

It is an undeniable reality that all organisms must have continuous access to resources obtained from their environment. Plants and algae, for example, require sunlight and inorganic nutrients, while animals and heterotrophic microbes must feed on the living or dead biomass of other organisms. Because their organisms must be nourished by environmental capital, the concept can also be extended to ecosystems in their totality. The necessary resources must be available in at least the minimal amounts needed to sustain life, and in larger quantities in ecosystems that are increasing in biomass and complexity, as occurs during succession.

The same reality holds for individual humans, our societies, and our economic systems. All people and their enterprises are subsidized by the harvesting of resources from the environment (including those taken from ecosystems). These necessities must be available in the minimal amounts needed to sustain human life, and in much larger quantities in economic systems that are growing over time. An obvious conclusion is that economic and ecological systems are inextricably linked. Indeed, this is an undeniable fact.

The main connections between economic systems and the natural world involve flows of resources from the environment (including ecosystems) into the human economy, and offsetting flows of disused materials, by-products, and heat (these are sometimes referred to as wastes) from the economy back to the environment. Associated with these interchanges of materials and energy are many kinds of damage caused to natural and managed ecosystems. The damages may be caused by disturbances associated with harvesting natural resources, by emissions of pollutants, and by other stressors related to anthropogenic activities, especially those occurring in heavily industrialized economies.

An ultimate goal of environmental studies to understand how the use of natural resources and changes in environmental conditions are related to a sustainable economic system and to the quality of human life. Ultimately, a sustainable economy is one that runs forever, and that operates without a net consumption of natural capital – the rates of resource use are equal to or smaller than the rates at which the resources are regenerated or recycled. This definition focuses on the resource-related aspects of sustainability. Also important, however, are environmental damages that may be caused by the extraction and management of natural resources. The social context must also be considered, particularly the ways that wealth is shared among the people who are participating in an economy.

In this chapter, we examine the broader issues related to the use of natural resources in economic systems. Initially, we examine the characteristics of non-renewable and renewable resources. Non-renewable resources are finite, do not regenerate, and therefore are diminished by use. In contrast, renewable resources can regenerate and may be managed to maintain or increase their productivity, and we describe practices that foster those goals. This is followed by an investigation of the reasons for a catastrophic but remarkably common phenomenon – the depletion of potentially renewable resources through excessive use. Finally, we consider the notion of sustainability, a topic that is critically important to the long-term health of both economic and ecological systems. This chapter deals with natural resources in a conceptual manner; Chapters 13 and 14 investigate the actual use of resources in the international and Canadian economies.

Natural Resources

All natural resources (also known as natural capital) can be divided into two categories: non-renewable and renewable.

Non-Renewables

Non-renewable resources are present in a finite quantity and do not regenerate after they are harvested and used. Consequently, as non-renewable resources are used, their remaining stocks in the environment are depleted. This means that non-renewable resources can never be used in a sustainable fashion – they can only be "mined." Examples of non-renewable resources include metal ores, petroleum, coal, and natural gas.

Although continuing exploration may discover additional stocks of non-renewable resources that can be exploited, this does not change the fact that there is a finite quantity of these resources present on Earth. For example, the discovery of a large amount of metal ore in a remote place may substantially increase the known, exploitable reserves of those non-renewable materials. That discovery does not, however, affect the amounts of the metal present on Earth.

Metals are often used to manufacture parts of buildings and machinery. To some degree, the metals can be recovered after these uses and recycled back into the economy, effectively extending the lifespan of their reserves. However, due to the growth and increasing industrialization of the economy, the demand for metals is accelerating. Because recycling cannot keep up with the increasing demands for metals, large additional quantities must be mined from their known reserves in the environment. For valuable metals, such as gold and platinum, there is a high efficiency of recycling, but it is much less so for iron and other less-costly metals.

Fossil fuels are the other major category of non-renewable resources. They are mostly combusted to provide energy for transportation and heating, which converts their organic compounds into carbon dioxide and water, which are released into the environment. Some of that CO_2 and H_2O may be absorbed by plants and other photosynthetic organisms and be converted back into organic materials, a process that might be interpreted as being a kind of recycling. However, the rate at which this happens is insignificantly small compared with the release of the CO_2 and H_2O by the combustion of fossil fuels, so these materials should be viewed as being as non-renewable as metals are.

A more minor use of fossil fuels is to manufacture various kinds of plastics. These synthetic materials can be recycled after initial uses, which does help to extend the lifespan of the reserves of fossil fuels. Nevertheless, because the dominant use of fossil fuels is as sources of energy, they essentially flow through an industrial economy, with little new recycling.

Image 12.1. Non-renewable resources can only be mined. This is a view of the Etaki open-pit diamond mine in the Northwest Territories. Three open pits can be seen as a cluster, plus another at the top-left of the image, along with an extensive tailings-disposal area and other infrastructure. Source: Jason Pineau, Wikimedia Commons; http://commons.wikimedia.org/wiki/File:Ekati_mine_640px.jpg .

Renewables

Renewable resources are capable of regenerating after harvesting, so potentially their stocks can be utilized forever. Most renewable resources are biological, although some are non-biological. **Biological Renewable Resources** Renewable resources that are biological in nature (bio-resources) include the following:

- wild animals that are hunted as food or for bio-materials, such as deer, moose, hare, ducks, fish, lobster, and seals
- forest biomass that is harvested for lumber, fiber, or energy
- wild plants that are gathered as sources of food

- plants cultivated as sources of food, medicine, materials, or energy
- the organic-based capability of soil to sustain the productivity of agricultural crops

Image 12.2. Renewable resources, such as timber and fish, are capable of regenerating after they are harvested. Provided they are not over-harvested or managed inappropriately, renewable resources can be harvested in a sustainable fashion. This photo shows a load of timber that was harvested on Vancouver Island. Source: B. Freedman.

Non-Biological Renewable Resources The following are renewable resources that are non-biological:

- sunlight, of which there is a continuous input to Earth
- surface water and groundwater, which are renewed through the hydrologic cycle
- winds, which are renewed through the heat-distribution system of the atmosphere
- water currents and waves, which are renewed through the heat-distribution system of the oceans, as well as the tidal influence of the Moon

Many renewable resources can be managed to increase their rates of recruitment and productivity and to decrease mortality. In the following section we explain how management practices can be used to increase the productivity of biological resources.

Although a renewable resource can regenerate after harvesting, it can also be badly degraded by excessive use or by inappropriate management. These practices can damage the ability to regenerate and may ultimately cause a collapse of the stock. If this happens, the renewable resource is being “mined”, or used as if it were a non-renewable resource. As such, it becomes depleted by excessive use. For this reason, ecologists commonly use the qualified term: potentially renewable resources.

Global Focus 12.1. Easter Island as a Metaphor for Spaceship Earth
A case of resource depletion that is relevant to the metaphor of "spaceship Earth" occurred on Easter Island, a small (389 km^2), extremely isolated place in the southern Pacific Ocean (Ponting, 1991; Diamond, 2004). Easter Island was first discovered by wandering Polynesians around the 9th century. The only foods these people brought with them were chicken and sweet potato (the climate is too temperate for tropical foods known to the Polynesians, such as breadfruit, coconut, taro, and yam). Initially, the Easter Islanders could hunt abundant fish and porpoises in the rich coastal waters of their island, and they could catch wild Polynesian rats, a species they had introduced.

By the 16th century, the Easter Islanders had developed a flourishing society, with a population as large as 15,000. Because of food surpluses, they had time to engage in a cultural activity that involved carving huge slabs of stone into human-faced monoliths, which they erected on great bases of stone at special places along the coast. The heavy monoliths (weighing up to 75 t) and their massive bases were carved at an inland quarry and then moved with enormous human effort (there were no draft animals) to their coastal sites, perhaps by rolling them on logs cut from the island's forest.

Image 11.3. Human-faced moai, which are large monoliths carved of volcanic stone on Easter Island. Source: Aurbina, Wikimedia Commons; http://en.wikipedia.org/wiki/Easter_Island#mediaviewer/File:Moai_Rano_raraku.jpg .

However, Easter Island was soon deforested by the aggressive cutting of trees for fuel, to construct buildings and fishing boats, and for use as rollers. Once the forest resource was gone, several key enterprises of the islanders collapsed. Stone monoliths could no longer be moved, sturdy homes could not be built, and fishing and porpoise hunting became impossible. It also became difficult to cook food and keep warm because the only other fuel available was the sparse biomass of shrubs and herbaceous plants.

In other words, the deforestation of their island caused the economy of this Polynesian society to collapse. The cultural and economic disintegrations were so great that when Europeans first arrived at Easter Island in 1772, the inhabitants could not remember why the stone monoliths had been erected. These people were living in squalid conditions in caves and reed huts, were engaged in warfare among rival clans, and were cannibals, possibly to supplement the meagre food available on their treeless island.

An obvious lesson of Easter Island is that even primitive societies are capable of over-exploiting the vital resources needed for subsistence. Undoubtedly, the Easter Islanders were keenly aware of their precarious circumstances – especially the limited resources available to sustain their society on a small and isolated island. As these vital resources became obviously diminished, the people likely discussed the need to conserve their economic base. However, any such deliberations came to naught, and there was an irreversible collapse of the economy and culture of these people.

Easter Island is a compelling metaphor for Earth as a planetary "island." Earth, too, has limited stocks of energy, minerals, and biological resources to sustain the human economy. Any of these natural resources can be rapidly depleted by excessive use. There was no alternate, resource-rich refuge to which the Easter Islanders could escape from their self-inflicted catastrophe. Likewise, as far as we know, there is no alternative to planet Earth.

Management of Renewables

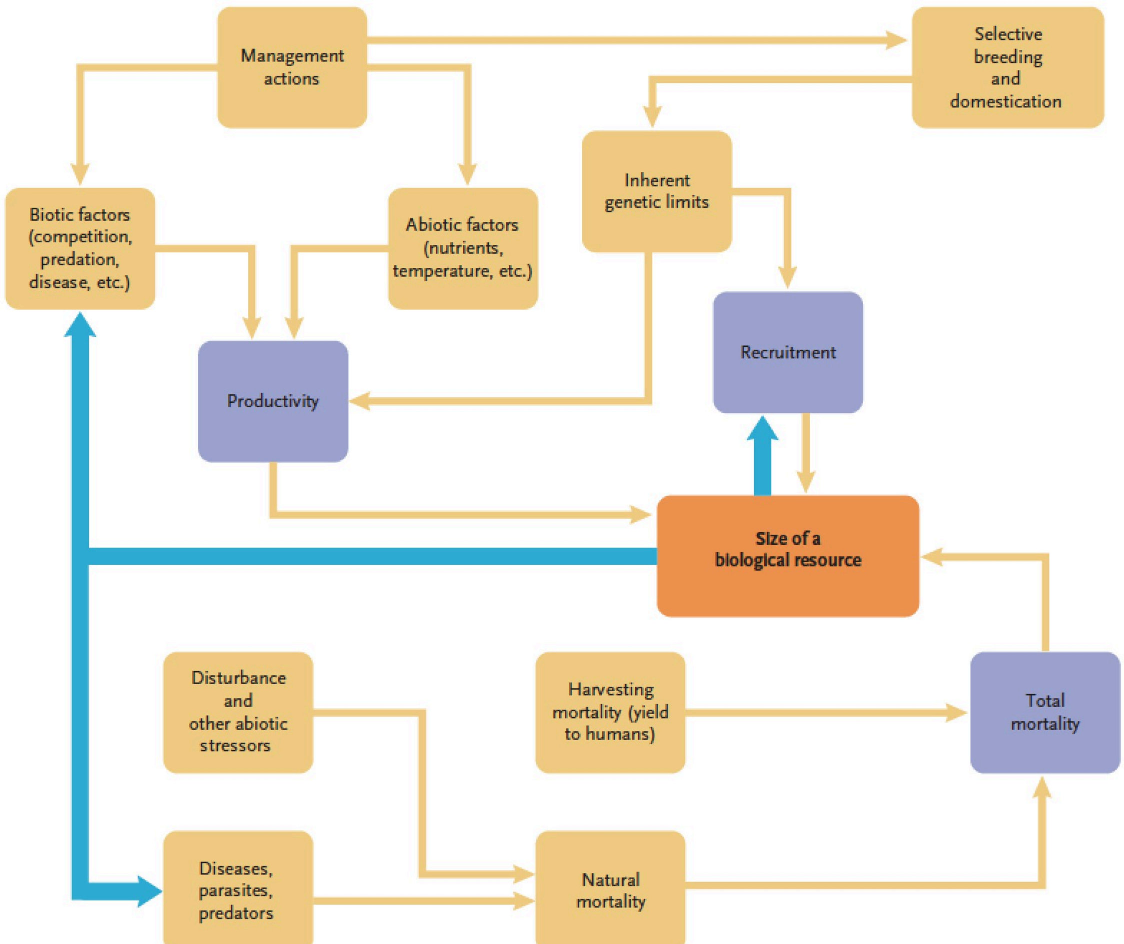
Potentially at least, populations of animals and plants, and their assemblages known as communities and ecosystems (such as a tract of forest), can be harvested in a sustainable manner – that is, without depleting the size of the resource or its capability to renewal. Essentially, this is due to the fact that, within limits, bio-resources are able to regenerate after some of their biomass is harvested. As long as the rate of harvesting does not exceed that of regeneration, a bio-resource can be used in a sustainable way.

Ultimately, the upper limits of the productivity of an individual organism is limited by genetically determined factors that influence its fecundity, longevity, and growth rate. To reach that potential limit of productivity, an organism must experience optimal environmental conditions. In a collective sense, genetic factors also set a ceiling on the potential productivity of populations or organisms, as well as communities and larger ecosystems. However, in the real world it is typical that environmental conditions are not optimal, and so the actual (or realized) recruitment, growth, and maturation of individuals and biomass are less than their potential amounts. As a result, it is possible to increase the size of a harvest by the use of management practices that enhance the productivity of bio-resources. When these practices are used in a coordinated way, they are called a management system.

In general, the various management practices are designed to alleviate environmental constraints on productivity. This is done by mitigating factors that may be preventing some recruitment, or are causing mortality, or are constraining the rate of productivity. In addition, the selective breeding of individuals with desirable traits may be used to alleviate genetically based constraints to productivity – ultimately, such genetic "improvements" may result in domesticated varieties of crops.

In any case, however, the expression of many genetic factors is influenced by environmental conditions, various of which restrict productivity (Figure 12.1). Therefore, in the real world of ecosystems, the actual productivity of bio-resources is less than their potential.

Figure 12.1. Factors Affecting the Yield of a Biological Resource. The biomass and productivity of a bio-resource are determined by the recruitment of individuals into the population, their growth rates, and their mortality through either harvesting or natural means. These factors are affected by both genetically determined and environmental influences. Often, environmental and biological factors can be managed to increase the productivity and size of the stock of a bio-resource. Source: Modified from Begon et al. (2005).



If resource managers understand the nature of constraints on the productivity of bio-resources, and can devise ways to reduce those influences, then the yield of harvested products can be increased. In any truly sustainable system of resource management, those increases in yield must be obtained without degrading the capability of the resource for renewal (they cannot be obtained by over-harvesting the resource or by degrading environmental conditions). The most important practices that are used to increase the productivity of bio-resources are described below. (Note, however, that while these are commonly used methods of increasing the productivity of bio-resources, all management practices cause some degree of ecological damage, as is examined in later chapters.)

Selective Breeding

In all species, there is some degree of genetically based influence on biological attributes of individuals such as fecundity, longevity, and productivity. Plant and animal breeders deliberately select individuals that display traits that are considered desirable and use them in breeding programs intended to develop “improved” varieties of crops. This is the basis by which all domesticated species used in agriculture were developed, and cultural selection is still an important way in which crop varieties are produced (see also Chapter 14). In addition, since the 1980s, new methods have been developed for transferring genetic information from one species to another – these have been used to create so-called transgenic crops (see Environmental Issues 6.1).

Enhancement of Recruitment

The rate of recruitment of new individuals into an exploited population can be increased in various ways. Some commonly used methods are described below.

- **Planting:** In intensively managed agricultural, aquacultural, and forestry systems, managers may try to achieve an optimally spaced monoculture of the crop. This is done so that the productivity will not be limited by competition with non-crop species or by individuals of the crop growing too closely together. The recruitment of plant crops is often managed by sowing seeds under conditions that favour their germination and establishment, while optimizing density to minimize competition. Sometimes young plants are grown elsewhere and then out-planted, a practice that is used to cultivate paddy rice, develop fruit-tree orchards, and establish plantations in forestry.
- **Regeneration of Perennial Crops:** Some management systems encourage perennial crops to regenerate by re-sprouting from surviving rhizomes or stumps after the above-ground biomass is harvested. This regeneration system is used with sugar cane and with stands of ash, aspen, maple, and poplar in forestry. In some cases, the regenerating population may have to be thinned to optimize its density.
- **Stock Enhancement:** Recruitment of many fishes, particularly salmon and trout, is often enhanced by stripping wild animals or hatchery stock of their eggs and milt (sperm). The eggs are then fertilized under controlled conditions and incubated until they hatch. The larval fish (called fry) are cultivated until they reach a fingerling size, when they are released to suitable habitat to supplement the natural recruitment of wild fish.
- **Site Preparation:** Certain practices favour the recruitment of economically preferred tree species in forestry. For instance, some pines recruit well onto clear-cuts that have been site-prepared by burning, as long as a supply of seeds is available. Seedlings of other tree species establish readily onto exposed mineral soil and are favoured by mechanical scarification that exposes that substrate by disrupting the organic surface mat.
- **Managing the Sex Ratio:** Recruitment of some hunted animals can be maintained by allowing only adult males to be harvested. For example, most species of deer are polygynous (males breed with more than one female). Consequently, a hunt can be restricted to males, on the assumption that the surviving bucks will still be able to impregnate all of the females in the local population.
- **Harvest Season:** Recruitment of some animals can be managed by limiting the hunting season to a particular time of the year. For example, restricting the hunt of waterfowl to the autumn allows ducks and geese to breed during the spring and summer so that recruitment can occur. Hunting in the springtime interferes with that reproduction.

Enhancement of Growth Rate

As noted previously, the productivity of all plants and animals is constrained by environmental influences, which include inorganic factors such as nutrient availability and temperature and biological ones such as competition and disease. Often, management practices can be used to manipulate environmental conditions to reduce their limitation on growth rate, allowing an increased harvestable yield. Sometimes a management system is used, involving a variety of practices applied in a coordinated manner. Some examples follow.

- **Agricultural Systems:** In intensive agricultural systems, high-yield varieties of crops are grown and managed to optimize their productivity. The management practices typically combine some or all of the following: fertilizer addition to enhance nutrient availability, irrigation to reduce the effects of drought, tillage (ploughing) or herbicide

use to decrease competition from weeds, fungicide use and other practices to control diseases, and insecticide use and other practices to lessen damage caused by insects and other pests.
- **Forestry:** The intensity of management used in forestry varies greatly, but crop-tree productivity can be increased through silvicultural practices such as thinning young stands to reduce competition among crop trees, using herbicide to control weeds, and using insecticide to cope with infestations of insects.
- **Aquaculture:** High-yield varieties of fish, crustaceans, or mollusks may be grown at high density in ponds or pens, where they are well fed and protected from diseases and parasites through the use of antibiotics and other chemicals.

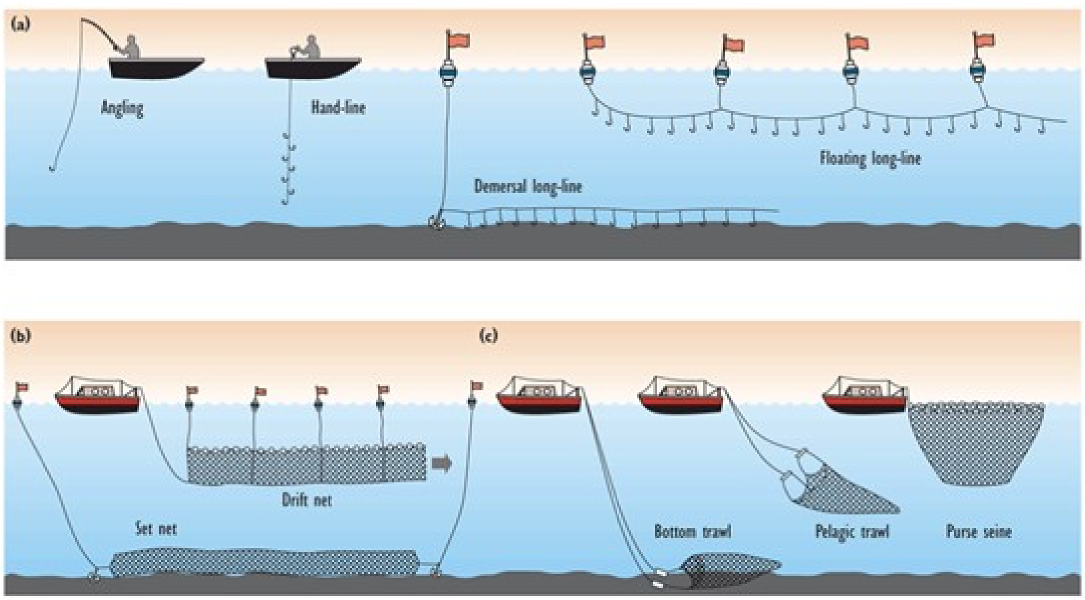
Management of Mortality Rate

Mortality of juveniles and adults can seriously affect the sizes of plant and animal stocks. However, by thinning out the stock, mortality also influences the intensity of competition and that can increase the growth rate of survivors. Natural mortality can be caused by predation, disease, or disturbance, while harvesting mortality is associated with use by humans. Resource depletion occurs when the total rate of mortality (natural plus harvesting) exceeds the regenerative capability of the stock.

- **Natural mortality** associated with predators, parasites, diseases, and accidents can be decreased in various ways:
    - ***Diseases, Parasites, and Herbivores:*** Mortality of crop plants caused by herbivorous insects may be managed by using insecticide or by changing the growth conditions to develop a habitat that is less favourable to the pest. Livestock are commonly affected by parasites, a problem that may also be reduced by using a pesticide. For example, sheep infested with ticks are dipped in chemical baths that kill the pests. Similarly, mortality caused by disease may be reduced by using medicines that treat the symptoms, by administering antibiotics to deal with bacterial infections, or by changing cultivation methods to decrease vulnerability. All such practices allow diseases, parasites, and herbivores to be controlled over the short term, but none are long-term solutions to these causes of productivity loss and mortality.
    - ***Natural Predators:*** It is uncommon for coyote, wolf, cougar, or bears to be important predators of livestock, but many farmers still consider any losses to these species to be unacceptable. Some hunters feel the same way about mortality that natural predators cause to hunted wildlife, such as deer, moose, and caribou. Consequently, in many regions these large predators have been relentlessly persecuted by shooting, trapping, and poisoning. An alternative to killing the predators is to restrict their access to livestock using fences or guard animals such as dogs and donkeys.
- **Harvesting mortality** must also be closely managed to ensure that the total mortality (natural plus anthropogenic) stays below the threshold for depleting the resource. For an ideal population, the maximum sustainable yield (MSY) is the largest amount of harvesting mortality that can occur without degrading the stock. Theoretically, a harvest rate less than MSY would leave a "surplus" of the stock to natural sources of mortality, while any greater than MSY would impair regeneration. Note that any harvest rate equal to or less than MSY would theoretically sustain the resource. Harvest-related mortality is influenced by many factors, including the amount and kinds of harvesting equipment and personnel, and the time the units spend harvesting. Resource managers can adjust the mortality by controlling the total harvesting effort, which is a function of both the means (such as the kinds of fishing boats and their gear) and the intensity (the number of boats and the amount of time each spends fishing) of harvesting.
    - ***Technology:*** Equipment has a great influence on harvesting rate. Consider, for example, the various methods of catching fish, summarized in Figure 12.2. These technologies vary greatly in efficiency, which might be indicated by the amount of fish caught per-person fishing, per-unit of energy expended, or per-unit of investment in equipment. In general, much greater harvesting mortality is associated with the more intensive technologies, such as drift nets, trawls, and seines, compared with simpler methods such as hand-lines. The

more efficient methods may also have a much greater by-catch of species that are not the target of the fishery and are often thrown away. Similarly, a hunter armed with a rifle is more efficient than one using a bow-and-arrow, and trees can be harvested more quickly using a feller-buncher than a chainsaw or an axe. (A feller-buncher is a large machine that cuts and de-limbs trees and then stacks the logs into piles.).

Figure 12.2. Fishing Technologies. Methods of catching fish vary enormously in their efficiency and in the associated harvesting mortality. (a) Line methods range from hand-lines with one or more hooks, to floating or bottom long-lines that extend for kilometers and have thousands of hooks. (b) A gill-net can be set on the bottom or attached to drifting buoys and can range up to tens of kilometers in length, catching fish and other animals as they try to swim through the mesh. (c) A trawl is an open, broad-mouthed net that is dragged along the bottom or through the water column, while a purse seine is positioned around a school of fish near the surface and then pulled shut with a bottom draw-line. Source: Freedman (2010).



- ◦ ***Selection of Species and Sizes:*** The great variation in selectivity of harvesting methods, with regards to both species and size, can be an important consideration in resource management. In a fishery, for example, a change in the net-mesh diameter influences the sizes of animals that are caught. Usually, it is advantageous to not harvest smaller individuals, which may not yet have bred and often have a smaller value-per-unit-weight than bigger animals. In forestry, size- or species-selective cutting might be used in preference to clear-cutting, perhaps to encourage regeneration of the most desirable tree species. Those methods also reduce environmental damage, by keeping the physical structure of the forest relatively intact. o ***Number of Harvesting Units:*** An obvious way to manage mortality associated with harvesting is to limit the number of units that are participating in a harvest. In a fishery, for example, the government could limit the number of fishers by issuing only a certain number of licenses. Usually, the kind of technology that the harvesters can use is also specified, such as the number of boats using a particular fishing gear. o ***Time Spent Harvesting:*** The harvesting effort is also influenced by the amount of time that each unit works. Often there is strong pressure on regulators to allow harvesting to occur for as long as possible, because of the great economic value of investments made in machinery and personnel. Even so, in some cases, the harvesting time is closely regulated. For example, certain herring fisheries in coastal waters of western North America are only allowed to operate for as little as several hours per year.
- **Regulatory tools** are legal and administrative procedures that managers use to achieve a measure of control over the harvesting effort, and therefore over the mortality associated with exploitation. Relatively direct controls

include licenses that regulate the numbers of participants, the technology they may use, their resource quotas, and the times and places they may harvest. Indirect tools can be used to influence the profitability of different harvesting strategies, such as the following:

- fines for non-compliance, which decrease profit by raising costs
- taxes on more harmful harvesting methods, or subsidies on less harmful ones, which influence profit by increasing or reducing costs, respectively
- buyouts of inappropriate or excess harvesting capacity (either equipment or licenses), which increase profit for the remaining harvesters by improving their relative allocation

Maximum Sustainable Yield

Potentially, all management options (including selective breeding, enhancement of growth and recruitment rates, and management of mortality rate) can result in larger yields of bio-resources. However, the factors that influence the size and productivity of stocks of renewable resources are imperfectly understood. Consequently, the management systems advocated by resource scientists are also imperfect. Despite this caveat about uncertainty, enough is usually known about ecological factors affecting bio-resources to design harvesting and management systems that will not degrade the capability for renewal.

At the very least, precautionary levels of harvesting that are small enough to avoid over-exploiting the resource can be predicted, even though the harvest might be smaller than the potential maximum sustainable yield. It is not necessary that harvests of natural resources are as large as are potentially attainable. If resource managers cannot predict an accurate MSY, then it is ecologically prudent to harvest at a rate known to be smaller than the MSY, but that is clearly sustainable. Of course, such strategies result in smaller harvests and less short-term profit. These are, however, more than offset by the longer-term economic and ecological benefits of adopting prudent strategies of resource use.

Moreover, the regional economic benefits of smaller (but sustainable) harvests can be enhanced by taking steps to ensure that the manufactured outputs of resource-dependent industries focus more so on "value-added" products. In forestry, for example, the export of raw logs might be prohibited, while local manufacturing of value-added products such as lumber, furniture, and violins would be encouraged. Similarly, a regional fishing industry might focus on the production and export of higher-valued products, such as prepared foods, rather than unprocessed fish. These kinds of integrations of resource harvesting and manufacturing can optimize the regional economic benefits of resource-based industries, while allowing smaller, sustainable harvests of the resource to take place.

Regrettably, non-sustainable rates of harvesting have been common in the real world of open, poorly regulated, bio-resource exploitation. This has happened even where so-called "scientific" management was being used. These facts become clear from the examples of resource degradation described in this chapter (and also in Chapters 14 and 26).

Non-Sustainable Use

Many potentially renewable resources have been used by humans in an unsustainable manner. Either these resources were excessively harvested (a condition known as over-harvesting or over-exploitation), or their post-harvest regeneration was inappropriately managed. Either of these can result in depletion or exhaustion of the resource by so-called mining (a term more usually applied to a non-renewable resource).

There are many examples of the non-sustainable use of potentially renewable resources. A few species have even been made extinct by excessive hunting, such as the dodo, passenger pigeon, and great auk (the latter two occurred in Canada; see Chapter 26). In other cases, seemingly abundant species were rendered endangered by over-harvesting, including American ginseng, Eskimo curlew, northern fur seal, plains bison, right whale, trumpeter swan, and other once-common species (Chapter 26). In fact, there are remarkably few examples of economically valuable, potentially renewable resources that have not been severely depleted at one time or another through excessive use or inappropriate management.

Additional examples of the mining of potentially renewable resources include the following:

- extensive deforestation of many parts of the world, which has resulted in losses of timber and fuelwood resources as well as environmental damages such as erosion and regional changes in climate (Chapter 23)
- extensive degradation of the quality of agricultural soil, resulting in declining crop yields and sometimes the abandonment of previously arable land (Chapter 24)
- widespread depletions of groundwater by over-use for irrigated agriculture, which is rapidly drawing down local and even regional aquifers (Chapter 24)
- exhaustion of fisheries, such as those of cod and other groundfish off the Atlantic Provinces, and salmon and herring off British Columbia (Chapter 14)
- depletion of many hunted resources – various species of fish, antelope, deer, furbearers, waterfowl, whales, and others (Chapter 14)

Not all cases of the mining of potentially renewable resources have occurred in modern times. Examples that are prehistoric are described in Global Focus 12.1 and 12.2. These well-known cases demonstrate that even relatively unsophisticated human societies with primitive technologies have caused enormous damage to their crucial resource base.

In some cases, an early depletion of potentially renewable resources was followed by efforts of conservation or improved management, which subsequently restored the depleted stocks (but not ones that had been made extinct). (In the sense used here, conservation refers to the “wise use” of natural resources, including recycling and other means of efficient utilization, as well as ensuring that the harvesting of renewable resources does not exceed their regeneration.) For example, regulating the hunting of white-tailed and mule deer has allowed those species to remain abundant in regions where habitat is suitable. Comparable successes have been achieved with other once-depleted animals, such as certain sportfish, ducks, and geese. Examples of these kinds of conservation successes are described as case studies in Chapter 26.

Overall, however, there is more bad news than good about future stocks and regeneration of many potentially renewable resources. Although some renewables are being used in a manner that is supportive of their future availability, many are not. If this situation does not change for the better in the near future, there will be grim consequences for the human economy, and also for biodiversity and natural ecosystems.

> Global Focus 12.2. Prehistoric Extinctions
> Paleontologists have found clear evidence of prehistoric mass extinctions of animal species, apparently caused by over-hunting by stone-age humans (Martin, 1967, 1984; Diamond, 1982, 2004). Although the extinctions occurred at different times and places, all of them coincided with the discovery and colonization of a landmass that was previously uninhabited by people. The extinct animals were seemingly naïve to predation by efficient groups of hunters and were unable to adapt to the onslaught. These mass extinctions represent cases of non-sustainable harvesting of wild-animal populations, which were potentially renewable bio-resources for the neolithic hunters.
>
> In North America, a wave of extinctions began about 11-thousand years ago, soon after people colonized the continent by migrating across a land bridge from Siberia. (The land bridge existed because sea level was much lower than today, as a result of so much water being tied up in glacial ice.) Within a relatively short time, at least 56 species of large mammals (weighing more than 44 kg), 21 smaller mammals, and several large birds had

become extinct. The extinctions included 10 species of horses (genus Equus), the giant ground sloth (Gryptotherium listai), four kinds of camels (family Camelidae), two buffalo (genus Bison), a cow (genus Bos), the saiga antelope (Saiga tatarica), and four kinds of elephants including the mastodon (Mammut americanum) and mammoth (Mammuthus primigenius). Predators and scavengers that depended on these large herbivores also became extinct, including the sabre-toothed tiger (Smilodon fatalis), the American lion (Panthera leo atrox), and a huge scavenging bird (Terratornis merriami). The best collection of fossil bones of many of the extinct animals has been excavated from the La Brea tar pits in southern California. However, bones of many species are widespread and some have been found in various places in Canada. As colonizing people spread from North America into Central America, and then into South America, extinctions of many other vulnerable species also occurred there.

Image 12.4. An artistic impression of a wooly mammoth (left) and an American mastodon (right). Source: Dantheman9758 at Wikimedia Commons; http://commons.wikimedia.org/wiki/File:MammothVsMastodon.jpg

Similar events of mass extinction have occurred elsewhere, also coinciding with the colonization of places by stone-age hunters. In New Guinea and Australia, waves of extinction occurred about 50-thousand years ago, following the discoveries of those islands by Melanesians migrating south from Asia. These extinctions involved the losses of many large marsupials, flightless birds, and tortoises.

In New Zealand, an extinction wave occurred less than 1,000 years ago, following the discovery of those islands by Polynesians. This swept away numerous large, flightless birds, including a 250-kg, 3-m giant moa (Dinornis maximus), 26 other species of moa, a goose (Cnemiornis calcitrans), a swan (Cygnus sumnerensis), a giant coot (Fulica chathamensis), a pelican (Pelecanus novaezealandiae), an eagle (Harpagornis moorei), and fur seals and various large lizards and frogs. The extinctions of the moas progressed as a wave from North Island to South Island over a two-century period following the Polynesian colonization. Great quantities of bones have been discovered at places where the moas were herded and butchered. Some of the bone deposits were mined by European colonists and used as phosphate fertilizer.

The human colonization of Madagascar occurred about 1,500 years ago. This also resulted in many extinctions, including the loss of 6-12 species of huge elephant birds, 14 lemurs, 2 giant tortoises, and other large animals. Prehistoric mass extinctions also occurred in Hawaii, New Caledonia, Fiji, the West Indies, and other island groups. All are believed to have resulted from over-hunting by newly colonizing people.

Clearly, the unsustainable use of bio-resources, resulting in irretrievable losses of species important to people, is not only a modern phenomenon. Prehistoric humans could also be rapacious, given appropriate opportunities in the form of naïve and edible species.

Patterns of Over-Exploitation

In cases where only a particular species is being harvested, over-exploitation generally involves an excessive harvesting rate, occurring without sufficient attention to regeneration. Under such conditions, the stocks are quickly mined, and they collapse to economic or biological extinction.

Sometimes, a "virgin" (or previously unexploited) resource is dominated by large, old-growth individuals, which are harvested selectively during the initial stages of resource "development." This changes the structure of the resource to one that is dominated by smaller, younger individuals. Because younger individuals are often relatively fast growing, the productivity of the resource is not necessarily smaller than that of the initial old-growth stock, although the total biomass may be less. However, if this kind of resource degradation is taken too far, the population may collapse in both productivity and biomass. The collapse may be caused by inadequate recruitment into the harvested population because the fecundity of younger individuals is not sufficient to offset the harvesting mortality.

Patterns of resource degradation are more complicated in the case of mixed-species resources, which are often over-exploited in a sequential manner. At first, only certain species in the virgin mixed-species resource may be considered desirable from the economic perspective. In addition, some individual organisms may be very large, especially in the case of old-growth resources. For instance, old-growth forest of coastal British Columbia is typically dominated by large individuals of valuable tree species, which are coexisting with many smaller individuals (see Chapter 23). Many pre-exploitation communities of fish, whales, and other species are also typically dominated by large individuals of desirable species.

The exploitation of a mixed-species resource usually involves a sequential harvest of commodities with progressively smaller economic value (measured as value per individual, as well as per unit of biomass and of harvested area). Initially, the largest individuals of the most valuable species are harvested selectively and are rapidly depleted. In an old-growth forest, for example, the largest logs of the most desirable species have the highest value per unit of biomass – they can be used to manufacture large-dimension lumber of precious species or costly veneer products. The intention of post-harvesting management is not to re-create another old-growth forest, because this would take too much time and would also involve an extended period of relatively low productivity (see Chapter 23). Instead, the site is typically converted into a second-growth forest.

Next, smaller individuals of the most desired species might be harvested selectively, along with the largest individuals of secondarily desired species. In a forest, the economic products might be smaller-dimension lumber. If management of the regenerating stand is intended to produce timber for manufacturing into lumber, the subsequent harvests would be on a relatively long rotation, say 60-100 years, depending on the growing conditions.

However, area-harvesting methods might then be used to harvest all individuals of all species for manufacturing into bulk commodities. In the case of forestry, trees might be clear-cut for the production of small lumber, pulp, industrial fuel, charcoal, or domestic fuelwood. Subsequent harvests for such purposes would be on a short rotation, perhaps 30-50 years. Sometimes the area-harvesting system is followed by management that regenerates a productive resource, although it has a different character from the original, natural ecosystem. In forestry, for example, natural mixed-species forest might be converted into a single-species plantation or perhaps into an agricultural ecosystem (see Chapter 23).

Intensive harvesting, sequential or otherwise, can also lead to a collapse of biological productivity and therefore to a huge loss of resource value. For instance, clear-cut forests sometimes regenerate into shrub-dominated ecosystems that resist the establishment of tree seedlings. This severe resource degradation may require expensive management to restore another economically useful forest.

Image 12.5. Ecologically rich old-growth forest in tropical countries is being rapidly cleared to provide agricultural land. The conversion results in destruction of the forest (the mining of a potentially renewable resource), often to develop agricultural land that may not be productive for very long. In this case, the rice paddies may be cultivated for many years, but the hillsides have been badly degraded by temporary agricultural use. This scene is from Sumatra, Indonesia. Source: B. Freedman.

Reasons for the Abuse of Natural Resources

To function over the longer term, an economy depends on a sustained input of natural resources. Given this vital context, it would appear to be economically self-destructive to degrade renewable resources by over-harvesting them or by inappropriate management. Nevertheless, this maladaptive behaviour has occurred frequently through human history. In fact, most uses of potentially renewable resources have been decidedly non-sustainable, and have caused stocks to become depleted. The most important reasons for this foolish behaviour are outlined below.

- The world's dominant cultures have developed an ethic that presumes that humans have the "right" to take whatever they want from nature for subsistence or economic benefits. This is an expression of the anthropocentric world view (Chapter 1). Particularly noteworthy is the so-called Judeo-Christian ethic (White, 1967), which is based on the Biblical story of creation. In that story, God directed humans to "be fruitful, and multiply, and replenish the earth, and subdue it," and to "have dominion over the fish of the sea, and over the fowl of the air, and over the cattle, and over all the earth and over every creeping thing that creepeth upon the earth" (Genesis 1:28). From a purely ecological perspective, this is an arrogant attitude, but it is typical of the world's dominant cultures and religions. Modern technological ethics have developed from this commanding world view and are now used to legitimize the rapid mining of natural resources and the collateral ecological damage.
- Individual people and their societies are intrinsically self-interested. This attitude is responsible for many cases of over-exploitation of resources in order to optimize short-term profit. At the same time, ecological damage

associated with the resource depletion is discounted as being unimportant. This is easily done because, in most economic systems, the consequences of ecological damage are usually shared broadly across society (by degradation of the common environment, or by tax monies being used to fix the problem), rather than being considered the responsibility of the persons or corporations who cause the damage.
- Natural resources are perceived as being boundless. Many people believe that nature and its resources are unlimited in their extent, quantity, and productivity. This is referred to as the cornucopian world view (Chapter 1; a cornucopia is the mythical horn of plenty that yields food in boundless amounts). In actual fact, Earth has limited stocks of resources available for use by humans, and most of these are being rapidly depleted.
- Investments of money in some sectors of the economy may accumulate profit faster than the growth rate of renewable resources. Consequently, apparent profit can be increased over the shorter term by liquidating natural resources and then investing the money earned in a faster-growing sector of the economy (see In Detail 12.1). Following this line of reasoning, the growth of many regional and national economies has been jump-started by economic "capital" gained through the non-sustainable mining of natural "capital."
- Not all of the true costs of over-exploitation are taken into account. The economic strategies suggested above only work if the ecological costs of over-exploitation are not paid for. In fact, some kinds of environmental damage can be interpreted as being "good" for the economy because they add to the gross national product (GNP). For example, the wreck of the Exxon Valdez in Alaska and the cleanup of the spilled petroleum were responsible for billions of dollars of "growth" in the GNP of the United States over several years (see Chapter 21). In actual fact, however, the environmental damages represent a depletion of natural capital and contribute to a "natural debt." When conventional economics (meaning economics as it is usually practiced) calculates the apparent profit gained through over-exploitation, it does not properly account for costs associated with resource depletion and other environmental damages. In theory, at least, ecological economics (a type of economics advocated by many enlightened economists and environmentalists) would fully cost those damages. An economic systems that tallies all costs, including those of environmental damage, is known as a full-cost accounting system.

Within an economic context that involves free access to common-property resources (these are owned by all of society), the above factors inevitably lead to the over-harvesting of potentially renewable resources. In a highly influential essay, Garrett Hardin (1968) called this frequently observed phenomenon "the tragedy of the commons." He explained this economic misadventure using the analogy of a publicly owned pasture (the "commons") to which all local farmers had open access for grazing their sheep. Individual, self-interested farmers believed that they would gain additional economic benefits by having as many of their own sheep as possible grazing the pasture. This led to an excessive aggregate use of the pasture, which damaged the forage resource. Hardin's major conclusion was that "freedom in a commons brings ruin to all," and this has generally been true of the ways in which many renewable resources have been abused.

Many nations are experiencing crises because of diminishing stocks of natural resources and the associated ecological damage caused by disturbances, pollution, and loss of biodiversity. Remarkably, many of these countries have not yet attempted to deal effectively with the resource depletion. With few exceptions, the design and implementation of intelligent strategies for using natural resources has so far proven to be beyond the capability of modern political and economic systems.

Nevertheless, people are definitely capable of designing and implementing systems that would conserve natural resources and the healthy ecosystems that are required to sustain economies. The solutions to resource-related predicaments require an integration of scientific knowledge and social change, along with the adoption of ecologically based economic policies that pursue true sustainability. Such solutions are far preferable to unfettered economic growth based on the depletion of natural resources.

In Detail 12.1. Investments and Renewable Resources
Consider a simple case: tree biomass in a forest is increasing at a rate of 5% per year, and interest rates on

secure financial investments are 10% per year. Because the forest resource is growing at 5% per year, its biomass would double about every 14 years. If, however, the forest was harvested, the products sold, and the resulting money invested at an interest rate of 10% per year, the quantity of money would double in only 7 years, so profit would be made twice as quickly.

Obviously, this kind of investment strategy only works if:

1. the objective is to gain short-term profit rather than to achieve long-term resource sustainability
2. the social perspective is that of individual people or corporations and not the society at large
3. the natural resource is perceived to have value only if it is harvested and converted into cash, and
4. only the costs of extraction are considered in the calculation of profit, while the costs of ecological damage and resource degradation are paid by society as a whole (in economic terms, they are treated as externalities).

Over the longer term, the liquidation of potentially renewable resources is clearly a losing strategy for society and for future generations. For individuals, firms, and local economies, however, liquidation can be a highly "profitable" strategy because they can accumulate wealth more quickly. Therefore, influential people often advocate and pursue this tactic. Consider the following statement in 1986 by Bill Vander Zalm, the Premier of British Columbia, one of the world's greatest exporters of forest products: "Let's cut down the trees and create jobs."[1] This is what has been happening, more or less, to many potentially renewable resources in most parts of the world.

[1]. Luinenberg, O. and S. Osborne. (compilers) 1990. The Little Green Book: Quotations on the Environment. Vancouver, BC: Pulp Press Publishers. ↩

Growth, Development, and Sustainability

To an economist, growth and development are different phenomena. Economic growth is a feature of an economy that is increasing in size over time. It is associated with increases in both the numbers of people and their per-capita use of resources. Particularly in developed countries, economic growth is typically achieved by a rapid consumption of natural resources. Non-renewable resources, such as metals and fossil fuels, are consumed in especially large quantities in a growing economy. Potentially renewable resources are also frequently mined, rather than being harvested on a sustainable basis.

In recent times, almost all national economies have been growing quite rapidly. Moreover, most economic planners, politicians, and businesspeople hope for additional increases in economic activity into the foreseeable future. They feel this way because economic growth is viewed as a means of generating more wealth for countries and companies, while providing a better life for citizens.

Unfortunately, there are well-known limits to growth – these constraints are related to the finite resources on planet Earth plus the laws of thermodynamics (Chapters 1 and 4). Consequently, economic growth can never be sustained over the longer term. In the perspectives of ecologists and environmentally minded economists, growth is not necessarily desirable: "Economic growth as it now goes on is more a disease of civilization than a cure for its woes" (Ehrlich, 1989).

Economic development is different from growth. It implies an improving efficiency in the use of materials and energy, and it thereby represents progress being made toward a sustainable economic system. In this sense, sustainable economic development involves the following actions:

- increasing the efficiency of use of non-renewable resources – for example, by recycling and re-using metals and other materials; by minimizing the use of energy for industrial, transportation, and space-heating purposes; and by improving the designs of other materials and products
- increasing the use of renewable materials in the economy, such as products manufactured from trees or agricultural biomass
- rapidly increasing the use of renewable sources of energy, such as electricity generated using hydro, solar, wind, or biomass technologies (see Chapter 13)
- improving social equity, ultimately to such a degree that all citizens (and not just a minority of wealthy people) have access to the necessities and amenities of life

Sustainable Development

Sustainable development refers to making progress toward an economic system that uses natural resources in ways that do not deplete their capital or otherwise compromise their availability to future generations of people. In this sense, the present human economy is obviously non-sustainable because it involves rapid economic growth that is achieved by vigorously mining both non-renewable and potentially renewable resources.

Many politicians, economists, resource managers, and corporate spokespersons have publicly stated that they are in favour of sustainable development. However, most of these people are confusing genuine sustainable development with “sustained economic growth,” which by definition is not possible.

The term “sustainable development” was first popularized in the widely acclaimed report Our Common Future, by the World Commission on Environment and Development, an agency of the United Nations. (This report, published in 1987, is often referred to as the Brundtland Report, after Gro Harlem Brundtland, the chair of the Commission at the time.) However, even this report obscured some important differences between economic growth and development. In fact, the Brundtland Report advocated a large expansion of the global economy: “It is . . . essential that the stagnant or declining growth trends of this decade [the 1980s] be reversed.” The report suggested that economic growth, coupled with a more equitable distribution of wealth, was required to improve the living standards of poorer peoples of the world. It further presumed that real progress toward a no-growth, equilibrium economy could not be made until society had achieved the equitable socio-economic conditions that are required for stopping both population growth and the rampant depletion of natural resources.

One of the recommendations of the Brundtland Report was that the global average per-capita income should grow by 3% per year (if maintained, this would double per-capita income every 23 years). However, because the global population was increasing at about 2% per year at the time, the economic growth rate would have to compensate, requiring a 5% per year increase in the total economy (3% plus 2%, resulting in a 14-year doubling time). Of course, in those regions where population growth is more rapid, such as much of Africa, south Asia, Latin America, and most cities (see Chapter 10), economic growth rates might have to be even higher in order to achieve a 3% per year increase in real per-capita income. Ultimately, the Brundtland Report estimated that a 5- to 10-fold expansion of the global human economy was needed in order to set the stage for attaining a condition of sustainable development.

The authors of the Brundtland Report believed that this growth would best be achieved through “policies that sustain and expand the environmental resource base.” Such policies would include the advancement of efficient technologies that could help to achieve economic growth while consuming fewer material and energy resources. In addition, a redistribution of some wealth from richer people and regions to poorer ones would be central to achieving the growth of average per-capita income that is championed in the Brundtland Report. It is important to understand that the Brundtland Report was developed through a consensus-building process that involved wide-ranging consultations among diverse interested parties. Therefore, representatives of many nations and cultures had to agree on its content. Considering the diversity of the interests involved, it is not surprising that the report advocated substantial economic growth as a component of its "development" strategy. The growth-related aspects of the report made it easier for politicians and business to support its recommendations.

From the ecological perspective, however, it is doubtful that a 5- to 10-fold increase in the human economy could be sustained. Many have argued that it would be much more sensible to pursue solutions that aggressively attack both economic growth (as it is currently achieved) and population growth. These solutions would include vigorous actions toward population control, a more equitable distribution of wealth, reduced use of resources by wealthier peoples of the world, more equitable access of women to education and social empowerment, development and use of more efficient technologies, and rigorous conservation of natural resources. These sustainable solutions are more difficult and unpopular than the policies advocated by most mainstream politicians and economists, but they appear to be necessary if a sustainable human economy is to be achieved.

In Detail 12.2. Economics, Environment, and Ecology

Conventional economics is a social science that examines the allocation of scarce resources (referred to as goods and services) among potential uses that are in competition with each other. A goal of economics is to understand and possibly manage the patterns of consumption of resources by individuals and by sectors of society. In economics, the worth (or value) of goods and services is assessed on an anthropocentric basis – that is, in terms of the direct or indirect usefulness to people and their welfare. In large part, value is determined by the supply of a resource compared to the demand for it. When the supply is abundant, goods and services are relatively cheap; when they are scarce, they become more expensive, which stimulates efforts to increase the supply and/or find inexpensive substitutes. Key assumptions of economics are that people seek to increase their well-being, and corporations strive to maximize their profit. As a result, their choices can be used to reveal their valuations and investments in goods and services. Such valuations are usually made in units of tradable currency (such as dollars), and they are routinely made for goods and services for which there are markets, such as the following:

- manufactured goods, including buildings, clothing, computers, and vehicles
- services, such as those provided by entertainers, farmers, physicians, and teachers
- natural resources used in the economy, including non-renewable ones (metals and fossil fuels) and others that are renewable (foodstuffs, fish, and timber)

However, conventional economics performs much less well in the valuation of resources for which there are no obvious markets. Such valuations require the use of surveys or the observation of behaviour (such as the numbers of people visiting a park, or those contributing money to an environmental charity). These sorts of valuations are difficult and somewhat controversial, but they are necessary if society is to implement a full-cost accounting system that acknowledges the fact that important environmental damage is associated with many economic activities. These kinds of valuations are made in the relatively new field of environmental economics, and they may involve finding the costs of the following kinds of damages:

- the depletion of natural resources, including its longer-term implications for the survival of future generations
- pollution and its ecological and human health effects
- disturbances that cause damage to natural ecosystems
- endangerment and extinction of species
- impairment of ecosystem services, which are a major part of the life-support system of the planet
- social effects of environmental damage, including unacceptable economic disparities (including poverty) and the disenfranchisement of indigenous people and socioeconomic groups

These kinds of environmental damage are widely recognized as being important, but their value is only partially captured by conventional economics. This is a great deficiency, because it means that the marketplace is not fully accounting for environmental damage as a real cost of doing business and an expense to be reckoned when calculating profit. Environmental economists argue that as long as these damages are being properly valuated and viewed as expenses, they can be objectively considered in cost-benefit analyses that are associated with decisions to undertake policies or engage in activities that carry risks for environmental quality (including any linkages with resource and ecological sustainability). This is a key part of the planning process known as environmental impact assessment (see Chapter 27), which is crucial in helping society to design and run its economy without causing unacceptable damage to the ecosystems that sustain people and all other species.

The field of ecological economics goes even further than the full valuation of environmental damage. Ecological economics arose as a conceptual fusion of economics and ecology (note that the names of these disciplines share the same root, ecos, derived from the Greek word oikos, meaning "household"). The most important feature of ecological economics is that it attempts to examine the relationships between ecosystems and economic systems in a non-anthropocentric manner (one that goes beyond any known usefulness to humans). In particular, ecological economics employs a variety of biophysical measures of scarcity and valuation. These include the embodied energy content (a comprehensive life-cycle assessment of the energy used to manufacture, transport, and eventually discard of a product) and the ecological footprint (the land area needed to support the needs for energy and materials of an individual, city, or country; see Chapter 25). These approaches can yield compelling results that help us to understand the consequences of our economic activities and encourage individuals, businesses, and society at large to make choices that are less damaging to the environment.

Sustainable Economies

The proper definition of a sustainable economy is one that can be maintained over time without causing a depletion of its capital of natural resources. Ultimately, a sustainable economy can be supported only by the "wise use" of renewable resources, which would be harvested at rates equal to or less than their productivity. Therefore, "economic development" should refer only to progress made toward a sustainable economic system. Unfortunately, there have been few substantial gains in this direction. This is because most actions undertaken by politicians, economists, planners, and businesspeople have supported rapid economic growth rather than sustainable economic development. In large part, they do this because they believe they are following the wishes of the public to have greater access to wealth and employment.

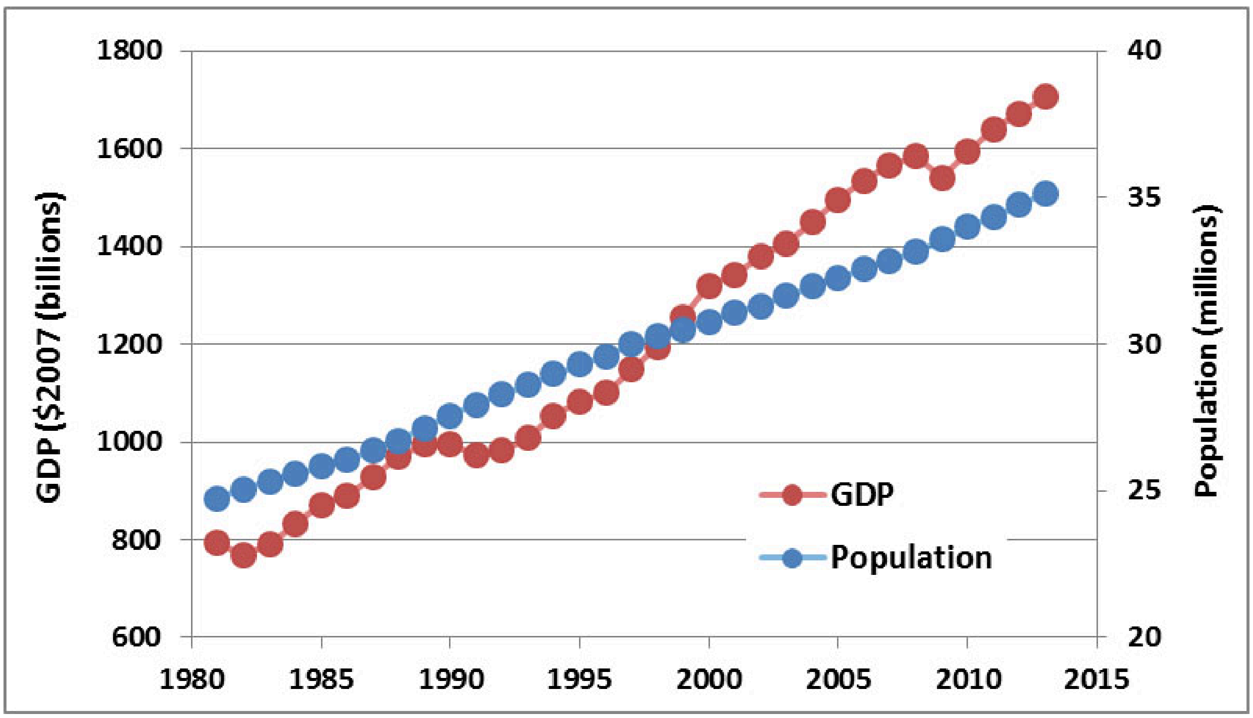
Because non-renewable resources are always depleted by their use, they cannot provide an ultimate foundation of a sustainable economic system. However, non-renewable resources do have an important role to play in a sustainable economy. Their use should, however, be tied to improving the stocks of comparable renewable resources so that a net depletion of capital does not occur. For example, if people want to use non-renewable coal, they might act to provide a compensating increase in forest area and biomass. This could result in no net consumption of potential energy (because tree biomass and coal are both fuels), and no net increase in the concentration of atmospheric carbon dioxide or other pollutants (because trees absorb CO_2 as they grow, and mature forest can store carbon for a long time if not disturbed). Of course, any non-renewable materials already in use in the economy should continue to be used and be recycled as efficiently as possible.

Symptoms of Non-Sustainability

As was previously mentioned, the dominant trends of local, national, and global economies are mostly toward vigorous economic growth, rather than toward sustainable development. The key indicators of these trends of non-sustainable growth are summarized below.

- **Rapid Growth of Economies:** Because of increases in both population and per-capita use of materials and energy, almost all economies are growing. This well-known fact is reflected by trends in many economic indicators, such as stock markets, growth indexes, and the gross domestic product (GDP). GDP is the value of all goods and services produced by a country in a year; it is equal to gross national product (GNP) minus net investment from foreign nations. Overall, the Canadian GDP grew by about 110% between 1981 and 2012, compared with a 40% increase in population (Figure 12.3). This implies an increase of per-capita GDP during the period, which reflects an improvement of individual wealth in terms of access to goods and services in the economy.

Figure 12.3. Growth of the Canadian Economy and Population. Gross domestic product (GDP) is an economic indicator that is related to the total size of a national economy. Because these data for Canadian GDP are standardized to constant 2007 dollars, the pattern of steady growth is not due to inflation. The data show a close correlation between growth of the Canadian population and the GDP (the r^2 value of the relationship is 0.984, which in a statistical sense means that 98.4% of the variation of population is accounted for by variation in GDP). Note, however, that the close visual convergence of the two curves is an artifact caused by adjustment of the vertical axes. Sources of data: GDP from Statistics Canada (2014) and population from Figure 11.1.



- **Depletion of Non-Renewable Resources:** All stocks of metal ores, petroleum, natural gas, coal, and other non-renewable resources are finite, being limited to what is present on Earth. These resources are being rapidly consumed, and their exploitable reserves will eventually become depleted. However, discoveries of additional exploitable stocks will extend the economic lifetimes of non-renewable resources, as will efficient recycling. Nevertheless, global stocks of non-renewable resources are being rapidly depleted (see Chapter 13).
- **Depletion of (Potentially) Renewable Resources:** Around the globe there are crises of depletion of renewable resources. In many regions, for example, once- enormous fish stocks are collapsing, deforestation is proceeding rapidly, the fertility of agricultural soil is declining, supplies of surface water and groundwater are being depleted and polluted, and hunted animals are becoming scarcer. Not all stocks of renewable resources are being severely depleted, but the declines are becoming more common and widespread (see Chapter 14).
- **Depletion of Non-Economic, Environmental Resources:** Some resources that are necessary for the health of

economic systems are not assigned value in the marketplace—that is, they are not valuated in dollars, and are not actively traded. Nevertheless, these resources are important to the health of the ecosystems that sustain the human economy. Examples of such non-valuated environmental resources include: (1) the ability of ecosystems to cleanse the environment of toxic pollutants such as sulphur dioxide and ozone, (2) ecological services such as the production of atmospheric O_2 and consumption of CO_2 (the latter being an important anthropogenic pollutant), and (3) ecosystem functions that support the productivity of conventional resources, such as the plant and algal productivity that ultimately allows the growth of stocks of hunted deer, fish, and other animals.

- **Depletion of Other Ecological Values:** Some ecological values are not directly or indirectly important in the human economy, but they still have intrinsic (or existence) worth. This makes these values significant, regardless of any perceived importance to human welfare (see Chapter 1). The most important examples of these ecological values are associated with biodiversity, especially the many species and natural ecosystems that are indigenous to particular regions. These biodiversity values are increasingly being threatened and lost in all regions of the globe (Chapter 26). Such losses would never be tolerated in an ecologically sustainable economy (that is, one in which resources are used in ways that do not compromise their future availability and do not endanger species or natural ecosystems; Chapters 1 and 27).

Modern economies deliver great benefits to people who are wealthy enough to purchase a happy and healthy lifestyle, replete with sufficient food, shelter, material goods, and recreational opportunities. For less-wealthy people, however, current economic systems may allow only minimal access to the most fundamental basics of subsistence. If a fairer, more equitable delivery of economic benefits to the poorer people of the world is to be achieved, then either non-sustainable economic growth or a substantial redistribution of some of the existing wealth will be required.

Ultimately, the global scale and long-term sustainability of the human economy will be limited by the ability of the biosphere to deliver renewable resources and ecosystem services. However, the limits of many potentially renewable resources have already been exceeded, resulting in stock declines or collapses. These well-documented damages should be regarded as warnings of the likely future of the human enterprise, unless there are marked improvements in resource-use systems. If critical resources are no longer available to support economic activity, the non-sustainable economy will be forced to contract in size, and may collapse.

It must be recognized that an ecologically sustainable economy might not be very popular with much of the public, or with politicians, government administrators, and business interests. These stakeholders would experience short-term pain (likely felt over decades) to achieve long-term, sustainable, societal gains. The pain would be associated with a less-intensive use of natural resources, the abandonment of the paradigm of economic growth, and the rapid stabilization – and perhaps downsizing – of the human population. The gains would be associated with an ecologically sustainable economic system that could support human society, and the rest of the biosphere, for a long time.

As we have repeatedly observed, people rely on natural resources to sustain their enterprise. Throughout history, resources that are essential to economies have been consumed to exhaustion (assuming there was a technological capability to do so). It is clear that better, more sustainable systems must be found that will allow us to use natural capital without depleting its stocks and without degrading ecosystems in unacceptable ways. Human societies desperately require these sustainable systems, but it remains to be seen whether we will design and implement them.

Conclusions

The human economy can function only if it has continuous access to an input of natural resources, of which there are two kinds: non-renewable and renewable. Non-renewable resources cannot regenerate, so they always become depleted as they are used. In contrast, renewable resources are capable of regeneration, so they can potentially be available forever. Nevertheless, excessive harvesting or inappropriate management can degrade potentially renewable resources, causing them to become diminished or even disappear. The human economy has been growing rapidly, and this has been achieved by the vigorous consumption and depletion of both non-renewable and potentially renewable resources. However, this process is clearly non-sustainable because it has relied on a rapid depletion of natural resources, while also causing other kinds of environmental damage, for example, to biodiversity. Ultimately, a sustainable human economy must be based on the wise use of renewable resources – meaning use that does not compromise their availability in the future. In addition, an ecologically sustainable economy would not cause unacceptable damage to other parts of the biosphere, such as putting other species and natural ecosystems at risk of extinction.

Questions for Review

1. What are the differences between non-renewable and (potentially) renewable natural resources? Give examples of each.
2. How can the productivity of biological resources be increased through management?
3. Describe three cases of the "mining" of (potentially) renewable natural resources. Why did the over-exploitation occur?
4. What are the key differences between conventional economics and ecological (environmental) economics?

Questions for Discussion

1. What are the differences between economic growth and development? Relate economic growth and development to the notion of sustainable development. Do you believe that the Canadian economy is making much progress toward sustainable development? Explain your answer.
2. Can you think of any examples of economically valuable, potentially renewable resources that have not been severely depleted through excessive use or inappropriate management? Explain your answer.
3. List three environmental values that do not directly contribute to the human economy, but are nevertheless important to the healthy functioning of ecosystems. Could these services be valuated (measured in dollars) in order to allow their degradation to be considered a true "cost" of doing business? What would be the benefits of such an ecological cost-accounting?
4. In this chapter, we defined sustainable development as "progress toward an economic system based on the use of natural resources in a manner that does not deplete their stocks nor compromise their availability for use by future generations of humans." We also defined ecologically sustainable development as "considering the human need for resources within an ecological context, and including the need to sustain all species and all components of Earth's life-support system." Discuss the key similarities and differences in these two kinds of economic sustainability.

Exploring Issues

1. Show how natural resources are important in your life by making a list of resources that you use daily for energy, food, or as materials in manufactured products.
2. You have been asked to help develop a plan for sustainable forest management on a large tract of land. What

practices would you recommend to ensure that the timber harvesting does not deplete the resource? What about other economic resources, such as fish, hunted animals, and opportunities for outdoor recreation? How would your plan also accommodate the need to sustain native species and natural ecosystems?

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Chapter 13 ~ Non-Renewable Resources

Key Concepts

After completing this chapter, you will be able to:

1. Describe the global and Canadian production and use of metals, fossil fuels, and other non-renewable resources.
2. Explain the heavy reliance of industrialized economies on non-renewable resources, and predict whether these essential sources of materials and energy will continue to be readily available into the foreseeable future.
3. Outline five major sources of energy that are available for use in industrialized countries, and describe the potential roles of these in a sustainable economy.

Introduction

As we noted in Chapter 12, the reserves of non-renewable resources are inexorably diminished as they are extracted from the environment and used in the human economy. This is because non-renewable resources are finite in quantity and their stocks do not regenerate after they are mined. Note that the word reserve has a specific meaning here – it is used to denote a known amount of material that can be economically recovered from the environment (that is, while making a profit).

Of course, continuing exploration may discover previously unknown deposits of non-renewable resources. If that happens, there is an increase in the known reserves of the resource. For example, the world's known reserves of nickel and copper have been increased during the past two decades because of the discovery of rich deposits of those metals in northern Quebec and Labrador. There are, however, limits to the number of "new" discoveries of non-renewable resources that can be made on planet Earth.

Changes in the value of non-renewable commodities also affect the sizes of their economically recoverable reserves. For example, if the value of gold increases in its marketplace, then it may become profitable to prospect for new stocks in remote places, to mine lower-grade ores, and to reprocess "waste" materials containing small quantities of this valuable metal. An improvement of technology may have the same effect, for instance, by making it profitable to process ores mine that were previously non-economic.

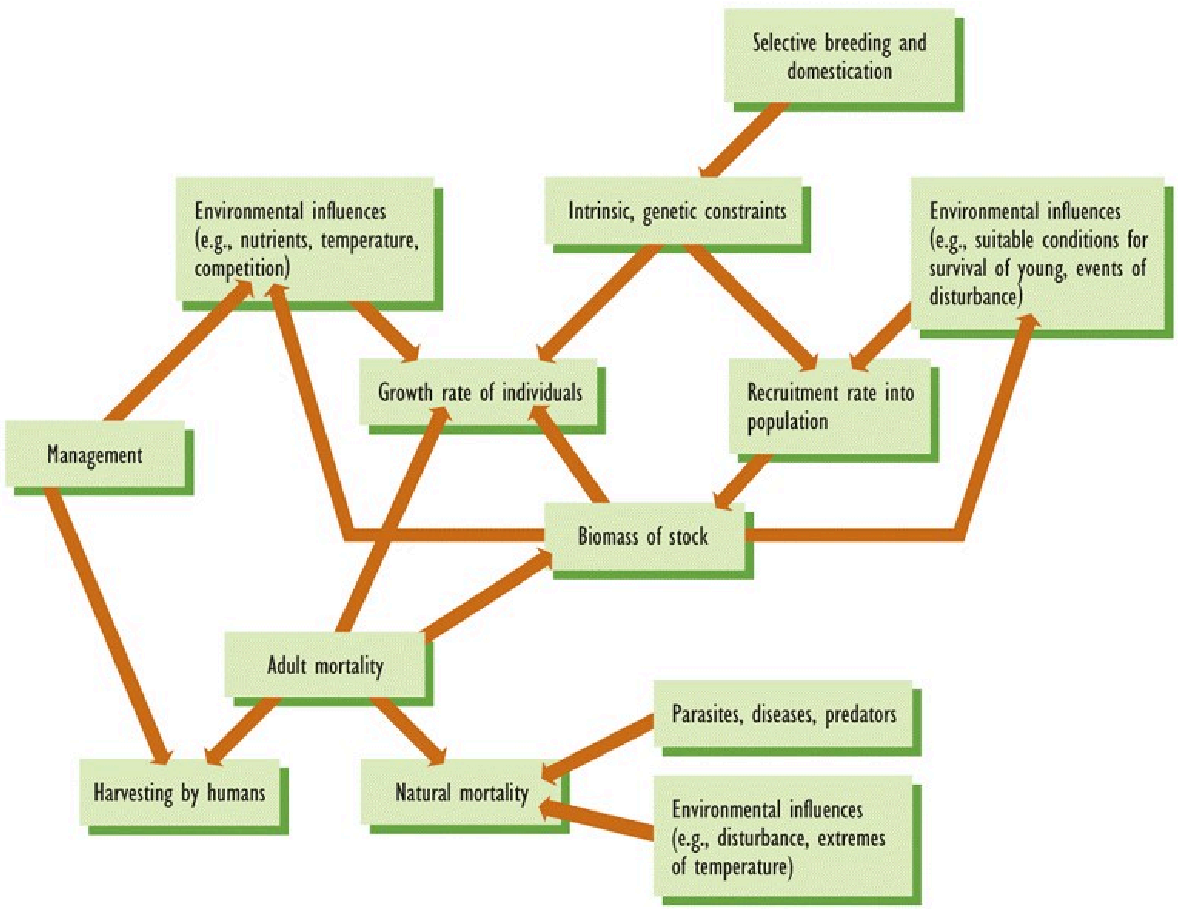
In addition, the life cycle in the economy of some non-renewable resources, particularly metals, can be extended by recycling. This process involves collecting and processing disused industrial and household products to recover reusable materials, such as metals and plastics. However, there are thermodynamic and economic limits to recycling, which means the process cannot be 100% efficient. Furthermore, the demand for non-renewable resources is increasing rapidly because of population growth, spreading industrialization, and improving standards of living along with the associated per-capita consumption. This has resulted in an accelerating demand for non-renewables that must be satisfied by mining additional quantities from the environment.

The most important classes of non-renewable resources are metals, fossil fuels, and certain other minerals such as gypsum and potash. The production and uses of these important natural resources are examined in the following sections.

Metals

Metals have a wide range of useful physical and chemical properties. They can be used as pure elemental substances, as alloys (mixtures) of various metals, and as compounds that also contain non-metals. Metals are used to manufacture tools, machines, and electricity-conducting wires; to construct buildings and other structures; and for many other purposes. The most prominent metals in industrial use are aluminum (Al), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), tin (Sn), uranium (U), and zinc (Zn). The precious metals gold (Au), platinum (Pt), and silver (Ag) have some industrial uses (such as conductors in electronics), but are valued mostly for aesthetic reasons, particularly to manufacture jewelry. Some of the more common metal alloys are brass (containing at least 50% Cu, plus Zn), bronze (mostly Cu, plus Sn and sometimes Zn and Pb), and steel (mostly Fe, but also containing carbon, Cr, Mn, and/or Ni). Metals are mined from the environment, usually as minerals that also contain sulphur or oxygen. Deposits of metal-bearing minerals that are economically extractable contribute to the known reserves of metals. An ore is an assortment of minerals that are mined and processed to manufacture pure metals. The stages in metal mining, processing, manufacturing, and recycling are summarized in Figure 13.1.

Figure 13.1. Metal Mining and Use. This diagram shows major stages of the mining, manufacturing, use, and re-use of metals, as well as the associated emissions of waste gases and particulates to the environment. Overall, the diagram represents a flow-through system, with some recycling to extend the lifetime of metals within the economy. Source: Modified from Freedman (1995).



Ore extraction by mining is the initial step in the process of bringing is metals into the material economy. This may be conducted in surface pits or strip mines, or in underground shaft-mines that may penetrate kilometers underground. In an industrial facility called a mill, the ore is crushed to a fine powder by heavy steel balls or rods within huge rotating tumblers. The ground ore is then separated into a metal-rich fraction and a waste known as tailings. Depending on the local geography, the waste tailings may be discarded onto a contained area on land, into a nearby lake, or into the ocean (see Chapter 18).

If the metal-rich fraction contains sulphide minerals, it is next concentrated in a smelter by roasting at high temperature in the presence of oxygen. This releases gaseous sulphur dioxide (SO_2) while leaving the metals behind. The concentrate from the smelter is later processed into pure metal in a facility called a refinery. The pure metal is then used to manufacture industrial and consumer products. The SO_2 may be processed into sulphur or sulphuric acid that can be used in various other industrial processes, or it may be released to the environment as a pollutant.

After the useful life of manufactured products has ended, they can be recycled back into the refining and manufacturing processes, or they may be discarded into a landfill.

High-quality ores are geologically uncommon. The deposits that are most economic for mining are typically located fairly close to the surface, and the ores have a relatively high concentration of metals. However, the thresholds vary depending on the value of the metal being processed. Ores with very small concentrations of gold and platinum can be economically mined because these metals are extremely valuable (per unit of weight). In contrast, less-valuable aluminum and iron must be mined as richer ores, in which the metals are present in high concentrations.

Data showing the global production of industrially important metals are given in Table 13.1. Note that for most metals the amounts consumed are somewhat larger than the annual production; this indicates that some of the consumption involves recycled material that has been reclaimed from previous uses. Also note the large increase in production of most metals since 1977. Iron and aluminum are the metals produced and used in the largest quantities. The life index (or production life, calculated as the known reserves divided by the annual rate of production) of aluminum is about 592 years, and for iron ore it is 58 years (Table 13.1). Life indexes for other metals listed in the table are less, which suggests that their known reserves are being quickly depleted. It is important to remember, however, that those known reserves are increased by new discoveries, changes in technology, and more favourable economics for the resource.

Table 13.1. Global Production, Consumption, and Reserves of Selected Metals. Data from: U.S. Bureau of Mines (1977) and U.S. Geological Survey (2014).

	Production (10^6 t/y)		Reserves (2013 ; 10^6 t)		Life Index
Metal	**1977**	**2013**	**Known**	**Likely**	
Aluminum	13.1	47.3	28,000	>50,000	592
Cadmium	0.017	0.022	0.5	1.6	22.7
Copper	7.7	17.9	690	4,900	38.5
Iron (ore)	831	2,950	170,000	800,000	57.6
Lead	3.4	5.4	89	2,000	16.5
Mercury	0.007	0.002	0.09	0.6	45
Nickel	0.77	2.47	74	130	30
Tin	0.23	0.23	4.7	11	20.4
Zinc	6.1	13.5	250	1,900	18.5
Steel (crude)	673	1,580	–	–	–

Canada is one of the world's leading producers of metals, accounting for 15% of the global production of nickel in 2006, 9% of aluminum, and 6% zinc (Tables 13.1 and 13.2). Much metal production is intended for export. Domestic consumption is about 39% of the value of production of all metals (Table 13.2). Metal-ore mining contributed $17-bilion to the GDP of Canada in 2011, and support activities (such as prospecting) another $4-billion, for a total of 1.3% of the GDP (Statistics Canada, 2014a).

The reserve life (life index) of Canadian reserves of metals is similar to or shorter than their global values (Table 13.2). Canadian reserves make up 15% of the global reserves of uranium and 5–10% of those of cadmium, nickel, silver, and zinc.

Table 13.2. Reserves, Production, and Consumption of Selected Metals in Canada, 2012. Note that bauxite (aluminum ore) is not mined in Canada, but large amounts are imported for processing. Data from: Natural Resources Canada (2014a) and U.S. Geological Survey (2014).

Metal	Reserves		Life Index	Production	Consumption
	(10^6 t)	% of Global	(years)	(10^3 t)	(10^3 t)
Aluminum	0	0	0	2,900	1,100
Cadmium	0.023	4.6	148	0.155	0.203
Cobalt	0.26	3.6	65	4	0.09
Copper	10	1.4	16	614	2.9
Gold	0.001	1.7	7.4	0.124	0.042
Iron ore	6,300	3.7	158	40,000	13,400
Lead	0.45	0.5	20	22.3	68.1
Molybdenum	0.22	2	29	7.62	2.01
Nickel	3.3	4.5	15	215	8.7
Platinum	0.0003	0.5	12	0.025	–
Silver	0.007	1.3	11	0.627	0.55
Uranium	0.49	8.8	65	0.0075	0.002
Zinc	7	2.8	17	414	150

Table 13.3. Provincial Production of Selected Metals in Canada, 2013. Data from: Natural Resources Canada (2014a).

Region	Gold (t/y)	Copper (10^3 t/y)	Zinc (10^3 t/y)	Nickel (10^3 t/y)
NL	0.61	56.3	12.2	60.1
PE	-	-	-	-
NS	-	-	-	-
NB	0.07	3.2	60.4	-
QC	35	25	130	32.1
ON	59.2	212	67.2	95.3
MB	5	30.4	79.8	27.1
SK	2.1	0.9	3.9	-
AB	0.03	-	-	-
BC	6	267	22.3	-
YK	2.8	18.4	68.6	-
NT	-	0.3	-	-
NU	13.1	-	-	-
Canada	124	613	414	215
Value ($\$10^9$)	$5.90	$4.60	$0.81	$3.40

Fossil Fuels

Fossil fuels include coal, petroleum, natural gas, oil-sand, and oil-shale. These materials are derived from the partially decomposed biomass of dead plants and other organisms that lived hundreds of millions of years ago. The ancient biomass became entombed in marine sediment, which much later became deeply buried and eventually lithified into sedimentary rocks such as shale and sandstone. Deep within those geological formations, under conditions of high pressure, high temperature, and low oxygen, the organic matter transformed extremely slowly into hydrocarbons (molecules that are composed only of carbon and hydrogen) and other organic compounds. In some respects, fossil fuels can be considered to be a form of stockpiled solar energy – sunlight that was fixed by plants into organic matter and then stored geologically.

Image 13.1. Because petroleum and other fossil fuels are non-renewable resources, their future reserves are diminished when they are extracted from the environment. This is an oil pump in southeastern Saskatchewan.

Source: B. Freedman.

In a geological sense, fossil fuels are still being produced today, by the same processes that involve dead biomass being subjected to high pressure and temperature. Because the natural geological production of fossil fuels continues, it might be argued that these materials are a kind of renewable resource. However, the rate at which fossil fuels are being extracted and used is enormously faster than their extremely slow regeneration. Under this circumstance, fossil fuels can only be regarded as being non-renewable.

Hydrocarbons are the most abundant chemicals in fossil fuels. However, many additional kinds of organic compounds may also be present, which incorporate sulphur, nitrogen, and other elements in their structure. Coal in particular is often contaminated with many inorganic minerals, such as shale and pyrite.

The most important use of fossil fuels is as a source of energy. They are combusted in vehicle engines, power plants, and other machines to produce the energy needed to perform work in industry, for transportation, and for household use. Fossil fuels are also used to produce energy to heat indoor spaces, an especially important function in countries with a seasonally cold climate. Another key use is for the manufacturing of synthetic materials, including almost all plastics. In addition, asphaltic materials are used to construct roads and to manufacture roofing shingles for buildings.

Coal is a solid material that can vary greatly in its chemical and physical qualities. The highest quality coals are anthracite and bituminous, which are hard, shiny, black minerals with a high energy density (the energy content per unit of weight). Lignite is a poorer grade of coal, and it is a softer, flaky material with a lower energy density. Coal is mined in various ways. If deposits occur close to the surface, they are typically extracted by strip-mining, which involves the use of huge shovels to uncover and collect the coal-bearing strata, which are then transported using immense trucks. Deeper deposits of coal are mined from underground shafts, which may follow a seam kilometers into the ground. Most coal in North America is extracted by strip-mining.

After it is mined, coal may be washed to remove some of the impurities and then ground into a powder. Most is then combusted in a large industrial facility, such as a coal-fired generating station, a use that accounts for about half of the global use of coal and 88% in Canada (Natural Resources Canada, 2014b). In addition, about 75% of the world's steel is manufactured using coal as an energy source, often as a concentrated material known as coke. Coal can also be used to manufacture synthetic petroleum.

Petroleum (crude oil) is a fluid mixture of hydrocarbons with some impurities, such as organic compounds that contain sulphur, nitrogen, and vanadium. Petroleum from different places varies greatly, from a heavy tarry material that must be heated before it will flow, to an extremely light fluid that quickly volatilizes into the atmosphere. Petroleum is mined using drilled wells, from which the liquid mineral is forced to the surface by geological pressure. Often, the natural pressure is supplemented by pumping.

A heavy form of petroleum called bitumen is also produced by mining and refining oil- sand, which is extracted in northern Alberta. Oil-sand deposits that are close to the surface are mined in immense open pits, while deeper materials are treated with steam so they will flow and are then extracted as a heavy liquid using drilled wells.

Once extracted, petroleum is transported by overland pipelines, trucks, trains, and ships to an industrial facility known as a refinery, where the crude material is separated into various constituents. The fractions may be used as a liquid fuel, or they can be manufactured into many useful materials, such as plastics and pigments. The refined fractions include the following:

- a light hydrocarbon mixture known as gasoline, which is used to fuel automobiles
- slightly heavier fractions, such as diesel fuel used by trucks and trains and a home-heating fuel
- kerosene, which is used for heating and cooking and as a fuel for airplanes
- dense residual oils, which are used as a fuel in oil-fired power plants and in large ships
- semi-solid asphalts that are used to pave roads and manufacture roofing products

Natural gas is also extracted using drilled wells. The dominant hydrocarbon in natural gas is methane, but ethane, propane, and butane are also present, as often is hydrogen sulphide. Most natural gas is transported in steel pipelines from the well sites to distant markets. Sometimes it is liquefied under pressure for transportation, particularly by ships. In Canada, however, it is distributed mostly through an extensive network of pipelines. Natural gas is used to generate electricity, to heat buildings, to cook food, to power light vehicles, and to manufacture nitrogen fertilizer.

Image 13.2. Continued exploration for non-renewable resources can discover new reserves. Because Earth is finite, however, there are limits to these discoveries, which are being approached rapidly. This enormous off-shore production platform was constructed to develop the Hibernia petroleum deposit on the Grand Banks off Newfoundland. Source: Dosya: Hibernia platform, Wikipedia Commons; http://tr.wikipedia.org/wiki/

Dosya:Hibernia_platform.jpg

Production, Reserves, and Consumption

The global production and reserves of fossil fuels are shown in Table 13.4. The production of petroleum increased by 29% between 1993 and 2013, natural gas by 64%, and coal by 83%. There is active exploration for all these fuels, and additional reserves are being discovered in various regions of the world. Fossil fuels are, however, being consumed extremely rapidly, particularly in developed and rapidly developing economies. Consequently, the expected lifetimes of the known reserves are alarmingly short, equivalent to 113 years for coal, 55 years for natural gas, and 58 years for petroleum.

These numbers should not be interpreted too literally, however, because ongoing exploration is discovering additional deposits, which add to the known reserves. This is illustrated by changes in the calculated reserve life of petroleum, which was 46 years in 1993, but twenty years later had actually increased to 58 years. Of course, this seemingly unexpected result is due to the fact that previously unknown reserves of petroleum had been discovered during that 20-year period, or rising prices had made once-uneconomic resources viable (such as the oil-sands of Alberta). Nevertheless, the discoveries will be limited by the finite amounts present on Earth, so the fact remains that the stocks of these non-renewable resources are being depleted rapidly.

Table 13.4. Global Production and Reserves of Fossil Fuels, 2013. "Proven" reserves are the total amounts of a resource that are known to exist. The reserve life is the reserves divided by the annual rate of extraction. Source: Data from British Petroleum (2014).

Fossil fuel	Proven reserves		Production		Reserve Life
	10^9 t	10^9 toe(1)	10^9 t	10^9 toe	(y)
Hard coal	403.2	198.2	-	-	-
Soft coal	488.3	240	-	-	-
Total coal	891.5	438.2	7.9	3.88	112.9
Crude oil	238.2	238.2	4.13	4.13	57.7
Natural gas	185.7(2)	167.7	3.37(2)	3.04	55.2

(1) toe = tonnes of oil equivalent, which allows all of the fossil fuels to be expressed in comparable units
(2) The reserves and production of natural gas are in 1012 m3

At the present time, petroleum is the world's most important fossil fuel resource, largely because it can easily be refined into portable liquid fuels that are readily used as a source of energy for many industrial and domestic purposes. In addition, petroleum is the major feedstock used to manufacture plastics and other synthetic materials.

About 46% of the world's proven recoverable reserves of petroleum occurs in the Middle East (Table 13.5). This fact underscores the strategic importance of that region to the global energy economy and its security. Saudi Arabia alone has 16% of the world's petroleum reserves, followed by Iraq, Iran, and Kuwait each with 6-9%. Note that the large reserves cited for Venezuela and Canada are largely for "non-conventional" sources of petroleum, such as very-heavy oil and oil-sand (respectively), which are relatively expensive to mine and refine. The world's most developed economies are in Europe, North America, and eastern Asia. Those in Europe and Asia depend heavily on petroleum imports from the Middle East, Russia, and Venezuela to maintain their consumption levels. This was once also the case for North America, but it has been much less so since about 2010 because of large increases in domestic production associated with petroleum in shale formations and oil-sand in northern Alberta.

The world's best-endowed countries in terms of total fossil-fuel resources are Russia and the United States, both of which have enormous reserves of natural gas, coal, and petroleum (Table 13.5).

Table 13.5. Reserves of Fossil Fuels in Selected Countries. The countries are listed in order of decreasing reserves of petroleum in 2013. Data are proven reserves, and are from British Petroleum (2008).

Country	Petroleum (10^9 t)	Hard Coal (10^9 t)	Soft Coal (10^9 t)	Natural Gas (10^{12} m^3)
Venezuela	46.6	0.5	-	5.6
Saudi Arabia	36.5	-	-	8.2
Canada	28.1	3.5	3.1	2
Iran	21.6	-	-	33.8
Iraq	20.2	-	-	3.6
Kuwait	14	-	-	1.8
U.A. Emirates	13	-	-	6.1
Russia	12.7	49.1	107.9	31.3
Libya	6.3	-	-	1.5
United States	5.4	108.5	128.8	9.3
Nigeria	5	-	-	5.1
Kazakhstan	3.9	21.5	12.1	1.5
China	2.5	62.2	52.3	3.3
Qatar	2.6	-	-	24.7
Brazil	2.3	-	6.6	0.5
Angola	1.7	-	-	-
Mexico	1.5	0.9	0.4	0.3
Algeria	1.5	-	-	4.5
Ecuador	1.2	-	-	-
Norway	1	-	-	2
India	0.8	56.1	4.5	1.4
Indonesia	0.5	-	28	2.9
U.K.	0.4	0.2	-	0.2
Australia	0.4	37.1	39.3	3.7

The production lives of proven recoverable Canadian reserves of fossil fuels are shown in Table 13.6. Remember, however, that the amount of the reserves is affected by new discoveries, the advent of technologies that make previously unrecoverable stocks economically viable, as well as increases in commodity prices that make it profitable to utilize once-marginal resources. In Canada, this has recently been the case of the oil-sand resource. Examination of the history of petroleum resources in Canada shows a remarkable jump in 1999, when the stocks made an leap from a value of 8.0-million tonnes (toe) in 1998, to 29.3-million toe the following year (BP, 2014). This immense increase of 265% occurred because resource analysts became convinced that the rapidly developing technologies for mining the immense oil-sand resource were economically viable, coupled with a rising value for petroleum, which also bolstered the case for developing the resource.

Most reserves of fossil fuels in Canada occur in the western provinces, as does most of the production (Table 13.7). In addition to conventional petroleum, Canada has a huge resource of oil-sand, from which a heavy bitumen is extracted that is upgraded to a synthetic petroleum (see Canadian Focus 13.1). There are about 14 million hectares of oil-sand deposits in northern Alberta, and the areas presently under development can potentially yield about 3.2 billion tonnes of synthetic oil (BP, 2014).

Table 13.6. Production, Consumption, and Reserves of Fossil Fuels in Canada, 2013. Percentage consumption refers to the fraction of Canadian production that is used within Canada. The reserve life is the proven reserves divided by the annual production. Source: Data from British Petroleum (2014).

Fossil Fuel	Canadian Production	Canadian Consumption	Percentage Consumption	Proiven Reserves	Reserve Life (y)
Petroleum (10^6 t)	193	103.5	54%	28,100	146
Gas (10^9 m^3)	154.8	103.5	67	2,000	13
Coal (10^6 t)	36.8(1)	20.3(1)	55	6,582	179

(1) toe = tonnes of oil equivalent, which allows all of the fossil fuels to be expressed in comparable units

Table 13.7. Provincial Production of Fossil Fuels, 2012. Where data are missing, the production was zero or small and not reported. Source: Data from Statistics Canada (2014b).

Region	Petroleum	Natural Gas	Coal
	(10^6 m^3/y)	(10^9 m^3/y)	(10^6 t/y)
NL	11.48	0.46	-
PE	-	-	-
NS	0.25	2.15	-
NB	-	0.11	-
QC	-	-	-
ON	0.08	0.15	-
MB	2.96	-	-
SK	27.36	5.6	-
AB	143.9	112.5	28.43
BC	2.28	35.17	-
YK	-	-	-
NT	0.84	0.19	-
NU	-	-	-
Canada	189.1	156.3	67.1

About 67% of the Canadian production of natural gas is consumed domestically, the rest being exported to the United States (Table 13.6). Similarly, about 55% of the coal production and 54% of petroleum is used domestically. However, these national data hide some important regional differences. In particular, a large fraction of the petroleum extracted in western Canada is exported to the United States, but this is offset by a substantial import of foreign oil to the eastern provinces. Overall, while Canada produced about 193-million (106) tonnes of petroleum in 2013, it consumed 104 x 106 t, exported 163 x 106 t, and imported 153 x 106 t (BP, 2014). The production value of crude oil was $45 billion in 2013, while that of oil-sand bitumen and its synthetic petroleum was $57 billion, and natural gas $16 billion (CAPP, 2014). That of coal was $4.6 billion (NRC, 2014b). Canada produces about 5% of the global production of natural gas, 5% of the petroleum, and 1% of the coal (BP, 2014). These are much larger than the 0.5% of the global population that lives in Canada.

Canadian Focus 13.1. The Oil Sands of Alberta

Oil-sand is a fossil-fuel resource that consists of a mixture of sand and clay with interstitial bitumen at a concentration of 10-12%. (Technically, these deposits are most accurately referred to as bitumen-sand, but sometimes the derogatory term of tar-sand is used.) Oil-sand occurs over a 140,000 km2 region of northern Alberta and, to a much lesser extent, in nearby Saskatchewan. Comparable deposits also occur in Venezuela.

The oil-sand resource of Alberta is immense. The total reserve is about 27.3-billion tonnes of petroleum equivalent (168-billion barrels), but the resource under "active development" in 2013 was 4.2-billion t (British Petroleum, 2014). For comparison, Saudi Arabian reserves of conventional petroleum, the largest in the world, are about 36.5-billion t.

In 2012, the production of crude bitumen plus synthetic petroleum in Alberta was 89.8-million tonnes, which was equivalent to 76% of the province's total oil production and 58% of Canada's (Statistics Canada, 2014c). About two-thirds of the petroleum is typically refined into gasoline and other liquid fuels, and the rest is used as asphalt to build roads and to manufacture roofing products.

Development of the oil-sand resource has moved quickly since the first activity began in the late 1960s. Between 1996 and 2013, a total of $376 billion was invested in new and ongoing projects, with $59 billion in 2013 alone (CAPP, 2014). In 2013, there were 13 oil-sand extraction projects. Assuming that the pace of development continues apace, comparably large investments will continue to be made over the next decade or so, especially if prices for crude oil remain high (most oil-sand operations need a selling point of about $80 per barrel to be economically viable). Most of the frenetic development is occurring near Fort McMurray, which has rapidly grown from a village in the 1960s to about 72-thousand in 2014.

Deposits of oil-sand that occur near the surface (less than about 75 m deep) are mined in open pits (strip-mined) using immense shovels, which along with the trucks they load, are the largest such machines in the world. The raw oil-sand is processed using heat and steam to yield a viscous bitumen (its room-temperature consistency is similar to molasses). The bitumen is modified with light hydrocarbon fluids to reduce its viscosity so that it can flow and be transported in a pipeline. The typical yield from mined oil sand is about 1 t of synthetic petroleum from 15 t of raw resource. About 75-90% of the bitumen present is recovered by the extraction process. The remainder, along with massive quantities of tailings (processed sand and clay), is back-filled into the huge quarries. Once the back-filled areas are filled, they will be contoured, top-dressed with previously stockpiled overburden (gravel, sand, clay, and organic muck from muskeg), and planted to restore a land-use for pasture or as forest. The industry is required to rehabilitate mined sites to a level of productivity at least that of the pre-existing ecosystem. Ultimately, about 20% of the total oil-sand resource lies close enough to the surface to potentially be extracted by open-pit mining. However, because this method was the first to be developed, about two-thirds of the recent production of oil-sand bitumen is from surface mines.

The other one-third of oil-sand bitumen production is from in situ ("in place") extraction of deposits deeper than 75 m. This is done in various ways, such as injecting steam into the deposit and then pumping the liquefied bitumen to the surface for further processing. Alternative extraction methods include the use of injected solvents to make the bitumen flowable so that it can be pumped to the surface. About 80% of the oil-sand reserves are potentially recoverable by in situ technology, which results in much less disturbance of the surface environment, compared with open-pit mining.

Image 13.3. View of an open-pit mine for the extraction of bitumen-sand in northern Alberta. Source: B.

Freedman.

Oil-sand mining and processing are energy-intensive activities that take place in huge industrial facilities. The energy to run machinery and processing facilities is obtained by burning fossil fuels, particularly natural gas, so the industry is a major emitter of greenhouse gases. The oil-sand industry has voluntarily committed to major investments in improved technology to decrease their intensity of energy use and CO2 emissions (see Canadian Focus 17.1.) By decreasing the energy intensity of their operations, the industry will emit smaller amounts of greenhouse gases per tonne of bitumen and synthetic that they produce. Nevertheless, because of the rapidly increasing scale of oil-sand operations in northern Alberta, there will be a large increase in the total amount of emissions. In fact, the growth of the oil-sand industry is responsible for most of the increase in Canadian emissions of greenhouse gases over the past decade or so.

There are additional important environmental effects of the mining and processing of oil sands. They include pollution of the atmosphere, groundwater, and surface water; the extensive destruction of natural habitats; and socio-economic disruptions of rural and Aboriginal communities. In the larger context, however, these damages must be viewed as an inevitable result of the apparent enthusiasm of Canadian society, politicians, and business interests to mine, sell, and use fossil-fuel resources at a rapid (and non-sustainable) rate. This is happening because of the perceived importance of these activities to the domestic and export economies of Canada.

Other Minerals

Other materials that are mined in large quantities in Canada include asbestos, diamonds, gypsum, limestone, potash, salt, sulphur, aggregates, and peat. Except for diamonds, these materials have a smaller commodity value (value per tonne) than metals and fossil fuels. Global or Canadian shortages of these materials are not imminent. The mining of these kinds of minerals contributed $11-bilion to the GDP of Canada in 2011 (Statistics Canada, 2014a).

Asbestos refers to s a group of tough, fibrous, incombustible silicate minerals that are used to manufacture fireproof insulation, cement additives, brake linings, and many other products. However, certain kinds of asbestos minerals have been linked to human health problems, particularly lung diseases. These hazards have greatly reduced the market for this otherwise useful mineral. As recently as 2010 about 0.18-million tonnes of asbestos were mined in Quebec, but the last two mines closed in 2011 (NRC, 2014a).

Diamonds are relatively new to the mining scene in Canada, with the first major discoveries not made until the 1990s. About 10.6-million carats of diamonds were mined in 2013, with a value of $2.0 billion. Almost all mining occurs in the Northwest Territories, with some also in Ontario, and with exploration elsewhere on the Canadian Shield.

Gypsum, a mineral composed of calcium sulphate, is used to manufacture plaster and wallboard for the construction industry. About 2.7-million tonnes of gypsum were mined in 2013, with a value of $38 million. All gypsum mining occurs in Nova Scotia.

Limestone is a rock composed of calcium carbonate. It is used to manufacture cement, as well as lime for making plaster. In addition, some limestone, and the related metamorphic rock known as marble, is quarried for use as building stone and facings. About 18-million tonnes of limestone were mined in 2013. It was used to make 11.8-million tonnes of cement with a value of $1.6 billion. Another 1.8-million tonnes of lime were manufactured, with a value of $306 million. Ontario, Quebec, and British Columbia have the largest cement industries, and Ontario the largest lime-making capacity.

Potash is a rock formed from the mineral potash feldspar, and it is mined to manufacture potassium-containing fertilizer. About 10.1-million tonnes of potash (K_2O) were mined in 2013, with a value of $6.1 billion. Potash is mined in Saskatchewan and New Brunswick.

Salt, or sodium chloride, is used in the chemical manufacturing industry, for de-icing roads, as "table salt," and as a food additive and flavouring. About 12.4-million tonnes of salt were mined in 2013, with a value of $645 million. The largest salt mines are in Ontario, Alberta, Saskatchewan, and Nova Scotia.

Sulphur is manufactured from hydrogen sulphide obtained from sour-gas wells (gas wells rich in H_2S), from pollution-control scrubbers (for SO_2) at metal smelters, and from deposits of native (or elemental) sulphur. Sulphur is used in the chemical manufacturing industries and to make fertilizer. About 6.4-million tonnes of sulphur were produced in 2013, with a value of $517 million. About 90% of the sulphur production is obtained from sour-gas wells in Alberta and Saskatchewan.

Aggregates include sand, gravel, and other materials that are mined for use in road construction and as fillers for concrete in the construction industry. Aggregates are a low-grade resource, having relatively little value per tonne. However, these materials may be available only in small quantities close to large cities, leading to local shortages. About 228-million tonnes were quarried in 2013, with a value of $1.75 billion. These materials are mined in all provinces and territories, at rates more or less related to the local construction activity.

Peat is a sub-fossil material that has developed from dead plant biomass that is hundreds to thousands of years old. It accumulates in bog wetlands, where it becomes partially decomposed (or humified). Peat is sometimes dried and burned as a source of energy, an important use in Ireland, parts of northern Europe, and Russia. In Canada, however, peat is mined for use as a horticultural material and to produce absorbent hygienic products such as diapers and sanitary napkins. About 1.3-million tonnes of peat were mined in 2013, with a value of $263 million. Most peat mining occurs in New Brunswick and Quebec.

Energy Use

It is critical for any economy to have ready access to relatively inexpensive and accessible sources of energy for commercial, industrial, and household purposes. The use of large amounts of energy is especially characteristic of developed countries, such as Canada. As has been examined previously, relatively wealthy, developed countries use much more energy (on a per-capita basis) than do poorer, less-developed countries.

Ever since people achieved a mastery of fire, they have used fuels for subsistence purposes, that is, to cook food and to keep warm. Initially, locally collected wood and other plant biomass were the fuels used for those purposes. Perhaps only one-million people were alive when fire was first domesticated, and their per-capita energy use was small. Consequently, biomass fuels were a renewable source of energy because the rate at which they were being harvested was much smaller than the rate at which new biomass was being produced by vegetation.

In modern times, however, the human population is enormously larger than it was when fire was first put to work. Moreover, many countries now have intensely industrialized economies in which per-capita energy usage is extremely high. The combination of population growth and increased per-capita energy use means that enormous amounts of energy are used in developed countries. The energy is needed to fuel industrial processes, to manufacture and run machines, to keep warm in winter and cool in summer, and to prepare food.

Most industrial energy supplies are based on the use of non-renewable resources, although certain renewable sources may also be important. For comprehensiveness, both non-renewable and renewable energy sources are discussed together in this section.

Sources of Energy

The world's major sources of industrial energy are fossil fuels and nuclear fuels, both of which are non-renewable. Hydroelectric power, generated using the renewable energy of flowing water, is also important in some regions, including much of Canada. Relatively minor energy sources, often called "alternative sources", include biomass fuels, geothermal heat, solar power, wind, and waves, all of which are potentially renewable.

Any of the above sources can be harnessed to drive a turbine, which spins an electrical generator that converts the kinetic energy of motion into electrical energy. Solar energy can also generate electricity more directly, through photovoltaic technology (see below). Electricity is one of the most important kinds of energy used in industrial societies, being widely distributed to industries and homes through a network of transmission lines. The following sections briefly describe how these various energy sources are used.

Image 13.4. Electricity generated by sing nuclear fuel or by burning coal, oil, or natural gas uses non-renewable sources of energy. This is an airphoto of the Bruce Nuclear Generating Station in Ontario, with Lake Huron in the background. Source: Chuck Szmurlo, Wikimedia Commons, http://commons.wikimedia.org/wiki/File:Bruce-Nuclear-Szmurlo.jpg

Fossil Fuels

Coal, natural gas, petroleum, and their refined products can be combusted in power plants, where the potential energy of the fuel is harnessed to generate electricity. Fossil fuels can also power machines directly, particularly in transportation, in which gasoline, diesel, liquefied natural gas, and other “portable” fuels are used in automobiles, trucks, airplanes, trains, and ships. Fossil fuels are also combusted in the furnaces of many homes and larger buildings to provide warmth during colder times of the year. The burning of fossil fuels has many environmental drawbacks, including emissions of greenhouse gases, sulphur dioxide, and other pollutants into the atmosphere.

Nuclear Fuels

Nuclear fuels contain unstable isotopes of the heavy elements uranium and plutonium (^{235}U and ^{239}Pu, respectively). These can decay through a process known as fission, which produces lighter elements while releasing 2-3 neutrons per nucleus and an enormous quantity of energy. The emitted neutrons may be absorbed by other atoms of ^{235}U or ^{239}Pu, causing them to also become unstable and undergo fission in a process known as a chain reaction. An uncontrolled chain reaction can result in a devastating nuclear explosion. In a nuclear reactor, however, the flux of neutrons is carefully regulated, which allows electricity to be produced safely and continuously.

Nuclear reactions are fundamentally different from chemical reactions, in which atoms recombine into different compounds without changing their internal structure. In nuclear fission, the atomic structure is fundamentally altered, and small amounts of matter are transformed into immense quantities of energy.

Most of the energy liberated by nuclear fission is released as heat. In a nuclear power plant, some of the heat is used to boil water. The resulting steam drives a turbine, which generates electricity. Most nuclear-fuelled power plants are huge commercial reactors that produce electricity for industrial and residential use in large urban areas (Image 13.4). Smaller reactors are sometimes used to power military ships and submarines, or for research. 235U is the fuel that is used in conventional nuclear reactors, such as the CANDU system developed and used in Canada. ^{235}U is obtained from uranium ore, which is mined in various places in the world. (Canada is a major player in uranium mining, most of which is exported; see Table 13.2.) Uranium produced by refining ore typically consists of about 99.3% non-fissile ^{238}U and only 0.7% 235U. Most commercial reactors require a fuel that has been further refined to enrich the ^{235}U concentration to about 3%. However, the Canadian-designed CANDU reactors can use non-enriched uranium as fuel.

Various elements, most of which are also radioactive (such as radon gas), are produced during fission reactions. One of these, ^{239}Pu, can also be used as a component of nuclear fuel in power plants. To obtain ^{239}Pu for this purpose (or for use in manufacturing nuclear weapons), spent fuel from nuclear generating stations is reprocessed. Other trans-uranium elements and any remaining ^{235}U (as well as non-fissile ^{238}U) can also be recovered and be used to manufacture new fuel for reactors.

So-called fast-breeder reactors are designed to optimize the production of ^{239}Pu (which occurs when an atom of ^{238}U absorbs a neutron to produce ^{239}U, which then forms ^{239}Pu by the emission of two beta electrons). Although fast-breeder reactors have been demonstrated, they have not been commercially developed. Breeder reactors produce "new" nuclear fuel (by producing plutonium) and thereby help to optimize use of the uranium resource. However, there are limits to the process because the original quantity of ^{238}U is eventually depleted. Therefore, both ^{235}U and ^{239}Pu should be considered to be non-renewable resources.

A number of important environmental problems are associated with nuclear power. These include the small but real possibility of a catastrophic accident such as a meltdown of the reactor core, which can result in the release of large amounts of radioactive material into the environment (as happened at the Chernobyl reactor in Ukraine in 1986). Nuclear reactions also produce extremely toxic, long-lived radioactive by-products (such as plutonium), which must be safely managed for very long periods of time (up to tens of thousands of years). Enormous quantities of these "high-level" wastes are stockpiled in Canada and in other countries that use nuclear power, but so far there are no permanent solutions to the problem of their long-term management. Another problem is the emission of toxic radon gas and radioactivity from "low-level" wastes associated with uranium mines, structural elements of nuclear power plants, and other sources.

Fusion is another kind of energy-producing nuclear reaction. This process occurs when light nuclei are forced to combine under conditions of extremely high temperature (millions of degrees) and pressure, resulting in an enormous release of energy. Fusion usually involves the combining of hydrogen isotopes. One common fusion reaction involves two protons (two hydrogen nuclei, ^{1}H) fusing to form a deuterium nucleus (composed of one proton and one neutron, ^{2}H), while also emitting a beta electron and an extremely large amount of energy.

Fusion reactions occur naturally in the interior of the Sun and other stars, and they can also be initiated by exposing hydrogen to the enormous heat and pressure generated by a fission nuclear explosion, as occurs in a so-called hydrogen bomb. However, nuclear technologists have not yet designed a system that can control fusion reactions to the degree necessary to generate electricity in an economic system. If this technology is ever developed, it would be an enormous benefit to industrial society. It would mean that virtually unlimited supplies of hydrogen fuel for fusion reactors could be extracted from the oceans, which would essentially eliminate constraints on energy supply. So far, however, controlled fusion reactions remain the stuff of science fiction.

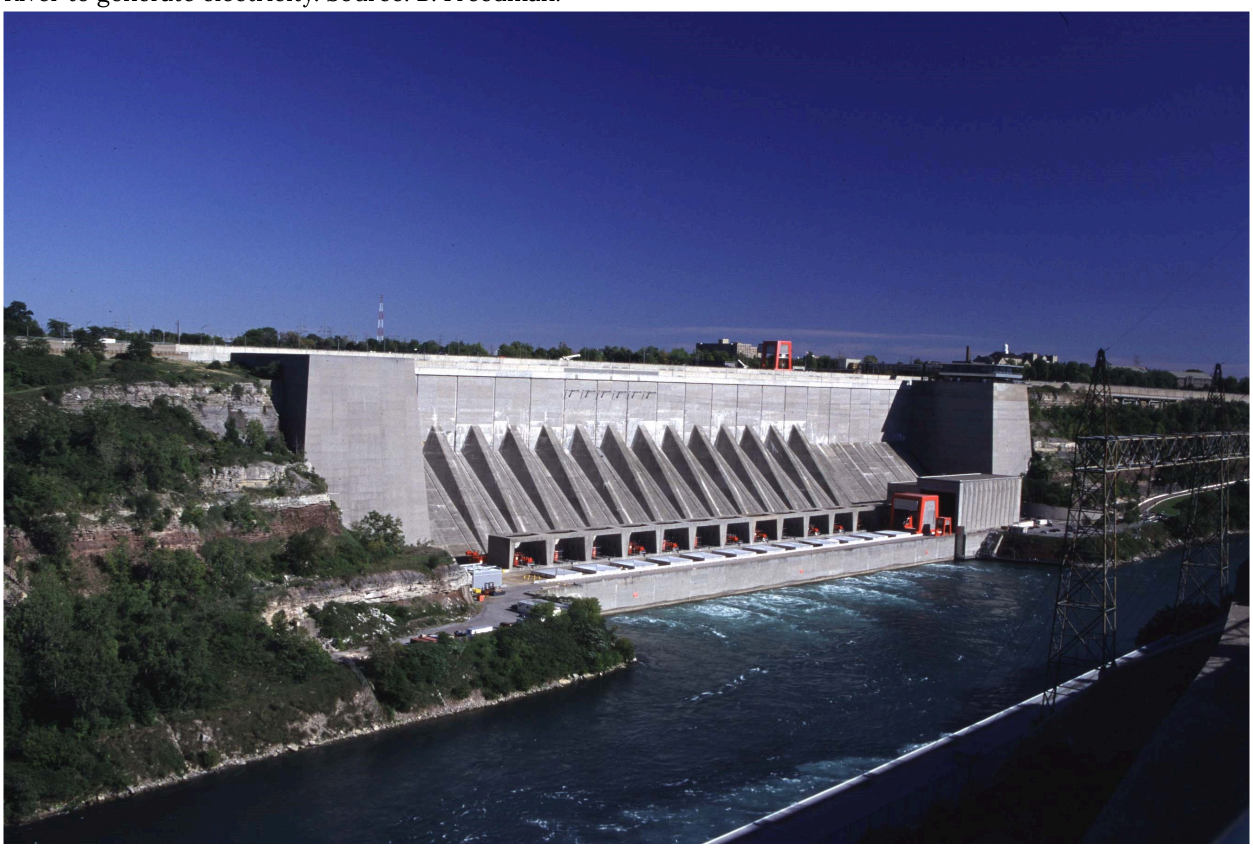
Hydroelectric Energy

Hydroelectric energy involves harnessing the kinetic energy of flowing water to drive a turbine that generates electricity. Because the energy of flowing water develops naturally through the hydrologic cycle, hydroelectricity is a renewable source of energy. There are two classes of technologies for the generation of hydroelectricity.

- Run-of-the-river hydroelectricity involves tapping the natural flow of a watercourse without developing a large up-river storage reservoir. Consequently, this electricity generation depends on the natural patterns of river flow and is highly seasonal.
- Reservoir-generated hydroelectricity involves the construction of a dam in a river to store a huge quantity of water in a lake-like waterbody. The reservoir accumulates part of the seasonal high flow so that the generation of electricity can occur relatively steadily throughout the year. Some enormous reservoirs have been developed by flooding extensive tracts of land that had previously been covered by forest and wetlands in various places in Canada, such as in British Columbia, Labrador, Manitoba, and Quebec.

Canada's largest hydroelectric generating facilities are located Churchill Falls in Labrador with a capacity of 5,429 megawatts (MW), La Grande-2 in northern Quebec with 5,328 MW, G.M. Shrum in British Columbia with 2,730 MW, and La Grande 4 and 3 in Quebec, with 2,651 and 2,304 MW, respectively. All of these facilities have large reservoirs to store water. Although hydroelectric energy is renewable, important environmental impacts are associated with use of this technology. Changes in the amount and timing of water flow in rivers cause important ecological damages, as does the extensive flooding that occurs when a reservoir is developed (see Chapter 20).

Image 13.5. Hydroelectricity is a renewable source of energy. This facility taps part of the flow of the Niagara River to generate electricity. Source: B. Freedman.



Solar Energy

Solar energy is continuously available during the day, and it can be tapped in various ways as a renewable source of energy. For example, it is stored by plants as they grow, so that their biomass can be harvested and combusted to release its potential energy (see Biomass Energy, below).

Solar energy can also be trapped within a glass-enclosed space. This happens because glass is transparent to visible wavelengths of sunlight, but not to most of the infrared. This allows the use of passive solar or "greenhouse" designs to heat buildings. Solar energy can also be captured using black, highly absorptive surfaces to heat enclosed water or another fluid, which can then be distributed through piping to warm the interior of a building.

Solar energy can also be used to generate electricity using photovoltaic technology (solar cells), which converts electromagnetic energy directly into electricity. In another technology, large, extremely reflective parabolic mirrors are used to focus sunlight onto an enclosed volume that contains water or another fluid, which becomes heated and generates steam that is used to drive a turbine to generate electricity.

Geothermal Energy

Geothermal energy can be tapped in the very few places where magma occurs relatively close to the surface and heats ground water. The boiling-hot water can be piped to the surface, where its heat content is used to warm buildings or to generate electricity. In addition, the smaller energy content of slightly warmed geothermal water, which is present almost everywhere, can be accessed using heat-pump technology and used for space heating or to provide warm water for a manufacturing process. Geothermal energy is a renewable source as long as the supply of groundwater available to be heated within the ground is not depleted by excessive pumping.

Wind Energy

The kinetic energy of moving air masses, or wind energy, can be tapped and used in various ways. A sailboat uses wind energy to move through the water, a windmill may be used to power the lifting of groundwater for use at the surface, and wind turbines are designed to generate electricity. Extensive wind-farms, consisting of arrays of highly efficient wind-driven turbines, have been constructed to generate electricity in consistently windy places in many parts of the world. In 2014, Canada had an installed wind-farm capacity of 8,517 MW, of which 24 had a capacity of greater than 100 MW (Canadian Wind Energy Association, 2014). The largest wind-farms are Seigneurie de Beaupré (QC, 272 MW), Gros-Morne (QC, 212 MW), Amaranth (ON, 200 MW), and Wolfe Island (197 MW).

Image 13.6. Wind is increasingly being used as a source of commercial energy in Canada. These wind turbines are operating near Tilbury in southwestern Ontario. Source: B. Freedman.

Tidal Energy

Tidal cycles develop because of the gravitational attraction between Earth and the Moon. In a few coastal places, tidal energy, the kinetic energy of tidal flows, can be harnessed to drive turbines and generate electricity. The Bay of Fundy in eastern Canada has enormous tides, which can exceed 16 m at the head of the bay. A medium-scale (20 MW) tidal-power facility has been developed at Annapolis Royal in Nova Scotia. There is potential for much more tidal power development within the Bay of Fundy, and there are ongoing technological studies to install additional facilities at various places there. The new installations will use tidal-powered turbines that are laid on the bottom or suspended in the water column, which avoids the environmental damage associated with a dam.

Wave Energy

Waves on the ocean surface are another manifestation of kinetic energy. Wave energy can be harnessed using specially designed buoys that generate electricity as they bob up and down, although this technology has not yet been developed on a commercial scale.

Biomass Energy

The biomass of trees and other plants contains chemical potential energy. This biomass energy is actually solar energy that has been fixed through photosynthesis. Peat, mined from bogs, is a kind of sub-fossil biomass.

Like hydrocarbon fuels, biomass can be combusted to provide thermal energy for industrial purposes and to heat homes and larger buildings. Biomass can also be combusted in industrial-scale generating stations, usually to generate steam, which may be used to drive a turbine that generates electricity. Biomass can also be used to manufacture methanol, which can be used as a liquid fuel in vehicles and for other purposes.

If the ecosystems from which biomass is harvested are managed to allow post-harvest regeneration of the vegetation, this source of energy can be considered a renewable resource. Peat, however, is always mined faster than the slow rate at which it accumulates in bogs and other wetlands, so it is not a renewable source of biomass energy.

Energy Consumption

The consumption of energy varies greatly among countries, largely depending on differences in their population and degree of development and industrialization (Table 13.8). In general, the per-capita use of primary energy (this refers to fuels that are commercially traded, including renewables used to generate electricity) in less-developed countries is less than about 1 toe per person per year. However, in the less-developed countries there is a relatively larger use of non-commercial or "traditional" fuels for purposes of subsistence and local commerce, such as wood, charcoal, dried animal manure, and food-processing residues such as coconut shells and bagasse (a residue of sugar cane pressing). The use of traditional fuels is not reflected in the data of Table 13.8.

Countries that are developing rapidly are intermediate in their per-capita energy consumption, but their rates of energy use are increasing rapidly due to their industrialization. In Malaysia, for example, the national consumption of primary energy increased by 167% between 1993 and 2013, while in South Korea it increased by 118%, in China by 270%, in India by 189%, and in Brazil by 103% (by comparison, the growth was 17% in Canada and 11% in the U.S.; WRI, 2014). While the use of energy has grown in these and other rapidly developing countries, their reliance on traditional fuels has dropped. This happens because traditional fuels are relatively bulky, smoky, and less convenient to use than electricity or fossil fuels, particularly in the urban environments where people are living in increasingly large numbers. In addition, the supplies of wood, charcoal, and other traditional fuels have become severely depleted in most rapidly developing countries, particularly near urban areas.

Relatively developed countries have a high per-capita consumption of energy (Table 13.8). Their energy use is typically more than 3 toe/person and almost entirely involves electricity and fossil fuels. The world's most energy-intensive economies, on a per-capita basis, are those of Canada and the United States (9.38 and 7.13 toe/person, respectively) , which have more than 40-50 times the per-capita usage of people living in the least-developed economies of the world.

Table 13.8. Consumption of Primary Energy in Selected Countries in 2013. Primary energy refers to fuels that are commercially traded, including renewables used to generate electricity. National energy consumption mostly reflects the size of the economy of a country and its population, while per-capita use allows for a comparison of the lifestyle-intensity of average people. Source: Data from BP (2014).

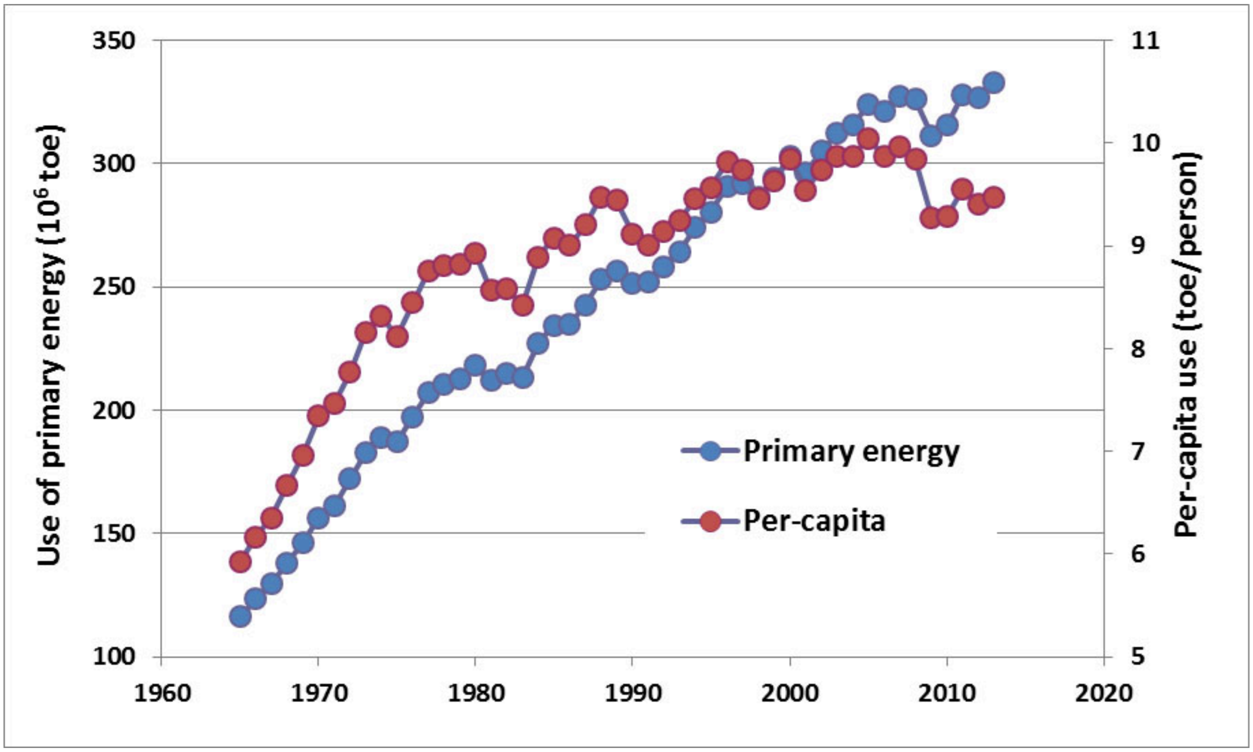
Country	Energy Consumption		
	National	Per-capita	Renewable
	(10^6 toe)	(toe/person)	(%)
Less-Developed Countries			
Bangladesh	27	0.17	0.9
Egypt	87	0.99	3.8
Pakistan	70	0.36	10.7
Peru	22	0.71	23
Philippines	32	0.32	14.3
Rapidly Developing Countries			
Brazil	284	1.41	35.4
China	2852	2.09	8.7
India	595	0.46	7
Russia	699	4.86	5.9
More-Developed Countries			
Canada	333	9.38	27.9
Germany	325	4.02	10.6
Japan	474	3.73	5.9
United Kingdom	200	3.1	6
United States	2266	7.13	5.3

In terms of the total amounts of energy being used, the largest consumers are China (2,852 toe in 2013), the United States (2,266), and Russia (699 toe). Canada is a highly developed country, but because of moderately-sized population and economy, it uses considerably less energy in total, about 333 toe.

The use of commercial energy in Canada increased by 116% between 1965 and 1990, and by 33% between 1990 and 2013, while per-capita consumption increased by 54% and 4% during the same periods, respectively (Figure 13.2). The fact that per-capita energy use increased much less quickly than national consumption suggests that Canadians have become more efficient in their use of energy, especially during the more recent period. Smaller automobiles, improved gas economy of vehicles, better insulation of residences and commercial buildings, and the use of more efficient industrial processes have all contributed to this increased efficiency. Nevertheless, although these gains of energy efficiency have been substantial, they have been more than offset by growth in the per-capita ownership of automobiles, consumer electronics, and other energy-demanding products and technologies. Also important have been large increases in industrial energy use associated with oil-sands developments in Alberta during the past several decades. These latter changes have caused the overall use of energy in Canada to increase substantially.

Figure 13.2. Trends in the Consumption of Primary Energy in Canada. Note the different scales of national energy consumption (1018 J) and per capita consumption (1012 J/person). Sources: Data from British Petroleum

(2013).



The intensive energy usage by Canadians reflects the high degree of industrialization of our national economy. Also significant is the relative affluence of average Canadians (compared to the global average). Wealth allows people to lead a relatively luxurious lifestyle, with ready access to energy-consuming amenities such as motor vehicles, home appliances, space heating, and air conditioning. Canada is also a large country, so there are relatively large expenditures of energy for travelling. In addition, the cold winter climate means that people use a great deal of energy to keep warm.

Energy Production

As was examined in Chapter 12, a sustainable enterprise cannot be supported primarily by the mining of non-renewable sources of energy or other resources. Therefore, a sustainable economy must be based on the use of renewable sources of energy.

However, most energy production in industrialized countries is based on non-renewable sources. Averaged across the relatively developed countries shown in Table 13.9, non-renewable fossil fuels and nuclear power account for 91% of the total use of energy. Renewable sources, such as hydroelectric, geothermal, solar, wind, and biomass fuels, account for only about 9%. With such a small reliance on non-renewable sources, it is clear that the major economies of the world are not close to having developed sustainable energy systems. Considering the rapid rate at which reserves of non-renewable energy resources are being depleted, one wonders how long the energy-intensive economies of developed nations can be maintained.

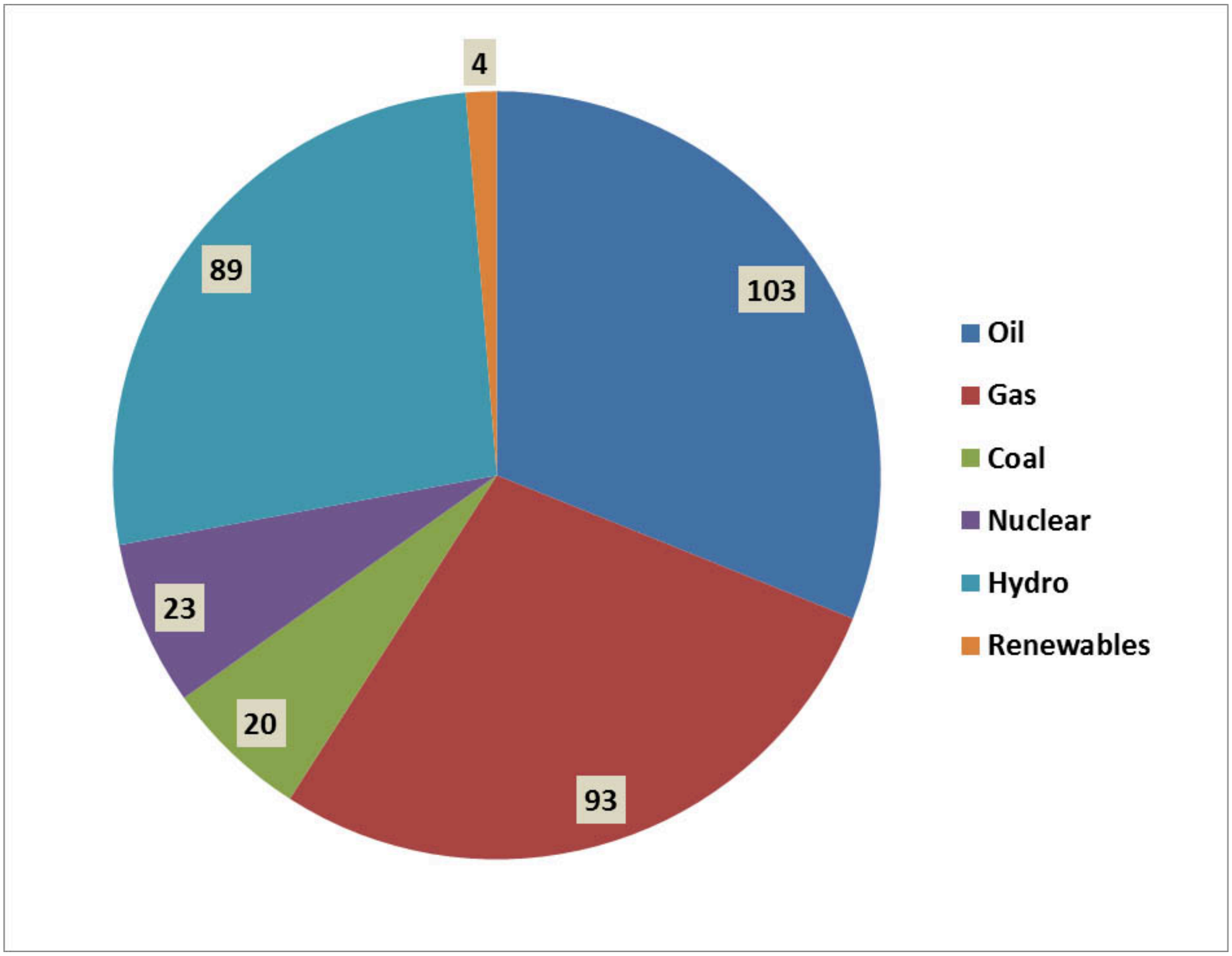
Table 13.9. Energy Consumption in Selected Countries in 2013. Data are in units of 106 tonnes of oil equivalent.

Source: Data from British Petroleum (2014).

	Oil	Gas	Coal	Nuclear	Hydro	Renewables	TOTAL
Sweden	14.3	1	1.7	15.1	13.9	5	**51**
Belgium	31	15.1	2.9	9.6	0.1	2.8	**61.7**
Argentina	29.4	43.2	0.7	1.4	9.2	0.7	**84.5**
Netherlands	41.4	33.4	8.3	0.6	<0.1	3	**86.8**
Australia	47	16.1	45	0	4.5	3.4	**116**
Spain	59.3	26.1	10.3	12.8	8.3	16.8	**134**
Italy	61.8	57.8	14.6	0	11.6	13	**159**
U.K.	69.8	65.8	36.5	16	1.1	10.9	**200**
Saudi Arabia	135	92.7	0	0	0	0	**228**
France	80.3	38.6	12.2	95.9	15.5	5.9	**248**
Brazil	133	33.9	13.7	3.3	87.2	13.2	**284**
Germany	112	75.3	81.3	22	4.6	29.7	**325**
Canada	104	93.1	20.3	23.1	88.6	4.3	**333**
Japan	209	105	129	3.3	18.6	9.4	**474**
India	175	46.3	324	7.5	29.8	11.7	**595**
Russia	153	372	93.5	39.1	41	0.1	**699**
U.S.	831	671	456	188	61.5	58.6	**2266**
China	507	146	1925	25	206	42.9	**2852**
World	**4185**	**3020**	**3827**	**563**	**856**	**279**	**12730**

Of Canada's total consumption of primary energy in 2013, 31% came from petroleum, 28% came from natural gas, 6% from coal, and 7% from nuclear energy (Figure 13.3). These non-renewable energy sources account for 72% of the total use of primary energy in Canada. Most of the remaining production comes from hydroelectricity (27%), which is renewable (although it can cause substantial environmental damage through flooding to create reservoirs, and can require large amounts of non-renewable resources for the construction of dams, transmission lines, and related infrastructure; see Chapter 20). Another 1.3% involves the use of other renewable sources of energy, such as wind and biomass. There are also, of course, environmental impacts of the harvesting of trees and other kinds of biomass for use as fuel (see Chapter 23).

Figure 13.3. Sources of Primary Energy in Canada. Overall, about 86% of commercial energy consumption is derived from non-renewable sources. The data are for 2006 and are in units of 106 tonnes of oil equivalent. Biomass includes both solid and liquid forms, and "other renewables" includes geothermal, solar, and wind. Source: Data from British Petroleum (2008)



Electricity produced by public or private utilities accounts for much of the energy used by industry, institutions, and residences in Canada. About 61% of the 615-million MW-hours of electricity produced in 2012 was generated from hydroelectric utilities, 22% from fossil-fuelled sources, and 15% by nuclear technology (Statistics Canada, 2013). Within the renewable sector, hydro accounted for 96% of the electricity production, wind for 3%, and others for 1%.

Conclusions

Non-renewable resources are always diminished as they are used. Although non-renewables can be used with great enthusiasm to achieve economic growth, they cannot be the basis of a sustainable economy. Only renewable resources can play that fundamental role. In this chapter we learned that the non-renewable resources that are vital to the functioning of modern "advanced" economies, such as that of Canada, are being rapidly depleted. For instance, the life index of the global reserves of copper is only about 39 years, while that of nickel is 30 years, and zinc 19 years. Among fossil fuels, the life index of the global reserves of petroleum is about 58 years, while that of natural gas is 55 years, and coal 113 years. While it is true that continuing exploration will find additional reserves of these and other non-renewable resources, there are limits to those further discoveries. In addition, about 72% of the consumption of primary energy in Canada is based on non-renewable sources, as is 39% of the electricity generation. Because the reserves of all non-renewable resources are being depleted rapidly, both in Canada and around the world, the longer-term sustainability of the energy-intensive economies of developed countries, and the lifestyles of their citizens, is highly doubtful.

Questions for Review

1. Using information from this chapter, describe the Canadian and global production and use of non-renewable resources.
2. Show how industrialized countries rely mostly on non-renewable resources to sustain their economies. Will this kind of resource use be able to continue for very long? Why or why not?
3. What are the various non-renewable and renewable sources of energy available for use in industrialized countries? What are the future prospects for increasing the use of renewable sources?
4. What are the key sources of energy and materials that are ultimately based on sunlight? Which of these resources would you consider to be renewable, and which not?

Questions for Discussion

1. Outline the ways in which you use energy, both directly and indirectly. For each of your major uses, how could you decrease your energy consumption? How would a decrease in energy consumption affect your lifestyle?
2. What are the apparent barriers to the widespread adoption of renewable sources of materials and energy in advanced economies (such as Canada)?
3. What are the roles of non-renewable and renewable resources in a sustainable economy?
4. Biomass, wind, and hydroelectricity are all examples of renewable sources of energy. Examine the energy-source distributions for several countries in Table 13.9 and discuss why they are not relying more on renewable sources of energy.
5. Make lists of the apparent benefits and risks associated with nuclear power. Focus on resource and environmental issues, such as the depletion of fossil fuels, emissions of greenhouse gases, and the long-term disposal of toxic and hazardous wastes.

Exploring Issues

1. A committee of the House of Commons is examining the sustainability of the Canadian economy. You are an environmental scientist, and the committee has asked you to advise them on improving the sustainability of the use of materials and energy. What would you tell them about the sustainability of present use? What improvements would you recommend?

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Chapter 14 ~ Renewable Resources

Key Concepts

After completing this chapter, you will be able to:

1. List the major classes of renewable resources and describe the character of each.
2. Identify ways by which renewable resources can be degraded by excessive harvesting or inappropriate management.
3. Describe the renewable resource base of Canada and discuss whether those resources are being used in a sustainable fashion.
4. Show how the commercial hunts of cod and whales have represented the "mining" of potentially renewable resources.

Introduction

Renewable resources are capable of regenerating after harvesting, so their use can potentially be sustained forever. For this to happen, however, the rate of use must be less than that of regeneration – otherwise, a renewable resource is being mined, or being used as if it was a non-renewable resource.

The most important classes of renewable resources are water, agricultural soil quality, forests, and hunted animals such as fish, deer, and waterfowl. In the following sections we examine the use and abuse of these potentially renewable resources. (We previously looked at renewable sources of energy, such as hydroelectricity, solar power, wind, and biomass, in Chapter 13.)

Fresh Water

Although water is extremely abundant on Earth, about 97% of it occurs in the oceans and is too salty for many uses by organisms or the human economy. Of the remaining 3% that is fresh water, almost all occurs in glacial ice and is not easily available for use by people or other species. The "available" forms of fresh water mostly occur in the surface waters of lakes and rivers, or as groundwater in soil or rocks. These limited stocks of fresh water are a vital resource for ecosystem processes and for many of the economic activities of people.

Surface Water

Surface water is a collective term for lakes, ponds, streams, and rivers. Fresh water from these bodies can be used for drinking, cleaning, agricultural irrigation, generation of hydroelectricity, industrial cooling, and recreation. Surface waters are abundant in regions where the climate is characterized by more precipitation than evapotranspiration, which allows the aqueous resource to be recharged (see Chapter 3). However, in drier regions surface waters are uncommon or rare, and this presents a natural constraint on ecological and economic development.

In regions where there is a low rate of recharge of surface water, excessive use for irrigation or industrial or municipal purposes (such as drinking, washing, and flushing toilets) can rapidly deplete the resource. A deficiency of surface water in an arid region can lead to conflicts between local areas, and even between countries. Each region wants to have access to as much water as possible to support its agricultural and industrial activities and to service its urban areas. This is the reason why severe competition for surface water is a chronic problem in drier parts of the world, particularly in the Middle East, much of Africa, and southwestern North America.

In the Middle East, for example, the watershed of the Jordan River is shared by Israel, Jordan, Lebanon, and Syria. All of these countries have a dry climate, and all demand a share of the critical water resource. Also in the Middle East, the watersheds of the Tigris and Euphrates Rivers originate in Turkey, while Iraq and (to a lesser degree) Syria are highly dependent down-river users that are threatened by hydroelectric and agricultural diversion schemes in Turkey. In northern Africa, the watershed of the Nile River encompasses territory in nine countries: Egypt, Ethiopia, Sudan, Rwanda, Burundi, Democratic Republic of Congo, Tanzania, Kenya, and Uganda. The collective needs of those countries for water exceed the limited capacity of even that great river.

In North America, the most contentious water-use conflicts involve the Colorado River and the Rio Grande, which are shared by the United States and Mexico. The use of water from these rivers is extremely intensive, particularly for irrigated agriculture. In fact, virtually all the flow of the Colorado River could potentially be used in the United States before it even reaches northern Mexico, where there is also a substantial demand. In addition, the chemical quality of the water is degraded by inputs of dissolved salts mobilized by agricultural practices in the U.S., a factor that severely compromises the potential use of any remaining river-water flow in Mexico. Because this binational problem is important, the two federal governments have negotiated a treaty that guarantees a minimum quantity of flow and water quality where the Colorado River crosses the international boundary. The Rio Grande has a similar problem, which is also being dealt with by a treaty between the two countries.

Even where surface waters are relatively abundant, their quality can be degraded by pollution by nutrients, hydrocarbons, pesticides, metals, or oxygen-consuming organic matter. Excessive nutrients can increase the productivity of surface waters, causing a problem known as eutrophication (see Chapter 20). Biological contamination by bacteria, viruses, and parasites from fecal matter of humans, pets, or livestock can render the water unfit for drinking or even for recreation (Chapter 25). Thermal pollution, due to the release of heat from power plants or factories, can also cause ecological damage in receiving waterbodies. The effects of acidification, metals, pesticides, and eroded materials can also be an important issue for surface waters, as is examined in detail in various following chapters.

Groundwater

Groundwater occurs in underground reservoirs of water known as aquifers, in which the fluid is present in the interstitial spaces and cracks of overburden and porous bedrock (see Figure 3.2 in Chapter 3). Groundwater can be an extremely valuable natural resource, especially in regions where lakes and rivers are not abundant. It is typically accessed by drilling and pumping to the surface.

Groundwater stores are recharged through the hydrologic cycle. This happens as water from precipitation slowly percolates downward through surface overburden and bedrock in a sometimes extensive area known as a recharge zone. In humid regions, where the amount of precipitation is greater than the quantity of water that is dissipated by evapotranspiration and surface flows, the excess serves to recharge groundwater. An aquifer that quickly recharges can sustain a high rate of groundwater pumping and can be managed as a renewable resource.

In drier environments, however, the amount of precipitation available to recharge groundwater is much smaller. An aquifer that recharges extremely slowly is essentially stocked with fossil water (or paleowater) that has accumulated over thousands of years or more. Such aquifers have little capability to recharge if their groundwater is used rapidly, so their stores are easily depleted. Slowly recharging aquifers are essentially a non-renewable resource, whose reserves are “mined” by excessive use.

The largest aquifer in the world, known as the Ogalalla, occurs beneath about 450-thousand km^2 of arid land in the western United States. The Ogalalla aquifer is recharged very slowly by underground seepage that mostly originates with precipitation falling on distant mountains. Most of the groundwater in the Ogalalla is fossil water that has accumulated during tens of thousands of years of sluggish infiltration. Although the aquifer is enormous (containing about 2.5 billion litres), it is being rapidly depleted by pumping at more than 170-thousand drilled wells. Most of the wells draw water for use in irrigated agriculture, and others for drinking and other household purposes. The level of the Ogalalla aquifer is decreasing by as much as 1 m/year in zones of intensive use, while the annual recharge rate is only about 1 mm/y. Clearly, the Ogalalla aquifer is being rapidly mined. Once it is effectively drained – which is likely to occur within several decades – irrigated agriculture in much of the southwestern United States may fail.

Groundwater resources are also threatened by pollution when chemicals are deliberately or accidentally discarded into the ground. For instance, groundwater may be polluted by gasoline leaking from underground storage tanks at service stations, degraded by the infiltration of agricultural fertilizer and pesticides, or contaminated by bacteria and nutrients seeping from manured fields or septic systems. Badly contaminated groundwater may not be usable as a source of drinking water, and even for the irrigation of crops.

It is important to understand that groundwater may be rendered persistently unusable as a source of drinking water if it has been contaminated by hazardous or toxic substances, such as hydrocarbons (gasoline, engine oil, or home-heating fuel), pesticides, nitrate originating with agricultural fertilizer, or Escherichia coli and other pathogens originating with the dumping of livestock manure or untreated urban sewage sludge. Because many aquifers recharge and turn over slowly, it may take decades or even centuries for these kinds of contaminants to be purged from the system. In general, the "dilution solution to pollution" does not work well when groundwater is the receiving medium. It is always precautionary to avoid activities that carry a risk of damaging the quality of water in an aquifer.

Groundwater can also be degraded by the intrusion of salt water, which can render the resource unfit for drinking or irrigation. In areas close to an ocean, deeper saline groundwater is typically overlain by a surface layer of fresh water (which is less dense than salt water and therefore "floats" above it). If fresh groundwater is withdrawn at a rate faster than the recharge capability of an aquifer, the deeper salt water will rise. Once this happens, it is extremely difficult to displace the salt water, and the ability of the aquifer to supply fresh water may have been destroyed.

Water Supply and Use

The regions of the world with the smallest per-capita water resources are Asia, Africa, and Europe, a pattern that partly reflects the high population densities of those continents. In general, Canada has abundant supplies of both surface water and groundwater. Nevertheless, water is scarce in relatively arid regions of our country, such as southern parts of the Prairie Provinces and southeastern British Columbia. There, the shortage of water for irrigation is a constraint on agricultural development, a problem that may intensify in the future, according to most climate-warming scenarios.

Groundwater is an important resource in some regions of Canada, particularly where surface water is not abundant or its chemical quality is poor. Often, groundwater is naturally cleaner than surface water and is therefore better suited for many purposes, especially household use. Sometimes, however, groundwater quality is impaired through naturally high concentrations of calcium, iron, and other chemicals.

In general, national patterns of water use are influenced by the degree and kind of economic development, the population size, and amounts of rainfall. Among the less-developed nations, those that depend heavily on irrigated agriculture have a relatively water use, with agriculture accounting for more than 85% of the total (Table 14.1). However, many less-developed countries with an arid climate, such as Ethiopia, Kenya, Somalia, and others, would also benefit greatly from having more irrigated agriculture. However, these countries do not have access to sufficient water for this kind of management, so per-capita water use, even while largely agricultural, remains small.

Table 14.1. Water Supply and Use in Selected Countries, 2014. Source: Data from FAO (2014a).

Country	Per-capita Supply (m^3/person.yr)	Per-capita Use (m^3/person.yr)	Sectoral Use (%)		
			Municipal	Industry	Agriculture
Less-Developed					
Algeria	300	176	24	15	61
Bolivia	53,800	199	6	2	92
Brazil	43,150	377	23	17	60
India	1,550	615	7	2	91
Indonesia	8,100	527	11	7	82
Nigeria	1,650	89	31	15	54
Pakistan	1,350	1,024	5	2	93
Saudi Arabia	83	913	9	3	88
Tanzania	1,950	144	10	<1	90
Developed					
Australia	21,100	1,145	15	11	74
Canada	82,500	1,590	19	69	12
Germany	1,900	387	16	84	<1
Japan	3,900	713	19	18	63
United States	9,600	1,575	14	46	40

Some developed countries have rather high per-capita water use. Canada and the United States, for example, use much of their surface water for generating hydroelectricity. In addition, the western United States has invested heavily in irrigated agriculture. Canadians use about 5 billion cubic metres of water per year from both surface-water and groundwater sources. Only about 4% of that total water usage is groundwater. However, about 12% of Canadians rely on groundwater for domestic use (Table 14.2).

Table 14.2. Use of Water by Households in Canada, 2011. Municipal sources refer to a centralized facility to treat and distribute water. Non-municipal sources are almost entirely private wells. Groundwater refers to the percent of household water that is derived from this source. Per-capita use refers to households. Source: Data from Environment Canada (2011) and Statistics Canada (2013).

	Source of Water (%)		Groundwater	Per-Capita Use
	Municipal	Non-Municipal	(%)	(L/person/day)
Canada	86	12	12	251
NL	85	15	6	395
NS	61	38	9	189
PE	52	48	100	292
NB	56	44	41	394
QC	87	13	8	386
ON	86	11	14	225
MB	88	11	8	199
SK	93	7	14	238
AB	91	9	5	209
BC	92	7	12	353

Water is used for myriad purposes in Canada, by all individuals as well as municipal, institutional, and industrial users. Averaged across the country, about 66% of the total water use is to cool thermal electric plants (fuelled by either fossil fuels or nuclear power), 13%, for manufacturing purposes, 11%, in municipalities (including residential use), 5%, in agriculture (mostly for irrigation), and 2%, for the mining and fossil-fuel industries (in 2005; Statistics Canada, 2013).

Within the home, about 35% of the total use of water is typically for showers and baths, 30%, to flush toilets, 20%, to do laundry, 10%, for drinking, and 5%, for cleaning (Environment Canada, 2014). The water returned to the environment after these various uses is typically degraded in quality because of the presence of various kinds of dissolved and suspended substances.

In addition, about 12% of the water used for various purposes is consumed during the process, This occurs because some of the water evaporates into the atmosphere so that the discharge of used water is smaller than the quantity initially withdrawn. This is particularly true of most agricultural uses, in which much of the applied water evaporates. This is a reason why about 58% of the water used in the Prairie Provinces is consumed during the process, compared with only 2% of that used in Ontario.

In addition, Canada manages the flow of tremendous quantities of surface water using dams and reservoirs (see Chapter 20). This is done to generate hydroelectricity, control flooding, accumulate water for irrigation, and manage municipal reservoirs. Canada has about 930 large dams (taller than 15m), of which 64% are primarily used to provide hydroelectricity; 9% are multipurpose, 9% to confine mining tailings, 6% for municipal water supply, 5% for irrigation, and 7% for other purposes (Environment Canada, 2010). There are thousands of additional smaller dams as well.

Environmental Issues 14.1. Bad Water at Walkerton

In 2000, the town of Walkerton in southern Ontario suffered a widespread outbreak of water-borne disease caused by contamination of the town's improperly treated water-supply system. After drinking tap water supplied by the town, hundreds of people suffered the debilitating symptoms of poisoning by toxic E. coli bacteria, and seven people died.

Like many towns and cities, Walkerton provides its citizens with drinking water, in this case extracted using a system of drilled wells. Unfortunately, E. coli polluted the groundwater in one of the wellfields. This was likely caused by livestock manure that had been spread on the surface of nearby agricultural fields. This practice is commonly used to discard the enormous amounts of fecal waste generated by livestock in Canada.

A subsequent inquiry discovered a remarkable combination of irresponsibility and incompetence on the part of town officials. Initially, the bacterial pollution was not detected by routine water-quality monitoring, but even when it was discovered, sensible action was not immediately taken to deal with the problem. According to the local Medical Officer of Health, officials in the Walkerton Public Utilities Commission knew about the E. coli pollution for several days before they informed the public about the hazard. Meanwhile, people continued to drink their tapwater, which resulted in hundreds of them becoming severely ill. Seven people died from their bacterial poisoning.

A post-disaster study reported that the Walkerton tragedy caused direct economic damage of about $6.9 million to the citizens and businesses of the town and decreased property values by $1.1 million. Additional economic costs included more than $9 million to fix the water system and $3.5 million spent on legal fees by the Government of Ontario. However, if the indirect costs of illness and suffering are also considered, the incident may have caused damages equivalent to $65–155 million.

Obvious lessons to be learned from the Walkerton tragedy include the need for (1) competent local maintenance and monitoring of public water supplies; (2) oversight of the local agencies by higher authorities (in this case, the Provincial Government); and (3) sensible regulation and close monitoring of the disposal and environmental effects of the enormous amounts of untreated livestock sewage that are produced in Canada.

Agricultural Resources

The production of an agricultural crop is measured in gross units, such as tonnes of wheat harvested on a farm, in a region, or in a country as a whole. The production is related to several factors, including the amount of land under cultivation and the productivity of the crop.

By comparison, the productivity is a rate function and is standardized per unit area and unit time, such as the tonnes of wheat harvested per hectare in a particular year. The productivity is related to the management system being used, plus a vital quality of the land that is referred to as site capability.

Ultimately, the amount of agricultural land in any region (and on Earth) is a limited resource. To some degree, the area of land suitable for cultivating crops can be increased by clearing the pre-existing natural forest and grassland that may be growing on fertile sites, and by draining certain kinds of wetlands. There are, however, finite areas of those kinds of natural ecosystems that are suitable for conversion into arable land. Only about 30% of Earth's surface is terrestrial, and most of that land is too cold, hot, dry, wet, rocky, or infertile to be converted into an agricultural land-use.

Image 14.1. Agricultural production relies on rainfall and site capability, which supply moisture, nutrients, and other factors crucial to plant growth. This is a view of a hayfield on Prince Edward Island. Source: B. Freedman.

Some countries still have substantial areas of natural ecosystems that are suitable for conversion. Most of those countries are less-developed and have a rapidly growing population, and they are actively pursuing this tactic of economic development by clearing tropical rainforest, savannah, and wetlands (see Table 14.3 for examples of recent changes). Other less-developed countries have few remaining areas of natural land that are suitable for agricultural development. In spite of their rapidly growing populations, these countries have not managed to create much additional cropland in the past several decades. For instance, this is the situation of Bangladesh, China, and India.

Table 14.3. Agricultural Land in Selected Countries. Land areas are for 2012; % refers to percentage change of 2012 compared with 1993 (a positive value indicates an increase). Source: Data from FAO (2014b).

	Cropland		Pasture and Meadows	
Country	(10^6 ha)	(%)	(10^6 ha)	(%)
Less-developed Countries				
Bangladesh	7.7	-10	0.6	0
Bolivia	4.3	100	33	-1
Nigeria	35	16	30.3	1
Tanzania	14.5	65	24	0
Vietnam	6.4	16	0.6	100
Rapidly Developing Countries				
Brazil	72.6	40	196	5
China	106.5	-14	392.8	2
India	156.2	-4	23.5	108
Indonesia	23.5	30	11	-7
Russia	87.9	-33	93	-22
Developed Countries				
Australia	47.1	0	358	-15
Canada	45.9	1	14.6	-9
France	18.3	3	9.5	-16
United States	155.1	-16	261	5

Most wealthier countries are not developing much additional agricultural land, largely because their areas with good potential are already being used. In fact, many developed countries have taken a great deal of land out of agricultural use since about 1980. The land withdrawals have occurred for two major reasons: (1) to reduce the production of certain crops, which keeps their prices relatively high, and (2) to conserve environmental quality through less intensive use of marginal land that is prone to erosion and other kinds of degradation. In addition, some high-quality agricultural land has been lost to urbanization in most developed countries, including Canada.

Site Capability

Agricultural site capability (or site quality) can be defined as the potential of an area of land to sustain the productivity of agricultural crops. Site capability is a complex ecological quality that depends on nutrients, organic matter, and moisture in the soil, plus additional factors that affect the productivity of crops. These factors are influenced by climate and drainage, by the vigour of ecological processes such as decomposition and nutrient cycling, and by the kinds of microbial and plant communities that are present.

Site capability is extremely important to the productivity of agricultural systems, and therefore to the production and availability of food. Because the beneficial qualities of cultivated land can be maintained and even improved by the use of appropriate management practices, site capability represents a potentially renewable resource. However, it can also be degraded by certain agricultural practices (see Chapter 24).

Ultimately, site capability for agriculture depends on seven interrelated factors: soil fertility, organic matter, bulk density (including compaction), resistance to erosion, moisture status, salinization, and the abundance of weeds. These factors are examined below:

Soil fertility is related to the ability of an ecosystem to supply the nutrients that are needed to sustain the productivity of a crop. Especially important are the sources of nitrogen, particularly inorganic forms such as ammonium and nitrate, as well as phosphate, potassium, calcium, magnesium, and sulphur. Soil fertility is influenced not only by the amounts of these nutrients, but also by factors that affect their availability to plants, such as:

- the cation exchange capacity, or the degree to which positively charged ions (these are cations) of such nutrients as ammonium (NH_4+), potassium (K^+), and calcium (Ca^{2+}) are bound by soil
- the anion exchange capacity, which is related to the binding of negatively charged ions (anions) such as nitrate (NO_3-), phosphate (PO_4^{3-}), and sulphate (SO_4^{2-})
- soil acidity or alkalinity, which are usually measured as pH, and affect the solubility of many nutrients as well as key aspects of microbial activity
- the rate of oxidation of organically bound nutrients into inorganic compounds that plants can take up and use more effectively in their nutrition
- the enhancement of nutrient availability through the addition of agricultural fertilizer or other practices

For example, consider the process of nitrification (see Chapter 5), an important function that is performed by certain bacteria and that transforms ammonium into nitrate. The rate of nitrification is greatly decreased in soil that is acidic or waterlogged, which results in much less availability of nitrate to crops. Soil fertility is also degraded if excessive amounts of nutrients are removed when crops are harvested, and also by the compaction of soil, depletion of soil organic matter, waterlogging, and acidification.

Soil organic matter consists of plant debris and humified organic material. Organic matter contributes to the ability of soil to form a loose, crumbly structure called tilth. Soil with good tilth is well aerated, allows plant roots to grow freely, and retains moisture, all of which are important factors that affect crop growth.

In addition, some nutrients are components of soil organic matter. These organically bound nutrients are slowly released for plant uptake through the process of decomposition, which in this respect can be viewed as a natural, slow-release, organic fertilization. Organic matter in the soil also helps to retain ionic forms of nutrients through cation and anion exchange capacity. Intensive cropping with insufficient return of crop residues typically results in a loss of soil organic matter and degradation of the valuable ecological services it provides.

Bulk density of soil (its weight per unit volume) has a large effect on tilth and drainage. It is generally preferable to have a low bulk density, but this can be degraded by the loss of soil organic matter and by compaction caused by the repeated passage of heavy machinery, especially when fields are wet. Soil that has been degraded by compaction may become wetter, lack oxygen, and have impaired nutrient cycling and poor root growth. These changes can result in a substantial decrease of productivity.

Resistance to erosion is degraded when soil is left without a cover of vegetation or crop residues during the winter, when contour ploughing is not practiced (such as when cultivation runs down a slope rather than along it), and when steep terrain is tilled. In contrast, sites are resistant to erosion if they are well vegetated, have good tilth, are flat, and the climate is not excessively wet or windy. In effect, erosion represent an important problem because it is a loss of soil mass, which occurs as particles are carried away by the forces of wind or running water. Any agricultural practices that increase the rate of erosion should be viewed as a mining of soil capital. In severe cases, erosion can strip away the relatively fertile, surface horizons of the soil. In the worst cases, bedrock may be exposed and the land is forever ruined for agricultural use.

Moisture status is another important aspect of site capability. In general, an intermediate moisture status (referred to as mesic) is preferred for the growth of most crops. Excessively dry (xeric) sites will produce a small yield, and crops may perish from drought. In contrast, excessively wet (hydric) sites tend to have cool soil with little or no oxygen present, which are conditions that are stressful to most crops.

The moisture status of sites is largely affected by climatic factors, especially the rates of precipitation and evapotranspiration. Soil moisture is also affected by the drainage characteristics – coarse-grained soils may drain too rapidly and have little ability to hold moisture, while heavy clay soils may not drain well enough, retaining water close to the surface. Soils with good tilth tend to have a degree of drainage midway between these extremes.

Salinization refers to the accumulation of various kinds of salts in the soil, particularly excessive amounts of sodium, magnesium, potassium, chloride, or sulphate. These and other salts are present in irrigation water and in certain kinds of fertilizer and they remain behind when water evaporates to the atmosphere. Salinization is a common problem in agricultural fields that are irrigated but do not have enough drainage to carry the salts downward into the soil and away, causing them to accumulate at the surface.

The abundance of weeds is important because when abundant, they provide too much competition for crop plants. The term "weed" can be defined as plants that are judged to be interfering with some human purpose (see Chapter 22). An increased abundance of weeds may be caused when a particular species of crop is cultivated in a continuous fashion, without rotation with other crops. An excessive abundance of weeds is commonly managed by tilling the soil and/or by using herbicide. In addition, a buildup of weed populations can be avoided by rotating crops and by using other management practices that provide less favourable conditions for the unwanted plants.

Degradation of Site Capability

Over the longer term, intensive agricultural management can result in a degradation of site capability. When this happens, the productivity of crops decreases, and in severe cases the land may no longer be suitable for agricultural use. Fortunately, such damage can often be avoided or repaired by changing the management system. For example, inorganic fertilizer may be applied to the soil in an attempt to compensate for declining fertility. Organic soil conditioners, such as compost and manure, can also be added to mitigate losses of organic matter, thereby helping to maintain the fertility and tilth of soil. In other cases, pesticides may be used to try to manage weeds and other pests. These management options are, however, intensive in their use of material and energy resources, and they may cause additional damage to the site and nearby ecosystems. Ultimately, truly sustainable agricultural systems involve the use of management strategies that conserve site capability while minimizing the use of nutrients, pesticides, and non-renewable sources of energy (see the section on Organic Agriculture in Chapter 24).

Production and Management

In 2014, more than 7.3-billion people were alive, and almost all were reliant on agricultural crops as their prime source of food. There are also relatively minor amounts of food that are harvested from the wild, such as by fisheries, but agricultural production is responsible for the great bulk of the modern human diet.

In addition, our associated domestic animals largely depend on the production of agricultural crops. The numbers of livestock are actually greater than those of people, including about 1.5-billion cows, 1.5-billion sheep, 1.2-billion goats, 1.0-billion pigs, and 22 billion chickens (Chapter 10). Although some of these domestic livestock forage on wild plants in unbroken pastures (which have not been seeded to agricultural forage plants), many are fed grain and hay that has specifically been grown for them. In fact, about 40% of the global production of grain is fed to livestock. Eventually, food products derived from the livestock are eaten by people, who are secondary consumers (and top predators) in this part of the agricultural food chain.

If a country has an excess of agricultural production over domestic consumption, then it has a surplus available for export, while those with a deficit must import some of their food (Table 14.4). In general, the greatest food-exporting nations have a relatively developed economy. Although many poorer countries export certain foods such as coffee, palm oil, sugar, tea, and other cash crops, most less-developed countries have food deficits or are only marginally self-sufficient. The food deficits must be made up by expensive purchases of food that was grown elsewhere or by donations from wealthier countries (the latter is known as food aid).

Table 14.4. International Trade of Agricultural Produce. Net trade is calculated as exports minus imports. A positive number is a net export, and a negative one a net import. Cereals include maize, rice, sorghum, and wheat. Pulses are legumes, such as peas, beans, and soybeans. Regions and countries are listed according to decreasing exports of cereals. Data are for 2011 and are in 10^6 tonnes per year. Source: Data from FAO (2014b).

	Cereals			Pulses		
	Exports	**Imports**	**Net Trade**	**Exports**	**Imports**	**Net Trade**
Region						
World	343.2	349.6	6.4	12.4	12.2	0.2
Europe	117.4	73.2	44.2	1.9	1.7	0.2
North America	106.7	7.3	99.4	5.3	0.4	4.9
Asia	48.6	139.2	-90.6	2.4	7.4	-5
South America	47.8	24.5	23.3	0.6	0.7	-0.1
Oceania	22.9	1.2	21.7	1.3	<0.1	1.3
Africa	5	70.9	-65.9	0.7	1.4	-0.7
Central America	1.3	22	-20.7	0.2	0.3	-0.1
Leading Exporters						
United States	86	5.5	80.5	1	0.3	0.7
France	32.9	2.1	30.8	0.6	0.1	0.5
Argentina	30.3	<0.1	30.3	0.5	<0.1	0.5
Australia	22.8	0.2	22.6	1.3	<0.1	1.3
Canada	20.8	1.7	19.1	4.3	0.1	4.2
Leading Importers						
China	1.3	5.4	-4.1	1	0.8	0.2
Mexico	1.1	16.9	-15.8	0.1	0.2	-0.1
Japan	0.3	25.2	-24.9	0	0.1	0.1
Egypt	0.2	17	-16.8	0.1	0.4	-0.3
South Korea	<0.1	13.1	-13.1	0	0.1	-0.1
Algeria	0	11.1	-11.1	0	0.3	-0.3

In terms of the gross food value provided to people, the world's most important crops are cereals, such as barley, maize, rice, sorghum, and wheat. Also important, but secondary, are tuber crops, such as cassava, potato, sweet potato, and turnip. In any country, the total production of cereals plus other crops is a function of the amount of land devoted to the cultivation of those species, multiplied by the average productivity.

Productivity (or yield, typically measured in tonnes of crop harvested per hectare per year) reflects the combined influences of site capability and the kind of management system that is being used. In agriculture, management practices are intended to mitigate some of the constraints that are limiting crop productivity, including those associated with site quality, inclement weather, insect infestations, weeds, and diseases. The productivity of cereals and other crops varies greatly among countries, but it is not necessarily lower in less-developed than in more-developed ones (Table 14.5). Although wealthier countries use highly mechanized management systems with inputs of fertilizer, pesticides, and sometimes irrigation water, less-wealthier countries may also use intensive management systems, albeit ones that depend more strongly on human and animal labour and with smaller material inputs.

Table 14.5. Agricultural Production in Selected Countries. Data are for 2013; % refers to the percentage change in yield between 1974 and 2013. Source: Data from FAO (2014b).

Country	Cereals			Roots & Tubers			Pulses		
	Production (10^6 t)	Yield (t/ha.y)	%	Production (10^6 t)	Yield (t/ha.y)	%	Production (10^6 t)	Yield (t/ha.y)	%
Relatively Undeveloped Countries									
Bangladesh	55.1	4.4	157	8.9	18.9	94	0.33	1.2	71
Bolivia	2.2	2	83	1.5	6	-10	0.11	1.44	59
Egypt	23.7	7.2	87	5.2	27.3	49	0.25	3.05	47
Nigeria	27	1.6	56	100.1	11.6	21	2.56	0.77	104
Pakistan	39.3	2.9	123	4.3	21.2	106	1.07	0.72	34
Vietnam	49.2	5.4	157	11.4	16.2	159	0.36	0.87	86
Rapidly Developing Countries									
Argentina	50.7	4.7	132	2.6	22.7	50	0.22	0.91	-16
Brazil	101	4.8	230	25.5	14.9	24	2.95	1.03	100
China	553	5.9	147	174.2	18	41	4.47	1.55	45
India	293.9	3	177	53.7	23.2	105	18.3	0.65	58
Indonesia	89.8	5.1	123	27.8	20.4	156	0.21	1.12	3
Mexico	33.2	3.4	110	1.9	26.3	129	1.66	0.87	29
Developed Countries									
Australia	35.6	2	47	1.3	37.8	99	2.7	1.41	90
Canada	66.4	4.2	141	4.6	32.5	49	6.11	2.52	89
France	67.5	7	69	7	43.4	82	0.79	3.64	90
Japan	11.8	6.1	8	4	26.9	34	0.08	2.01	39
U.S.A.	436.6	7.3	145	21	44.5	69	2.23	2.04	0
World	2,780	3.9	104	835.9	14.9	32	73	0.9	35

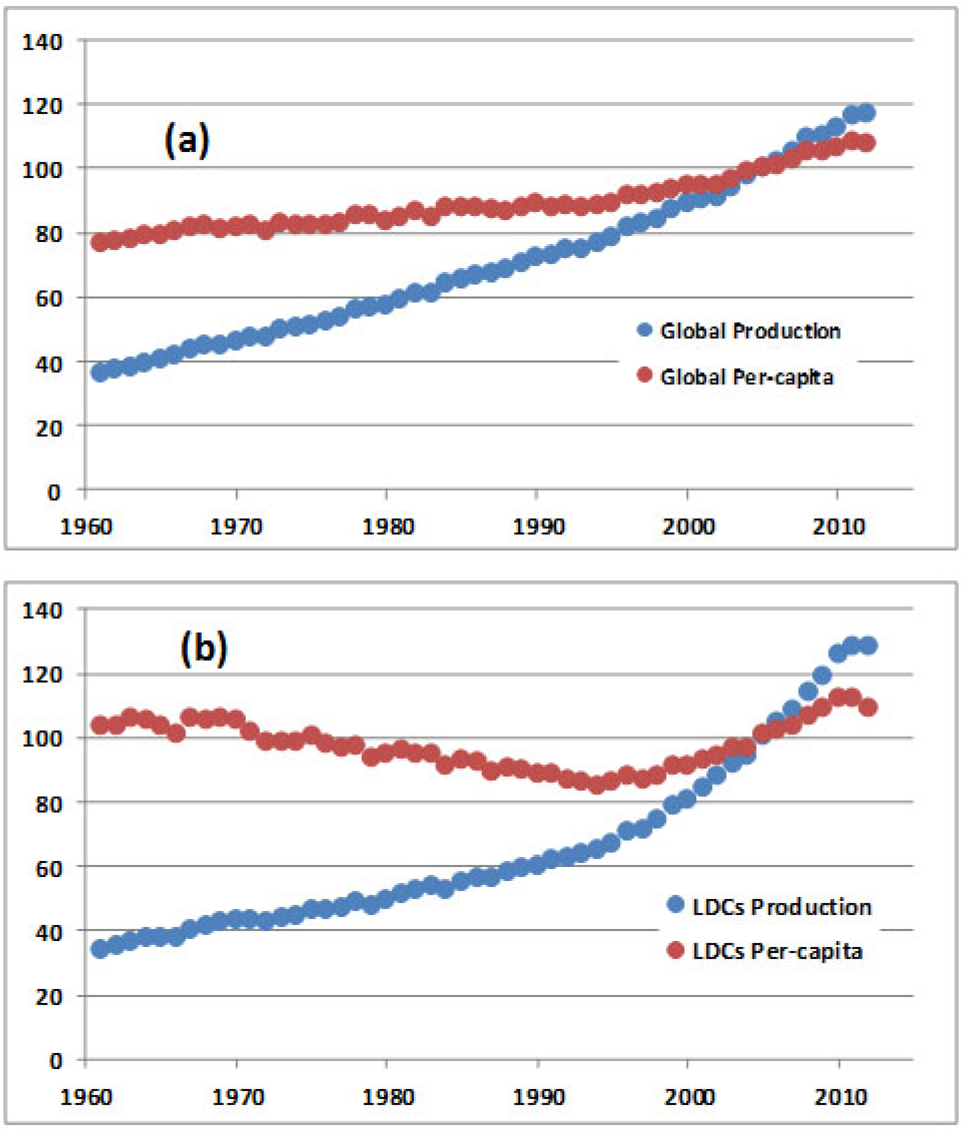
Note also that Table 14.7 also has data that shows how the yield of crops has increased over the past four decades (from 1974 to 2013; note that a 100% increase means there was a doubling of yield). The increases in productivity are rather impressive, and are due to crop varieties that have been selectively bred to respond well to intensive management systems, as well as to increased use of management practices such as the use of fertilizer, pesticides, and irrigation. The improved rates of yield have been key to increased rates of agricultural production during the same period. Of course, many of the benefits of increased agricultural production have been absorbed by large increases in population, especially in less-developed countries.

These trends are also shown by indicators of food production that are compiled by the Food and Agriculture Organization of the United Nations (Figure 14.1). The index is a composite indicator that takes into account the production of all important crop species, with the data being expressed relative to the base period 2004-2006 (for which the value is set to 100). The index covers all edible agricultural products and is a price-weighted summation measured in constant dollars, so that inflation is not an issue. Therefore, the index shows whether agricultural production has increased (> 100) or decreased (< 100) during the time period, both on a total and per-capita basis.

The global data show a strong and steady increase of overall agricultural production from 1961 to 2012, although the increase is much more moderate in the per-capita data (Figure 14.1a). In other words, most of the increase in global agricultural production during the past half-century has been eroded (on a per-capita basis) by population growth. Not surprisingly, this pattern is even more striking in the data for the least-developed countries, which show little improvement in per-capita food production over the period.

These observations suggest that there is a food "treadmill", in which increases in food production, obtained by converting natural habitats and adopting more intensive management practices, are being mostly offset by population growth. The metaphor of a treadmill is apt in this case, because on that sort of running machine a great deal of effort is expended, but the runner stays in about the same place.

Figure 14.1. Changes in two indicators of agricultural production. The production index data (a), as well as the per-capita index (b), are relative to the period 2004-2006, which are set to a scale of 100. Separate graphs are shown for global values and least-developed countries. Source: Data from FAO (2014b).



It is important to understand that high yields that are obtained by the use of intensive agricultural systems are heavily subsidized by large inputs of non-renewable resources. For example, the most important agricultural fertilizers are inorganic compounds of nitrogen, such as urea or ammonium nitrate, both of which are manufactured using natural gas. The second- and third-most important fertilizer nutrients are compounds of phosphate and potassium, which are produced from mined minerals. In addition, most pesticides are manufactured from petrochemicals, using energy-intensive technologies. Moreover, the mechanization of agricultural systems involves the use of tractors pulling heavy equipment for tilling, harvesting, and other purposes. The manufacturing of these machines requires large amounts of non-renewable energy and materials, such as metals and plastics. Furthermore, the machines run on non-renewable fuels, such as gasoline or diesel.

Table 14.6 compares indicators of the intensity of agricultural management among selected countries. There is great variation among countries, with some less-developed ones using practices that are intensive as some developed ones. In general, however, the intensity of management is greater in wealthier countries, with greater use of fertilizer and pesticide, more mechanization, and larger more industrial farms.

Table 14.6. Intensity of Agricultural Management in Selected Countries. Fertilizer data are combined applications of inorganic nitrogen, phosphorus, and potassium fertilizer (for 2012). Pesticide data combined applications of insecticide, herbicide, fungicide, and bactericide (for 2011, or the most recent year for which there were data). Tractor data are for 2011 or most recent. Water use is the percent of total withdrawals that are used for agriculture. Source: Data from FAO (2014b).

Country	Fertilizer	Pesticide	Tractors	Water Use
	(kg/ha)	(g/ha)	(no./km^2	(%)
Relatively Undeveloped Countries				
Bangladesh	255	1.6	0.04	88
Bolivia	13	9.6	0.18	
Egypt	474	-	3	86
Nigeria	5	-	0.07	53
Pakistan	176	-	2.2	94
Vietnam	211	2.1	1.8	95
Rapidly Developing Countries				
Argentina	53	8.8	0.85	66
Brazil	198	1.1	1.2	55
China	443	-	0.64	65
India	152	0.2	1.5	90
Indonesia	133	-	0.01	82
Mexico	61	4.6	0.88	77
Russia	15	-	0.27	20
Developed Countries				
Australia	44	0.7	0.66	74
Canada	66	1	1.4	
France	128	2.7	6.5	12
Japan	234	10.9	42.1	63
U.S.A.	116	1.7	2.6	40

As was just noted, some agricultural systems used in less-developed countries are quite intensive and result in high yields. For example, in many humid tropical countries, rice is cultivated using a system known as paddy. Although some paddy-rice agriculture has been mechanized, it is often carried out on smaller-scale family farms. Typically, water buffalo are used to plough and till the dyked, flooded fields (each of which is a paddy). People then hand-transplant young rice plants, weed the crop with hoes, and eventually harvest by scything and gathering sheaves of the plant stalks. In places with evenly spaced precipitation through the year and naturally fertile soil, such as parts of Java, Sumatra, and the Philippines, as many as three rice crops can be grown each year. This non-mechanized paddy system can achieve high yields with relatively small inputs of inorganic fertilizer or pesticide.

Other agricultural systems used in less-developed countries are much less productive than paddy rice, generally because of suboptimal rainfall and less fertile soil. The least productive systems are used in semi-arid regions. Under such conditions, it is not possible to cultivate many plant crops. However, livestock such as camels, cows, goats, and sheep can roam extensively over the landscape, harvesting the sparse production of native forage. The dispersed plant biomass of semi-arid ecosystems is too small in quantity and too poor in nutritional quality for direct harvesting and use by people. However, grazing livestock are able to convert the poor-quality forage into a form (such as meat or milk) that people can utilize as food.

Increasingly, the agricultural systems used in less-developed countries are becoming more intensive in their management. In this sense, they are rapidly proceeding toward the kinds of systems used in developed countries. Indicators of this change include increasing use of fertilizer, pesticides, and mechanization. Another indicator is the increasing size of farm holdings, which occurs as the agricultural activities become commercialized and owned by large companies. These changes have resulted in increasing yields in many less-developed countries over recent decades (see Table 14.7). These increases of productivity are largely due to the cultivation of "improved" varieties of crop plants as well as the adoption of intensive agricultural practices.

The industrialization of agricultural production in these countries also results in important social changes. Of particular importance is the rapid amalgamation of small family farms into larger commercial units. This results in the displacement of many poor people from agricultural livelihoods. These economic refugees then migrate to towns and cities, which causes the rate of urbanization to be much faster than what would be expected from population growth alone.

Agriculture in Canada

Canada is one of the world's great agricultural nations and a major contributor to the international trade in food. Canada's production of cereals was 66-million tonnes in 2013, which ranked 8th in the world and comprised 2.3% of the global production (FAO, 2014). In that same year Canada exported 21×10^6 t of grain, which ranked 5th in the world.

The gross domestic product (GDP) associated with agricultural production is about $22-billion, of which 73% is crops and 27% livestock (in 2011; Statistics Canada, 2014a). Canadian exports of agricultural products in 2011 had a value of $41-billion, and imports $31-billion, for a net trade surplus of $10-billion for the agricultural sector (FAO, 2014).

At the beginning of the twentieth century, more than 80% of the Canadian labour force was employed in agriculture. At the time, farming mostly relied on animal and human labour as sources of energy for cultivation and harvesting. Most farms were relatively small, family-operated enterprises, run mainly as subsistence operations to produce food and other crops for use by the family. Any surplus production was traded in local markets for cash or manufactured goods. The agricultural surplus was eventually sold in Canadian cities or exchanged internationally by traders. Much of today's agricultural activity in less-developed countries still has this sort of socio-economic character.

Today, however, most Canadian agriculture involves highly mechanized, industrial operations. Only about 2.2% of the national workforce is employed in farming (in 2011; Statistics Canada, 2014b). Virtually all cultivation, harvesting, and processing is accomplished by large fossil-fuelled machines. Tractors haul cultivating, seeding, and spraying machines, and self-contained harvesters harvest and process crops. Canadian farmers use about 733-thousand tractors (in 2008; FAO, 2014).

Canada has an immense land base, some 10-million km^2, making it the second-largest country in the world (after Russia). However, the area suitable for agriculture is largely confined to southern parts of the country. The ability of land to support agricultural uses is categorized by a system known as the Canada Land Inventory. The distribution of the most productive lands for agriculture is shown in Table 14.7.

Table 14.7. Distribution of Class 1–3 Land in Canada. Soil capability classes 1-3 are suitable for the cultivation of crop species, with 1 being best and 3 less so. Classes 4 and 5, used for pasture or rough grazing, are not reported here. Not all of the high-quality land is used for agriculture – some has been converted to urban and suburban land-uses. Data are expressed in 103 km^2. Source: Data from Hoffman et al. (2005).

		Capability Class		
Province	**Land Area**	**1**	**2**	**3**
Newfoundland	373.9	0	0	0.07
Prince Edward Island	5.7	0	2.6	1.4
Nova Scotia	53.3	0	1.7	10.2
New Brunswick	71.5	0	2.1	13.8
Quebec	1365.1	0.2	10.7	13.6
Ontario	917.7	27.6	23.3	25.6
Manitoba	553.6	2.1	29.6	24.5
Saskatchewan	591.7	12.3	73.3	104.5
Alberta	642.3	6.7	38.7	61
British Columbia	925.2	0.08	1.6	5.3
Canada	9094	49.1	183.7	260

Most of the highest-capability land is located in southern regions of Canada, where the growing season is relatively long and moist, and on sites with relatively flat terrain and fertile soil. Southern Ontario, for example, has 56% of the class-1 land in Canada, while Saskatchewan has 25%; Alberta, 14%; and Manitoba, 4%. Unfortunately, some of the best-quality land has been lost to urbanization, which swallowed up 7,400 km2 of prime agricultural land between 1971 and 2001, more than doubling the total amount lost to this process (Hoffman et al., 2005). In total, more than 7% of class-1 agricultural land has been converted. This loss of the best agricultural land has serious consequences for the production of crops, particularly high-value ones such as soft fruits in the Niagara region of Ontario and the Okanagan Valley of southern British Columbia.

As was previously examined, the quality of land for agriculture is influenced by such factors as soil fertility, organic matter concentration, drainage, and the abundance of weeds. All of these qualities can be degraded by inappropriate land management. It is important to monitor changes in these site factors over time, in order to track changes in the sustainability of agriculture. Unfortunately, suitable monitoring data do not yet exist in most areas, although programs are being designed.

There are, however, some general indications that soil fertility and other site factors are declining in quality over much of the agricultural land base. For example, in order to maintain the productivity of many agroecosystems, large amounts of fertilizer and soil conditioners must be added to the system. Similarly, herbicide, insecticide, fungicide, and other pesticides must be used to manage pests (see Chapter 22). The need to use intensive management practices to maintain productivity could, in itself, be considered a symptom of unsustainable stress on the agroecosystem. In addition, most fertilizers, pesticides, and their mechanized application systems are based on the mining and use of non-renewable resources, which representing another element of non-sustainability (see also Chapter 24).

Huge amounts of fertilizer are used to increase crop productivity in Canada. In 2011, fertilizer was applied to 25 million hectares of farmland, more than a three-fold increase over 1971 (Table 14.8). In 2013, agricultural land was fertilized with 2.5-million tonnes of nitrogen and 0.9 million tonnes of phosphate. Compared with rates of fertilizer use in 1970, these represent increases of about 10-fold and 3-fold, respectively.

Table 14.8. Agricultural Land-Use and Crops in Canada. Data are in millions of hectares (10^6 ha). Data from Statistics Canada (2014c).

	1971	1991	2001	2011	2014
Farmed area	68.7	67.8	67.5	64.8	-
Land in crops	27.8	33.5	36.4	35.4	-
Summer fallow	10.8	7.9	4.7	2.1	-
Seeded pasture	4.1	4.1	4.8	5.5	-
Natural pasture	25.9	22.2	21.6	21.8	-
Grains: total	20.8	22.8	18.8	19.4	13.8
Wheat	7.9	14.2	10.9	8.6	9.3
Oats	6.7	3.1	1.9	1.8	0.9
Barley	5.7	4.5	4.7	4	2.1
Corn	0.6	1.1	1.3	1.4	1.4
Soybean	0.2	0.6	1.1	1.2	2.2
Canola	2.2	4.3	3.8	5.9	7.8
Potato	0.11	0.12	0.1	0.15	0.2
Fertilizer use	6.9	21.6	24	24.9	-
Herbicide use	8.6	21.6	25.9	26.7	-
Insecticide + fungicide use	0.9	2.8	5.8	8.7	-

The use of pesticides to deal with insect pests, weeds, and fungal pathogens is also intensive in Canadian agriculture. In 2011, herbicide was applied to 25-million hectares of farmland, representing a three-fold increase over 1971 (Table 14.10). Insecticide was applied to 3.2-million hectares and fungicide to 5.5-million hectares, together representing a 9-fold increase over 1971.

Canadian agricultural systems also utilize crop varieties that have been selectively bred to increase their potential productivity and resistance to pests and pathogens, to respond vigorously to fertilizer addition and other intensive management practices, and to grow well under regional climatic regimes. This is not to say that these varieties are optimally adapted to intensively managed agroecosystems. New pests and diseases often develop, so the crop-breeding industry must continuously respond to changes in ecological conditions.

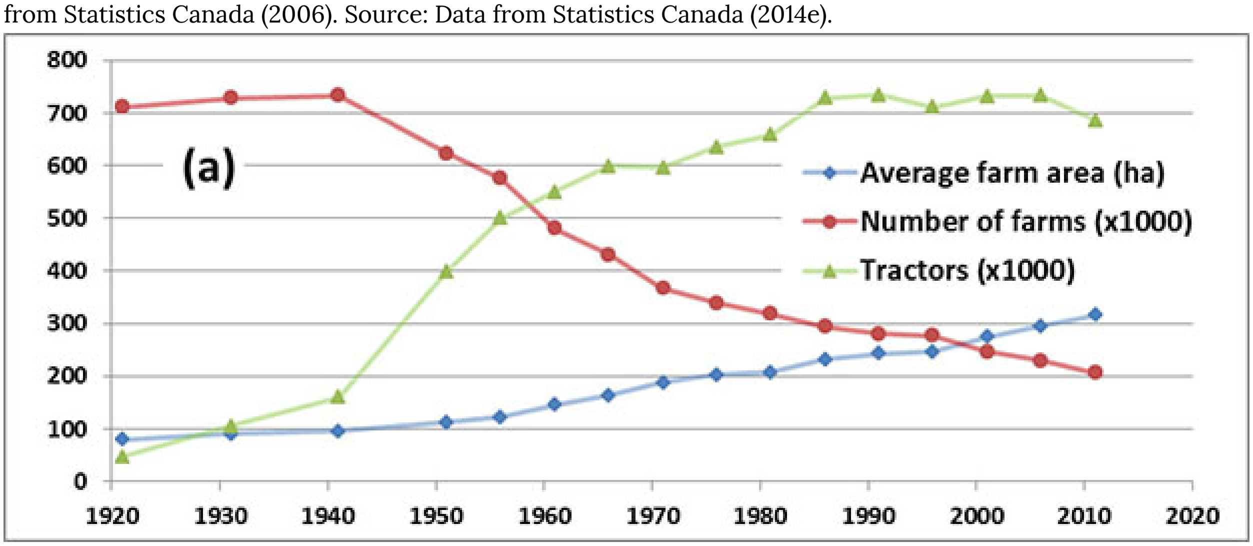
Overall, the intensification of industrial agriculture has greatly increased the production of crops in Canada. Similarly large increases in production have been accomplished in other countries that have adopted intensive and mechanized agricultural systems. This includes the United States, most countries of Western Europe, and, increasingly, Brazil, China, India, Russia, Ukraine, and other rapidly developing countries. Increases in agricultural production have been accomplished mainly through intensified management and the cultivation of improved crop varieties, rather than by increasing the areas of cultivated land.

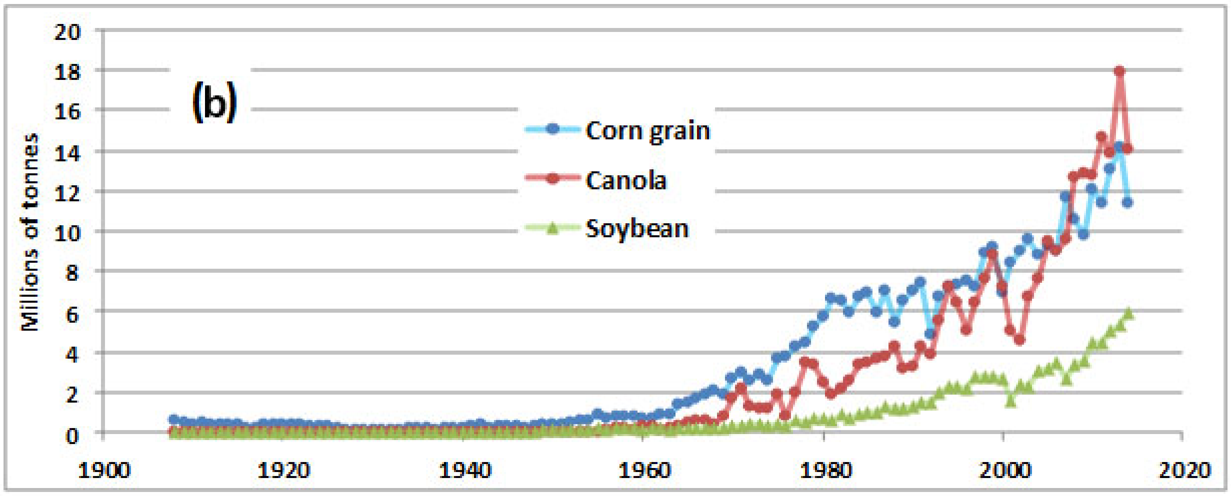
About 65-million hectares of land are cultivated on 206,000 farms in Canada (2011 data). This area is equivalent to about 7% of Canada's landmass. Over time, however, the number of farms has decreased markedly, even while their average area has increased (Figure 14.2a). Farming has also become greatly intensified in Canada, in terms of mechanization and the use of fertilizer and pesticides. In recent years, the largest production and areas of crops have been wheat (27 x 10^6 t in 2014), canola (14 Mt), corn (maize; 12 Mt), barley (7 Mt), and soybean (6 Mt) (Figure 14.2b,c). In addition, new crops have been introduced to Canada and are grown over large areas, especially canola (oil rapeseed), lentils, soybeans (Figure 14.2b).

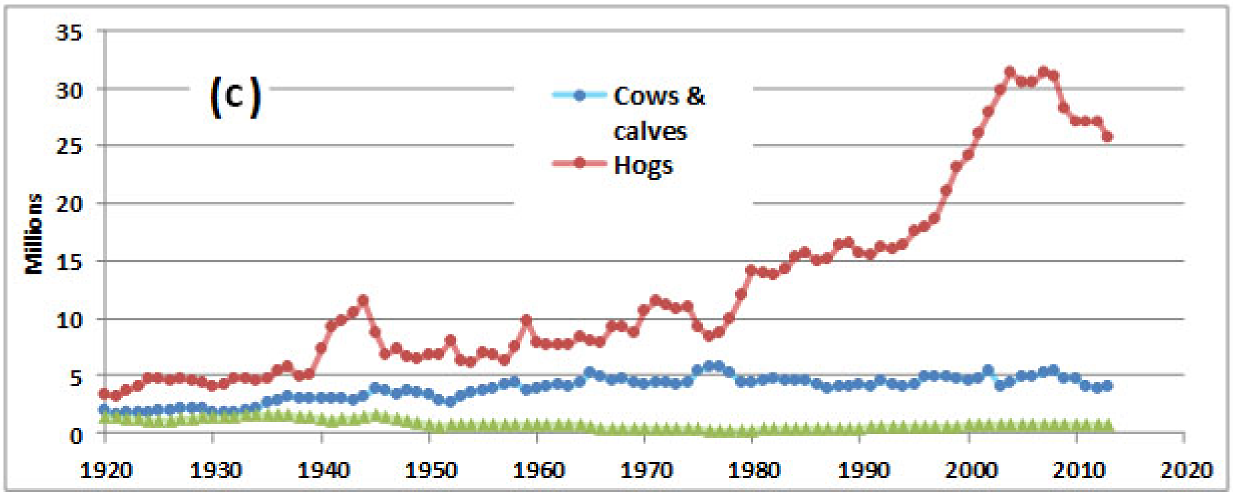
Animal husbandry has also become intensive in Canada. Most production of chickens, cows, and pigs now occurs on so-called factory farms. This is an industrial system that involves raising livestock indoors under densely crowded conditions. The livestock are fed to satiation with nutritionally optimized diets, while diseases are managed with antibiotics and other medicines. Productivity may be enhanced with growth hormones (see Chapter 24).

More than 167-million chickens are raised annually for meat and eggs on Canadian farms, most of them in operations of an industrial scale and intensity (Statistics Canada, 2014f; FAO, 2014b). As well, more than 8-million turkeys are raised, mostly on factory farms. Larger livestock include about 16-million cows (including 2-million milk cows), 26-million pigs, 0.8 million sheep, and 0.9 million horses. Dairy cows and pigs are raised mostly on factory farms. Most beef cows spend part of their lives grazing outdoors in pastures or on semi-natural prairie. However, prior to slaughter, most of the animals are rounded up and then kept in crowded feedlots, where they are well fed so that they can gain weight rapidly. Sheep, goats, and horses are raised under less intensive conditions.

Figure 14.2. Historical Changes in Agricultural Activity in Canada. (a) The number and size of farms and tractors as an indicator of mechanization ; (b) production of select crops; (c) livestock slaughtered. Source: Modified from Statistics Canada (2006). Source: Data from Statistics Canada (2014e).







In overview, it is clear that since the beginning of the 20th century there has been an enormous increase in agricultural production. This has fed similarly rapid increases in the global populations of people and domestic animals. The rapid intensification of agriculture is, however, substantially dependent on the use of non-renewable sources of energy and materials, a fact that challenges the sustainability of the production systems. Moreover, intensive agricultural systems cause important damages to the environment, many of which are examined in later chapters, especially in Chapter 24.

Canadian Focus 14.1. Weather Extremes and Agriculture

Climatic factors, such as heat, wind, and soil moisture, have an important influence on agricultural production. Harvests can be bountiful when climatic conditions are good, but if they occur as extreme events, crops can be wiped out. For instance, periods of extended dry conditions, or drought, are occasionally present in the Prairie region, where large areas have only a marginal availability of soil moisture for key crops such as wheat and canola (Agriculture Canada, 2014; Canada History, 2013).

The most devastating period of drought during the past century occurred from 1929 to 1937, when low precipitation and over-cultivation of prairie soil caused the land to turn to a fine dust that blew away during windstorms. The dust accumulated as dunes and windrows, covering roads and buildings and making life difficult or impossible for many rural people in the affected regions. Since then, the precipitation regime has been more moderate and there has been a widespread adoption of soil-conservation practices, such as planting lines of trees and windbreaks, fallowing of fields as part of a crop rotation, and additional measures.

Nevertheless, events of severe drought continue to occur in the prairie region. For example, during 2001 much of western Canada experienced some of the driest growing conditions ever recorded. Large southern regions of Alberta, British Columbia, and Saskatchewan had record-low precipitation and severe drought. This resulted in widespread decreases in yield and even crop failures in the drought-stricken areas. Drought was also severe in 2002, although the most severely stricken areas were further north, in central Alberta and nearby Saskatchewan. In the southernmost Prairie Provinces, where drought was most severe in 2001, moisture was normal or better in 2002. Drought has been generally less of a problem since those years.

Years of severe drought have a destabilizing influence on the agricultural economy of the Prairie region. In 2002, owing to the cumulative effects of three consecutive years of poor spring runoff (due to below-average snowfall) and sparse precipitation during the growing season, the amount of forage available in drought-stricken areas was critically low. Many ranchers had to sell off most or all of their cattle, including vital breeding stock, because they were unable to grow enough forage to feed their animals and were unable to pay the high cost of importing feed.

The production of crops was also hard hit. The national production of non-durum wheat, which is mostly grown in the Prairie Provinces, was only 12-million tonnes in 2002, compared with 18-million tonnes in 2001 and 21-million tonnes in 2000 (an overall 44% decrease). The production of canola was also markedly down, from 7-million tonnes in 2000 to 5-million tonnes in 2001 and 3-million tonnes in 2002 (a 55% decrease). Although Canada is normally an exporter of grain to global markets, in 2002 we imported wheat from Russia.

Farmers have a number of management options available to them during periods of drought. For instance, they can practice summer fallow, a practice in which the land is not cultivated in some years in order to conserve its vital soil moisture. Farmers can also choose to grow crops that are relatively tolerant of drought, such as field-pea or wheat. If surface water or groundwater are available, irrigation may be an option.

The practice of agriculture has always been somewhat risky in the Prairie region, and farmers can suffer terribly from the economic and emotional damage of drought. During such times, it is essential that affordable crop insurance and other means of financial support be available to the agricultural community. This should, in fact, be a national priority – all Canadians are fed by the produce grown by farmers, and we must share with them the consequences of the ecological and economic risks inherent in their agricultural enterprise.

Forest Resources

Forests of various kinds are extremely important terrestrial ecosystems. They cover extensive areas of the surface of Earth, and fix and store huge amounts of biomass. The global cover of forest is about 40-million km^2, of which 56% is in temperate and boreal regions and 44% in tropical regions (2012 data; FAO, 2014b). The present forest area is about half of what it was before humans began to cause deforestation about 10-thousand years ago, mostly to develop agricultural land. Although temperate and boreal forests now cover an area comparable to the tropical forest, their production is only about half as large, and they store only 60% as much biomass. There are also another 3-billion hectares of open woodlands and savannah. The most heavily forested regions are in North and South America, Europe, and Russia, all of which have more than 30% forest cover.

Worldwide, an immense area of about 25 million hectares of forest is cleared or harvested each year. Tree biomass is harvested for three major reasons:

1. as a fuel for subsistence, that is, to burn as a source of energy for cooking and warmth
2. as an industrial fuel, used to generate electricity or to produce steam or heat for a manufacturing process
3. as a raw material to manufacture lumber, paper, composite materials such as plywood and waferboards, and other

products, such as synthetic rayon and celluloid In addition, forests may be cleared not so much for their biomass, but to create new agricultural or urbanized land. These longer-term ecological conversions result in deforestation, which is a permanent loss of forest cover.

The net primary production of global forests has been estimated to be about 49-billion tonnes per year, of which an extraordinary 28% is used by humans (Vitousek et al., 1986). Human use can be divided into the following categories:

- short-term clearing of forests for shifting cultivation in less-developed countries (45%)
- more permanent conversion of forests to agricultural land-uses (18%)
- harvesting of tree biomass (16%)
- productivity of trees in plantations (12%)
- loss during harvest (9%)

Image 14.2. Clear-cutting is the most common method of harvesting forests in Canada. Mechanized harvesting systems are used in most areas, such as this machinery that fells and de-limbs trees, cuts them into convenient lengths, and hauls the wood to a roadside. Source: B. Freedman.

Changes in Forest Cover

Forest resources in many countries are being rapidly depleted by high rates of clearing. This is particularly true in many tropical countries, where deforestation is largely driven by increasing populations and the resulting need for more agricultural land and wood fuels. Also important are the economic and industrial demands for tree biomass to manufacture into charcoal and products for international trade.

The global rate of deforestation was 6.1-million hectares per year between 1990 and 2010 (UNEP, 2014). These are high rates of forest loss, and they appear to have increased since the late 1990s. Satellite data for Amazonia, for example, suggest that the rate of clearing increased by about 50% in 1996-1997, which was a relatively dry year that was favourable for removing tropical forest by burning for conversion into pasture or fields for growing soybeans.

The rates of deforestation of some less-developed and rapidly developing countries are shown in Table 14.11. Recently, some of these countries have been losing their forests at extraordinary rates. For instance, between 1990 and 2010, Nigeria lost 48% of its forest cover at an average rate of 2.4% per year. Another African country, Burundi, lost 41% of its forest during that period, while Honduras in Central America lost 36%. The rapid deforestation that is occurring in most developing countries represents the mining of potentially renewable lumber, fuelwood, and other uses of tree biomass. In addition, deforestation in tropical and subtropical regions causes terrible ecological damages, such as endangerment and extinctions of biodiversity. These topics are examined in Chapters 23 and 26.

In contrast to the rapid deforestation that is occurring in most less-developed countries, the forest cover of many developed ones has recently been stable or increasing (Table 14.9). This is happening in spite of industrial harvesting of timber resources in many of those countries, largely to manufacture lumber and paper. This is because the industrial forestry that is typically pursued in Canada, the United States, and Western Europe allows, and even works to encourage the regeneration of another forest on harvested sites. Consequently, there is no net loss of forest cover, although the character of the ecosystem may change because of the management system being used, especially if tree plantations replace the natural forest (see Chapter 26).

Table 14.9. Forest Resources and Forestry Production in Selected Countries. Forest area is for 2010; deforestation is the change in forest area between 1990 and 2010 (if positive, the forest increased), expressed over the entire period and as an annual average. Harvesting data for industrial roundwood and fuelwood are for 2012. Source: Data from FAOSTAT (2014) and UNEP (2014).

Country	Forest	Deforestation		Roundwood	Fuelwood
	(10^6 ha)	% 1990-2010	%/yr	10^6 m^3	10^6 m^3
Relatively Undeveloped Countries					
Bolivia	57.2	-9	-0.5	0.9	2.4
Burkina Faso	5.7	-17.5	-0.9	1.2	13.1
Cambodia	10.1	-22	-1.1	0.1	8.2
Ecuador	9.9	-28.6	-1.4	2.1	5
Guatemala	3.7	-23	-1.2	0.7	18.8
Honduras	5.2	-36.2	-1.8	0.4	8.5
Myanmar	3.2	-19	-1	5.1	38.3
North Korea	5.7	-30.9	-1.6	1.5	6.1
Nigeria	9	-47.5	-2.4	9.4	64
Pakistan	1.7	-33.2	-1.7	3	29.7
Zimbabwe	15.6	-29.5	-1.5	0.5	8.9
Rapidly Developing Countries					
Brazil	519.5	-9.6	-0.5	146.8	145
China	206.9	31.7	1.6	144	182.1
India	68.4	7	0.4	23.2	308.2
Indonesia	94.4	-20.3	-1	62.6	54.9
Malaysia	20.5	-8.6	-0.4	17.8	2.7
Mexico	64.8	-9.2	-0.5	5	38.8
Russia	809.1	0	0	136.4	14.6
Developed Countries					
Canada	310.1	0	0	151.2	1.4
France	16	9.7	0.5	29.8	26.3
Germany	11.1	3.1	0.2	42.9	9.5
Japan	25	0	0	18.5	0.1
Sweden	28.2	3.4	0.2	63	59
U.S.A.	304	2.6	0.1	320.7	40.4
World	4,033	-3.2	-0.2	-	-

Although most developed countries now have a stable or increasing forest cover, this has not always been the case. Many of these countries were being actively deforested as recently as the beginning of the 20th century. Most of the early deforestation occurred in order to develop land for agriculture. For instance, most of Western Europe was still forested as recently as the Middle Ages (up until about 1500), as was eastern North America up until one to three centuries ago. Extensive deforestation also occurred during the First World War, when European countries were engaged in "total war" economies and were harvesting wood as quickly as possible, often for use as pit props in underground coal mining. Large parts of these regions are now largely devoid of forest cover, which has been replaced by agroecosystems and urbanized land.

This process of deforestation largely stopped around 1920 to 1930. At that time, forested areas began to increase in many developed countries. This happened because many small farms of marginal agricultural capability were abandoned and their inhabitants migrated to urban areas to seek work. Over time, the land reverted to forest. In much of Europe, this involved the establishment of plantations (tree-farms), usually of conifer species. In other regions there was a natural afforestation as tree-seeds established new populations on disused rural land. For example, because of these socio-economic and ecological dynamics, the area of forest in much of the Maritime Provinces has approximately doubled since the beginning of the twentieth century. Similar changes have occurred in other developed regions of the world.

Harvesting and Managing Forests

Globally, the net trend is one of rapid deforestation. Between 1990 and 2010, about 7-million hectares of forest per year were lost to deforestation (UNEP, 2014). Almost all of this aggressive deforestation is associated with the conversion of tropical forest into agricultural land, but the harvesting of forest products is also important in some regions. Globally, only about half of the original forest area remains.

During 2013, the global consumption of wood averaged 3.6-billion cubic metres, representing a 1% increase from a decade earlier (Table 14.11). The wood consumption included the following:

- 0.96×10^9 m^3 of sawn and veneer timber (a 7% decrease from 2004)
- 0.43×10^9 m^3 of wood panels such as plywood (45% increase)
- 0.40×10^9 m^3 of fibre such as pulpwood, used to make paper (12% increase)
- 1.70×10^9 m^3 of industrial roundwood (no change)
- 1.88×10^9 m^3 of fuelwood (2% increase; 90% was consumed in less-developed countries)

In Canada, an enormous industrial complex depends on the harvesting of forest biomass, largely for manufacturing into lumber, composite materials such as plywood and waferboard, and pulp and paper. The total value of products manufactured from forest resources in 2013 was $53-billion (Canadian Forest Service, 2014).

Most of Canada's production of forest products is intended for export, providing foreign earnings that are crucial to maintaining a positive balance of trade. In 2013, Canadian exports of forest products had a value of $33.7-billion, and the net contribution to the international balance of trade was $12.7-billion (this is the value of exports minus imports within the forestry sector (Canadian Forest Service, 2014). By comparison, Canada's overall balance of trade in 2012 was minus $6.7-billion, and it would have been worse without the positive contribution of the forestry sector (Statistics Canada. 2014g). Overall, Canada is the world's leading exporter of forest products, accounting for 9% of global trade.

For comparison to the net earnings from the export of forest products ($12.7-billion), those of other key economic sectors in Canada in 2013 were:

- energy, +$69.6 billion
- metals and minerals, +$20.2 billion
- agriculture and fish, +$14.8 billion
- automotive and aircraft, −$14.4 billion
- consumer goods, −$45.5 billion
- industrial machinery, equipment, electronics, −$52.5 billion

Of course, to achieve the great economic benefits of forestry, large areas of mature forest must be harvested each year. In 2013, 638-thousand hectares of mature forest were harvested, which is considerably less that the 1-million hectares that was the annual harvest from 1995 to 2006 (Natural Resources Canada, 2013). The large decrease reflects a general downturn in global markets for forest commodities, especially for paper products. About 90% of the harvesting is by clear-cutting, and the rest by more selective methods. About 80% of the industrial harvest was conifer trees (softwoods) and 20% broad-leafed trees (hardwoods). The area of forest harvested was equivalent to about 0.4% of the area of "productive" forest of Canada (which is located in more southern regions and is relatively productive and accessible) and 0.2% of the total area of forest.

Almost all of the industrially harvested area in Canada is allowed to regenerate to forest. Deforestation, or long-term conversion to non-forest land-uses, is relatively uncommon in Canada. The recent amount of deforestation has been about 46-thousand hectares per year (in 2010), of which agricultural conversions were responsible for 41%, oil and gas activities for 24%, municipal conversions for 10%, forestry for 8%, industry for 7%, road-building for 6%, and others the rest (Natural Resources Canada, 2013). However, it should be understood that much of the harvested forest is not regenerating well because it is poorly stocked with commercially valuable tree species. For example, about 15% of Crown land harvested since 1975 is considered to be understocked.

In addition, the regeneration of trees on most of the harvested area (this is known as reforestation) is encouraged by the planting of seedlings and other aspects of silvicultural management. In 2012, about 67% of the harvested area was planted with tree seedlings. Many of the planted areas are managed quite intensively to develop tree plantations, a system that represents the application of an agricultural model to the growing of trees, also known as agroforestry. Tree farms are generally more productive of biomass than natural forest, but they lack many elements of native biodiversity and other ecological and aesthetic values (Chapter 23). Other aspects of intensive forestry management may include the thinning of overly dense tree regeneration, the use of herbicide to reduce the abundance of non-crop plants (or "weeds"), and the use of insecticide if there is an irruption of insects that threaten the tree cop, such as spruce budworm (Chapter 22).

Almost all the non-planted tracts of the harvested area (33% of the total) also regenerates back to forest. However, this occurs through a "natural regeneration" of tree species. Natural regeneration may involve seedlings that existed on the site prior to harvesting and survived the disturbance (known as advanced regeneration), seedlings that established from seeds dispersed onto the site from nearby forest, or seeds dispersed by mature seed-trees left on the site.

Overall, from the industrial perspective, forestry as it is practiced in Canada appears to be conserving its primary economic resource – the area of forest and the productivity of tree biomass. Supporting this bold statement are three observations: (1) there is little net deforestation in Canada, and most of what does occur is not directly due to forestry practices; (2) almost all harvested sites regenerate back to another forest, which will be available for harvesting again once the trees grow to an appropriate size; and (3) except in some local areas, for short periods of time, the amount of timber harvesting does not exceed the landscape-scale forest productivity. Of course, not all considerations are so positive. For instance, as was previously noted, natural regeneration has resulted in extensive areas that are, from the economic perspective, understocked with commercial tree species.

Moreover, additional environmental considerations must be weighed before Canadian industrial forestry can be considered to be ecologically sustainable (in the sense that was explained in Chapters 1 and 12). These issues, to be examined in Chapter 23, include the following:

- long-term effects of harvesting and management on site capability, which may become degraded by nutrient losses and erosion
- effects on populations of fish, deer, and other hunted species, which are also an economic "resource"
- effects on indigenous biodiversity, including native species and naturally occurring ecosystems (such as old-growth forest)
- effects on hydrology and aquatic ecosystems
- implications of forestry for carbon storage (this is important with respect to anthropogenic influences on the greenhouse effect; Chapter 17)

These ecological values can be severely degraded by forestry, and this detracts from the ecological sustainability of this industrial activity.

Table 14.10. Forest Resources and Forestry Production in Canada. Land classified as "productive" of timber has a sufficiently high productivity and stocking of trees to be economically exploitable, while "non-productive" forest is considered to be non-economical. Harvest data are for 2013. Increases are from 1990. Source: Data from Natural Resources Canada (2013).

Province	Forest Land (10^6 ha)	Harvest (10^3 ha)	Planted (10^3 ha)
NL	20.1	17.1	5.1
PE	0.3	2.9	0.2
NS	4.3	31.9	9.6
NB	6.2	59.3	18.8
QC	84.6	167.9	82.5
ON	68.3	120.9	33.2
MB	36.3	14.8	5.1
SK	24.3	14.8	3.1
AL	36.4	81.5	60.1
BC	64.1	174.6	153
YK	22.8	0.3	-
NT	33.3	<0.1	-
NU	0.9	-	-
Canada	402	637.8	370.7

Fish Resources

Wild populations of fish have long been exploited as food. In recent decades, there have been enormous increases of the rate of harvesting of wild fish, and also in the cultivation of certain species in semi-domestication, a practice known as aquaculture. Like crop plants, livestock, and forests, populations of fish can be harvested in a sustainable manner, which would allow the yields to be maintained. However, fish stocks can also be over-harvested to the degree that their regeneration is impaired. When this happens, productivity declines and the bio-resource can disastrously collapse. Regrettably, the recent history of many of the world's major fisheries provides abundant examples of over-exploitation causing rapid declines in resources.

The global harvest of fish, crustaceans, and shellfish in 2012 was about 91-million tonnes. This included 66-million tonnes of marine fish (representing a 4% decrease over 1993), 10 x 10^6 t of freshwater fish (a 91% increase), 1.7 x 106 t of diadromous fish (these are mostly salmon that migrate between salt and fresh water; +6%), and 44 x 10^6 t of fish grown in aquaculture (294% increase) (Table 14.11).

Table 14.11. Fish Catches and Aquaculture in Selected Countries. Data are in 10^6 t/y in 2012, with percentage increase since 1993 given in brackets. Countries are listed in order of decreasing catches of marine fish (data include diadromous fishes). Source: Data from FAO (2014).

Country	Wild Fishery		Aquaculture	
	Marine	Freshwater	Marine	Freshwater
Global	65.5 (-4)	10.3 (+90)	6.7 (+28)	37.4 (+293)
China	9.7 (+71)	1.6 (+122)	0.2 (+693)	23.0 (+259)
Peru	4.2 (-53)	<0.1	<1	<1
Chile	2.3 (-60)	<0.1	0.8 (962)	<1
Japan	2.9 (-52)	<0.1	0.3 (-14)	<0.1
Indonesia	4.8 (+93)	0.4 (+24)	0.6 (221)	2.1 (657)
U.S.A.	4.0 (-8)	<0.1	<0.1	0.2 (-27)
Canada	0.44 (-56)	0.02	0.1 (+222)	0.5 (+404)

Image 14.3. Bottom-dragging is a technology used to harvest fish or scallops by drawing an open net along the sea floor, which in some respects is the marine equivalent of clear-cutting a forest. This boat is used to drag for scallops off southwestern Nova Scotia. Source: B. Freedman.

Canada is a major fishing nation, with an annual harvest of 803-thousand tonnes of marine fish in 2013, with a value of $2.1 billion (Table 14.14). There was also a substantial harvest of freshwater fish, equivalent to 29 x 10^3 t and a value of $67 million. Aquaculture is also becoming increasingly important. The total harvest of fish in 2013 was 174-thousand tonnes, with a value of $834 million. Total exports of fish products had a value of $4.15-billion. The exports were partly offset by fish imports of $2.74-billion, for a net trade balance of $1.41-billion in this economic sector.

The most important marine species harvested are summarized in Table 14.12. Note that these data are for Canadian landings only. Some foreign nations also fish waters within Canada's 320 km management jurisdiction, but their landings are not included in the table.

Table 14.12. Landings of Selected Fishes in Canada. Catch biomass is in 10^3 t/y, and economic value is in millions of dollars. Data are for 2012. Source: Data from Fisheries and Oceans Canada (2014a).

Species	Atlantic		Pacific		Canada	
	Quantity	Value	Quantity	Value	Quantity	Value
	10^3 t	$106	10^3 t	$106	10^3 t	$106
Groundfish						
Hake	11.6	8.7	46.9	11.6	58.5	20.3
Cod	11	14.6	1.3	1.2	12.3	15.8
Turbot	13.4	58	-	-	13.4	58
Redfish	15	11.8	16.6	17.7	31.6	29.5
Haddock	9.3	20.1	-	-	9.3	20.1
Total	79.9	163.3	89.3	95.3	169.2	258.6
Pelagic and other finfish						
Salmon	0	0	9	24.3	9	24.3
Herring	114	44.3	9.4	5.1	123.4	49.4
Total	157.6	107.5	32.3	37.6	190	145.1
Shellfish						
Lobster	74.8	662.8	-	-	74.8	662.8
Crab	99.3	435.6	2.9	27.3	102.3	462.9
Shrimp	148.9	345.2	0.4	1.4	149.3	346.6
Scallop	53.3	114.3	-	-	53.3	114.3
Total	419.7	1623	7.9	80.2	427.6	1703
Aquaculture						
Fish	59.3	361.4	72.7	380.8	132	742.2
Shellfish	32.6	64.4	8.7	18.8	41.3	83.2
Total	91.9	425.8	81.4	399.6	173.3	825.4
All Marine	673.9	1908	129.5	213.1	803.4	2107
All Inland	-	-	-	-	29.3	67.3

In 1992, the total catch of cod in Atlantic Canada was 239-thousand tonnes, of which 80% was landed by Canadian vessels and 20% by the foreign fleet working within the 320-km management zone (see Canadian Focus 14.2). The 1992 catch was, however, much smaller than what had been attained in previous decades, which averaged as much as 598-thousand tonnes during 1982–1986 (81% was Canadian landings). In fact, the declining harvest reflected a collapse of the cod stocks throughout eastern Canadian waters, a resource calamity that resulted in the closure of virtually the entire fishery in 1992. The cod stocks were still largely closed to commercial exploitation in 2014 (when this was written), and will likely remain so for several years. In 2012, the cod landings in the Atlantic region were 11-thousand tonnes, only 5% of the catch in 1992. The devastation of cod stocks in the northwestern Atlantic Ocean, mostly caused by Canadian over-fishing, is a world-class example of the mining of a potentially renewable bio-resource.

Canadian Focus 14.2. Mining the Cod
In 1497, John Cabot explored waters around Newfoundland on behalf of the English Crown. On his return, he wrote with enthusiasm that the Grand Banks were so "swarming with fish [that they] could be taken not only with a net but in baskets let down [and weighted] with a stone." At that time, cod (Gadus morhua) was a bountiful resource on the Grand Banks, a relatively shallow marine ecosystem of 25-million hectares. Large cod stocks also occurred off Labrador, Nova Scotia, the Gulf of St. Lawrence, and New England.

By 1550, hundreds of ships were sailing from coastal Europe, catching cod and preserving it by drying or salting to sell in their home markets. By 1600, about 650 ships were fishing off Newfoundland, and by 1800, it was about 1,600 vessels. Between 1750 and 1800, the average landings were 190-thousand t/y which increased to 400-460-thousand t/y during 1800-1900, and almost 1-million t/y between 1899 and 1904 (Mowat, 1984; Cushing, 1988).

In those early times, the cod were harvested using hand-lines, long-lines, traps, and seines. Many men fished from small dories, often launched from a larger mother ship, such as one of the celebrated fishing schooners that sailed from Newfoundland or Nova Scotia. Although this technology is inefficient, the total fishing effort was large and therefore so was the catch. Consequently, some near-shore cod stocks became depleted, although not those of the offshore banks.

The fishery greatly intensified during the twentieth century because of such technological innovations as the following:

- the development of more efficient netting technologies, particularly trawls and monofilament gill nets
- the use of sonar equipment to locate schools of fish
- increases in ship-borne capacity to store and process fish, which allowed vessels to stay at sea for a longer time

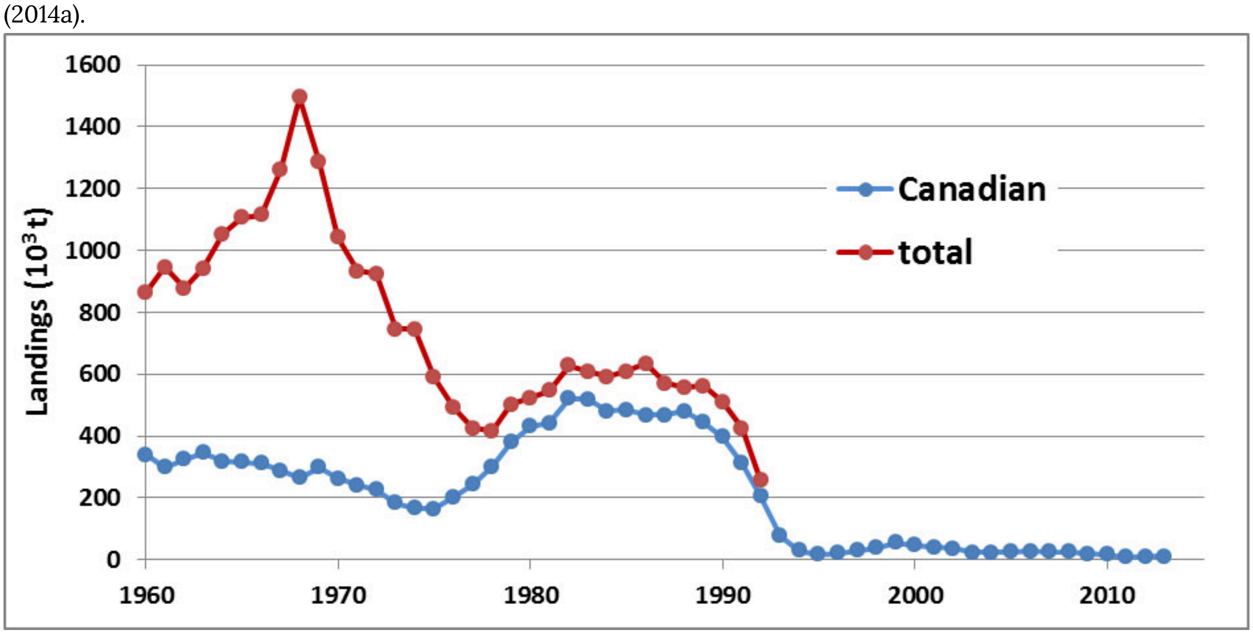
The improved technology allowed enormous catches to be made, particularly in the 1960s when the fishery was essentially an unregulated, open-access enterprise. By this time, unsustainably high catches were causing cod stocks to collapse (see Figure 1).

Image 14.4. Before the stocks of cod were heavily exploited, individual fish were much larger than they are today. Huge "mother cod" are now exceedingly rare. This is unfortunate because they have much greater spawning capacity than smaller cod. This photo was taken in Battle Harbour, Labrador in the 1890s. Source:

National Archives of Canada.

Because the declining stocks of cod were causing an economic crisis to occur in the Atlantic fishery, in 1977 the Government of Canada declared a 320-km wide fisheries-management zone within which quotas of fish were allocated. The conservation actions resulted in short-lived increases in cod stocks and landings. However, exploitation levels were still too high, and the fishery experienced an even more serious collapse. In 1992, the federal government declared a moratorium on commercial fishing for cod, a ban that was still largely in force in 2014 (when this was written). Because only small populations of adult cod are available for spawning, the recovery of the stocks has been slow. However, if allowed, the cod may eventually recover to again be a bounteous resource.

Figure 14.3. Recent History of Landings of Cod off Eastern Canada. Note the large decrease in overall landings, and the increasing proportion of Canadian landings after the declaration of a 320-km management zone in 1977. A moratorium on cod fishing was declared in 1992, but there have been some by-catch and sporadic quotas since then. Data are in thousands of tonnes. Sources: Statistics Canada (1994) and Fisheries and Oceans Canada (2014a).



Several explanations have been proposed for the collapse of cod stocks in the Northwest Atlantic, each based on more or less convincing logic and information. The most important of these are discussed below (Freedman, 1995; Hutchings and Myers, 1995).

The hypothesis of over-exploitation suggests that the cod resource was exploited faster than it could regenerate, which caused a decline that became especially acute from the 1970s to early 1990s. The excessive harvesting was caused by several factors. Over the years, scientists had estimated the size and productivity of cod stocks and their maximum sustainable yield (MSY). The scientific information was, however, imperfect. First, it is extremely difficult to estimate the abundance of fish in the open ocean. In addition, a population model being used in the 1980s to determine stock size and to set quotas was systematically overestimating cod biomass and MSY, and that resulted in the allocation of unsustainable fishing quotas.

Moreover, politicians and other decision makers in Canada (and everywhere else) are influenced by socio-economic considerations in addition to the advice of scientists. In the context of cod, these pressures come from individual fishers, their associations, and fish companies. These interest groups all need cash flows and livelihoods, in a context where there are few alternatives to fishing for employment and revenue generation. These powerful socio-economic influences led to political decisions to set larger quotas than were being recommended by fishery scientists, a factor that has contributed to the mismanagement of cod stocks and many other resources.

Most of the Grand Banks falls within Canada's 320-km management zone. Some parts, however, extend into international waters, where, until 1995, there was an unregulated multinational fishery. Because cod and most other marine species are mobile and do not recognize the boundaries of management zones, foreign over-fishing in international waters compromised efforts to conserve the stocks. However, between 1977 and 1991, Canadians landed about 85% of the cod caught in the Northwest Atlantic, and their fishery was being regulated. Humans are not the only predators of marine resources. The harp seal (Pagophilus groenlandicus) is the most abundant marine mammal in the Northwest Atlantic (more than 7-million). The seal population consumes about 1 million tonnes of food per year. However, this seal's prey consists of a wide variety of species, especially crustaceans and small fish such as capelin (Mallotus villosus) and Arctic cod (Boreogadus saida). Even though the cod stocks collapsed at the same time that the seal population was increasing, the minor role of cod in their diet makes it unlikely that seals were an important cause.

Finally, some people believe that the recruitment of cod may have been somehow impaired by environmental changes, including several years of cold surface-water temperatures in parts of the Northwest Atlantic. However, there is no direct evidence to support such an environment-related cause of the collapse of the cod stocks. The simplest and most compelling hypothesis offered to explain the collapse of cod stocks is this: the valuable resource was exploited at an intensity that exceeded its capability for renewal. In other words, the cod stocks of the Northwest Atlantic, one of the world's greatest potentially renewable bio-resources, were fished to commercial extinction.

Other Hunted Animals

Marine Mammals

Marine mammals have been subjected to intensive commercial hunting in many oceanic regions. Initially, they were hunted mostly as a source of oil, which in pre-petroleum times was a valuable commodity as a fuel in lamps and for cooking. A few marine mammals, including Steller's sea cow, the Caribbean monk seal, and the Atlantic grey whale, became extinct because of over-hunting, and many other species or populations became endangered (see Chapter 26).

Among the best-known commercial hunts of marine mammals are those of the great whales of all oceans of the world and the harp seal of eastern Canada.

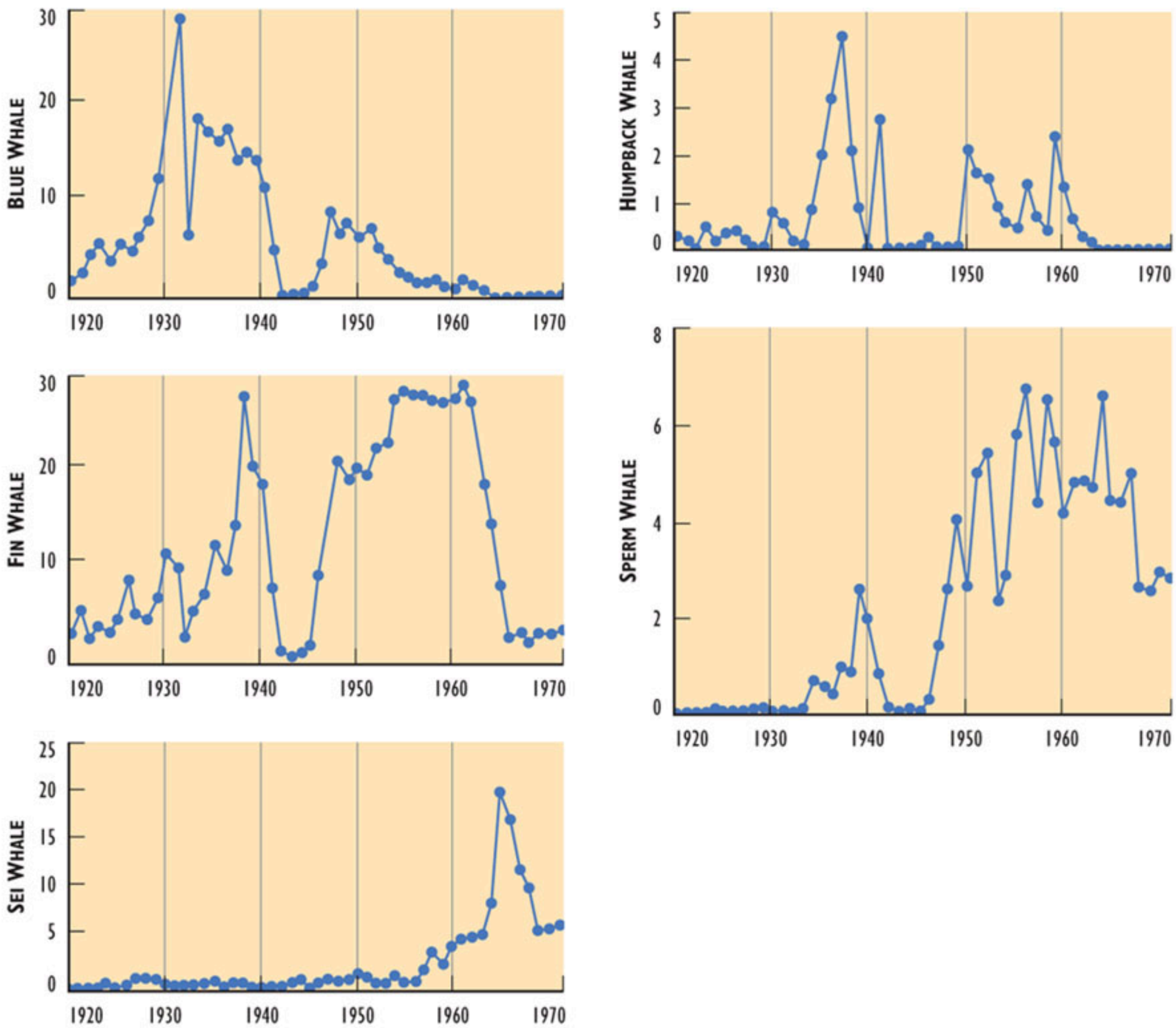
Whaling

People have been hunting whales for centuries. The first species to be commercially hunted was the northern right whale (Balaena glacialis), which was considered the "right" whale to kill because it swims slowly and close to shore and floats when dead. Early records tell of hunts in the Bay of Biscay (coastal Europe) in the eleventh century. Men would row or sail near a right whale, harpoon it, allow it to tow their boat until exhausted, and then repeatedly lance the animal until it bled to death. The carcass would then be towed to shore and butchered, and the blubber rendered by boiling into a valuable oil. Even this crude hunt was enough to exterminate the right whale from European waters.

The development of steam ships made it possible to hunt swifter whales, such as the roquals (blue, fin, sei, and minke). The invention of the harpoon gun in 1873, and later the exploding-head harpoon, made it easy to kill even the biggest whales. By 1925, huge factory ships would spend months or years in remote waters, processing whales killed by a small fleet of boats, sometimes guided to their prey by spotter aircraft. Whales of all species and sizes could be efficiently located, killed, and processed. This onslaught resulted in a rapid, and profitable, depletion of whale stocks.

With only a few exceptions, whale populations were not over-harvested to extirpation, but rather to commercial extinction – to a small population that was no longer profitable to find and kill. The sequential exploitation of a whale community is best illustrated by the hunt in Antarctic waters, where five species initially co-existed in great abundance (Figure 14.2).

Figure 14.4. Whaling in Antarctic Waters. Annual catches in thousands of whales. Source: Data from Ellis (1991).



In response to concerns about declining populations of whales, the International Whaling Commission (IWC) was established in 1949. The IWC was given a mandate to develop and implement conservation-related controls over the multinational, highly capitalized, competitive, and profitable whaling industry. Unfortunately, the initial efforts of the IWC were not very successful, partly because it is so difficult to estimate whale stock sizes and recruitment and to determine accurate sustainable yields. More importantly, the major whaling nations were not particularly co-operative, and the IWC was not aggressive in setting and enforcing quotas small enough to ensure that whale populations would not be depleted. These problems are to be expected whenever a for-profit enterprise is allowed to regulate and police itself. According to J.L. McHugh, a former commissioner and chairperson of the IWC, "From the time of the first meeting of the Commission … almost all major actions or failures to act were governed by short-range economic considerations rather than by the requirements of conservation" (cited in Ellis, 1991).

Because of its enormous size, with the largest males reaching 32 m and 136 tonnes, the blue whale (Balaenoptera musculus) was initially the most profitable species in the Antarctic seas. The original population in those waters was about 180-thousand, and as many as 29-thousand were killed in a single year (Figure 14.2; note that during the Second World War, as few as 59 animals were harvested in a year). Between 1955 and 1962, declining stocks meant an annual harvest of only 1-2-thousand. After 1965, killing this species was prohibited by the IWC. In total, about 331,000 blue whales were killed in Antarctic waters between 1920 and 1965. The present Antarctic population of blue whales is fewer than 2,000, only about 1% of their initial abundance. The global population is now about 3,000 individuals, compared with an initial 250-thousand.

As blue whales became depleted, the fin whale (B. physalus) became the favoured species of the Antarctic hunt. This is the second-largest species, up to 21 m long. As many as 29-thousand animals were harvested in a year, causing this species to decline, though not to commercial extinction. More than 704-thousand fin whales were killed in this region. The present population is less than 85-thousand animals, about 21% of the original abundance. The global abundance is about 163-thousand, compared with an initial 700-thousand.

As the largest species became difficult to harvest because of their increasing rarity, initially “less desirable” species were hunted. These were the sei whale (B. borealis), humpback whale (Megaptera novaeangliae), sperm whale (Physeter macrocephalus), and minke whale (B. acutorostrata). These smaller species were also over-harvested, and their populations also declined.

Toward the end of the hunt in the Antarctic Ocean, the population of blue whales had been reduced by about 99%, humpback whales by 97%, sei whales by 82%, and fin whales by 79%. By the early 1980s, whalers were killing mostly the relatively small (up to 9.1 m long) and abundant minke whale. Finally, in 1982, the IWC announced a moratorium on Antarctic whaling, to begin in 1985-1986. Japan and the former USSR continued a commercial hunt until 1986-1987. Since then, only Japan has whaled in the Southern Ocean, killing hundreds of minke whales in most years for the purposes of “research,” as well as fin whales.

Industrial whaling also depleted whale stocks in the Northern Hemisphere. Early European explorers found large populations of northern right whales in waters off Atlantic Canada, and these valuable animals were soon hunted. The Basque hunt of 1530-1610 killed about 25-40-thousand right whales (but few afterward because of the severely depleted stocks). The right whale survives today in the western Atlantic as an endangered population of about 350 animals, only 3-4% of the original abundance. Although this species has been protected from hunting for more than 50 years, its abundance is not increasing much. This is probably because of mortality caused by accidental collisions with ships and entanglement in fishing gear.

Soon after the right whales were depleted off eastern North America, populations of bowhead whales (Balaena mysticetus) were discovered in Arctic Canada, Alaska, and eastern Siberia. Like right whales, the slow-swimming bowhead could be easily overtaken by whaling boats and killed. The population of about 55-thousand bowheads in the western Arctic was soon depleted. Bowhead whales are now rare, although their populations are increasing. These animals are no longer hunted commercially, although a hunt by Inuit in northern Alaska kills 20-40 animals per year. Since 1996, Canadian Inuit have been allowed to again hunt a few bowhead whales, a practice that is permitted because of the importance of this species in their culture.

A final example of depletion of a whale stock involves the grey whale (Eschrichtius robustus) of western North America. This species winters and breeds in warm waters off Mexico and migrates up the Pacific coast to summer in the western Beringean Ocean. Commercial hunting began in 1845 and largely ended by 1900 because the stock had been reduced to an endangered several thousand animals. These were protected from further hunting, and the grey whale has since increased to about its pre-exploitation abundance of about 24-thousand animals. However, the species remains extirpated off Western Europe and is critically endangered in eastern Asia.

In total, more than 2.5 million whales of all species were killed during the commercial hunts of the past four centuries. Although there is now a ban on commercial whaling, Norway and Japan are still hunting minke whales, each killing several hundred per year. These and several other countries are lobbying aggressively for a return to a limited commercial hunt. In recent years, Japanese whaling interests have announced intentions to harvest larger numbers of minke whales, as well as fin whales and humpback whales in Antarctic waters. This was obviously a commercial harvest, but because biological and ecological data were collected, it was undertaken under the umbrella of "scientific" whaling.

Seal Hunting

Seals breed on land or sea ice, often in dense populations, and during the past several centuries, huge numbers have been commercially slaughtered for their skin, blubber, meat, and other products. Until the mid-twentieth century, seal hunting was an unregulated enterprise that severely depleted the resource, with several species made extinct and many regional and local extirpations (see Chapter 26). Since then, conservation measures have protected most seal populations. Some severely depleted species have managed to increase in abundance, such as the California sea lion (Zalophus californianus), northern fur seal (Callorhinus ursinus), and northern elephant seal (Mirounga angustirostris) in Pacific waters near North America.

One of the largest commercial hunts has involved the harp seal (Pagophilus groenlandicus), an abundant species of the northern Atlantic Ocean. These seals breed prolifically on pack ice in the Gulf of St. Lawrence and around Newfoundland and Labrador, and then summer in the eastern Arctic. Harp seals are especially vulnerable to hunters in April, when large numbers of newborn pups, called whitecoats because of the colour of their birth fur, lie about on the pack ice. Because they are not yet aquatic, the pups are easily approached and killed. Adults are also concentrated at that time and can be caught in nets, shot on the ice, or clubbed if they try to defend their young. The skins of harp seals are a valuable commodity, and many people enjoy eating their meat.

Historically, the largest hunts were by Newfoundlanders, but hunters from Labrador, Nova Scotia, Prince Edward Island, and Quebec have also been active. The numbers harvested in any year mostly depended on the ice conditions, which affect how close sealers can get to the whelping aggregations of seals. During the heyday of this enterprise, more than 600-thousand animals were harvested annually, as occurred in 1831, 1840, 1843, and 1844 (Busch, 1985). Overall, about 21-million harp seals were taken between 1800 and 1914. This vast slaughter of a large wild animal has only a few parallels, including the massacre of bison in the nineteenth century (Chapter 26), the modern hunt of kangaroos in Australia, and that of deer in the Americas.

Another 12-million harp seals were taken between 1915 and 1982, with up to 380-thousand in one year (1956). Since then, the harvests have been smaller, mostly because of intense controversy about a commercial harvest of wild animal babies and the consequently diminished market for seal products. For instance, in 1984 the European Union (EU) banned the import of whitecoat pelts, which resulted in reduced harvests in Canada, from 190-thousand per year in 1981-1982 to 19-80-thouand per year during 1983-1990. (Note that young harp seals are not called whitecoats after they are 9-10 days old, when they begin to shed their white fur. At the time, older young could still be imported to the EU, but the most lucrative market had been for whitecoats. In 2010, the EU banned the importing of all sea products.)

In recent decades, animal-rights and conservation advocates, as well as elements of the popular media, have engaged in sensationalized reporting of the hunting of harp seals in Atlantic Canada. This has resulted in the hunt being widely regarded as a cruel and barbaric enterprise, mostly because baby seals, which are extremely attractive animals, were the object of the hunt. The young seals were killed by clubbing or shooting, which are humane methods of slaughter. However, some sealers were not competent in these killing methods, and videos have shown that during the rush to harvest young seals, animals might be inadequately clubbed and then skinned while apparently "alive" (or at least still twitching – the seals were likely brain-dead). Video images like this are extremely upsetting to most people, and they have been widely publicized by well-organized opponents of the Canadian hunt of harp seals.

Many people, however, do not agree with the portrayal of the seal hunt as being unusually "cruel and brutal." They contend that the commercial harvesting of wild seals is no more ruthless than the slaughter of domestic livestock. For example, each year tens of millions of large mammals and hundreds of millions of chickens are raised and slaughtered annually in Canada, often under cruel conditions, to provide meat and other products (see also Chapter 24). Clearly, there are elements of cruelty in the commercial slaughter of both wild animals and livestock. An analysis of the ethics of killing animals should also, however, recognize that seals are wild creatures while livestock are specifically bred, raised, and killed for consumption by humans. It is up to philosophers, and to individual consumers of animal products, to determine which of these commercial slaughters, if either, represents the greater moral outrage.

Although the intense hunting caused harp seals to decrease in abundance, the species was never depleted to the degree of biological or commercial endangerment. This was not a result of a conservation ethic by the sealers or their industry. In fact, sealers typically killed as many harp seals as they could, particularly before 1970 when the Canadian government began to regulate the hunt through a quota system. In general, only the physical difficulty of hunting in treacherous pack ice limited the numbers of seals that could be found and killed, and so prevented a severe depletion of their stocks.

When the commercial hunt was reduced in the late 1980s, the global abundance of harp seals was about 3 million animals, including 2 million in Canadian waters. Even then, the harp seal was among the world's most populous large wild animals. In 2014, its abundance in Canadian waters was more than 7.4-million (there are also up to 0.6-million hooded seals and 0.5-million grey seals; Fisheries and Oceans Canada, 2014b). In fact, the rapidly increasing harp seal population is alarming some people, who are concerned that the seals are "eating too many fish" (although there is little evidence to support this idea; see Canadian Focus 14.2).

In any event, harp seals are again being harvested. The harvest is intended to cull the seal population somewhat, while providing economic benefits through the sale of meat, hides, and other products (including penises, for which there is a market in eastern Asia). The most recent quota allowed the harvest of 400-thousand harp seals in 2013-2014, including adults and recently moulted young (but not whitecoats). The quota for hooded seals was 8,200, and grey seals 60-thousand. However, the actual harvests are much smaller, largely because of collapsed markets in the European Union and elsewhere. The actual harvest of harp seals in 2013 was 94-thousand, with a markey value of the raw pelts being about $3-million. A nominal goal of the management plan is to reduce the abundance of harp seals to about 3.85 million.

Terrestrial Hunting

Many terrestrial animals are also hunted in large numbers, including big mammals such as bears, deer, gazelles, kangaroos, and pigs. Many birds are also hunted, particularly grouse, pheasants, shorebirds, and waterfowl. Much hunting of wild animals is undertaken for subsistence purposes, but sport hunting is also important in some regions.

Hunting is a popular activity. Many Canadians hunt on a regular basis, whether for subsistence, as a blood sport, or for both reasons. The most commonly hunted large mammals are species in the deer family, but other animals are also taken. The most important big-game species in Canada are the following (annual harvests during 2011-2013):

- white-tailed deer (Odocoileus virginianus), 201-thousand
- moose (Alces alces), 72-thousand
- mule deer (Odocoileus hemionus), 73-thousand
- caribou (Rangifer tarandus), at least 10-thousand
- black bear (Ursus americanus), 21-thousand
- elk (Cervus canadensis), 11-thousand
- pronghorn antelope (Antilocapra americanus), 1,400
- wolf (Canis lupus), 2,800

(Note that these data were compiled from information provided by provincial and territorial governments, using the most recent available information. However, the data are incomplete in that they are based on incomplete surveys of hunters, and kills due to poaching (illegal hunting) are not included. In addition, hunting by Aboriginal persons is not usually reported or is considered proprietary information, especially in northern regions of Canada.)

Image 14.5. Many white-tailed and mule deer are harvested by hunters each year in Canada. This mule deer was photographed in Jasper National Park, Alberta. Source: B. Freedman

Although the demand for wild furs has declined in recent decades, fur-bearing animals are still trapped in large numbers in Canada. During 2011-2013, at least 900-thousand furbearers were trapped annually, including 295-thousand muskrat, 170-thousand beaver, 75-thousand marten, 72 000 squirrels, 52-thousand raccoons, 73-thousand coyotes, 55-thousand mink, and 27-thousand fox. An additional 1.46 million mink were raised and harvested on fur farms.

Image 14.6. About one million geese are harvested by hunters each year in Canada. This snow goose was photographed on its nest on Ellesmere Island. Source: B. Freedman

Waterfowl are also harvested in large numbers. In total, about 1.2-million ducks were taken by hunters in 2013, along with 1.1-million geese (Canadian Wildlife Service, 2013; U.S. Fish and Wildlife Service, 2014). This is considerably smaller than the U.S. harvest from this essentially same population of migratory waterfowl, which totaled about 13.7-million ducks and 3.4-million geese in 2013. The most commonly hunted game birds in Canada (harvested in 2013) are the following:

- mallard (Anas platyrhynchos), 547-thousand
- black duck (Anas rubripes), 100-thousand
- green-winged teal (Anas crecca), 83-thousand
- wood duck (Aix sponsa), 71-thousand
- ring-necked duck (Aythya collaris), 31-thousand
- northern pintail (Anas acuta), 56-thousand
- gadwall (Anas strepera), 40-thousand
- lesser scaup (Aythya affinis), 32-thousand
- 21 additional duck species, 278-thousand
- Canada goose (Branta canadensis), 726-thousand
- snow goose (Chen caerulescens), 225-thousand
- white-fronted goose (Anser albifrons), 75-thousand
- murres (Uria lomvia and U. aalge), 114-thousand
- woodcock (Scolopax minor), 20-thousand
- sandhill crane (Grus canadensis), 5-thousand

- coot (Fulica americana), 2-thousand

Some of the species that are hunted or trapped in Canada have declining populations over at least some of their range where they are exploited. This is the case of many southern populations of caribou, wolf, and grizzly bear, and of some waterfowl, such as canvasback and redhead ducks. This is not to say that these species should be considered endangered in Canada, but it does indicate that it is necessary to monitor their population changes to ensure that over-hunting does not cause them to decline to an unacceptable degree.

Conclusions

Renewable resources are the only fundamental basis of a sustainable economy. In this chapter, we learned that the most important kinds of renewable resources in Canada and the rest of the world are fresh water, agricultural products, forest biomass, fish, and hunted birds and mammals (renewable sources of energy were examined in Chapter 13). Some of these are wild resources that are harvested from natural ecosystems, while others are managed in agricultural systems to achieve higher yields (including in agroforestry and aquaculture). In general, Canada is rich in renewable natural resources, with a bountiful surplus of many of them available to export to other countries. Nevertheless, Canada also provides cases of the depletion of potentially renewable resources by excessive harvesting or inadequate management of the regeneration.

Questions for Review

1. What is meant by a renewable natural resource? Explain the principle by referring to one of the following: surface water and groundwater, agricultural site capability, timber, or a hunted animal.
2. What are the most important renewable resources in Canada? Indicate, giving reasons, whether you think those resources are being used in a sustainable manner.
3. Use data on natural resources in Chapters 13 and 14 to develop a "resource profile" for the province or territory where you live. Consider the relative importance of non-renewable and renewable resources in the economy and the implications for longer-term sustainability.
4. What are the criteria for ecological sustainability?

Questions for Discussion

1. Identify a potentially renewable natural resource that has been over-harvested and depleted in your region. What are the reasons for the unsustainable use of the resource?
2. Should relatively abundant species of whales (such as the minke) or harp seals be hunted? Your answer should consider whether the species can be harvested in a sustainable manner, and should also address the ethics of hunting wild animals.
3. What are the political and economic problems of sharing water resources between countries or regions?
4. Although food can be purchased in a store, it does not really come from there – it is actually harvested from wild ecosystems or is cultivated in agriculture. Consider the food that you eat and the ethical and environmental issues associated with its production. You may find this question to be particularly interesting if you focus on meat, which is lethally harvested from millions of animals each year in Canada.

Exploring Issues

1. The Minister of the Federal Department of Fisheries and Oceans has been asked to allow the resumption of whale hunting in Canadian waters. The minister asks for your advice on the matter, and you decide to develop lists of benefits and damages that would occur if the hunting were allowed. Prepare these lists and explain how each item relates to the ecological sustainability of a potential whale harvest.

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PART V: ENVIRONMENTAL DAMAGES

Chapter 15 ~ Environmental Stressors

Key Concepts

After completing this chapter, you will be able to

1. Describe the environmental stressors, their causes, and how ecosystems respond to changes in their intensity.
2. Explain the differences between contamination and pollution.
3. Provide examples of natural stressors and explain how knowledge of them can help us understand anthropogenic stressors.
4. Outline the differences among toxicology, environmental toxicology, and ecotoxicology.
5. Explain the differences between voluntary and involuntary risks.
6. Identify how a risk assessment is done of a predicted exposure to a toxic chemical.

Environmental Stressors

Environmental stressors (stressors) are factors whose influence is to constrain productivity, reproductive success, and ecosystem development (see Chapter 9). To some degree, stressors affect all organisms as well as their populations, communities, and ecoscapes (landscapes and seascapes). Stressors may be natural in origin, being associated with such environmental influences as:

- competition, predation, disease, and other interactions among organisms
- constraints related to climate or to inadequate or excessive nutrients, moisture, or space
- disturbances such as wildfire and windstorms

The effects of natural stressors are not always negative. Some individuals, populations, and communities may benefit from the effects of natural stress, even while others suffer a degree of damage.

Increasingly, however, stressors associated with human activities are the most critical influence on species and ecosystems. In too many cases, anthropogenic stressors are causing important damage to resources that are needed to sustain people and their economy, and also to natural biodiversity and ecosystems.

Image 15.1. Wildfire, windstorms, and insect outbreaks can be extensive disturbances that affect ecosystems at a landscape scale. This photo shows a stand of eastern hemlock (Tsuga canadensis) trees that has been killed by several years of defoliation by a native moth (Iridopsis ephyraria) in Nova Scotia. Source: B. Freedman.

Environmental stressors may occur as an intense, short-lived event of destruction, also known as a disturbance. Alternatively, stressors may exert their influence over an extended period of time – that is, in a chronic manner. The interaction of organisms with a stressor at a particular place and time is called exposure. Exposure can be instantaneous or it may accumulate over time. If an exposure is intense enough, it will cause some sort of biological or ecological change, called a response, to occur. It is important to understand, however, that individuals, populations, and communities are capable of tolerating a range of intensity of stressors without suffering significant damage. In other words, certain thresholds of biological or ecological tolerance must be exceeded before damage is caused (Image 15.2).

Image 15.2. Stressors are environmental factors that affect organisms and ecosystems. They may exist at varying intensities of exposure, as is suggested by the metaphor of a water faucet, whose dial if turned to the right will increase the flow of water, or decrease or stop it if turned the other way. For actual stressors, if a threshold of biological or ecological tolerance is exceeded, then a response will occur. Source: B. Freedman.

Damage occurs when one or more stressors elicit responses that can be interpreted as a degradation of environmental quality. Such responses may include illness or death caused by an exposure of wild animals to pesticides, or as a reduction of the productivity of ecosystems, or the endangerment of vulnerable elements of biodiversity. In this chapter, we examine a conceptual framework for the study of damage caused by stressors. In the following 11 chapters, we deal with specific kinds of stressors and examine case studies of the kind of damage they may cause to occur.

Kinds of Stressors

The diverse kinds of environmental stressors are grouped into classes, although they are not entirely exclusive.

- Physical stress is a disturbance in which there is an intense exposure to kinetic energy, which causes damage to habitats and ecosystems. Examples include such disruptive events as a hurricane or tornado, a seismic sea wave (tsunami), the blast of a volcanic eruption, an explosion, or trampling by heavy machinery or hikers.
- Wildfire is another disturbance, which involves the uncontrolled combustion of the biomass of an ecosystem. A wildfire can be ignited by people, or naturally by lightning. A severe fire consumes much of the biomass of an ecosystem, but even a less-severe wildfire may kill many organisms by scorching and poisoning by toxic gases.
- Chemical pollution occurs when one or more substances occur in a concentration high enough to elicit physiological responses in organisms, potentially causing toxicity and ecological change. Chemical stressors include pesticides, gases such as ozone and sulphur dioxide, and toxic elements such as arsenic and mercury. Pollution may also be caused by excessive nutrients, which can distort productivity and other ecological functions. Note that the mere presence of a potentially toxic agent does not necessarily cause pollution. (The distinction between contamination and pollution is examined later in this chapter.)
- Thermal pollution is caused by the release of heat (thermal energy) into the environment, which results in ecological stress because species vary in their tolerance of temperature extremes. Thermal stress may occur at natural springs and submarine vents where geologically heated water is emitted. It is also associated with discharges of hot water from power plants.
- Radiation stress is caused by excessive exposure to ionizing energy. The radiation may be emitted by nuclear waste or explosions, or it can be diagnostic X-rays or solar ultraviolet energy.
- Climatic stress is associated with insufficient or excessive regimes of temperature, moisture, solar radiation, wind, or combinations of these.
- Biological stressors are associated with interactions occurring among organisms, such as competition, herbivory, predation, parasitism, and disease. For example, individuals of the same or different species may compete for essential resources that are limited in supply. Herbivory, predation, parasitism, and disease are trophic interactions, in which one species exploits another. Exploitation can be anthropogenic, as when humans harvest wild animals or trees, or it can be natural, perhaps associated with defoliating insects or disease-causing pathogens.
- Biological pollution occurs when people release organisms beyond their natural range. This might involve the introduction of alien species that invade and alter natural habitats, or it may be the release of pathogens into the environment through discharges of raw sewage.

Image 15.3. Biological "pollution" is caused when species are introduced into habitats beyond their natural range, where they may cause ecological damage. This non-native lupine (Lupinus polyphyllus) has been introduced to eastern Canada, where it thrives in gardens and along roadsides. Although an attractive wildflower, it displaces indigenous plants. Source: B. Freedman.

Ecological Responses

An ecosystem that has been affected by a disturbance typically suffers mortality among its species, along with damage to its structural properties (such as species composition and biomass distribution) and functional attributes (such as productivity and nutrient cycling). Once the disturbance event is over, a process of recovery through succession begins. If the succession proceeds for a long enough time, it will restore another mature ecosystem, perhaps one similar to that existing before the disturbance.

Chronic stressors operate over longer periods of time (rather than as events), and they include climatic factors and many kinds of chemical and thermal pollution. Depending on the intensity of exposure, organisms may suffer acute toxicity resulting in tissue damage or even death, or a less-obvious chronic damage that results in decreased productivity.

Exposure to a higher intensity of environmental stressors can result in evolutionary changes if individual organisms vary in their tolerance and those differences are genetically based. Under such conditions, natural selection in favour of tolerant individuals will eventually result in increased tolerance at the population level. At the community level, relatively vulnerable species will be reduced or eliminated from the habitat if the intensity of stress increases markedly. The niches of those species may then be occupied by more tolerant members of the community, or by invading species that are capable of exploiting a stressful but weakly competitive habitat.

A prolonged intensification of stress will cause longer-term ecological change to occur. Consider, for example, a case in which a new metal smelter is constructed in a forested landscape. If the smelter emits toxic sulphur dioxide gas, the toxic stress will damage the tree-sized plants of the forest and eventually cause them to give way to shrub-sized and herbaceous vegetation. If the long-term stress is extremely severe, the landscape could entirely lose its vegetation. This kind of damage has actually occurred around a number of Canadian smelters, such as those near Sudbury (Chapter 16).

This kind of ecological damage involve changes in the composition and dominance of species in communities, in the spatial distribution of biomass, and in functions such as productivity, litter decomposition, and nutrient cycling. Because a smelter is a discrete point source of environmental stress, the ecological responses eventually stabilize as gradients of community change that radiate outward, in a downwind or downstream direction from the source of pollution.

The intensity of a stressor may also decrease in time and space. When this happens, the ecological responses are, in many respects, the reverse of the damage that occurs when the stress intensifies. These changes represent a process of recovery through succession. In the case of the Sudbury smelters, emissions of pollutants have decreased greatly because of the installation of pollution-control technologies. This has resulted in much less toxic stress in the surrounding environment, which has allowed some ecological recovery to occur (Chapters 16 and 18).

Ecologists have described the general attributes of ecosystems that have been subjected to severe stress for a period of time. In general, as environmental stress intensifies significantly (such as by increasing pollution), the following changes are observed:

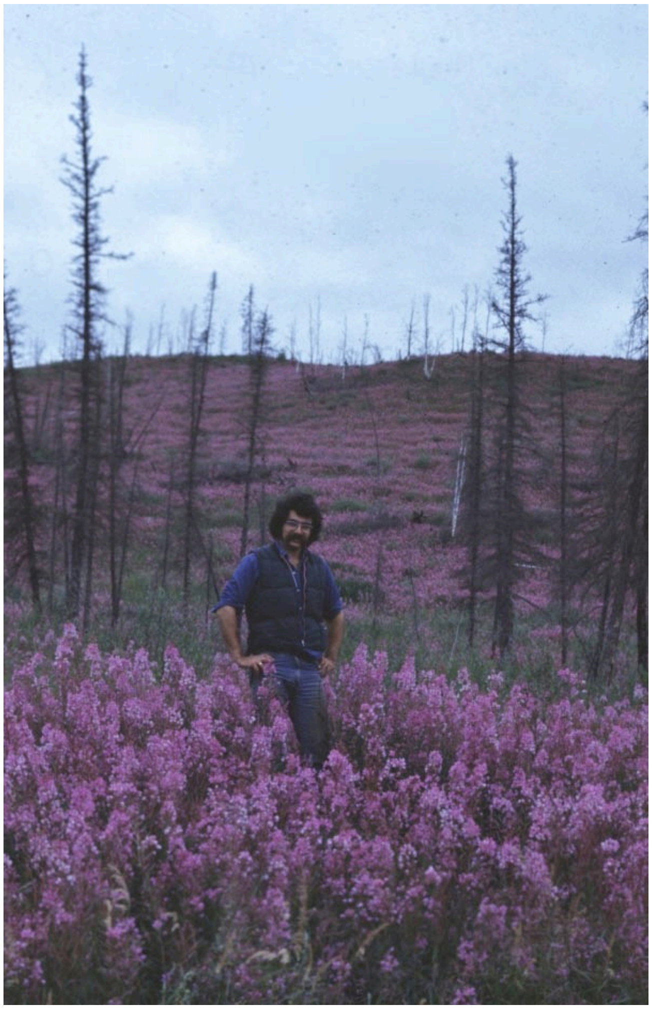
- mortality increases, especially of the most vulnerable species
- species richness decreases
- the stocks of nutrients and biomass become depleted
- the rate of community respiration exceeds that of production, so the net production becomes negative.
- sensitive species are replaced by more-tolerant ones
- top predators and large-bodied species may be lost from the ecosystem
- previously self-maintaining ecosystems may require active management to sustain their desirable attributes, for example, to maintain declining populations of rare or economically valuable species that have become threatened

Ecosystems that are chronically exposed to intense stress (such as climate-stressed tundra) eventually stabilize. Typically, the stable ecosystems are low in species richness, simple in structure and function, and dominated by relatively small, long-lived species. As well, they have low rates of productivity, decomposition, and nutrient cycling.

If an increase in environmental stress has an anthropogenic causation, then the resulting ecological changes are often considered to represent damage and are viewed as a degradation of environmental quality and ecological integrity (these terms are examined in Chapter 27).

Image 15.4. Natural disturbances such as wildfire initiate a process of ecological recovery known as succession. This photo shows a burned area of boreal forest near Inuvik in the Northwest Territories. The community at this early stage of succession is dominated by an herbaceous plant called fireweed (Epilobium angustifolium).

Source: B. Freedman.



Contamination and Pollution

Pollution is caused by an exposure to chemicals or energy at an intensity that exceeds the tolerance of organisms. As such, pollution is judged to have occurred when it can be shown that organisms have suffered toxicity, or other kinds of ecological damage can be demonstrated. Pollution can affect humans and other species, as well as communities and ecoscapes. Pollution is often caused by an exposure to chemicals in large enough concentrations to poison at least some organisms. However, pollution can also be caused by non-toxic exposures, such as the excessive fertilization of a waterbody, a release of waste heat into the environment, or the discharge of raw sewage containing pathogens.

Contamination refers to those much more common situations in which potentially damaging stressors are present in the environment, but at an intensity too low to cause measureable damage. For instance, a certain chemical may occur in a higher concentration than is normally encountered in the environment. However, if its concentration is too low to cause measurable toxicity to at least some organisms, or to affect other ecological components or processes, the chemical is a contaminant rather than a pollutant.

In fact, metals such as aluminum, cadmium, lead, mercury, and zinc are present in all parts of the environment, including all organisms, in at least a trace concentration. If the detection limits of the available analytical chemistry are sensitive enough, this “universal contamination” by metals can easily be demonstrated. Although all metals (and any other chemicals) are potentially toxic, they must be present in a high enough concentration for a long enough period of time to actually poison organisms and cause ecological damage. In other words, the exposure must exceed biological tolerances before damage is caused and pollution can be said to occur.

Pollution and contamination are often judged with a human-focused bias. People decide whether pollution is causing “damage” at some place and time, and how important the effects might be. This anthropocentric bias tends, quite naturally, to favour humans and those species, communities, and ecosystem functions that are recognized as supporting the human economy, or may be appreciated for other reasons, such as aesthetics.

Interestingly, certain species, communities, and ecological processes will actually benefit from most kinds of pollution. For example, particular species may take advantage of ecological opportunities made available when pollution reduces the abundance of a previously dominant species. Many of the case studies described in following chapters involve situations in which opportunistic species of plants, animals, and microorganisms have benefited from ecological changes caused by pollution.

Pollution Can Be Natural

Pollution is not only caused by human activities – in some cases, it is a purely natural phenomenon. “Natural” sources of pollution include emissions of particulates and gases such as sulphur dioxide from volcanoes, seeps of petroleum on the ocean floor, high concentrations of metals in certain soils and rocks, and the heat of geothermal springs. Natural pollution may cause severe ecological changes (which humans may view as being a kind of damage). The effects can be as intense as those caused by anthropogenic pollution. Nevertheless, although the fact of natural pollution is interesting and well recognized, it does not justify human activities that cause similar kinds of damage.

Studies of the ecological effects of natural pollution can provide insight into the potential longer-term effects of anthropogenic emissions. This is because many examples of natural pollution are ancient, and the resulting patterns of ecological change may be similar to those caused by more recent anthropogenic emissions.

One interesting example occurs at the Smoking Hills in the Northwest Territories. This is a remote wilderness, and is little influenced by people. At several places along the seacoast and nearby rivers, erosion has exposed deposits of bituminous shale. These carbon-rich deposits have spontaneously ignited at various places and have been smouldering for centuries and fumigating the nearby tundra with sulphur dioxide. The SO2 is toxic to plants and also causes soil and water to become highly acidic. The natural pollution has severely damaged terrestrial and aquatic habitats of the tundra at the Smoking Hills (see Chapter 16).

Another example of natural pollution occurs when metal-rich minerals occur close to the surface of the ground, which results in toxic conditions for vegetation. For example, plant ecologists have studied soil containing “serpentine” minerals, which are rich in nickel and cobalt. When they occur in high concentrations, these metals are toxic to most plants. Habitats containing serpentine minerals develop a distinctive plant community that is dominated by low-growing species that can tolerate the toxic stress of the metal-rich soil (see Chapter 18).

An additional case of natural pollution involves certain species of marine phytoplankton that occasionally become abundant and cause ecological damage. In events called toxic blooms, these algae release biochemicals that are poisonous to a broad range of animals that are exposed through the food web. In some cases, humpback whales have died at sea after eating fish polluted with saxitoxin, a potent neurotoxin synthesized by dinoflagellate algae. The algal toxins are also a risk to people eating fish polluted by this and other chemicals, such as domoic acid.

Research and discussion of naturally occurring pollution is useful and informative in environmental science. However, in this book, we emphasize pollution caused by human activities and its resulting damage. This focus is sensible because anthropogenic pollution is increasing rapidly in many countries, including Canada. Consequently, there is a pressing need to avoid or manage the damage that pollution can have on people as well as natural ecosystems.

Anthropogenic Pollution

In the modern world, an enormous amount of pollution is associated with human activities. This has caused important damage to human health and to managed and natural ecosystems. People cause pollution in diverse ways, and we examine them in following chapters. Most commonly, anthropogenic pollution is associated with these kinds of activities:

- accidental or deliberate emissions of chemicals into the environment, such as sulphur dioxide, metals, pesticides, and petroleum
- releases of substances that react in the environment to synthesize chemicals of greater toxicity – this is known as secondary pollution (as occurs when ozone is created by photochemical reactions in the atmosphere)
- emissions of chemicals that degrade stratospheric ozone, such as chlorofluorocarbons
- releases of waste industrial heat, as when a power plant discharges hot water into a river or lake
- discharges of nutrient-laden sewage or fertilizer into waterbodies
- emissions of greenhouse gases that threaten global climate
- releases of alien species that cause damage when they invade managed or natural habitats, or are pathogens of people, crops, or native species

Image 15.5. Many human activities result in emissions of pollutants into the environment. This image shows a 380-m smokestack at a metal smelter near Sudbury, Ontario. Source: B. Freedman.

Disturbance

A disturbance is an episodic but intense disruption that causes severe biological and ecological damage. An event of disturbance is followed by a sometimes lengthy period of ecological recovery through the process known as succession. There are two broad types of disturbances: community-replacing disturbances and microdisturbances.

- A community-replacing disturbance is extensive in scale and results in a catastrophic destruction of one or more original communities. Natural examples are caused by wildfire, windstorm, avalanche, and glaciation, while anthropogenic ones include clear-cutting and ploughing. These large-scale disturbances may be followed by a successional recovery that eventually regenerates a community similar to what was destroyed. Younger communities in the successional sequence (or sere) are relatively dynamic in their structural and functional properties. They are typically dominated by species that are abundant only during the initial stages of recovery, when competition is not so intense. Community changes in later stages are somewhat less dynamic, until a late-stage community is re-established.
- A microdisturbance involves a local disruption that only affects a small area within an otherwise intact community. Anthropogenic microdisturbances include the selective harvesting of individual large trees or particular animals, while leaving the community otherwise intact. Ecological changes are relatively rapid within a habitat patch that

has been affected by a recent microdisturbance, but at the stand level the community is stable. So-called patch- or gap-phase successional dynamics occur in all natural forests but are particularly important during the later stages of succession. This is especially the case in older-growth forest, where individual trees might die from disease, insect attack, or a lightning strike, creating a gap in an otherwise intact canopy.

Natural Disturbance

Disturbance is a natural force that affects all ecosystems. For example, a wildfire may kill mature trees over a large area, but that event of destruction is followed by regeneration through succession. Fire is common in the boreal forest and in drought-prone ecosystems such as prairie and savannah. On average, about 2-million hectares of forest burns each year in Canada, mostly in fires started by lightning. Wildfire transforms the habitat conditions and also causes severe pollution by the emission of particulates and gases such as carbon dioxide and nitrogen oxides to the atmosphere.

Other natural agents of disturbance include hurricanes, tornadoes, floods, and even glaciation (over geological time). These also cause large-scale ecological damage, which is followed by successional recovery. After glaciation, which involves prolonged burial and abrasion of the land by an enormous mass of ice, the post-melting recovery is initiated by immigrating organisms that colonize the raw landscape.

A volcanic eruption or earthquake can generate one or more devastating oceanic waves, or tsunamis. In 1883, the cataclysmic eruption of the volcanic island of Krakatau in Indonesia created a 30-m tsunami wave that killed about 36-thousand people. In 2004, more than 225-thousand people were killed by a tsunami in the Indian Ocean (see Global Focus 3.1). In 2011, a subsea earthquake generated a tsunami of up to 40.5 m that devastated coastal regions, travelled up to 10 km inland over low-lying terrain, caused at least 18-thousand deaths, destroyed hundreds of thousands of buildings, and created a technological crisis when flooding rendered inoperable the control systems of a large nuclear power plant.

The blast and heat of a volcanic eruption can also damage ecosystems, as occurred in 1980 when Mount St. Helens in Washington erupted in a more-or-less sideways blast. The explosion blew down 21-thousand ha of conifer forest, killed another 10-thousand ha by heat injury, and otherwise damaged an additional 30-thousand ha. There were also devastating mudslides, and a huge area was covered with particulate ejecta (known as tephra) that settled from the atmosphere 50-cm or more deep.

A volcanic eruption can also emit huge amounts of sulphur dioxide, particulates, and other pollutants high into the atmosphere. About 2-5 million tonnes of SO2 (expressed as the sulphur content, or SO2-S) are emitted by volcanoes in a typical year, and an individual eruption may emit more than 1-million tonnes. This natural SO2 contributes to the acidification of precipitation and to other environmental damage (Chapter 19).

Natural population outbreaks (irruptions) of herbivores, predators, or pathogens can also result in intense damage to natural habitats. For instance, the spruce budworm (Choristoneura fumiferana) periodically defoliates huge areas of conifer forest in eastern Canada (more than 55 million hectares in 1975). This causes extensive mortality of fir and spruce trees and other ecological damages (Chapter 22). A recent outbreak of the mountain pine-beetle (Dendroctonus ponderosae) has caused similarly extensive damage to pine forests in western Canada and the northwestern U.S., with about 36-million ha affected. A marine example is the green sea urchin (Strongylocentrotus droebachiensis), which occasionally irrupts in rocky subtidal habitats off Nova Scotia. These invertebrates can over-graze mature “forest” of the kelps Laminaria and Agarum, resulting in a “barren ground” with much less productivity and biomass. After the population of sea urchins collapses, the kelp forest quickly re-establishes.

Microdisturbances are also a common feature of natural ecosystems. Examples of these smaller-scale disturbances include the deaths of individual large trees within an otherwise intact forest, perhaps caused by disease or an accident (such as a lightning strike). This creates a natural gap in the canopy, beneath which a microsuccession occurs as plants compete to take advantage of temporary resource opportunities such as extra light. The foliage of mature trees eventually fills the gap. Similarly, the death of an individual coral head within an otherwise intact reef initiates a microsuccession within that marine ecosystem.

Ecologists try to understand the effects of natural disturbances and to apply that knowledge to design management systems that allow resources to be harvested or otherwise used while controlling the resulting ecological damage. For example, understanding the characteristics of gap-phase disturbances in an old-growth forest can aid in the design of a selective harvesting system that emulates the natural disturbance regime. The use of that kind of system will leave the physical and ecological integrity of the forest substantially intact, even while individual trees are periodically harvested for commercial use. Those individuals would be replaced by natural regeneration. In view of the natural, gap-phase disturbance dynamics of old-growth forest, clear-cutting followed by the planting of tree seedlings might be considered a less "natural" management system. However, clear-cutting might be an appropriate practice to use when harvesting forest that is adapted to community-replacing disturbances, such as wildfire or insect outbreaks (see Chapters 22 and 23).

Anthropogenic Disturbance

Humans also disturb ecosystems in diverse ways, many examples of which are described in the following chapters. Anthropogenic disturbances are associated with many activities, such as the conversion of ecosystems, the harvesting of natural resources, introductions of alien species, construction of roads and buildings, and warfare.

The harvesting of both renewable and non-renewable resources always causes disturbances to ecosystems. So does the post-harvest management of renewable resources. For instance, intense disturbance is caused by strip-mining the surface for coal or oil-sand. Similarly, harvesting a forest by clear-cutting represents a community-replacing disturbance, which is followed by regeneration through succession. Additional disturbances may be associated with silvicultural management, such as scarification to prepare the land for planting tree seedlings, and herbicide spraying to decrease the abundance of weeds. Harvesting may also be selective, as when particular species or sizes of trees or fish are targeted for harvesting. This may represent a kind of gap-phase disturbance.

The conversion of natural ecosystems into agricultural or urbanized land-uses also represents a severe disturbance. In these cases, the successional recovery is closely managed to foster the development of an anthropogenic ecosystem. Usually, the habitats are dominated by alien species of plants and animals, and sometimes by the bricks and concrete of the built environment. These conversions displace almost all of the original native species and natural communities.

People have deliberately or accidentally introduced many species beyond their natural range. Often, the introduced aliens become invasive of natural habitats, in the sense of displacing native species and causing other kinds of ecological damage. North American examples include the introduction of zebra mussels (Dreissena polymorpha) into the Great Lakes, purple loosestrife (Lythrum salicaria) into wetlands, and starlings (Sturnus vulgaris) and domestic pigeons (rock doves, Columba livia) into urban areas.

Warfare also produces a wide range of community-replacing and microdisturbances through explosions, the passage of heavy vehicles over the landscape, spills of fuel and other toxic chemicals, hunting to provide food for large numbers of soldiers, and even (as occurred during the Vietnam War) extensive spraying of herbicide onto forest and agricultural areas.

Anthropogenic Stressors in Context

To summarize, pollution and disturbance can be natural phenomena. Since life began, both of these environmental stressors have affected the structure and function of ecosystems. In modern times, however, pollution and disturbance associated with human activities are becoming increasingly important causes of damage. The prevention of anthropogenic pollution and disturbance, and repair of damage already caused, are among the most important challenges of the global environmental crisis.

Ecotoxicology

Toxicology is the science of the study of poisons. It examines their chemical nature and effects on the physiology of organisms. If the dose (exposure) is large enough, any chemical, even water, can cause toxicity.

Environmental toxicology is a broader field than conventional toxicology. In addition to studying the biology of poisoning, it also examines environmental factors that influence the exposure of organisms to potentially toxic chemicals. Important topics in environmental toxicology are the following:

- the cycling and transportation of potentially toxic chemicals
- their transformation into other substances (which may be more, or less, poisonous than their precursors)
- the determination of sinks where chemicals may accumulate in especially high concentrations, including within the bodies of organisms

Ecotoxicology has an even broader domain because it studies the direct poisonous influences of chemicals as well as indirect ones. Examples of indirect ecological influences include changes in habitat or in the abundance of food. For instance, the use of a herbicide in forestry or agriculture will affect the biomass and species composition of the vegetation on a treated area. These are important changes in the habitats of animals. Even if the herbicide does not poison animals that are exposed to the spray, they may be affected by changes in their habitat. A complex of factors influences the ecotoxicological risks associated with exposure to chemicals in the environment. The most important factors are: (1) biological sensitivity, (2) the inherent toxicity of the chemical being considered, (3) the intensity of the exposure, and (4) any indirect effects that might be caused. These considerations are examined below:

> In Detail 15.1. What Is Toxicity? In the biological sense, a chemical can poison an organism if it detrimentally affects some aspect of its metabolism. This effect is called toxicity. A toxic chemical may, for example, disrupt the functioning of an enzyme system or interfere with cellular division. However, the legal definition of toxic substance, as stated by the Canadian Environmental Protection Act, is as follows: "A substance is defined as toxic if it enters or may enter the environment in a quantity or concentration or under conditions that: (1) have or may have an immediate or long-term harmful effect on the environment; (2) constitute or may constitute a danger to the environment on which human life depends; or (3) constitute or may constitute a danger in Canada to human life or health."
>
> This definition has legal standing in Canada, and it is used in the management and regulation of a wide variety of chemicals.
>
> However, this definition is inadequate in some important respects, particularly because it deals only with extremely toxic chemicals, under conditions in which they occur in high concentrations. Substances whose acute toxicity is less may cause subtle, long-term damage to people, other species, and important ecological values. These kinds of exposures are not dealt with by this definition.

1. Biological Sensitivity

Sensitivity to chemical exposures varies greatly among individual organisms and species. Studies in toxicology, which are typically conducted under controlled laboratory conditions, often compare the susceptibility of different organisms to toxic substances. Acute toxicity is defined as occurring when a short-term exposure to a chemical in a high concentration results in biochemical or anatomical damages or even death (a common acute endpoint). Chronic toxicity involves a longer-term exposure to low to moderate concentrations of a chemical. Over time, chronic exposures may cause biochemical or anatomical damage, or perhaps a lethal condition such as cancer.

Data in Table 15.1 illustrate the sensitivities of a number of species to the extremely toxic chemical, TCDD (2,3,7,8-tetrachlorodibenzo-p-dioxin). TCDD has no industrial or medicinal uses, but it is incidentally synthesized during high-temperature combustions in incinerators, during forest fires, in the chlorine bleach whitening process for wood pulp, and in the manufacturing of certain industrial chemicals, particularly trichlorophenol, which is used to produce the herbicide 2,4,5-T and the antibacterial agent hexachlorophene. These syntheses can result in the emission of TCDD into the environment, where humans and other organisms may be exposed. Because of its toxicological notoriety, TCDD and its chemical relatives are relatively well-studied substances.

The data in Table 15.1 suggest that species differ greatly in their sensitivity to TCDD. Among the species for which data are available, the guinea pig is especially vulnerable to TCDD, whereas hamsters and frogs are less so. Sensitivity to chemicals also varies with the route of exposure and with the sex and age of animals.

Table 15.1. Acute Toxicity of TCDD to Various Animals. The animals were exposed to TCDD under laboratory conditions. Oral exposure involves ingestion into the stomach; dermal exposure consist of absorption through the skin; intraperitoneal exposure involves injection into the abdominal cavity. LD50 (lethal dose for 50% mortality) is the dose that kills half of a population of experimental animals. LD50 is measured in units of amount of chemical per unit of body weight (e.g., μg/kg). Source: Data from Tschirley (1986).

Species	**Exposure**	**LD_{50} (μg/kg)**
Guinea pig (male)	oral	0.8
Guinea pig (female)	oral	2.1
Rabbit (male & female)	oral	115
Rabbit (male & female)	dermal	275
Rabbit (male & female)	intraperitoneal	252-500
Monkey (female)	oral	<70
Rat (male)	oral	22
Rat (female)	oral	45-500
Mouse (male)	oral	<150
Mouse (male)	intraperitoneal	120
Dog (male)	oral	30-300
Dog (female)	oral	>100
Hamster (male & female)	oral	1,157
Hamster (male & female)	intraperitoneal	3,000
Frog	oral	1,000

Illustrations of data showing acute and chronic toxicities are presented in Table 15.2. The chemical illustrated here is glyphosate, a herbicide that is widely used in agriculture, forestry, and horticulture (see Chapter 22). The data suggest that, if the concentration of glyphosate is large enough, it will cause acute toxicity. However, long-term tests of chronic toxicity did not demonstrate observable effects at the examined levels of exposure. Note also, that the experimental doses needed to cause acute toxicity, and those tested for chronic toxicity, are much higher than exposures that would be encountered during the routine use of glyphosate as a herbicide.

Table 15.2. Acute and Chronic Toxicity of Glyphosate. The toxicity data are from controlled exposures under laboratory conditions. Acute toxicity is measured by the oral LD50, while chronic exposures are from long-term feeding experiments. The data for chronic exposure are no-effect levels, which are doses at or below which there is no observable effect. Source: Modified from Freedman (1991).

Species	**Type of Exposure**
Rat	acute: oral LD_{50}: 5600 mg/kg
	chronic: fed for 90 days with food containing 2000 mg/kg; no observable effects
	chronic: fed for 2 years with food containing 100 mg/kg; no observable effects
	chronic: 3 generations fed food containing 300 mg/kg; no observable effects
Mouse	acute: oral LD_{50}: 1570 mg/kg
	chronic: fed for 18 months with food containing 300 mg/kg; no observable effects

2. Inherent Toxicity

Chemicals vary enormously in their intrinsic, or relative, toxicity. Some chemicals are extremely toxic in minute doses, while others will only cause poisoning at a much higher intensity of exposure. This is illustrated by data in Table 15.3, which compares the acute toxicity of a wide range of chemicals. There are two central messages:

- chemicals vary enormously in relative toxicity
- at a large enough dose, any chemical may be toxic

Table 15.3. Acute Toxicity of Various Chemicals. Toxicity is indicated by oral LD50 data from controlled laboratory tests. The LD50 data are in units of mg of chemical per kg of body weight, and the test species was the rat. Source: Data from Freedman (1995).

Chemical	Oral LD_{50} (mg/kg)
TCDD (dioxin isomer)	0.01
tetrodotoxin (globefish toxin)	0.01
saxitoxin (paralytic shellfish neurotoxin)	0.3
carbofuran (insecticide)	10
strychnine (rodenticide)	30
nicotine (alkaloid in tobacco)	50
caffeine (alkaloid in coffee, tea)	200
DDT (insecticide)	200
fenitrothion (insecticide)	250
2,4-D (herbicide)	370
2,4,5-T (herbicide)	500
acetylsalicylic acid (Aspirin)	1,700
sodium hypochlorite (household bleach)	2,000
sodium chloride (table salt)	3 750
glyphosate (herbicide)	5 600
ethanol (drinking alcohol)	13 700
sucrose (table sugar)	30 000
distilled water	44 000*
isotonic saline	68 000*

3. Exposure

Exposure has a fundamental influence on toxicity. It may be defined as the dose of chemical that any individual or group of organisms receives per unit of time. Exposure to any potentially toxic chemical is affected by many factors, including environmental influences. For example, the exposure of a mouse in an agricultural field sprayed with an insecticide could be affected by such factors as the spray rate, kind of equipment being used, weather, persistence of the chemical (how long it remains active), and the behaviour and choices of food and habitat of the mouse. If a toxicologist is evaluating the exposure of people to potentially toxic substances, there would be a consideration of the amount ingested with solid and liquid food, the intake while breathing, and the amounts present in both working and ambient (or non-occupational) environments.

4. Indirect Effects

Also important in ecotoxicology are the indirect effects of toxic chemicals, or effects other than the direct poisoning of organisms. Indirect effects are most commonly associated with changes in habitat or in the condition of the immune system of an organism. In some cases, indirect damage is worse than the direct toxic effects of chemicals. For instance, the use of a herbicide in forestry causes changes in vegetation, which affects animals that live in the habitat, even if the herbicide itself is not directly toxic to them.

All Chemicals Are Toxic

The above discussion suggests that if an exposure is intense enough, even routinely encountered chemicals may be poisonous. In fact, even water can be toxic if a person drinks enough in a short period of time. This happens because the physiological capacity to regulate salts in the blood plasma can be overwhelmed by drinking too much water too quickly, causing a toxic syndrome called hyponatremia. Depending on body weight, the lethal dose for an adult is 5-10 L, ingested over an hour or less. Similarly, if the dose is large enough, carbon dioxide, table sugar (sucrose), table salt (sodium chloride), Aspirin (acetylsalicylic acid), drinking alcohol (ethanol), and other routinely ingested chemicals can cause poisoning (Table 15.3).

This fundamental rule of biology was first emphasized by Philip von Paracelsus (1493-1541), a Swiss physician and alchemist who is considered to be the father of "modern" toxicology. One of his most famous conclusions can be paraphrased as "Dosage determines poisoning."

In perhaps all cases, there are thresholds of tolerance to potentially toxic chemicals. The tolerance occurs because organisms have physiological mechanisms to excrete toxins from the body, to metabolize them into less-toxic substances, or to sequester (store) them in certain body tissues where they will not cause damage. Organisms also have mechanisms to repair damage caused to tissues or biochemical systems, providing that the chemical exposures are not too high and excessively damaging. For a chemical to cause toxicity, the capacities of these physiological systems must be overwhelmed.

Interpretation of Damage

The notion of physiological thresholds of tolerance helps to define the difference between contamination and pollution, which we examined previously. The idea of thresholds also indicates why it is best to frame the discussion in terms of "potentially" toxic exposures to chemicals. This is especially the case when the actual environmental concentrations are not known, and when the biological risks of extremely small doses are not sufficiently understood. However, the notion of biological thresholds of tolerance is somewhat controversial, and not all toxicologists would agree with the explanation just given. Those scientists believe that exposure to even one or a few molecules of some kinds of chemicals may be of toxicological importance. This is particularly true of chemicals that are thought to be carcinogenic at extremely small exposures, and also of radionuclides and highly energetic forms of ionizing energy, such as X-rays and gamma radiation.

Often, the risks to humans exposed to chemicals are interpreted differently from those of other species, particularly wild animals and plants. This is because the prevailing cultural attitudes place much greater value on the life and health of individual people than on those of other species. As such, there is a special reluctance, both social and regulatory, to permit human exposures to many kinds of potentially toxic chemicals.

However, regulations and guidelines tend to be considerably less strict for human exposures that occur in a workplace, as compared with non-occupational exposures. This recognizes the fact that considerable risks are inherent in the activities and environmental conditions of many occupations. Particularly significant hazards confront firefighters, police officers, members of the armed forces, operators of heavy machinery, and workers in chemical industries. Within limits, chemical exposures associated with earning a living are generally interpreted as a "cost of doing business", and may therefore be judged to be acceptable.

Such attitudes can, however, change markedly over time. Certain occupational hazards that were once considered routine and tolerable are now viewed as unacceptable. For instance, when synthetic organic insecticides, such as DDT, were first introduced in the mid-1940s and 1950s, people were remarkably casual about using them. Workers often applied these insecticides with only minimal attention to avoiding exposure to themselves and others. Such poorly controlled usages would be unthinkable today, especially in relatively well-regulated countries such as Canada.

In addition, many people willingly choose to expose themselves to toxicologically significant doses of certain chemicals. These choices include taking up hazardous occupations, smoking cigarettes, and ingesting medicines and recreational drugs. The consequences of these sorts of "voluntary" exposures are interpreted using criteria that are different from those applied to "involuntary" ones.

If chemicals cause toxicity to species other than humans, the importance of that effect is interpreted on the basis of the following considerations:

- Are measurable changes seen in the populations of affected species? From an ecological perspective, population-level damage is the most important consideration, even while it is acknowledged that the death of an individual organism is regrettable. Populations of all species have a certain degree of resilience and can tolerate some mortality caused by toxic chemicals without suffering an overall decline.
- Are affected species important in maintaining the integrity of their community? Ecological philosophies suggest that all species have intrinsic value. Nevertheless, species do vary greatly in their contribution to the functioning and structure of their community. So-called keystone species have a dominant influence (Chapter 9). Substantial changes in their abundance should be judged as relatively important compared with damage inflicted on more minor species.
- Is the damage of economic importance? This consideration involves damage to resources that are needed by humans and therefore have economic value. In this sense, damage is judged to be relatively important if it is caused to hunted animals such as deer or trout, to trees that can be harvested to manufacture pulp or lumber, or to vital ecological services such as the provision of clean water and air. From a purely utilitarian perspective, damage caused to non-economic values, both species and services, may be viewed as being less important.
- Other considerations, less tangible than those just mentioned, involve appraising damage in aesthetic or ethical terms. These considerations are also important, but they are difficult to interpret in terms of risks or benefits to human welfare. As a result, aesthetic or ethical considerations are rarely reflected in regulatory criteria or in the management of potentially toxic chemicals in the environment.

Environmental Risks

Broadly interpreted, environmental risks are hazards – a likelihood of suffering damage or misfortune as a result of exposure to a biological or environmental circumstance. Risks are associated with driving an automobile, flying in an airplane, participating in sports, hiking in the wilderness, being exposed to toxic chemicals, and getting out of bed in the morning. Environmental risks interact with biological factors to determine the likelihood of experiencing damage of some kind, such as developing a cancer or suffering an injury.

Statisticians assign probability values to many kinds of risks using data based on previous experience, such as the frequency of automobile accidents or cases of poisoning with a chemical such as a particular medicine. This approach is illustrated in Table 15.4, which summarizes recent causes of mortality in Canada. These data suggest that the average Canadian has an annual risk of dying of about 0.7% (calculated as the total annual mortality divided by the national population).

Table 15.4. Causes of Mortality in Canada. These data summarize the most important causes of deaths among

Canadians (in 2011). Source: Data from Statistics Canada (2014).

Risk Factor	Deaths	%
Medical Causes		
Diseases of the heart	47,627	19.7
Cerebrovascular diseases	13,283	5.5
Cancers	72,476	29.9
Influenza & pneumonia	5,767	2.4
Respiratory diseases	11,184	4.6
Alzheimer's & Parkinson's	6,356	2.6
Diabetes	7,194	3
Liver and kidney diseases	3,294	1.4
Accidents	10,716	4.4
Suicide	3,728	1.5
Homicide	527	0.2
All other causes of death	59,922	24.8
All causes of mortality	242,074	100

Data concerning less-common environmental risks are more difficult to acquire. Usually they must be developed from predictive models based on knowledge of medical science and likely exposures to environmental influences. However, both of these kinds of information are imperfect because they are based on an incomplete understanding of interactions between environmental influences and biological responses. Consequentlythe calculated risk factors are inaccurate and sometimes controversial. These issues are particularly important for diseases, such as cancers, that have an extended latency period (often several decades) between exposure and development.

Cancers are a leading cause of mortality in Canada and in other relatively wealthy countries. Remarkably little is known, however, about the specific environmental and biological factors that predispose organisms to developing various types of cancer. Table 15.5 summarizes data from a study that estimated the risks of dying from cancer that are associated with several potentially contributing factors. Of the approximately 0.5 million cancer deaths that occur each year in the United States, dietary factors are believed to be the most important predisposing factor, accounting for about 35% of the mortality, followed by tobacco smoking (30%), infections (10%), and reproductive and sexual behaviour (7%). Of the various risks, smoking is most easily preventable: this voluntary exposure is responsible for about 86% of lung cancers, as well as other diseases (Canadian Cancer Society, 2005). About half of Canadian smokers will die from a smoking-related ailment, most before the age of 70.

The population of Canada is 10.8% that of the United States, while the number of cancer-related mortalities is 11.3% that of the United States. These similar proportions, along with the comparable lifestyles of Canadians and Americans, suggest that the estimated risks in Table 15.5 are also relevant to Canadians.

Table 15.5. Estimated Risks of Cancer Mortality. Cancers are grouped by their possible causes, in terms of environmental exposures. The data are the best estimates for the U.S. population, with the range of estimates in

brackets. Sources: Modified from Gough (1989) and Canadian Cancer Society (2008).

Risk Factor	**Relative Cause of Cancer Mortality (% of total)**
Diet factors	35 (10-70)
Smoking tobacco	30 (25-40)
Infections	10 (1-?)
Reproductive and sexual behaviour	7 (1-13)
Occupational exposures	4 (<2-8)
radiation in workplace	0.01
pesticide application	<0.02
chemicals in workplace	<0.06
Geophysical factors	3 (2-4)
sunlight exposures	2
indoor radon	2 (1-4)
Alcohol consumption	3 (2-4)
Exposure to pollution	2 (<1-5)
secondary tobacco smoke	1
indoor organic chemicals	0.3
pesticides on food	0.9 (0.6-1.2)
hazardous toxic air pollutants	0.3 (0.2-0.4)
chemicals in drinking water	<0.1 (0.04-0.09)
other pesticide exposures	0.02 (0.02–0.03)
Medicines and medical procedures	1 (<1-3)
Exposures to food additives	<1 (–5-2)
Exposures from consumer products	<1

Image 15.6. Smoking entails a voluntary exposure to a wide range of chemicals that are known to be toxic. In addition, non-smokers are involuntarily exposed to sidestream smoke by sharing space with smokers in public spaces or their home. Source: B. Freedman.

In spite of excellent data (and common sense) about the known risks of many activities, people often choose to expose themselves to obvious risks of injury or disease. Examples of risky activities include skiing down a steep slope, bungee jumping, smoking cigarettes, and drinking alcohol. Moreover, people are also exposed to hazards over which they have little control – that is, to involuntary risks, such as crime, polluted outdoor air, and pesticides in food. Perceptions of risk are an important consideration. One survey of Canadians indicated that people are aware of and concerned about a wide range of risks to their health and well-being (Table 15.6). People are especially concerned about health-related risks associated with lifestyle choices, such as smoking cigarettes, using recreational drugs or alcohol, and behaviour involving exposure to AIDS (HIV virus). People are also concerned about exposures to potentially toxic levels of chemicals in the atmosphere, drinking water, and foods.

Table 15.6. Public Perception of Risks of Various Environmental and Medical Hazards. The data, based on a national survey of 1503 Canadians, indicate the percentage of the survey group that chose the designated

category. The totals do not add to 100% because some respondents said they "didn't know." Source: Data from Krewski et al. (2006)

Risk Factor	Perceived Risk (% response)		
	High	Moderate	Slight-None
Smoking cigarettes	82	15	3
Obesity	72	24	4
Unprotected sex	69	24	6
Stress	63	31	6
Physical inactivity	61	31	6
Wait lists for health care	60	28	10
Fast food	53	35	11
Poverty	49	35	15
Air pollution	49	39	12
Pesticides	45	38	15
Homelessness	43	33	18
Family violence	42	36	19
Sun-tanning	42	41	16
Street crime	38	38	24
Nuclear power plants	34	29	25
Unemployment	33	42	17
Breast implants	32	31	22
Drinking alcohol	31	46	22
Genetically modified foods	28	33	33
Flu epidemics	28	46	26
High-voltage power lines	25	29	43
Genetic makeup	19	39	35
Prescription drugs	18	41	40
West Nile virus	18	34	46
Blood transfusions	16	36	46
Tap water	14	40	46
Medical X-rays	7	31	61
Vaccines	6	27	66
Laser eye surgery	5	28	56
Natural health products	5	29	64

Clearly, people understand that environmental factors pose risks to human health. Often, however, they have little understanding of the actual risks, as opposed to the perceived risks. Sometimes, people view certain high risks to be inconsequential while considering much smaller risks as being unduly important. Nevertheless, public perceptions of risks have an extremely important influence on politicians, policy makers, and bureaucrats in government and industry, and on their decisions concerning the management and regulation of environmental and health hazards.

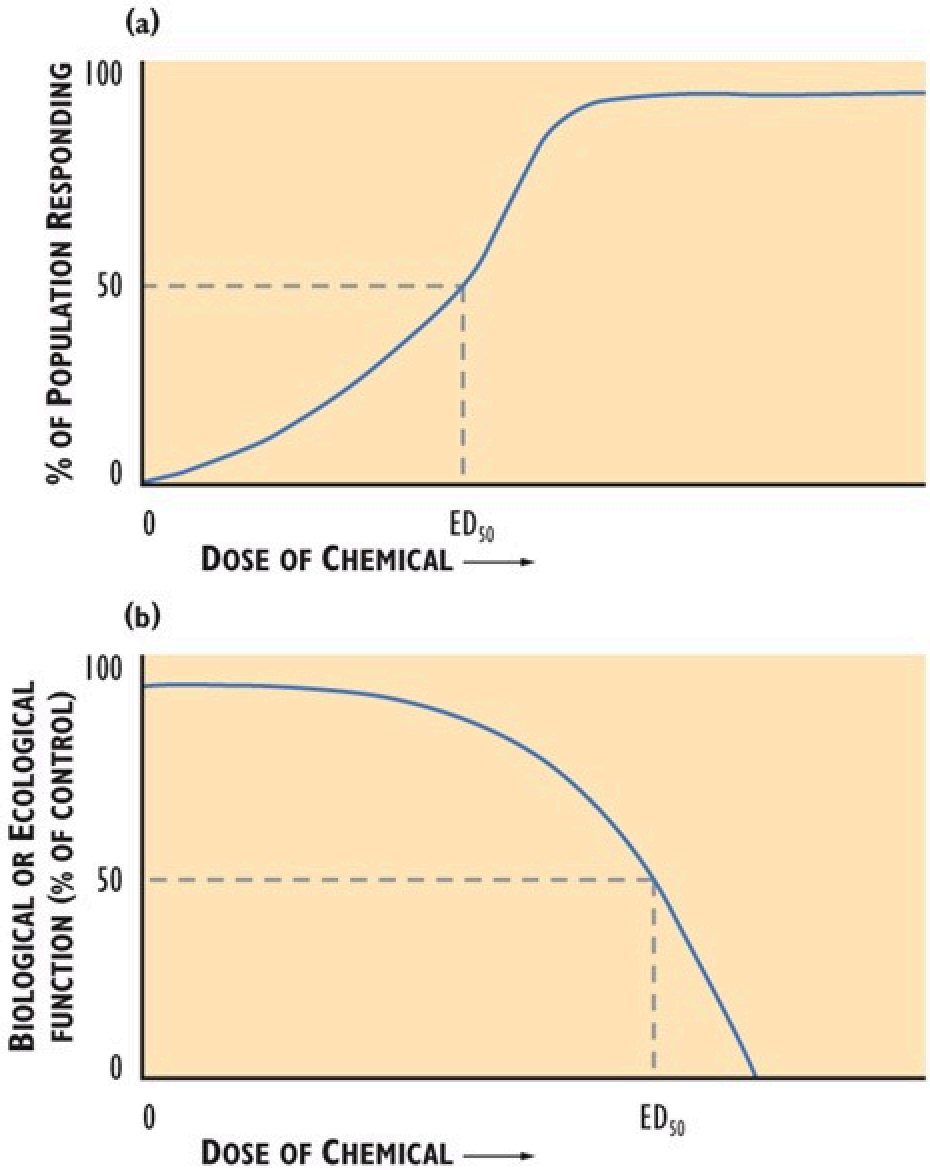
Environmental Risk Assessment

An environmental risk assessment is an evaluation of the risks associated with a hazard in the environment. A risk assessment may quantify the threats to people, as well as to other species and to broader ecological values. A risk assessment requires knowledge of three factors:

1. the likelihood of encountering the hazard
2. the likely intensity of the hazard
3. the biological damage that is likely to result from the predicted exposure

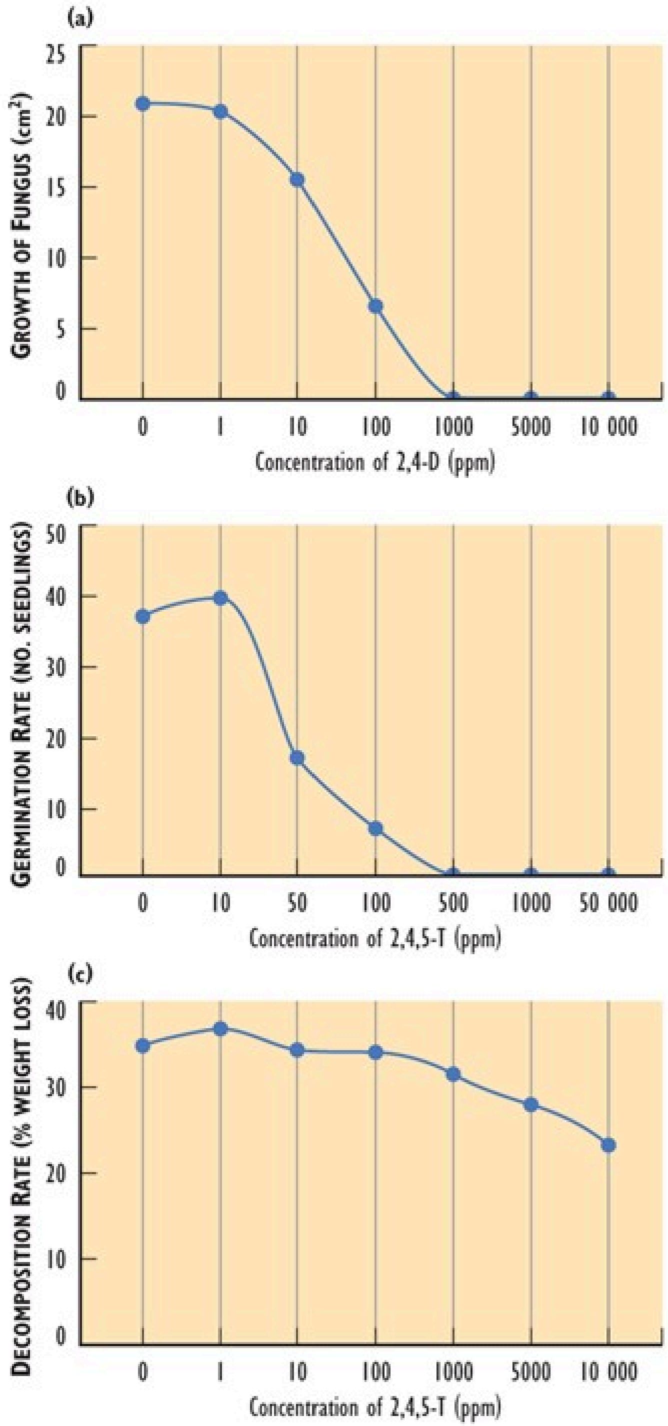
A meteorologist, for example, may predict the probability that a particular place will be struck by lightning under various weather conditions. The likelihood is much greater during a thunderstorm than during sunny conditions, and is greater beneath a large tree in an open field than beside a shrub in a ditch. The energy content of a typical lightning strike is also known, as is the biological damage to a person who might be struck. With this information, it is relatively straightforward to model the risks of a lightning-caused injury associated with standing in the middle of an open field, or under a tree in that same field, on a sunny day or during a thunderstorm. This is a simple example of an environmental risk assessment. A risk assessment for potentially toxic exposures to chemicals can be conducted for individual organisms, for populations, or for ecological functions such as productivity, decomposition, and nutrient cycling. To assess the risks associated with exposure to chemicals, one requires knowledge of two factors: the intensity of exposure (the anticipated dose) and the biological damage that is likely to be caused by the predicted exposure. The integration of these two types of information is known as a dose-response relationship (Figure 15.1).

Figure 15.1. Conceptual Models of Dose-Response Relationships. Model (a) suggests that the larger the dose encountered, the greater the proportion of the population that is affected. ED50 represents the dose that affects 50% of the test population (effective dose). If the biological response being measured is death, the term LD50 is used, or te dose killing 50% of the population (lethal dose). Model (b) suggests that larger doses have a more pronounced effect on physiology (or on an ecological function). In this case, the rate of a biological function is plotted versus the chemical exposure, and the data are expressed as a percentage of the control rate (in the absence of the chemical). In this curve, ED50 represents the dose needed to decrease the rate of the function by 50%.



A dose-response relationship can be determined by conducting experiments in which, for example, populations of organisms are exposed to various amounts of a chemical. Results of simple dose-response experiments involving several herbicides are shown in Figure 15.2.

Figure 15.2. Examples of Dose-Response Curves. Note the extremely wide ranges of doses that were examined in these experiments. Each experiment includes a control treatment involving a zero dose of the chemical. Graph (a) describes effects of the herbicide 2,4-D on growth rate of a mycorrhizal fungus, Hebeloma longicaudum. Graph (b) illustrates effects of the herbicide 2,4,5-T on the germination of seeds from the surface organic mat of a clear-cut. Graph (c) shows effects of 2,4,5-T on the decomposition of leaf litter. Sources: Data from Estok et al. (1989), Fletcher and Freedman (1989), and Morash and Freedman (1989).



It is sometimes possible to infer dose-response relationships by studying patterns of damage in the real world. For instance, the intensity of pollution can be determined at various distances from a large point source of emissions, such as a power plant or smelter. The exposure to pollution can then be related to the pattern of ecological damage that may be observed along the gradient of toxic stress. Patterns of pollution and ecological damage around a large smelter near Sudbury are one example of such a relationship (see Chapters 16 and 18).

An exposure assessment investigates all of the ways by which organisms may encounter a potentially toxic level of a chemical. For example, humans may be exposed to mercury through various pathways, each of which can be quantified (either measured or calculated using a predictive model). The principal avenues of exposure include: inhaling mercury vapour present in the atmosphere, ingesting mercury dissolved in drinking water, and consuming the metal in foodstuffs, especially in certain kinds of fish and animal organs. Also included among the principal avenues of exposure are miscellaneous sources such as certain pigments used in ceramics and paints, and mercury-amalgam dental fillings.

The assimilation rate of a chemical into the bloodstream and organs varies greatly among the exposure pathways. Assimilation depends on several factors, including the metabolic characteristics of the organ into which the chemical is being absorbed, such as the lungs, the gastrointestinal tract, or the skin. The physical-chemical form of the substance also affects its uptake dynamics. For instance, mercury can occur as an elemental vapour or liquid, as inorganic compounds such as mercuric chloride, and as organomercurial complexes such as methylmercury (an especially bioavailable and poisonous compound). The total exposure for a person is the sum of the chemicals assimilated through all pathways, which typically vary greatly in their effect.

The relative importance of various sources of a chemical depends to some extent on a person's lifestyle and occupation. These influence how often and to what degree the various sources are encountered. Dental workers, for example, may come into contact with mercury vapours because this metal is sometimes used to make fillings. In addition, a diet rich in certain species of large oceanic fish, such as halibut, shark, swordfish, and tuna, is relatively rich in mercury (see Chapter 18). Therefore, both dental workers and big-fish consumers may have a higher risk of mercury exposure.

Once an exposure assessment has been undertaken, the biological hazards can be predicted on the basis of known dose-response relationships. Unfortunately, dose-response information is often incomplete, or even lacking. For instance, most hypotheses about potential dose-response relationships in humans are actually inferred from research that has been conducted in laboratories using other mammals, such as dogs, mice, monkeys, pigs, and rats. These species have physiological, anatomical, and behavioural characteristics that are broadly similar to those of humans, but they also differ in important respects. Consequently, most assessments of human exposure to trace levels of environmental chemicals are inaccurate.

In addition, the information about dose-response relationships is almost non-existent for wild species and for ecological functions such as productivity and nutrient cycling. As with human-focused assessments, it is common to use data for surrogate (or proxy) species, which are believed to be typical in their dose responses.

For example, a study may be undertaken to predict the potential effects of inputs of particular chemicals to a certain lake. It is highly unlikely that relevant dose-response data will be available for the species of fish in the ecosystem. Consequently, predictions will typically be made using information for proxy species, such as rainbow trout (Salvelinus gairdneri) or fathead minnow (Pimephales promelas). These fishes have been well studied in toxicological laboratories and are widely used as indicators. Similarly, the potential effects on the zooplankton community might be predicted using information available for well-studied species, such as the water fleas Daphnia magna and Ceriodaphnia dubia, while the risk assessment for phytoplankton might use data for the unicellular algae Selenastrum capricornutum and Chlorella vulgaris.

The results of a risk assessment for an ecosystem or a part of it (such as a community), if based on laboratory studies of surrogate species, are always uncertain. This is especially true if the potential effects are being predicted of chemical exposures in a natural environmental context. Such risk assessments are, however, the best that can be done under most circumstances because there is rarely enough funding or time to do more comprehensive studies. Nevertheless, because these methods deliberately overestimate the potential risks, they provide conservative guidance for management purposes.

In Detail 15.2. Mutagens, Teratogens, and Hormone Mimics Mutagens, teratogens, and hormonally active substances are trace chemicals and other agents that are present in the environment and have the potential to affect the genetics or metabolism of animals when present in minute concentrations. They may be naturally present or associated with anthropogenic emissions. Relatively intense exposures of wild animals to these agents may occur in aquatic habitats that are affected by effluent from factories, sewage, or pesticide-treated fields. Human exposures are associated with smoking (including involuntary exposures), eating fatty meats (especially if barbequed) and some other foods, and living in an urban environment that is generally polluted with a range of substances.

A mutagen is a substance or agent that induces a genetic mutation, meaning a change in the coding sequence of nucleic acids in DNA or RNA. Exposure to mutagens may result in mutations that are "harmless," meaning the genetic change is not known to result in a serious biochemical consequence. In other cases, however, a mutation may result in a deformity or disease, such as many kinds of cancer. A cancer may be an endpoint of mutations occurring in body (somatic) cells, while mutations of sperm and egg cells may result in heritable changes that can be passed to offspring. An environmental mutagen is one that is encountered in the environment. Incidents of genotoxicity have been observed in wild animals, such as occurrences of fish tumours and frogs born with excess limbs. In humans, genotoxicity may be associated with some kinds of cancer and with congenital birth defects, which normally occur in about 3% of births. Genotoxocity may be caused by exposure to various chemicals and other agents. Potent mutagens that are used in biomedical research include ethylmethanesulfonate and nitrosoguanidine. Other sources of laboratory and environmental genotoxicity include the following:

- highly energetic (ionizing) radiation associated with ultraviolet-B, X-rays, and gamma radiation
- polycyclic aromatic hydrocarbons (PAHs), such as benzo(a)pyrene
- polychlorinated biphenyls (PCBs) and certain pesticides
- methyl mercury and some other metals
- aflatoxin present in mouldy nuts and grains
- dimethyl nitrosamine present in nitrite-treated foods
- diesel exhaust
- effluent from pulp mills
- tobacco and barbecue smoke

A teratogen is an agent that induces abnormal development of an embryo or fetus. It may act through mutagenicity or by some other means, such as physical irritation of cells or tissues. A famous example of teratogenic damage was caused by thalidomide, a medication that was prescribed as a sedative to pregnant women from 1950-1961. Thalidomide proved to be capable of crossing the placenta and caused devastating limb abnormalities (extreme shortening or absence of limbs) in the fetus, and its medical use resulted in an epidemic of seriously deformed children. Another well-known teratogen is ethyl alcohol (alcohol in drinks), which if taken in excess during pregnancy can cause fetal alcohol syndrome. Exposure to rubella virus during pregnancy can also lead to severe deformity of a fetus. An environmental teratogen is encountered in the environment, and this exposure may have increased the incidence of deformities of wild animals, including mollusks, fish, and amphibians.

A hormonally active substance is a hormone or another chemical that has a similar effect on the regulation of biochemistry. Hormones are chemical messengers that travel through the circulatory system until they reach specific receptor cells in target organs, where they regulate physiology. They are produced in the endocrine system, which consists of various glands, such as the adrenal gland, ovaries, pancreas, pituitary gland, testes, and thyroid gland. Hormones help to regulate growth, development, metabolism, deposition of fat, maintenance of the electrolyte balance in fluids, sexuality, and behavioural responses to external stimuli (such as excitement and fright). Examples of hormones include the following:

- adrenaline (epinephrine) and noradrenaline (norepinephrine), which are adrenal hormones that stimulate the body to react to a stressful condition by increasing the blood pressure, blood sugar, and heart rate (this is sometimes known as a “flight or fight” response)
- estrogen, a female sex hormone produced by the ovaries, and androgens, male hormones produced by the testes
- insulin, formed by the pancreas to regulate the use and storage of carbohydrates (including blood sugar)
- thyroid hormone, which influences the growth and metabolism of virtually all body cells

Because hormones are necessary for healthy physiology, development, and behaviour, any serious disruption of their activity can have severe consequences for organisms. Some chemicals present in the environment, including natural ones and others that are anthropogenic, can cause such interference and are known as hormone mimics. For example, certain plants contain so-called phytoestrogens that can affect the hormone physiology of animals feeding upon them. Examples of plants with relatively high levels of phytoestrogens include soybean (Glycine max), red clover (Trifolium pratense), flax (Linum vulgare), and black cohosh (Cimicifuga racemosa). Some women use herbal preparations of these plants to relieve symptoms of menopause. Other natural phytoestrogens have been used in birth-control pills to control human fertility.

Many other substances present in the environment are also hormonally active, including a wide array of chemicals released by human activities. Even at extremely small exposures, they may mimic or block the action of certain hormones, resulting in a physiological change. This may have detrimental effects on wild and domestic animals and also on people. The following anthropogenic chemicals are thought to be hormonally active through environmental exposures:

- organochlorines, including dioxins (such as TCDD), polychlorinated biphenyls (PCBs), and the insecticides DDT, dieldrin, and lindane
- other kinds of pesticides, including atrazine, permethrin, and trifluralin
- tributyltin, which is used as a marine antifoulant
- alkylphenols used as surfactants, such as nonylphenol
- certain placticizers, such as dibutyl phthalate and butylbenzyl phthalate
- natural hormones and synthetic steroids from contraceptives that are released to the environment in sewage or occur as residues in food, including estradiol, estrone, and testosterone
- phytoestrogens in pulp-mill effluents, including coumestans, isoflavones, and lignans

The biological effects of environmental mutagens, teratogens, and hormonally active substances are not yet well understood. Although the presence of many of these agents in the environment has been widely noted, scientists do not yet know the level of contamination at which an unacceptable amount of biological damage may result. This has resulted in controversy about the potential effects of these bioactive chemicals on wild animals and humans: some people recommend a highly precautionary approach, while others believe that more evidence of consequential damage is needed before stringent control practices are implemented. Although there are observations of some local populations of wild animals suffering significant damage, there is not yet convincing evidence of effects on people from environmental exposures to these agents. Of course, any significant level of genetic or developmental damage to humans would be deemed to be unacceptable.

References: Phillips and Venitt (1995), Machachlan and Guillet (2002), Servos et al. (2008)

Conclusions

Environmental stressors are factors that can constrain the productivity and reproduction of organisms, or the development of ecosystems. The stressors can be natural or anthropogenic and may operate over the short term (acute) or long term (chronic). Stressors may cause physical disruption, as when a forest is affected by a wildfire, windstorm, or timber harvest. Other stressors operate by causing toxicity, as when organisms are exposed to solar ultraviolet radiation or to pesticides. Environmental risks are associated with exposure to a wide variety of factors in the environment. A major activity in environmental science is the study of these risks and the prediction of their effects on people, other species, and ecosystems.

Questions for Review

1. What are the various kinds of environmental stressors? Provide an example of each.
2. Explain the difference between pollution and contamination?
3. How do toxicology, environmental toxicology, and ecotoxicology differ?
4. Use the data in Table 15.4 as the basis of a brief essay about the risks of death. Make sure that you relate the risks to environmental exposures, where appropriate.

Questions for Discussion

1. Identify examples of naturally occurring pollution and disturbance in the region where you live. What considerations determine how society judges the importance of the natural and anthropogenic sources?
2. Compare the ecological effects of a community-replacing disturbance and a gap-phase microdisturbance. How is knowledge of these effects useful for designing ecologically appropriate practices for resource harvesting and management? Use old-growth forest as an example.
3. What do you consider to be the five most important risks to your health? Compare your list with the data in Tables 15.4 and 15.5. What are the similarities and differences? Why do they exist?
4. If all chemicals are potentially toxic, should society allow any exposure to these potential health risks? Discuss this statement and its conceptual fallacy.

Exploring Issues

1. How can the data presented in Table 15.2 for the herbicide glyphosate be used to assess the probability of people or animals suffering toxicity when this chemical is used in agriculture, forestry, or around the home (these are all common uses)? What additional information would you need to perform a comprehensive risk assessment for this chemical? What about consideration of the indirect effects on wild animals caused by changes in vegetation in treated areas?

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Chapter 16 ~ Gaseous Air Pollution

Key Concepts

After completing this chapter, you will be able to

1. Outline the major sources of emission of air pollutants associated with sulphur, nitrogen, and hydrocarbons.
2. Explain the difference between primary and secondary pollutants.
3. Contrast the environmental problems associated with stratospheric and tropospheric ozone.
4. Examine the importance of air pollutants to ecosystems and to human health.
5. Outline the lessons to be learned from natural pollution at the Smoking Hills.
6. Describe the patterns of pollution and ecological damage near point sources of air pollution.

Introduction

Gaseous air pollutants are emitted from various natural sources, such as volcanoes and forest fires. However, anthropogenic emissions of some gases may be greater than the natural ones, and are increasing because of population growth and industrialization.

In ancient times, there was not much pollution. Nevertheless, even then local problems would have occurred. For instance, smoky wood fires used for cooking and warmth would likely have caused poor-quality air to occur inside of badly ventilated dwellings. Hunting cultures often used fire to drive game animals and improve local forage, and those burns would have resulted in large emissions of particulate carbon (soot), carbon dioxide, and other gases that would have temporarily impaired air quality. Overall, however, these effects were relatively minor.

Of course, as people became more numerous and industrialized, air pollution increasingly developed into a much bigger problem. When the Industrial Revolution began (around 1750), coal quickly became the major fuel used to generate heat and energy for machines, and that resulted in increasingly worse air pollution. The widespread use of coal led to severe pollution by sulphur dioxide (SO_2) and soot in the industrial towns and cities of Europe and the Americas. Since 1900, burgeoning industrialization and new technologies such as power plants and automobiles have further increased the emissions of pollutants.

Air pollution can be especially severe in situations when the lower atmosphere is stable and calm. These conditions often occur beneath an atmospheric phenomenon called an inversion, in which a layer of cool air is trapped beneath a higher layer of warmer air (the more usual pattern is for temperature to cool with increasing altitude). An atmospheric inversion is a relatively stable condition that prevents polluted ground-level air from mixing with cleaner air from higher altitudes (see In Detail 16.1). If an atmospheric inversion is accompanied by fog, the pollution is known as smog (a word derived from "smoke" and "fog"). As recently as the 1950s, occasional so-called "killer smogs" rich in SO_2 and soot caused the deaths of thousands of urban people, and many more suffered from respiratory distress (pollution rich in SO_2 is also called reducing smog). The most famous killer smogs occurred in London, Glasgow, some other industrial centres of Europe, and near Pittsburgh in the United States (these are described later).

Once scientists recognized the severe damage that was being caused by air pollution, governments began to pass laws to decrease the emissions. Pollution control became particularly vigorous after medical researchers discovered clear evidence of links between air quality and human diseases and deaths. Particular attention was paid to air pollution in urban environments, where the killer smogs were most frequent. Governments typically responded with important control actions, such as the following:

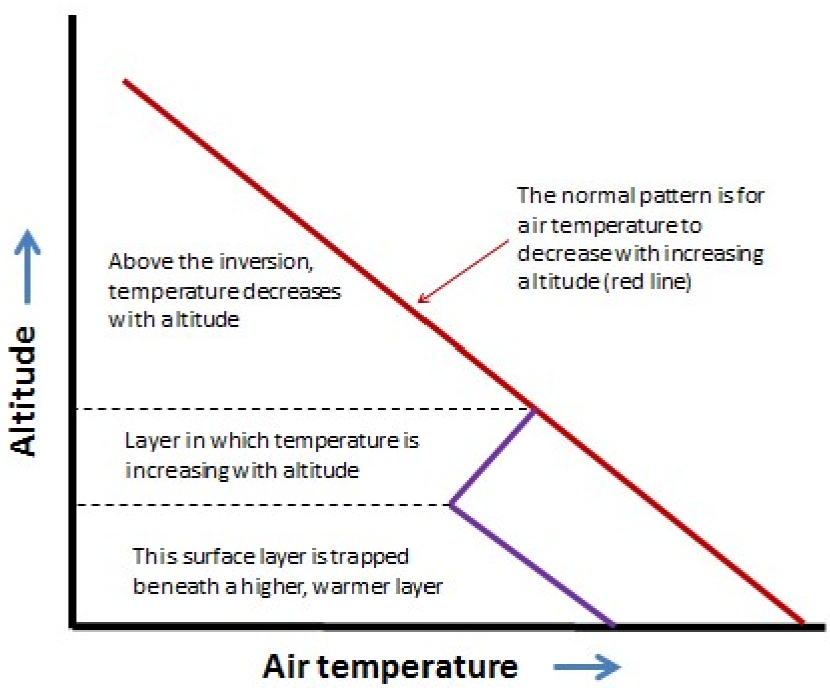
- switching from coal, which is a relatively "dirty" fossil fuel, to "cleaner" ones such as natural gas or oil, or to alternative energy technologies such as nuclear power and hydroelectricity
- constructing tall smokestacks to spread emissions over a much wider area so that ground-level exposures become less common and less intense – this tactic is the "dilution solution to pollution"
- centralizing energy production in large power plants to replace much of the relatively dirty and inefficient burning of coal in home fireplaces and furnaces, thereby permitting better control of emissions
- treating waste gases to remove some of their pollutant content, thereby reducing emissions to the atmosphere

Because of these helpful regulatory actions, the importance of reducing smogs became much less in many countries. However, so-called oxidizing smog has become more important causes of damage in many regions. Oxidizing smog develops in the atmosphere through complex photochemical reactions in which hydrocarbons and nitrogen oxides are transformed into ozone (O_3) and other gases. Ozone and other oxidizing gases harm vegetation and irritate the respiratory system and eyes of people. Oxidizing smog develops under sunny conditions if hydrocarbons and nitrogen oxides are present from automobile and industrial emissions, and especially if the presence of an atmospheric inversion reduces dispersion of the polluted air mass.

In this chapter, we examine the most important gaseous pollutants. Their sources of emission, chemical transformations, and toxicity are described, and Canadian case studies are used to demonstrate the ecological damages that may be caused.

In Detail 16.1. Normally, the temperature of the atmosphere decreases with increasing altitude. Under certain conditions, however, a layer of relatively cool air may become trapped under a layer of warmer air, a phenomenon known as an atmospheric inversion (or temperature inversion; see Figure).

Figure 16.1. Normally, air temperature decreases with increasing altitude (red line), but during an atmospheric inversion, a ground-level layer of cooler air is trapped beneath warmer air (blue lines).



An atmospheric inversion may develop on a clear, cloudless night. Under such conditions, the ground surface cools quickly as it radiates heat that was absorbed during the day. This can result in a layer of cool air occurring beneath a higher layer of warmer air. Hilly terrain is particularly vulnerable to developing atmospheric inversions because relatively dense cool air can flow downward from hilltops and accumulate in valleys. Sometimes during the summer, stable atmospheric conditions may develop at higher altitude, capping a still-mixing air mass at ground level.

An atmospheric inversion can be rather stable. Until it is dispersed by vigorous winds, it can trap and accumulate air pollutants that are emitted during the inversion event. Severe episodes of air pollution can occur when stable inversions develop and are maintained for several days.

Some places regularly develop less-persistent inversions, such as Los Angeles, Mexico City, and Greater Vancouver. In these places, the inversions develop in the morning but are typically dispersed during the afternoon. In the meantime, however, oxidizing air pollutants such as ozone can accumulate into a photochemical smog.

Sulphur Gases

Emissions and Transformations

Sulphur dioxide (SO_2) is one of the most important of the gaseous air pollutants. SO_2 is a colourless but pungent gas. Humans can detect its bitter taste at a concentration of only 0.3-1 ppm (parts per million; for SO_2, 1 ppm = 2.6 mg/m^3). Hydrogen sulphide (H_2S), another sulphur gas, can be detected as a foul odour, reminiscent of rotten eggs, at concentrations lower than 1 ppb (parts per billion; for H_2S, 1 ppm = 1.4 mg/m^3) (unless otherwise indicated, specific data cited in this and other chapters in this section on environmental damages are from Freedman, 1995).

After they are emitted to the atmosphere, SO_2 and H_2S become oxidized to other compounds, and ultimately form sulphate (SO_4^{2-}; see In Detail 16.2). Because the sulphate ion carries negative charges, it is an anion (this refers to any ion, atom, or molecule with a negative charge). Because H_2S is quickly oxidized to SO_2, its atmospheric residence time is less than one day (this is the time to complete disappearance of an initial amount). SO_2 oxidizes more slowly, at a rate of < 1-5% per hour, depending on sunlight, humidity, strong oxidants such as ozone, and the presence of metal-containing particulates that may act as catalysts. A typical residence time of SO_2 in the atmosphere is about four days. Consequently, SO_2 may disperse a long distance from its point of emission before it becomes oxidized or is deposited to a terrestrial or aquatic surface. This kind of dispersal is referred to as long-range transportation of air pollution (LRTAP).

Atmospheric sulphate, formed by the oxidation of SO_2 or H_2S, can combine with positively charged ions (cations) to form various compounds. Most atmospheric sulphate occurs as tiny particulates, especially ammonium sulphate ($(NH_4)_2SO_4$). This is the most prominent component, along with ammonium nitrate (NH_4NO_3), of the fine particulate haze that often impairs visibility in cities. Haze also occurs in some rural areas where pollutants have been imported by LRTAP from emission sources elsewhere. Other cations that combine with sulphate include calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+). Often, however, there are not enough of these cations to balance all of the negative charges of the sulphate (SO_4^{2-}) present. Under such conditions, hydrogen ions (H^+) serve to balance some of the negative charges, resulting in an aerosol containing sulphuric acid (H_2SO_4), the most important component of acidic precipitation (see Chapter 19).

Volcanoes are natural sources of emission of sulphur gases. On average, volcanoes emit about 12-million tonnes of sulphur gases per year, of which 90% is SO_2 and 10% is H_2S. However, the enormous 1991 eruption of Mount Pinatubo in the Philippines emitted 7-10-million tonnes of SO_2 (expressed as the sulphur content, or SO_2-S). The much smaller eruption of Mount St. Helens in Washington State in 1980 vented about 0.2-million tonnes of SO_2-S. Natural emissions of SO_2 also occur during wildfires.

The global anthropogenic emissions of SO_2 are about 150-million tonnes per year, or 3.8-times the natural releases (Table 16.1). Fossil-fuel combustion accounts for about half of the anthropogenic emissions. Coal and petroleum contain mineral compounds of sulphur, such as pyrite (FeS_2), as well as organic sulphur compounds. When these fuels are burned, the sulphur becomes oxidized to gaseous SO_2, which may be vented to the atmosphere. Hard coals mined in eastern North America contain 1-12% sulphur, softer coals from western regions have <0.3-1.5%, crude oil has 0.8-1.0% residual fuel oils such as bunker -C have 0.3-0.4%, and motor fuels such as diesel and gasoline have 0.04-0.05%. Other important sources of SO_2 emissions are manufacturing processes (23% of global emissions), the smelting of metal ores (7%), and the burning of natural habitats during agricultural conversions (most of the rest).

Table 16.1. Global Emissions and Other Characteristics of Important Air Pollutants. Emission data are for 2000. Sources: Modified from Freedman (1995) and NEAA (2015).

Pollutant	Emissions		Typical Concentration		Residence Time
	Natural	Anthropogenic	Background	Polluted Air	
	(10^6 t/y)	(10^6 t/y)	(ppm)	(ppm)	
SO_2	40	150	0.0002	0.2	4 days
H_2S	100	3	0.0002	–	<1 day
CO	33	1077	0.1	40-70	<3 years
NO_x (as NO)	430	83	<0.002	–	5 days
NO_x (as NO_2)	658	127	<0.004	0.2	–
NH_3	1160	12	0.01	0.02	7 days
N_2O	18	12	0.31	–	4 years
Volatile Organics	200	186	<0.001	–	?
CH_4	1600	321	1.7	2.5	4 years
Particulates	3700	3900	–	–	–
O_3	–	–	0.03	0.08	–

Anthropogenic emissions of SO_2 have increased enormously since the beginning of the Industrial Revolution. Emissions in 1860 were about 5-million tonnes, compared with about 150-million tonnes in 2000. Since then, most of the wealthier countries have invested heavily in clean-air technologies for power plants and other industrial users of coal and oil in order to reduce emissions of damaging SO_2 to the atmosphere. The clean-air actions include the following:

- the installation of technologies to capture SO_2 from post-combustion waste gases (this is known as flue-gas desulphurization or scrubbing)
- the removal of some of the sulphur content of fuels (known as fuel desulphurization or coal washing)
- the installation of particulate-control devices (such as electrostatic precipitators) to greatly reduce the emissions of particulates (although this has little effect on SO_2 emissions)
- switching to low- or no-sulphur fuels such as natural gas, or to no-sulphur energy technologies such as

hydroelectricity and nuclear power (known as fuel-switching)

- energy conservation to reduce the overall demand for fuel and associated emissions of pollutants
- building taller smokestacks to disperse emissions of SO_2 more widely, which helps to decrease the local ground-level pollution

However, future global emissions are bound to increase. China, India, and other rapidly industrializing countries supply much of their burgeoning energy needs by burning coal and petroleum fuels. In China, coal is the major source of industrial energy, accounting for 68% of the energy supply (in 2013; Table 13.9). Due to increasing industrialization, emissions of SO_2 in China increased from 10-million tonnes in 1980 to 34-million tonnes in 2000, a 3.4-fold increase in only 20 years.

The amounts of SO_2 emissions differ greatly among nations, depending on their population, their kind of industrialization, and the fuels they mostly use. For instance, Canadian emissions of SO_2 are about 22% of those of the United States (Table 16.2). However, the population of Canada is only about 11% that of the United States (Chapter 10). Therefore, per-capita emissions of SO_2 are about double in Canada than in the United States.

Table 16.2. Comparison of Emissions of Air Pollutants in Canada in the United States. Data are in units of millions of tonnes per year (10^6 t/y). Percent refers to the percentage of total emissions by country. Sources: Modified from Environment Canada (2014) and Environmental Protection Agency (2014).

Pollutant	**Emissions**		**Typical Concentration**		**Residence Time**
	Natural	**Anthropogenic**	**Background**	**Polluted Air**	
	(10^6 t/y)	**(10^6 t/y)**	**(ppm)**	**(ppm)**	
SO_2	40	150	0.0002	0.2	4 days
H_2S	100	3	0.0002	–	<1 day
CO	33	1077	0.1	40-70	<3 years
NO_x (as NO)	430	83	<0.002	–	5 days
NO_x (as NO_2)	658	127	<0.004	0.2	–
NH_3	1160	12	0.01	0.02	7 days
N_2O	18	12	0.31	–	4 years
Volatile Organics	200	186	<0.001	–	?
CH_4	1600	321	1.7	2.5	4 years
Particulates	3700	3900	–	–	–
O_3	–	–	0.03	0.08	–

About 66% of Canadian emissions of SO_2 are from large industrial sources, particularly metal smelters, while 24% are from "fuel combustion," which is mostly fossil-fuelled power plants. In comparison, 84% of U.S. emissions are from power plants, and 10% from industrial sources. Most of this difference is due to two factors: a relatively large proportion of electricity generation in Canada is from nuclear and hydro technologies, which do not emit SO_2, and metal smelting is a major industry in Canada.

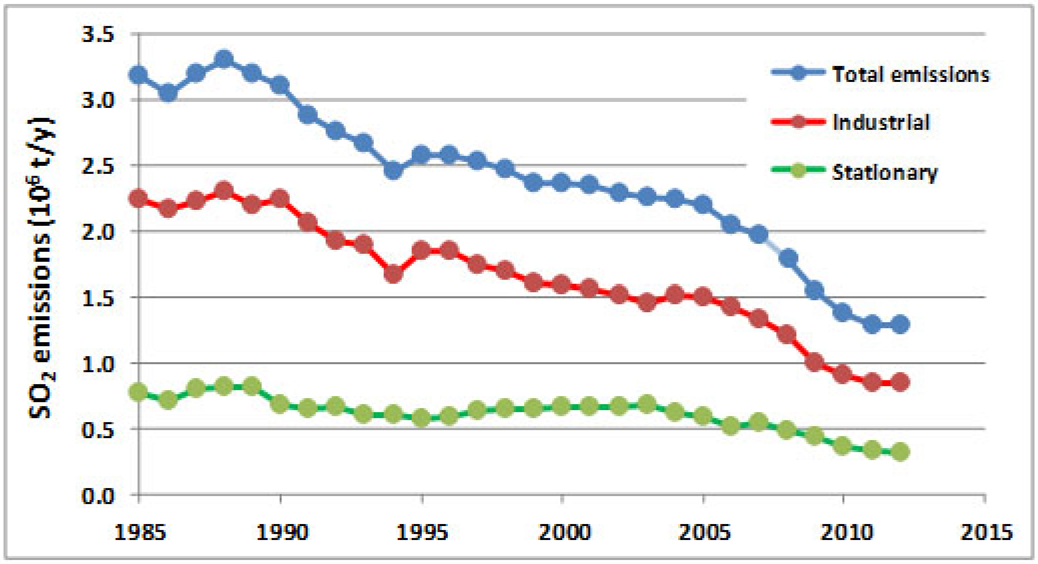
Because of human-health and environmental damages associated with SO_2 and other air pollutants, most developed nations have acted to reduce their emissions. In Canada, emissions of SO2 were reduced by about 41% between 1985 and 2012 (Figure 16.1), compared with a 32% reduction in the United States. In both countries the reductions were achieved by several methods:

- switching to low- or no-sulphur fuels for some major uses, especially for electricity generation

- removing sulphur from some fuels prior to combustion, mostly by coal washing
- reducing energy demands through conservation
- installing scrubbers to remove SO_2 from post-combustion waste gases before they are vented to the atmosphere

However, as is shown in Figure 16.1, reductions of emissions from industrial sources (especially metal smelters) and stationary sources (mostly coal-fuelled power plants) have been especially important. The large reductions of SO_2that have been achieved in North America during the past several decades cost many billions of dollars to achieve, and they should be regarded as an important "success story" of pollution control.

Figure 16.2. Reductions of emissions of sulphur dioxide in Canada. Source: Data from Environment Canada (2014).



In contrast to SO_2, the global emissions of sulphide gases are mostly from natural sources (Table 16.1). The largest sources are H_2S emitted from anoxic sediment in shallow marine and inland waters, and dimethyl sulphide ($(CH_3)_2S$) produced by phytoplankton and out-gassed from oceanic waters. The natural emission of H_2S is about 100-million tonnes per year, and dimethyl sulphide, 15-million tonnes per year (both expressed as sulphur equivalent, or as tonnes of S). Anthropogenic emissions of H_2S are about 3-million tonnes per year, and are mostly from chemical industries, sewage-treatment plants, and livestock manure.

The global emission of all sulphur-containing gases is equivalent to almost 300- million tonnes of sulphur per year. About half of the global emission is from anthropogenic sources.

Clean air typically contains less than 0.2 ppb of SO_2 or H_2S. Concentrations of SO_2 and H_2S in air that is polluted by emissions are highly variable. They are typically about 0.2 ppm in urban atmospheres but can exceed 3 ppm close to large emission sources.

Toxicity of Sulphur Gases

Concentrations of H_2S in the environment are rarely high enough to be toxic to plants. However, accidental emissions from sour-gas plants (where H_2S is removed from natural gas) may cause local vegetation damage. In contrast, concentrations of SO_2 in cities and near industrial sources are often high enough to injure wild and cultivated plants. Near certain metal smelters, vegetation has been severely damaged, as we examine later.

An exposure to 0.7 ppm SO_2 for one hour will result in acute injury to most plant species, as will 0.2 ppm over an eight-hour period. It is important to note, however, that certain species are extremely sensitive to SO_2 exposures (they are hypersensitive) and can suffer acute injuries at concentrations lower than those just noted.

In addition, plants will often exhibit a reduction in yield when exposed to concentrations of SO_2 that are lower than those required to cause an acute injury. This type of response, which occurs without symptoms of acute tissue damage, is referred to as "hidden injury". Hidden injuries to wild and agricultural vegetation are measured by enclosing plants in experimental chambers and exposing them to either air containing ambient levels of SO_2, or that that has been filtered through charcoal to remove that gas. If productivity is greater in the filtered air, it follows that the ambient SO_2 was causing a hidden injury. Studies of pasture grasses have found that exposure to SO_2 concentrations averaging only 0.04 ppm would cause hidden injuries as reductions of yield.

The Canadian air-quality guideline for ambient SO_2 in the atmosphere is a maximum of 450 μg/m^3 (0.17 ppm) over a one-hour exposure (Table 16.3). This guideline is based on the concentration that causes acute foliar (leaf) injuries to most agricultural plants. Although regions meeting this guideline would not show much acute damage to vegetation, relatively sensitive species might be affected through hidden injuries, possibly resulting in significant losses of yield.

Table 16.3. Air Quality Guidelines for the Protection of Human Health and the Environment in Canada. Note that in terms of the dose received by an organism, a longer-term exposure to lower concentrations of chemicals can be equivalent to a shorter-term exposure to a higher concentration. $PM_{2.5}$ refers to particulates smaller than 2.5 micrometers. The data are guidelines, except where standards for implementation in 2015 are marked as *. Source: Modified from CCME (2014) and Environment Canada (2013).

Pollutant	**Time**	**Maximum Concentration**		
		Desirable	**Acceptable**	**Tolerable**
SO_2 (μgg/m^3)	annual	30	60	–
	24 h	150	300	800
	1 h	450	900	–
NO_2 (NO_x, μgg/m^3)	annual	0.06	0.1	–
	24 h	–	0.2	0.4
	1 h	–	0.4	1
CO (mgg/m^3)	8 h	6	15	20
	1 h	15	35	–
O_3 (μgg/m^3)	annual	–	30	–
	8h	30 (63*)	50	–
	1 h	100	160	300
$PM_{2.5}$ (μgg/m^3)	annual	10*	–	–
	24 h	28*	–	–

Humans and most other animals are much less sensitive to SO_2 than plants are. Guidelines for allowable exposures of people to SO_2 and other potentially toxic gases accommodate the fact that, in terms of dose received, longer-term exposures to low concentrations can be as important as higher acute exposures.

Guidelines for occupational exposures to air pollutants are frequently greater than those for ambient exposures. In North America, it is recommended that occupational exposures to SO_2 be no higher than 2 ppm (5.2 mg/m^3) over the long term, and no higher than 5 ppm (13 mg/m^3) for shorter exposures. However, some people are relatively sensitive to SO_2, and concentrations less than 1 ppm (2.6 mg/m^3) may cause them to suffer asthma or other distresses related to impaired lung function. In addition, some studies have suggested that long-term exposures of large human populations to sulphate particulate aerosols (which are ultimately derived from gaseous SO_2) in cities may result in small increases in the incidence of respiratory and circulatory diseases, most probably in hypersensitive people.

In Detail 16.2. Air Pollution Chemistry
Air pollutants are emitted as particular chemicals, which may then be transformed into other compounds through reactions occurring in the atmosphere. Several examples follow.

Oxidation of SO_2
$SO_2 + OH \rightarrow HO{\bullet}SO_2$ (1)
$HO{\bullet}SO_2 + O_2 \rightarrow HO_2 + SO_3$ (2)
$SO_3 + H_2O \rightarrow H_2SO_4$ (3)
$H_2SO_4 \rightarrow 2H^+ + SO_4^{2-}$ (in aqueous solution) (4)
Note that the SO_4^{2-} produced is important as a constituent of acid rain and as particulate ammonium sulphate ($(NH_4)_2SO_4$), which are important pollutants.

Oxidation of NO
$NO + HO_2 \rightarrow NO_2 + OH$ (5)
$NO_2 + OH \rightarrow HNO_3$ (6)
$HNO_3 \rightarrow H^+ + NO_3^-$ (in aqueous solution) (7)
Similarly, the NO_3^- produced is important in acid rain and as particulate ammonium nitrate (NH_4NO_3).

Formation and Destruction of Stratospheric O3
O_2 + UV radiation $\rightarrow O + O$ (8) $O + O \rightarrow O_2$ (9)
$O + O_2 \rightarrow O_3$ (10)
O_3 + UV radiation $\rightarrow O_2 + O$ (11)
Reaction 11 is an ultraviolet photodissociation of O_3. Ozone can also be consumed by reactions with NO, NO_2, N_2O, and with ions or simple molecules of chlorine (especially ClO), bromine, and fluorine. These reactions are too complex to describe here.

Formation and Destruction of Ground-Level O_3
$O + O_2 \rightarrow O_3$ (10)
NO_2 + UV radiation $\rightarrow NO + O$ (12)
$NO + O_3 \rightarrow NO_2 + O_2$ (13)
$NO + RO_2 \rightarrow NO_2 + RO$ (14)
The formation of O_3 (reaction 10) requires atomic O, formed by the photodissociation of NO_2 (reaction 12). Ozone can be consumed by reaction with NO (an emitted gas), which regenerates NO_2 (reaction 13). Atmospheric O_3 can, however, accumulate if other reactions (such as reaction 14) convert NO to NO_2, because these operate in competition with reaction 13 for NO. (The species RO_2 includes various chemicals known as peroxy radicals, formed by the degradation of organic molecules by reaction with hydroxyl radicals, followed by the addition of molecular O_2. RO is the chemically reduced form of RO_2.)

Nitrogen Gases

Emissions and Transformations

The most important of the nitrogen-containing gases are nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), and ammonia (NH_3). NO and NO_2 are often considered together as a complex, referred to as NO_x.

Ammonia (NH_3), a colourless gas, is emitted mostly from wetlands, where it is produced during the anaerobic decomposition of dead biomass. Natural emissions of NH_3 are about 1.2-billion tonnes per year (Table 16.1). Sources of anthropogenic emissions include fossil-fuel combustion (4-million tonnes per year) and animal husbandry (0.2-million tonnes per year). The residence time of NH_3 in the atmosphere is about seven days (the NH_3 is eventually oxidized to nitrate).

Nitrous oxide (N_2O) is a colourless, non-toxic gas that produces a mild euphoria when inhaled. This gas is also known as "laughing gas" and is used as a mild anaesthetic in medicine, and sometimes as a recreational drug. Because N_2O is a rather unreactive compound, it has a long residence time in the atmosphere of about four years. Most N_2O emissions are associated with microbial denitrification in soil and water. These are equivalent to about 18-million tonnes per year, while industrial emissions are 12-million tonnes per year. Agricultural soil fertilized with nitrate can have high rates of N_2O emission, and modern agricultural practices are thought to have increased global emissions by about 40%.

Nitric oxide (NO) is a colourless and odourless gas, while nitrogen dioxide is reddish, pungent, and irritating to respiratory and eye membranes. Natural emissions of NO_x are about 430-million tonnes per year (expressed as NO; the same emissions expressed as NO_2 are 658-million tonnes per year). The most important natural emissions of NO_x are due to bacterial denitrification of nitrate in soil, fixation of atmospheric nitrogen gas (N_2) by lightning, and oxidation of biomass nitrogen during fires (see Chapter 5).

Anthropogenic emissions of NO_x, about 83-million tonnes per year (expressed as NO), result mostly from the combustion of fossil fuels, especially in automobiles and power plants (Table 16.1). These emissions are mostly NO, which is secondarily oxidized to NO_2 by reactions in the atmosphere. Ultimately, most atmospheric NO_x gases become oxidized to nitrate (NO_3–), an ion that is important in the acidification of precipitation and ecosystems (Chapter 19).

Toxicity of Nitrogen Gases

It is rare that concentrations of NH_3 or NO_x gases are high enough to injure vegetation. The environmental damage associated with NO_x is focussed on the photochemical reactions by which ozone, a much more toxic gas, is produced (see below), and also the acidification of precipitation and ecosystems.

Ambient concentrations of NH_3 and NO_x are rarely high enough to bother humans. Guidelines for long-term exposures in an occupational setting are 25 ppm (34 mg/m^3) for NO and 5 ppm (10 mg/m^3) for NO_2. Occupational guidelines for short-term exposures are 35 ppm (47 mg/m^3) and 5 ppm (10 mg/m^3), respectively. Intense occupational exposures to NO_x can cause impaired pulmonary function in humans.

Organic Gases and Vapours

Emissions and Transformations

Hydrocarbons are a diverse group of chemicals whose molecular structures containing various combinations of hydrogen and carbon atoms. The simplest hydrocarbon is methane (CH_4), a gas. Larger hydrocarbons with greater weight and more complex structure may occur as vapours, liquids, or solids (Chapter 22). Other volatile organic compounds (VOCs) may contain oxygen, nitrogen, and other light elements in addition to carbon and hydrogen, and include alcohols, aldehydes, and phenols.

The background concentration of methane in the atmosphere is about 1.7 ppm (1 ppm = 0.65 mg/m^3), while all other hydrocarbons and volatile organics together amount to less than 1 ppb (Table 16.1; the conversions to mg/m^3 are variable depending on the molecular weight). Most emissions of CH_4 are natural and are associated with the fermentation of organic matter by microbes in anaerobic wetlands. Smaller amounts are out-gassed from deposits of fossil fuels, during wildfires, and from burping and flatulent ruminant animals (such as cows and sheep) and termites, which produce CH_4 as they digest their plant foods. The global natural emissions of CH_4 are about 1.6-billion tonnes per year, and the natural emissions 0.3-billion tonnes per year.

Atmospheric hydrocarbons other than CH_4 are referred to as non-methane hydrocarbons. Natural emissions of these and many organics occur mainly as gases and vapours that evaporate from living vegetation, along with smaller quantities that out-gas from deposits of fossil fuels. The largest emissions from forests typically occur during hot, sunny days. Natural emissions of non-methane hydrocarbons are about 200-million tonnes per year, compared with anthropogenic emissions of 186-million tonnes per year (Table 16.1). The most important anthropogenic sources are unburned fuel emitted from vehicles and aircraft, releases during fossil-fuel mining and refining, and evaporation of solvents.

Toxicity of Organic Gases and Vapours

Organic gases and vapours can be toxic, but atmospheric concentrations are rarely high enough to damage vegetation or animals. The environmental importance of these gases and vapours lies mainly in their role in the photochemical reactions that produce toxic ozone. In addition, CH4 is an important greenhouse gas that affects global warming (Chapter 17). In some workplaces, however, relatively toxic organics such as benzene and formaldehyde may be important pollutants.

Ozone

There are two different ozone-related environmental issues: (1) O_3 in the stratosphere and (2) O_3 in the troposphere (ground-level ozone). High concentrations of ozone are naturally present in the upper-atmospheric layer known as the stratosphere, which begins at about 8-17 km above the Earth's surface, depending on the latitude and season. Stratospheric O_3 causes no damage and is not an air pollutant. Rather, by absorbing solar ultraviolet radiation, stratospheric $_3$helps to protect organisms on the surface pf the planet from many damaging effects of exposure to this harmful part of the electromagnetic spectrum. In contrast, O3 in the lower$_3$ atmosphere (the troposphere) is an important air pollutant that is damages vegetation, materials, and human health. Ozone is removed from the atmosphere by interactions with other gases, organic vapours, and terrestrial and aquatic surfaces (including vegetation).

Ground-Level Ozone

Ground-level ozone (O_3) is the most damaging of the so-called photochemical air pollutants. Less important are peroxyacetyl nitrate (PAN), hydrogen peroxide (H_2O_2), and other oxidant gases. Oxidizing smog is rich in O_3 and the other oxidant gases. These chemicals are secondary pollutants, meaning they are not actually emitted to the atmosphere (as are primary pollutants such as SO_2 and NO_x). Instead, they are synthesized within the atmosphere by photochemical reactions (chemical reactions that require light, especially ultraviolet wavelengths). These proceed at faster rates and result in a buildup of oxidants if NO_x and hydrocarbons are present in high concentrations, a condition that is typically due to anthropogenic emissions.

Some regions tend to develop a weak atmospheric inversion in the morning. Because an inversion is relatively stable and resists the in-mixing of cleaner air from above or beyond, this condition encourages the development of oxidizing smog during the morning and early afternoon. Later in the day, the inversion is typically broken up by stronger winds, and the air pollution is dispersed. Such inversions and their ozone-rich smog are common phenomena around the Los Angeles basin, Mexico City, Vancouver, and elsewhere.

The concentrations of ground-level O_3 vary greatly among different regions of North America. Average concentrations in the southwestern United States are relatively high, at about 100 ppb (1 ppb = 2 $\mu g/m^3$), and they generally range from 40–60 ppb in other regions of the United States and in southern Canada.

Canada, the United States, and other countries have developed air quality standards for O_3. These are intended to reflect concentrations that would prevent severe damage to agricultural and wild vegetation. For some time, the American O_3 standard was 80 ppb (160 $\mu g/m^3$) (for an average one-hour exposure), but in 1979 this was relaxed to 120 ppb (240 $\mu g/m^3$). The authorities made the change because the original standard of 80 ppb was frequently exceeded over large regions and so was essentially unenforceable. In fact, even the 120 ppb criterion is commonly exceeded in some regions, particularly in the southwestern United States.

The Los Angeles basin suffers especially intense photochemical air pollution. Concentrations of O_3 can exceed 500 ppb (one-hour average), and they typically exceed 100 ppb for more than 15 days during the summer. Maximum O_3 concentrations are lower in other cities of North America, typically reaching up to 150-250 ppb (one-hour average). These concentrations are well within the range at which O_3 can cause acute injury to plants, which is why O_3 is such an important air pollutant. The emissions of ozone precursors (NO_x and hydrocarbons) occur mainly in cities, but extensive ecological damage is caused when polluted air masses are transported to rural areas dominated by agricultural or natural vegetation.

In Canada, the regions that most often experience ozone pollution are the lower Fraser Valley in southwestern British Columbia, the Windsor-Quebec City corridor, and the southern Maritimes (Environment Canada, 1999). The lower Fraser Valley, a coastal lowland bounded by mountains to the east, often has atmospheric inversions and receives large emissions of ozone precursors from the Greater Vancouver area to the west. Some places in the lower Fraser Valley have maximum O3 concentrations of about 100 ppb.

The Windsor–Quebec City corridor also has local emissions associated with people and industries (about 60% of the Canadian population lives in the region), but this area also receives ozone and its precursors in air masses blowing from highly populated regions in the United States. Many places in the corridor have O3 concentrations of 110-160 ppb, and values up to 190 ppb have been measured.

The southern Maritime region is affected mainly by ozone-rich air masses blowing in from industrial parts of southern Ontario, Quebec, and the northeastern United States. Some places in southern New Brunswick and western Nova Scotia have O_3 concentrations of up to 90-110 ppb.

Toxicity of Ozone

Humans and some animals are sensitive to O_3, which can irritate and damage membranes of the eyes and respiratory system and cause a loss of lung functioning. The guideline for long-term exposure to O_3in an occupational setting is 100 ppb (196 $\mu g/m^3$), and it is 300 ppb (589 $\mu g/m^3$) for short-term exposures. However, sensitive people can be affected by O_3-related symptoms at lower concentrations. Exposure to O_3 can result in asthmatic attacks and can exacerbate bronchitis and emphysema.

Ozone causes important damage to wild and agricultural plants over widespread areas. Foliar injuries are often distinctive to O_3, and they diminish the photosynthetic capacity of plants and thereby reduce their productivity. Acute injuries are caused to most species by two- to four-hour exposures to 200-300 ppb O_3, while long-term exposures to only 40-100 ppb may cause hidden injuries (and reduced yield). However, many species are more sensitive and suffer acute and hidden injuries at lower concentrations. Some varieties of tobacco (Nicotiana tobacco), for example, can suffer acute foliar injuries from a two- to three-hour exposure to only 50-60 ppb, and spinach (Spinacea oleracea), from one to two hours at 60-80 ppb. Sensitive species of conifer trees may suffer acute injuries from exposures to 80 ppb O_3 over 12 hours.

Researchers have grown agricultural plants in experimental chambers that received ambient air, or air filtered through charcoal, which removes any O_3. These studies have been useful in defining the extent of damage caused to agricultural crops by exposure to ambient O_3. One series of field experiments demonstrated that crop yields were reduced in all regions of the United States. The worst damage occurred in the southwest, where sunny conditions and large emissions of NO_x and hydrocarbons result in especially high O_3 concentrations. That study estimated that crop damage due to O_3 was equivalent to 2–4% of the total agricultural yield in the United States, with economic losses equivalent to more than $5 billion per year. Because O_3-related damage to vegetation occurs over extensive areas of North America, it is by far the most important air pollutant in agriculture. Ozone is probably also the leading air pollutant causing damage to forests and other natural ecosystems.

Stratospheric Ozone

In contrast to ground-level ozone, ozone in the stratosphere protects life on Earth from the damaging effects of solar ultraviolet (UV) radiation. This is the reason why the fact that stratospheric ozone is being destroyed by anthropogenic emissions of certain gases is cause for alarm.

Ozone is produced in the stratosphere by natural photochemical reactions. They involve the absorption of solar UV radiation by oxygen molecules (O_2), which creates highly reactive oxygen atoms (O) that join with other O_2 molecules to form O_3 (see In Detail 16.2). These reactions proceed relatively quickly in the stratosphere because high-energy UV radiation is abundant there. As a result, O_3 concentrations are typically 200-300 ppb in the stratosphere, about 10 times greater than in the ambient troposphere.

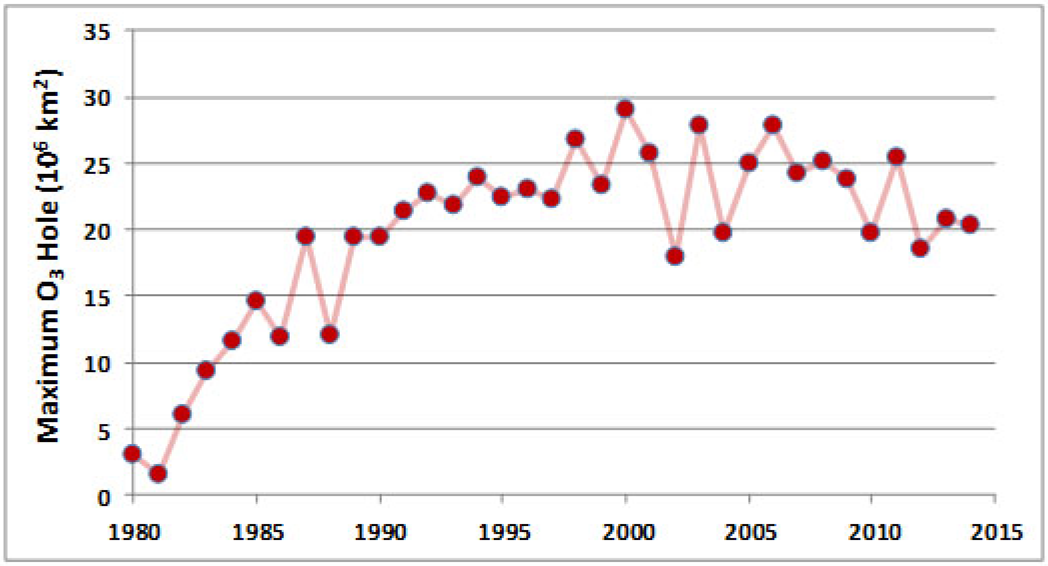
Stratospheric O_3 provides a critical environmental service. It efficiently absorbs most of the incoming high-energy UV radiation, which can be extremely damaging to organisms. In particular, DNA is a strong absorber of UV and can be damaged by this radiation. This can increase the risk of developing skin cancers, including melanoma, an often-fatal malignancy. Other health risks from UV exposure include the development of cataracts in the eyes and suppression of the immune system. UV radiation also damages plants, in part because chlorophyll (the key photosynthetic pigment) is degraded by UV absorption, which may lead to decreases in productivity. The waxy covering of the cuticle of foliage is also damaged by UV radiation.

Stratospheric O_3 can be destroyed by various processes, including reactions with the trace gases $NO_x$and N_2O and with reactive ions of bromine, chlorine, and fluorine. Because of anthropogenic emissions, the concentrations of some of these O_3-consuming chemicals have been increasing in the stratosphere, leading to concerns about the depletion of stratospheric O_3. It is widely believed that emissions of chlorofluorocarbons (CFCs), particularly the industrial gases known as freons, have been especially important in this regard. Because CFCs are extremely unreactive in the troposphere, they eventually migrate up to the stratosphere, where they are bombarded with UV radiation and slowly degrade (photodissociate) to release free chlorine. The chlorine efficiently reacts with and destroys O_3.

The O_3-destroying reactions proceed most effectively under extremely cold and stagnant conditions in the stratosphere, such as those occurring above polar latitudes at the end of the Antarctic and Arctic winters. These polar-focused O_3 depletions result in the development of so-called ozone holes during the early springtime. These phenomena have been observed regularly since the early 1980s. The O_3 holes over Antarctica are particularly extensive and typically involve decreases of the O_3 concentration of 30-50% during the spring. Smaller depletions of O_3 occur above the Arctic, including northern Canada. The affected areas in the Northern Hemisphere are much smaller than their counterparts in Antarctica.

The sizes of the ozone holes in Antarctica vary from year to year, but there has been a trend of strong increases since 1980, when the first accurate data began to be collected (Figure 16.3). Although the seasonal losses of O_3 only take place over polar regions, lower latitudes are also affected when the O_3-depleted air becomes dispersed during the breakup of the holes. This temporarily reduces the stratospheric O_3 concentrations throughout the hemisphere, though not nearly to the same degree as occurs in the holes themselves.

Figure 16.3. Changes in the maximum annual size of the ozone "hole" over Antarctica. Source: Data from National Weather Service (2015).



Environmental Issues 16.1. The Montreal Protocol – A Success of Regulatory Action
Soon after it became widely recognized that emissions of chlorofluorocarbons (CFCs) and other chemicals were degrading the stratospheric ozone layer, world governments took action to deal with the problem. In 1987, the United Nations Environment Program (UNEP) organized an international meeting in Montreal, where intense negotiations led to a treaty called The Montreal Protocol on Substances That Deplete the Ozone Layer. The Montreal Protocol is an international agreement that committed all parties (signatory nations) to a schedule for phasing out the production and use of CFCs and other substances known to be harmful to the ozone layer. The treaty required the signatory nations to freeze their production and consumption of CFCs at 1986 levels by 1989, and to further reduce them to 50% of 1986 levels by 1998.

Initially, the governments of many countries were reluctant to ratify the protocol because they did not want to impose strict controls on the manufacturing and use of chemicals they thought were necessary for the functioning of their economies. This was particularly true for nations of the European Community, the former Soviet Union, and Japan. However, Canada, the United States, Norway, and Sweden strongly advocated control measures, and they managed to convince the reluctant nations to phase out their use of ozone-depleting substances. The Montreal Protocol came into force on January 1, 1989, and was then ratified by 40 countries, which accounted for about 82% of the global use of CFCs.

The Montreal Protocol was subsequently improved by a series of amendments to eliminate the use of halons by 1994; of CFCs, methyl chloroform, HBFCs (hydrobromofluorocarbons), and carbon tetrachloride by 1996; of methyl bromide by 2010; and of HCFCs (hydrochlorofluorocarbons) by 2030. The amended protocol was ratified by many additional countries, including China and India, huge nations that had not participated in the initial negotiations. By 2009, 197 countries were parties to the Montreal Protocol, making it the first such treaty to achieve universal approval. The amendments also established the Montreal Protocol Multilateral Fund to provide financial support to help developing nations become rapidly less dependent on ozone-depleting chemicals.

The Montreal Protocol and its subsequent amendments have been called a “success story” in the regulatory control of pollution. Many developed countries (including Canada) accelerated and surpassed their original reduction targets, and less-developed countries have committed to not allowing the use of ozone-depleting substances in their economies. This success was achieved because of the following:

1. There was international recognition of a clear threat to the global environment
2. The threat was associated with particular substances that could be easily controlled, as they were manufactured in only a few places and were used for relatively discrete purposes
3. Economically acceptable substitutes were quickly developed to replace the uses of ozone-depleting substances

In summary, rigorous information, effective international and national institutions, a spirit of co-operation, effective leadership by inspired leaders, and the availability of alternative technologies combined to bridge political differences in favour of the pursuit of a shared environmental interest. This is why the Montreal Protocol and its implementation are a success story of environmental regulatory action.

Air Pollution and Health

An extraordinary case of a natural emission of gas causing human deaths involved the release of a large volume of CO_2 from a lake in Cameroon, West Africa. Lake Nyos is a 200-m-deep volcanic lake in which the deep waters are naturally supersaturated with CO_2, similar to bottled soda water. One night in 1986, a large amount of sediment apparently slumped into the steep-sided lake, causing some of its bottom water to churn to the surface. The water de-gassed its CO_2 content as a dense air mass, which then flowed into low areas in the surrounding landscape. The CO_2-rich air asphyxiated about 1,700 sleeping people and 3,500 livestock as far as 25 km from the lake, plus uncounted wild animals. Atmospheric CO_2 is capable of causing severe toxicity at concentrations greater than 8-10%; its “normal” level is about 0.04%. Plants are much less vulnerable to CO_2 toxicity, so no vegetation was damaged by this rare and astonishing natural event.

Anthropogenic emissions of other gaseous pollutants have sometimes caused increases in human mortality and diseases. Some people, especially those with chronic respiratory or heart diseases, are especially vulnerable to the effects of air pollution. Exposures of people to toxic gases can occur within several contexts, including the following.

- The ambient environment: The urban atmosphere typically contains relatively high concentrations of potentially toxic chemicals. This is true in general, but air quality is especially bad during smog events, often caused by poor dispersion during an atmospheric inversion. Consequently, city people living their normal lives are routinely exposed to higher concentrations of air pollutants than those living in cleaner, rural environments.
- The working environment: Many people are exposed to high concentrations of pollutants as a consequence of their occupation. Of course, the specific exposures depend on the job – workers in metal smelters may be exposed to sulphur dioxide and metallic particulates, auto mechanics may be affected by exhaust fumes containing carbon monoxide and hydrocarbons, and laboratory workers may inhale various organic solvents.
- The indoor environment: Buildings are often contaminated by gases and fumes. For example, space heaters, furnaces, and fireplaces burning wood, kerosene, or fuel oil may emit carbon monoxide into the indoor environment. All high-temperature combustions emit nitric oxide, and many synthetic materials and fabrics vent formaldehyde and other organic vapours. These chemicals can accumulate if indoor air is not exchanged

frequently with cleaner, outdoor air.
- Tobacco smoke: The smoking of tobacco is a leading source of easily avoidable air pollution. Smoking is also the most important cause of preventable diseases, especially lung cancer and heart disease (see Chapter 15). People inhale a great variety of toxic gases and fumes when they smoke tobacco (and also marijuana). In addition, non-smokers are indirectly exposed to lower concentrations of those chemicals because of the lingering residues of "second-hand smoke" that may occur in indoor atmospheres.

All of these exposures to air pollutants have important implications for human health. However, the pollution of the ambient urban environment is the focus of the following paragraphs.

Since the beginning of the Industrial Revolution in Western Europe in the mid-18th century, people living in cities and working in certain types of factories have been exposed to high concentrations of air pollutants. Especially important have been sulphur dioxide, soot, and other emissions associated with the combustion of coal and other fossil fuels. The most severe exposures to pollutants in urban environments typically occurred during prolonged atmospheric inversions, which prevent the dispersion of emissions and result in smogs rich in SO_2 and particulates.

Coal has long been used in many places to heat homes and other buildings. The associated emissions have been regarded as a problem in cities and towns in Europe since at least 1500. With the beginning of the Industrial Revolution, which initially used coal as its principal energy source, air pollution worsened markedly. The first convincing link between air pollution and a substantial increase in the death rate of an exposed human population was made in 1909, in relation to a noxious smog during an inversion in Glasgow, Scotland, when about one-thousand deaths may have been caused.

The most infamous "killer smog" in North America occurred in 1948 in Donora, Pennsylvania. An inversion and fog persisted in the Donora Valley for four days, but emissions from several factories continued, resulting in a build-up of high concentrations of SO_2 and particulates in the atmosphere. The smog resulted in increased mortality in the local population (20 deaths in a population of only 14 100). An additional 43% of the population became ill, 10% severely so. The most common symptoms were irritation of the eyes and respiratory tract, sometimes accompanied by coughing, headache, and vomiting.

The world's most notorious killer smog afflicted London, England, in 1952, when an extensive inversion and fog stabilized over southern England. In London, emissions of pollutants, mostly from coal combustion, transformed the natural "white fog" into a venomous "black fog." Visibility was terrible – people lost their way while walking or driving, even falling off wharves into the Thames River, and airplanes became lost while trying to taxi at the airport. The smog lasted for four days, but it was followed by another 14 days with a higher-than-usual death rate. Overall, about 3,900 deaths were attributed to this episode of noxious pollution. Most of the affected people were elderly or very young, or had pre-existing respiratory or heart diseases.

Until the early 1960s, severe episodes of urban air pollution were common in the cities of North America and Western Europe. Most of the smogs were caused by the widespread burning of coal in fireplaces and furnaces in homes, electrical utilities, and factories. The poor-quality urban air affected the health of people and animals and also damaged vegetation. In many cities, only certain kinds of plants that can tolerate air pollution could grow. Examples of pollution-tolerant trees that are commonly grown in urban Canada include Norway maple (Acer platanoides), silver maple (A. saccharinum), linden (Tilia europaea), tree-of-heaven (Ailanthus altissima), and ginkgo (Ginkgo biloba).

To deal with the problems of this kind of smog, governments brought in legislation that has required large reductions in the emissions of air pollutants, particularly in cities. In Canada, for example, the enactment of various federal, provincial, and municipal laws related to air emissions has substantially improved urban air quality. Air quality has been similarly improved under legislation enacted in the United States, Britain, and other wealthier countries since the 1960s.

Of course, the killer smogs were particularly severe events of air pollution. More typically, the urban atmosphere is contaminated by much smaller concentrations of SO_2, NO_x, O_3, volatile organic compounds, and particulates. Many studies have investigated the effects of chronic exposures to those lower exposures to air contaminants on human health. The results of some studies suggest that modern urban air quality is sufficiently degraded to cause chronic damage to human health, especially by increasing the incidences of lung disease, asthma, and eye irritation. However, other studies have not found this to be the case. In any event, effective actions have been taken in Canada and other relatively wealthy nations. Visibly threatening, even lethal, episodes of air pollution like those described above no longer occur in those countries, although they could return if control standards were relaxed.

Unfortunately, in the cities of countries with rapidly growing economies, such as Brazil, China, India, Indonesia, and Mexico, poorly regulated industrial and urban growth is resulting in awful declines in air quality. Although not yet well studied in terms of human diseases, these appear to be modern tragedies of urban air pollution.

Canadian Focus 16.1. Smog in Canadian Cities
Smog is a serious problem in many cities and also in some rural areas because of LRTAP from urban areas. Smog is typically characterized as a noxious mixture of pollutants visible as a brownish-yellow or greyish-white haze. The key components are the following:

- O_3 gas, along with SO_2 and NO_x
- organic vapours
- fine particulates (< 10 µm diameter), including acidic droplets of H_2SO_4 and HNO_3, particulates of NH_4NO_3 and $(NH_4)_2SO_4$, and organics from diesel exhaust and other combustion sources

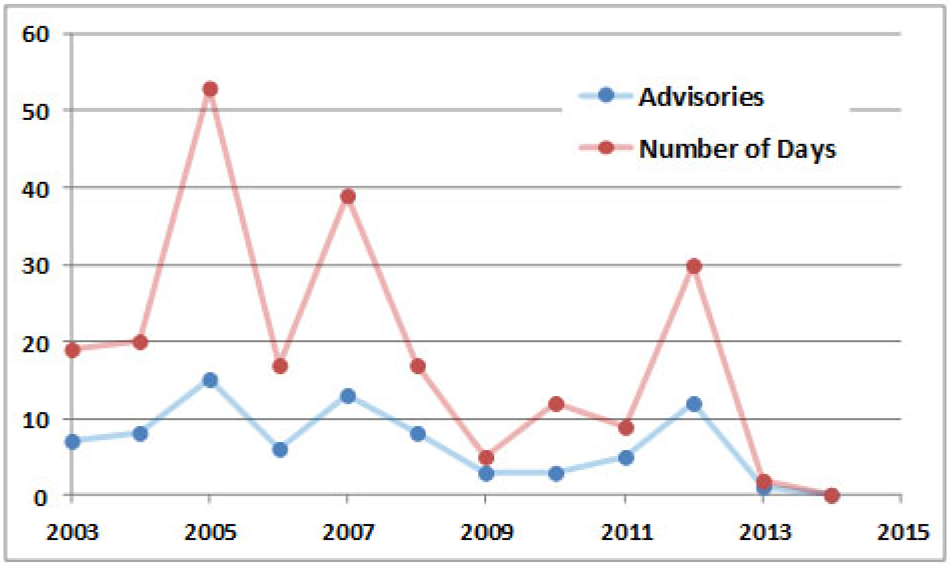
Smog is widely regarded as a major cause of environmental damage, because it causes toxicity to vegetation and deteriorates building surfaces and other materials. Smog is also known to cause diseases and discomfort in many people. The elderly and children are especially vulnerable, as are people with existing heart or lung diseases (particularly asthma, bronchitis, and emphysema). Even healthy adults, however, may be affected on days with severe smog. The key causes of toxicity are ozone, other gases, and the finest particulates (<2.5 µm), which can penetrate into the smallest lung cavities (known as alveoli) and cause irritation and other problems.

However, the data showing an association of smog and human diseases are epidemiological – that is, they involve discovering statistical relationships among the concentrations of atmospheric pollutants and the prevalence of certain maladies. In southern Ontario, for example, there is a predictable increase in hospital admissions of people suffering from respiratory ailments at times when concentrations of ozone and/or sulphate particulates are high. Although it is rarely possible to link a specific disease in a particular person to an exposure to air pollution, statistical estimates by the Ontario Medical Association suggested that smog is annually responsible for about 9,500 premature deaths and $7.8 billion in health-related costs in Ontario (OMA, 2015).

Because of the importance of smog as a stressor of urban Canadians, governments have initiated programs to monitor air pollutants and predict their concentrations so that "smog alerts" can be issued to the public. Environment Canada, in partnership with provincial and municipal governments, routinely issues advisories in smog-prone cities, usually on the day before a high level of ozone is predicted. Similarly, some provinces and municipalities have developed air-quality indices to provide daily advisories. The intent is to encourage people and industries to take actions to reduce air pollution and to avoid unnecessary exposure by staying inside buildings and by not engaging in outdoor exercise that involves deep breathing.

In 2005, Ontario experienced its worst-ever smog summer, with 53 days between June and September having air so polluted by ozone and other chemicals that it was considered a health hazard. The smog was caused by emissions from the many vehicles and other sources in that well-populated region, coupled with weather that was hotter and sunnier than normal (those conditions favour the photochemical formation of ozone), as well as LRTAP from other regions. It appears that this sort of health-threatening smog is well established in extensive, highly populated regions of southern Ontario and elsewhere in Canada.

Figure 16.4. History of smog advisories in Ontario. Source: Data from Ontario Ministry of the Environment (2014).



Case Studies of Ecological Damage

In this section we examine two case studies of ecological damage caused by air pollution. The first example describes "natural" air pollution at the Smoking Hills, a remote locality in the Arctic. The second examines ecological effects of emissions from large smelters near Sudbury, Ontario.

The Smoking Hills

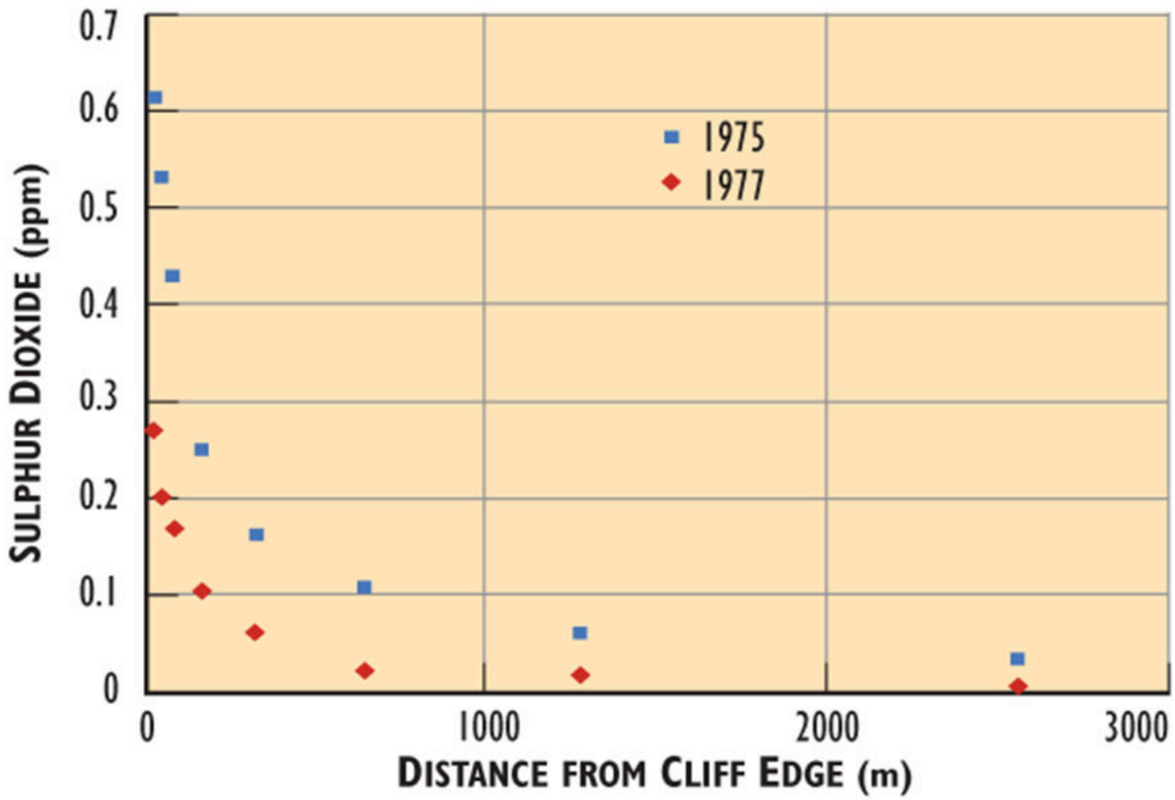
The Smoking Hills are located in the Northwest Territories on the coast of the Beaufort Sea. At various places along the coast and nearby rivers, seams of bituminous shale occur as exposed strata in steep places were erosion is occurring. The shale contains pyritic sulphur, which becomes oxidized to sulphate when exposed to atmospheric oxygen through erosion of the cliffs. The oxidation produces heat (the reaction is exothermic), which under insulating conditions can increase the temperature enough to spontaneously ignite the bituminous materials. These smoulder and release SO_2, which fumigates the nearby tundra. The first recorded sighting of the Smoking Hills was in 1826 by John Richardson, an explorer. However, the burns were long known to local Inuit and are likely thousands of years old.

Image 16.1. Natural air pollution at the Smoking Hills is caused when seams of bituminous shale spontaneously ignite and release sulphurous plumes that blow inland and fumigate the nearby tundra. Source: B. Freedman.

Winds at the Smoking Hills often blow the SO_2-laden plumes (air masses) inland at ground level, such that they fumigate the tundra. The pollution is most intense at the edge of the cliff, where the plumes begin to spread inland. Concentrations of SO_2 at the cliff edge are as high as 2 ppm, and then rapidly decrease inland in a more or less exponential manner (Figure 16.3). This gradient of air pollution occurs because the gases become progressively diluted in the ambient atmosphere with increasing distance from the points of emission.

Figure 16.5. Sulphur Dioxide at the Smoking Hills. The data are averages of 8- and 14-day sampling periods, respectively. The averages include times when SO_2 concentrations were high, as well as those when the

sampling sites were not fumigated because the plumes were blowing out to sea. Source: Data from Gizyn (1980).



The pollution by SO_2 has severely acidified the soil. Acidic conditions in freshwater ponds reach pH 2 or less, compared with pH 8 or more outside the fumigation area (see In Detail 19.1 for an explanation of pH as a measure of acidity). The extreme acidification causes metals to become dissolved from minerals in soil and aquatic sediment (Table 16.4). High concentrations of solubilized metals are toxic to terrestrial and aquatic organisms. In addition, sulphate occurs in high concentrations in both soil and water. This is mostly a result of the dry deposition of SO_2 from the atmosphere and its subsequent oxidation to SO_4^{2-} within the ecosystem (see Chapter 19).

Table 16.4. Chemistry of Tundra Ponds at the Smoking Hills. The data are in ppm and are averages for ponds within the pH range. Source: Data from Havas and Hutchinson (1983).

pH	No. Ponds	Aluminum	Iron	Manganese	Nickel	Sulphate
1.8–2.5	4	270	500	61	6.3	8200
2.6–3.5	14	5.5	18	15	0.21	890
3.6–4.5	9	1.1	1.2	3.6	0.04	156
4.6–5.5	1	<0.6	0.5	2.3	0.04	813
5.6–6.5	1	<0.2	0.2	1.8	0.06	713
6.6–7.5	4	<0.8	<0.1	0.7	0.02	360
7.6–8.5	8	<0.7	0.1	<0.5	<0.01	106
8.6–9.7	5	<0.2	0.1	0.5	0.01	31

The high concentration of SO_2 in the air and the acidity and soluble metals in soil and water result in the fumigated habitats being highly toxic to most plants, animals, and microorganisms. Close to the edge of the seacliff in fumigated areas, where the pollution is most intense, no vegetation grows at all – there is total ecological degradation. Farther inland, the pollution becomes less severe, and a few pollution-tolerant plants can grow. The most notable of these are arctic wormwood (Artemisia tilesii), polargrass (Arctagrostis latifolia), a lichen (Cladonia bellidiflora), and a moss (Pohlia nutans). These few tolerant plants have replaced the many species of unpolluted tundra, which includes arctic willow (Salix arctica), mountain avens (Dryas integrifolia), and more than 70 others (Freedman et al., 1990).

Pollution-tolerant species also occur in acidic ponds at the Smoking Hills. Even the most acidic ponds, which have a pH as low as 1.8, support at least six species of algae. These are extremely tolerant of acidity and dissolved metals and are not found in non-acidic waterbodies. In contrast to the acidic ponds, the unpolluted ponds are alkaline, with pH greater than 8, and they support rich algal communities of more than 90 species. A few acid-tolerant invertebrates also occur in acidic ponds (but only at pH greater than 2.8), including a crustacean (Brachionus urceolaris) and an insect midge (Chironomus riparius). The invertebrate fauna of non-acidic ponds is much richer in species and more productive (Havas and Hutchinson, 1983).

Image 16.2. Soil and surface waters at the Smoking Hills have been severely acidified by the deposition of sulphur dioxide. The acidity causes metals to go into solution, exacerbating the toxic conditions. This pond has been affected by atmospheric SO_2 and by acidic, metal-laden drainage water that has passed through roasted shale. Source: B. Freedman.

The most important lesson to be learned from the Smoking Hills is that “natural” pollution can cause ecological damage that is as intense as that associated with anthropogenic emissions. Clearly, SO_2 can damage ecosystems regardless of the source of the pollution. In addition, the natural pollution at the Smoking Hills has stressed ecosystems for a long time – at least thousands of years – and the ecological effects have likely reached a steady-state condition. The study of the Smoking Hills provides some understanding of the long-term effects of severe air pollution:

- it causes a simplification of biodiversity and ecosystems to occur
- productivity and nutrient cycling are impaired
- unusual communities of pollution-tolerant species develop

Metal Smelters near Sudbury

In 1883, while blasting through bedrock during construction of the Canadian Pacific Railroad, a worker with some knowledge of prospecting discovered a rich body of metal-bearing ore in the vicinity of Sudbury, Ontario. The principal metals in the ore are nickel and copper. However, valuable quantities of iron, cobalt, gold, silver, and other metals are also produced from the mines, as are sulphur and selenium.

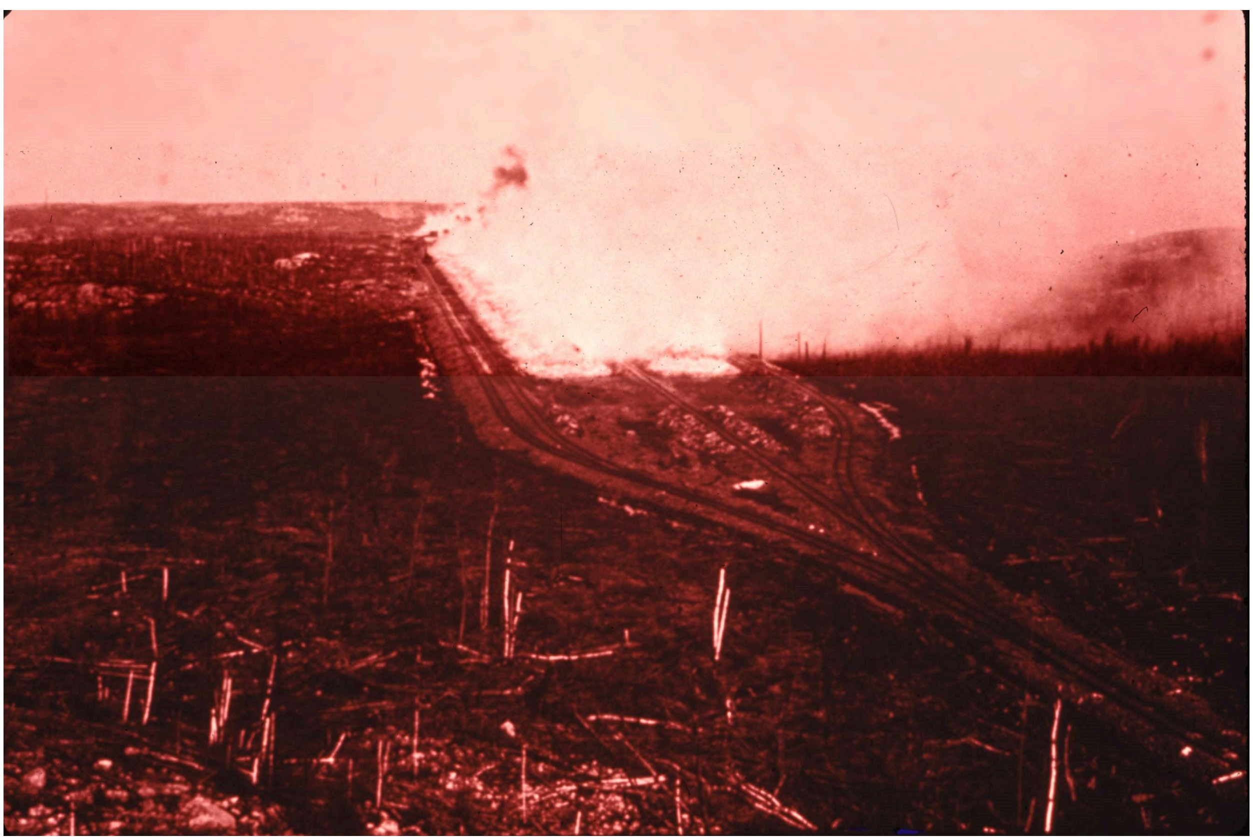
One of the world's largest industrial complexes has been developed to mine and process the rich ore bodies near Sudbury. The facilities have included underground mines, an open-pit mine, ore-processing mills with tailings-disposal areas, smelters, metal refineries, sulphuric-acid plants, and various other installations. The industrial activities around Sudbury provide a key economic base for a regional population of more than 160-thousand people.

The metals in the Sudbury ore occur as sulphide minerals, meaning they are combined with sulphur in compounds such as nickel sulphide and iron sulphide. Consequently, an important step in processing the ore is to roast the material at a high temperature in the presence of oxygen, which converts the sulphides into gaseous SO_2. The roasting increases the concentration of valuable metals in the residual material, which can then be smelted and refined into pure metals (see Figure 13.1).

The large-scale roasting and smelting in the Sudbury area have resulted in huge emissions of SO_2 and metal-containing particulates to the atmosphere, causing severe pollution and ecological damage. Until 1928, the roasting was conducted in huge open pits known as roast beds, which consisted of a layer of locally harvested cordwood over-heaped with sulphide ore. The wood was ignited, and the heat kindled the metal sulphides, releasing additional thermal energy because the oxidation is an exothermic reaction. The roast bed became hot enough to support a self-sustaining combustion of the ore, which would burn and smoulder for several months, after which the reactions were quenched with water. When the nickel and copper concentrates had cooled, they were collected and shipped to a refinery for further processing.

As is evident in the accompanying images, this crude roasting process resulted in intense ground-level fumigation of the landscape with toxic SO_2, acidic mist, and metallic particulates. The pollution devastated ecosystems near the roast beds. The denuding of terrestrial habitats resulted in massive erosion of soil from slopes, exposing the bedrock, which became pitted and blackened by reaction with the sulphurous fumes.

> Image 16.3. A view of a roast bed near Sudbury, around 1925. The top photo shows a roast bed being prepared with a bottom layer of wood (in the foreground), upon which heaps of sulphide ore were piled using the track-mounted gantry. When the wood was ignited, heat from the burning wood ignited the sulphide ore, which would smoulder for several months, giving off dense plumes of $SO_2$and metal-laden particulates. After the sulphur was oxidized and driven from the ore into the atmosphere, the fires were quenched and the metal concentrates collected and taken away for further processing. The plumes killed nearby vegetation, caused local soil and lakes to become toxic because of acidity and metals, and resulted in severe erosion and exposure of naked bedrock. Source: Inco Limited Archives.



The 30 roast beds that operated in the Sudbury region emitted about 270-thousand tonnes per year of SO_2 plus huge but undocumented amounts of metallic particulates. These early ground-level emissions caused the worst of the ecological damage in the Sudbury area.

In 1928, the government of Ontario prohibited any further use of roast beds. All roasting was then conducted at smelters located at Coniston, Copper Cliff, and Falconbridge, all in the vicinity of Sudbury. A smelter is a huge facility that contains roasting chambers within a building. Most of their emissions of waste gases and particulates are vented high into the atmosphere through a smokestack, which allows the pollutants to be dispersed and greatly reduces the severity of local ground-level pollution.

The largest smelter was built at Copper Cliff in 1929. Initially it had a single smokestack, with two others added in 1936. In 1972, the three stacks were replaced with a single 381-m "superstack" (at the time, the world's tallest chimney, but now the second-tallest). At the same time, the Coniston smelter was closed and its production shifted to Copper Cliff. The Falconbridge smelter, with smokestacks of 93 m and 140 m, is owned by another company. The commissioning of the superstack in 1972 allowed pollutants to be vented high enough into the atmosphere to make ground-level fumigations infrequent events. This resulted in a great improvement of air quality in the Sudbury area. Tall smokestacks facilitate the dispersion and mixing of emissions into ambient air. This is sometimes referred to as the "dilution solution to pollution."

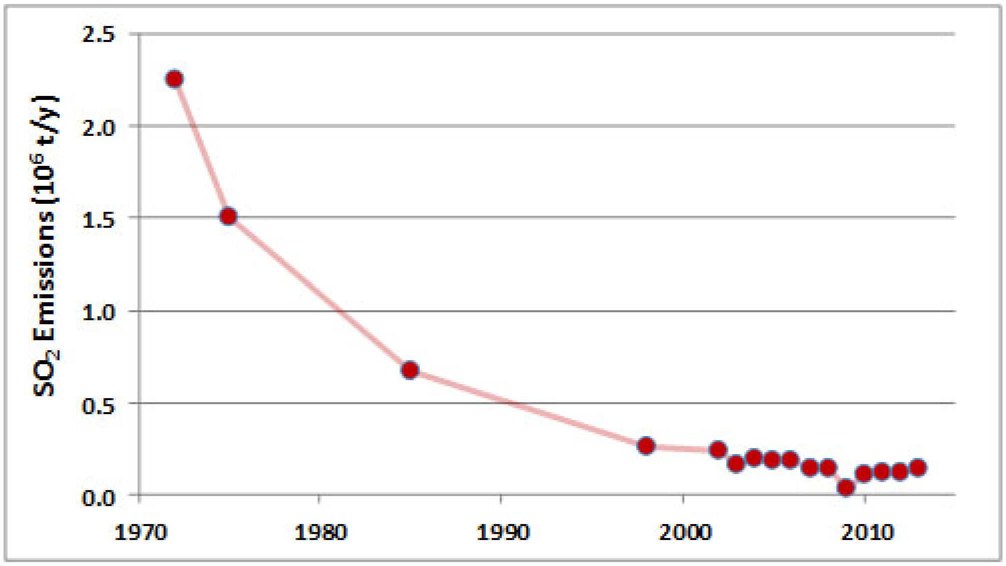
Because the superstack is so tall, its emissions are well dispersed into the regional atmosphere. Little of the vented SO2 is deposited locally, a fact reflected by the relatively good air quality in the region since 1972. In fact, studies have indicated that only about 1% of the SO_2 emissions are deposited within 40 km of the superstack. This means that 99% of the SO_2 is exported over a longer distance, which avoids local damage but contributes to the acidification of precipitation over a large region (see Chapter 19). The plume from the superstack can be detected chemically at distances 150 km or more away.

The emissions of pollutants have also been reduced by other methods. Devices such as electrostatic precipitators are used to recover metal-containing dusts from the smelter flue-gases, while SO_2emissions have been reduced by installing wet scrubbers, building sulphuric-acid plants, and constructing a facility to separate iron sulphides from the more valuable minerals of nickel and copper.

Emissions of SO_2 in the Sudbury area peaked during 1960-1972, when discharges from the three smelters averaged about 2.25 million tonnes per year. At that time, Sudbury was the world's largest source of anthropogenic SO_2 emissions, responsible for about 4% of global releases. Emissions of $SO_2$from the smelters have decreased greatly since that time, to about 0.14×10^6 t/y during 2006-2013 (Figure 16.4; Environment Canada, 2014). The decreases are due mainly to expensive investments in pollution abatement technologies, including equipment for flue-gas desulphurization. Although greatly diminished, the emissions of SO_2 remain large.

Figure 16.6. Reductions of Emissions of Sulphur Dioxide from the Copper Cliff Smelter. Source: Data from

Freedman (1995) and Environment Canada (2014).



The post-superstack air quality in the Sudbury region represents a great improvement over the sulphurous past. Toxic fumigations with SO_2, acidic mists, and metallic particulates were much more frequent and intense when roast beds were in use, as well as prior to 1972 when the smelters had shorter stacks and little pollution-abatement technology. Almost all of the worst of the ecological damage in the region resulted from the earlier emissions of pollutants. Other disturbances added to that damage, however, including the clear-cutting of forests to provide fuel for roast beds and the starting of wildfires by prospectors and by sparks from steam-powered railroad engines. The modern emissions of SO_2 and other pollutants in the Sudbury region, while still large, are well dispersed and only infrequently cause acute biological damage. In fact, a substantial ecological recovery has occurred since the superstack was commissioned in 1972.

Large areas of land and surface water in the Sudbury region were severely damaged by pollution from the roast beds and smelters. The smelters are large, point-sources of emissions, so the severity of ecological damage decreased rapidly with an increasing distance away. Over the years, ecologists have documented vegetation damage in the area. In 1970, about 100 km^2 of land around the smelters was characterized as "severely barren" and another 360 km^2 had "impoverished" vegetation, including a lack of conifers in the forest (Watson and Richardson, 1972). White pine (Pinus strobus), an economically important tree, is sensitive to air pollution and it showed diagnostic SO_2-injuries over an area of about 6,400 km^2.

Image 16.4. This hillside has been damaged by emissions of pollutants close to the Copper Cliff smelter. The worst damage was caused by roast beds, but fumigations from the smelter were also important. Following the devastation of the forest that once grew here, soil eroded into nearby basins. The naked bedrock became blackened and pitted through reactions with acidic fumigations. Source: B. Freedman.

Pollution was especially damaging around Copper Cliff, the location of the largest smelter. The most degraded habitats occur within several kilometres of this facility and support almost no forest. Hills and slopes in this zone are extensively denuded of vegetation, their soil is eroded, and the exposed bedrock has been blackened by reaction with acidic fumigations. Only a few plant species that have evolved pollution-tolerant populations grow in this area, including several species of grasses, other herbaceous plants, and stunted, shrub-sized plants of some trees (see also Chapter 18).

The intensity of pollution-related stress rapidly lessens at greater distances from the smelters (there is a spatial gradient), and damage to vegetation is correspondingly less intense. About 3-8 km from the Copper Cliff smelter, remnants of forest survive where the local topography provided a degree of shelter from the pollution. However, denuded and blackened hilltops are still common in this patchily vegetated zone. Trees in the remnant stands are stunted, with many dead branches and other injuries. The trees include relatively pollution-tolerant species such as red maple (Acer rubium), white birch (Betula papyrifera), red oak (Quercus rubra), trembling aspen (Populus tremuloides), and large-toothed aspen (P. grandidentata). The forest cover beyond 8 km is almost continuous, but the biomass and biodiversity of the stands are impoverished. Beyond 20-30 km from the smelters, the forests are little affected by pollution and mixed stands of conifer and hardwood trees occur, as is typical of the region (Freedman and Hutchinson, 1980).

Lakes close to the Sudbury smelters were also severely degraded by atmospheric pollution. More than 7-thousand waterbodies in the region were acidified by the deposition of SO_2 and contain elevated concentrations of toxic nickel, copper, and other metals. The polluted water bodies contain species-poor communities of tolerant algae, plants, and zooplankton. They lack fish, mostly because of their acidity.

However, great improvements in ground-level air quality since the building of the superstack in 1972 have resulted in dramatic ecological recoveries in the Sudbury area. Where eroded soil collected in moist basins, wet meadows developed. These are dominated by hairgrass (Deschampsia caespitosa), whose local populations are genetically tolerant to toxic nickel and copper in the soil (see Chapter 18). Other plants have also benefited from the reduction in air pollution, although their recovery is still impeded by residual soil toxicity associated with acidification and metals.

Lakes are also recovering in the region. In a set of 44 lakes that were monitored since 1981, including 28 that were highly acidified (to pH 5.0 or less), only 6 were that acidic in 2004 and 14 had recovered to pH 6.0, a level that would support most of the aquatic biota typical of the region (Keller et al., 2007). The concentrations of smelter-related metals, such as copper and nickel, are also much less, although still elevated compared with background conditions. In 1972, the pH of Baby Lake was 4.0-4.2, and it was almost devoid of algae and had no invertebrates or fish (Havas et al., 1995). However, by 1985 it had recovered to pH 6.8 and by 1995 to pH 7.2, and metals also decreased in concentration. Those improvements in water quality allowed the lake to be colonized by a diversity of phytoplankton, aquatic plants, invertebrates, and even small fishes.

Since the early 1970s, the ecological recovery of some degraded areas has been assisted by various management practices. The most important of these has been the liming of soil to reduce the acidity and thereby alleviate toxicity associated with metals. Also important have been the sowing of grasses and other plants that are known to be tolerant to the toxic conditions, the addition of fertilizer, and the planting of tree seedlings. Similar efforts in lakes have involved liming to reduce their acidity and metal toxicity, which has promoted the recovery of the biota. These efforts of reclamation, along with the natural regeneration that has occurred because of the greatly decreased pollution since the superstack was built, have helped to greatly improve degraded habitats in the Sudbury region.

The case of Sudbury is perhaps the world's best-documented example of ecological damage caused by toxic gases and metals emitted from smelters. There are, however, additional examples of this sort of damage around other smelters in Canada, affecting smaller areas, such as the smelters at Flin Flon, MB, Rouyn-Noranda, QC, Trail, BC, and Yellowknife, NT.

These smelters are all large, point-sources of emissions of pollutants into the atmosphere. All developed pronounced spatial gradients in the intensity of pollution, which decreased exponentially with increasing distance from the source of emissions until the ambient condition is reached. The patterns of ecological damage track these spatial gradients of toxic stress.

Conclusions

Gaseous air pollutants, such as sulphur dioxide and nitric oxide, are emitted from a variety of sources, which range from large power plants and smelters to individual automobiles and home furnaces. In contrast, secondary pollutants such as ozone are not emitted but are formed in the atmosphere by photochemical reactions involving sunlight and emitted oxides of nitrogen and hydrocarbons. If their concentrations are high enough, gaseous pollutants (often in combination with particulates) can be a risk to human health, and they may cause severe ecological damage. Because these risks are now well known, many governments have taken steps to reduce the emissions of the most important air pollutants. This is particularly the case for relatively developed countries, such as Canada. Although the emissions of air pollutants in wealthy countries remain large, they are generally stabilizing or even decreasing. However, in rapidly growing economies, such as China and India, hasty and poorly controlled industrialization is resulting in rapidly worsening air pollution.

Questions for Review

1. Compare the natural and anthropogenic emissions of sulphur and nitrogen compounds. Why do the sources of emission vary between regions and countries?
2. Why are high concentrations of ozone in the lower atmosphere considered an environmental problem? Why does this differ from the stratosphere, where too little ozone is a problem?
3. Explain are the differences between primary and secondary air pollutants? Give examples of each.
4. Why has air pollution decreased so much in the Sudbury region, and what have been the ecological responses to this environmental improvement?

Questions for Discussion

1. Compare, in broad terms, the patterns of ecological damage caused by "natural" pollution at the Smoking Hills with those caused by smelters near Sudbury. Why is it useful to study the ecological effects of natural pollution?
2. Existing clean-air technologies could be used to greatly reduce the emissions of air pollutants everywhere. Considering the damage that pollutants cause to human health, ecosystems, and other values, why are these technologies not being used more extensively? Consider factors associated with economics, politics, scientific uncertainty about pollution damage, and the benefits of having cleaner air. Contrast the lack of action with the successes achieved in controlling the emissions of ozone-depleting substances through the Montreal Protocol.
3. Epidemiological (statistical) research suggests that human health may be affected by ambient levels of air pollutants in urban areas, particularly through increased incidences of respiratory diseases, such as asthma. However, the statistical data are rather weak, and only a relatively small proportion of the urban population appears to be affected. What are some issues that decision makers must consider when deliberating about additional controls on the release of air pollutants in urban areas?
4. Like most other smelters built during the twentieth century, the ones at Sudbury caused obvious damage to ecosystems and human health. Why were those large industrial facilities not shut down or better controlled by the governments of the day? Today, new smelters are being built in Canada and in other countries. Are there risks of those industrial facilities repeating the mistakes of the past?

Exploring Issues

1. You have been asked to assess the potential ecological effects of building a new metal smelter in a region that is now wilderness. The smelter will emit sulphur dioxide to the atmosphere. Based on what you know about pollution damage at the Smoking Hills, around Sudbury, and at other smelters, what would be the most important considerations to incorporate into the environmental impact assessment? Focus on the potential effects on terrestrial and aquatic ecosystems.

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Chapter 17 ~ Atmospheric Gases and Climate Change

Key Concepts

After completing this chapter, you will be able to:

1. Outline the physical basis of Earth's greenhouse effect, and describe how human influences may be causing it to intensify.
2. Explain the term greenhouse gas (GHG).
3. Describe how the various GHGs vary in their effectiveness and influence on the greenhouse effect.
4. Identify which GHGs have been increasing in concentration in the atmosphere, and give the reasons for those changes.
5. Explain the probable climatic consequences of an intensification of the greenhouse effect, and describe possible economic and ecological effects.
6. Discuss strategies for reducing the intensity of the human influence on the greenhouse effect.

Introduction

In this chapter we examine how Earth's naturally occurring greenhouse effect keeps the surface of the planet relatively warm. We also describe how certain atmospheric constituents influence this phenomenon. These constituents are known as greenhouse gases (GHGs) and they work by slowing the rate by which Earth is able to cool itself of absorbed solar radiation. It is well documented that the concentrations of some of the GHGs, particularly carbon dioxide, are increasing because of emissions associated with various human activities. Potentially, these increased concentrations could intensify the greenhouse effect, which would result in global warming. This would be an extremely important environmental change, with potentially devastating consequences for the human economy and natural ecosystems.

The Greenhouse Effect

Earth's greenhouse effect is a well-understood physical phenomenon, and it is critical in maintaining the average surface temperature of the planet at about 15°C. Without this influence, the surface temperature would average about -18°C, or 33° cooler than it actually is. This would be frostier than organisms could tolerate over the long term, because at -18°C water is in a solid state. Liquid water is crucial to the proper functioning of organisms and ecosystems. At Earth's actual average temperature of 15°C, water is unfrozen for much or all of the year (depending on location). This means that enzymes can function and physiology can proceed efficiently, as can the many important ecological processes that involve liquid water.

Image 17.1. The combustion of fossil fuels for transportation and commercial energy is the leading anthropogenic source of emissions of carbon dioxide to the atmosphere. Source: B. Freedman.

To understand the nature of Earth's greenhouse effect, it is necessary to comprehend the planet's energy budget. As we examined in Chapter 4, an energy budget is a physical analysis that deals with the following:

1. all of the energy coming into a system
2. all of the energy going out
3. any difference that might be internally transformed or stored

Solar electromagnetic radiation is the major input of energy to Earth. On average, this energy arrives at a rate of about 8.4 J/cm^2•min. Much of the incoming solar radiation penetrates the atmosphere and is absorbed by the surface of the planet. However, the surface temperature does not increase excessively because Earth dissipates the absorbed solar energy by emitting long-wave infrared radiation. The surface temperature is determined by the equilibrium rates at which (1) solar energy is absorbed by the surface, and (2) the absorbed energy is re-radiated in a longer-wavelength form (see Figure 4.2 for a diagram of the greenhouse effect).

If the atmosphere were transparent to the long-wave infrared radiated by the surface, then that energy would travel unobstructed to outer space. However, this is not the case because so-called greenhouse gases (GHGs; also known as radiatively active gases or RAGs) are present in the atmosphere. GHGs efficiently absorb infrared radiation, and become heated as a consequence. They then dissipate some of this thermal energy through yet another re-radiation. (This re-radiated energy has a longer wavelength than the electromagnetic energy that was originally absorbed. This is necessary to satisfy the second law of thermodynamics.) The re-radiated energy of the GHGs is emitted in all directions, including back toward the surface. The net effect of the various energy transformations and re-radiations involving atmospheric GHGs is a reduction in the rate of cooling of Earth's surface. Thus, the equilibrium temperature of the planet's surface is warmer than it would be if the GHGs were not present in the atmosphere.

The process just described is known as the greenhouse effect because its physical mechanism is similar to the warming of a glass-encased space by solar radiation. The encasing glass of a literal greenhouse is transparent to incoming solar radiation. The solar energy is absorbed by, and therefore heats, internal surfaces of the greenhouse, such as plants, soil, and other materials. These warmed objects then dissipate their absorbed energy by re-radiating longer-wave infrared energy. However, much of the infrared is absorbed by the glass and humid atmosphere of the greenhouse, which are somewhat opaque to those wavelengths of electromagnetic radiation. That absorption of some re-radiated infrared slows the rate of cooling of the greenhouse, causing it to heat up rapidly on sunny days. (In addition, a greenhouse is an enclosed space, so it traps heat because its warmed interior air cannot be dissipated by convection higher into the atmosphere, with cooler air drawn in below.)

Radiatively Active Gases

Water vapour (H_2O) is the most important of the radiatively active constituents of Earth's atmosphere, accounting for about 36% of the overall greenhouse effect, followed by carbon dioxide (CO_2; about 20%). Lesser roles are played by trace concentrations of methane (CH_4), nitrous oxide (N_2O), ozone (O_3), carbon tetrachloride (CCl_4), and chlorofluorocarbons (CFCs).

These latter compounds are, however, much stronger absorbers of infrared energy than is CO_2 (on a per molecule basis, they are more efficient GHGs). A molecule of CH_4 is about 28 times more effective than one of CO_2 at absorbing infrared radiation, while N_2O is 265 times more effective (these are known as greenhouse warming potentials, with CO_2 assigned a value of 1.0; Table 17.1).

There is no evidence that the concentration of water vapour in the atmosphere has increased recently. However, concentrations of CO_2 and other GHGs have increased markedly during the past several centuries because of emissions associated with human activities (Table 17.1). Prior to 1750, the atmospheric concentration of CO_2 was about 280 ppm, whereas in 2014 it had reached 399 ppm, which is a 43% increase. Other GHGs have also increased during this period. The increases have been especially rapid since the middle of the twentieth century, coinciding with enormous increases in population, industrialization, and deforestation.

Because the various GHGs are known to influence the greenhouse effect, it is reasonable to hypothesize that their increasing concentrations will intensify that process. A stronger greenhouse effect could lead to global warming. Such an environmental change should be viewed as being an anthropogenic intensification of Earth's naturally occurring greenhouse effect. Overall, the increased concentration of CO_2 is estimated to account for about 57% of this possible enhancement of the greenhouse effect, while CH_4 is responsible for 15%, tropospheric O_3 for 12%, halocarbons for 8%, and N_2O for 5% (Table 17.1).

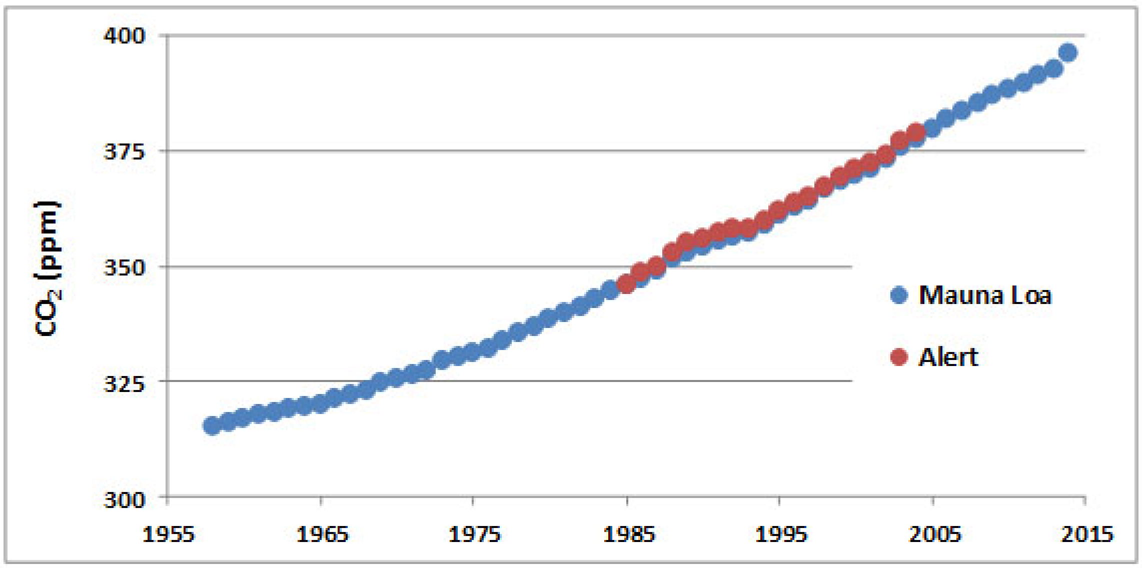
Table 17.1. Increases and Characteristics of Greenhouse Gases. Source: Data from Blasing, 2014.

Gas	Concentration		Global Warming Potential	Lifetime	% Radiative Forcing
	1750	2014			
CO_2 (ppm)	280	396	1	100-300 y	57
CH_4 (ppm)	0.72	1.83	28	12 y	15
N_2O (ppm)	0.27	0.33	265	121 y	5
O_3 (ppm)	0.24	0.34	17	days	12
CCl_4 (ppt)	0	84	1730	days	<1
CFCs (ppt)	0	836	5k-10k	45-100 d	8
HCFCs (ppt)	0	266	0.8k-2.0k	9-17 d	2

Atmospheric Carbon Dioxide

Concentrations of CO_2 in the atmosphere have been increasing steadily for at least the past century. The data record supporting this change is excellent and demonstrates one of the most convincing examples of long-term changes of any aspect of environmental chemistry. For example, atmospheric CO_2 has been monitored continuously since 1958 at a remote observatory located on Mauna Loa, a mountain on the island of Hawaii (Figure 17.1). Data are also shown for Alert, a high-Arctic station located at the northern tip of Ellesmere Island, Nunavut. The data from both places clearly show steadily increasing concentrations of CO_2 in the atmosphere during the past five decades.

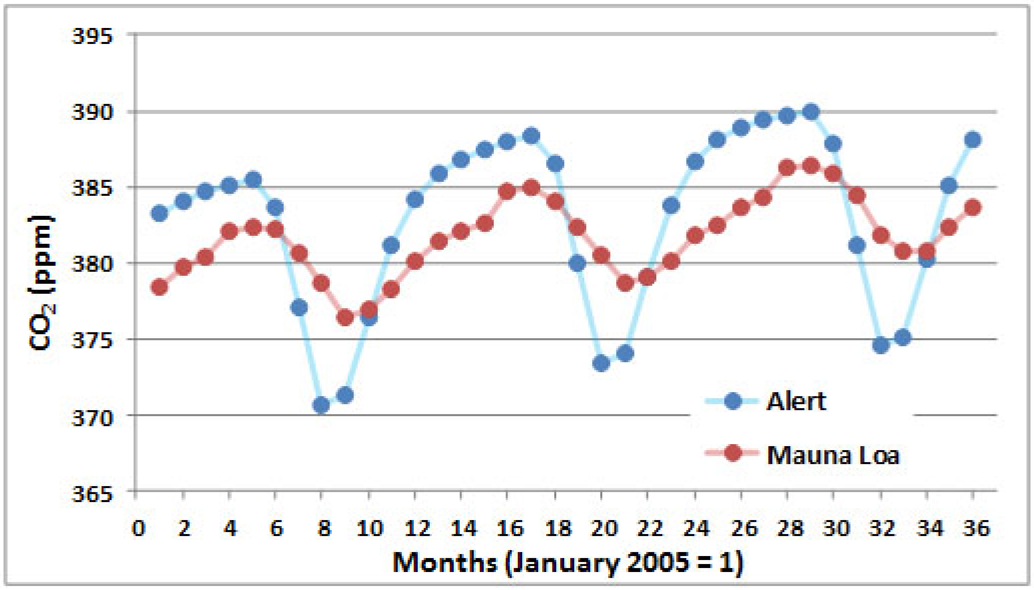
Figure 17.1. Increases in Atmospheric CO_2. These data are from measurements made on an equatorial station on Mauna Loa, Hawaii, and in the High Arctic in northern Ellesmere Island, Nunavut. Each datum represents an annual average. Note that prior to 1750, the concentration of CO_2 in the atmosphere was about 280 ppm (see text). Source: Data from Keeling et al. (2014).



A seasonal cycle of CO_2 concentration is illustrated in Figure 17.2, again using data from Mauna Loa and Alert. The annual periodicity is caused by high rates of CO_2 uptake by vegetation of the Northern Hemisphere during the growing season. This seasonal CO_2 fixation occurs at rates that are high enough depress its overall concentration in the global atmosphere. The effects if larger in the Arctic than at the Equator, although both regions have the same annual average concentration of CO_2.

Figure 17.2. Seasonal Changes in Atmospheric CO_2. These data are based on measurements made at Mauna Loa,

Hawaii, and Alert, Ellesmere Island. Source: Data from Keeling et al. (2008, 2014).



The increased concentrations of atmospheric CO_2 are due to emissions associated with various human activities. The two most important sources of anthropogenic emissions are examined in more detail in the following sections:

- the combustion of fossil fuels, during which the carbon content of the fuel is oxidized to CO_2, which is emitted to the atmosphere
- deforestation, an ecological conversion in which mature forests that store large amounts of organic carbon are converted into ecosystems that contain much less, with the difference being made up by a released of CO_2 to the atmosphere

CO_2 from Fossil Fuels

Fossil fuels are the most important source of energy in industrialized countries, followed by hydroelectricity, nuclear power, and relatively minor sources such as wood, solar, and wind energies (Chapter 13). The rates of utilization of coal, petroleum, natural gas, and oil sand have increased enormously during the past century, mostly to satisfy surging energy demands for industry, transportation, and space heating. The manufacturing of cement also results in large emissions of CO_2 to the atmosphere.

In total, since about the beginning of the Industrial Revolution in 1750, about 365-billion tonnes of CO_2-C (carbon in the form of CO_2) have been released to the atmosphere from the consumption of fossil fuels and the production of cement (Boden et al., 2013). Half of these fossil-fuel CO_2 emissions have occurred since the mid-1980s.

Between 1860 and 1869, during the middle part of the Industrial Revolution, the combustion of fossil fuels, mainly coal, resulted in the global emission of about 422-million tonnes of CO_2 per year (Boden et al., 2013). By the year 2012, global emissions from fossil-fuel combustion had increased by a factor of 80, to 35.4 billion tonnes per year (Figure 17.3). About 95% of the commercial emission of CO_2 in 2012 was due to the combustion of fossil fuels, of which 43% was from liquid hydrocarbons, 33% from coal, and 18% from natural gas. The remaining 5% is associated with cement manufacturing and gas flaring (Table 17.2).

Figure 17.3. Global CO_2 Emissions by Major Sources. Source: Data from Boden et al. (2013).

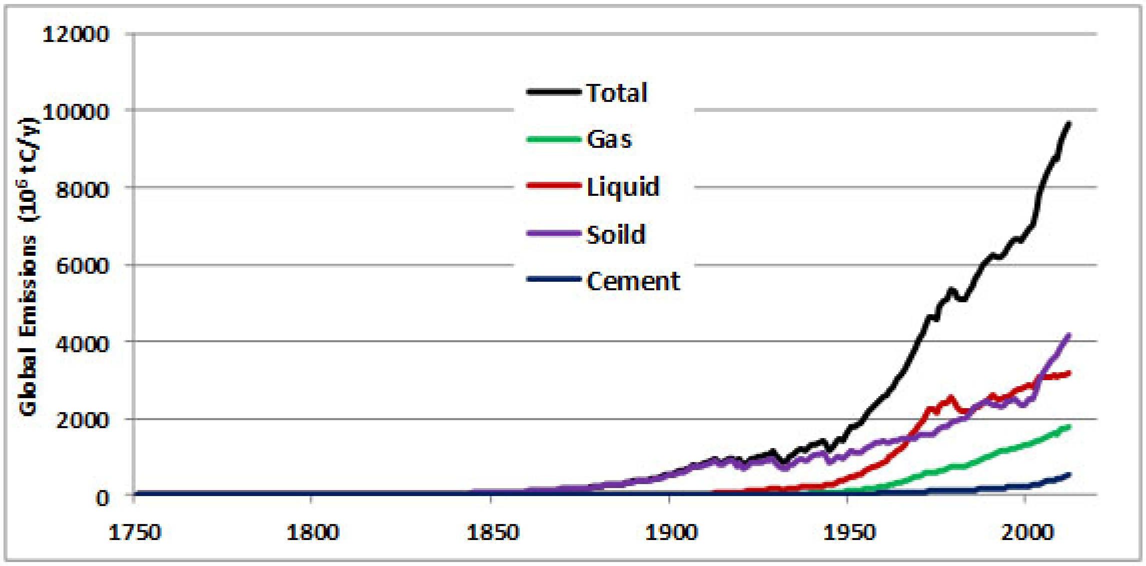
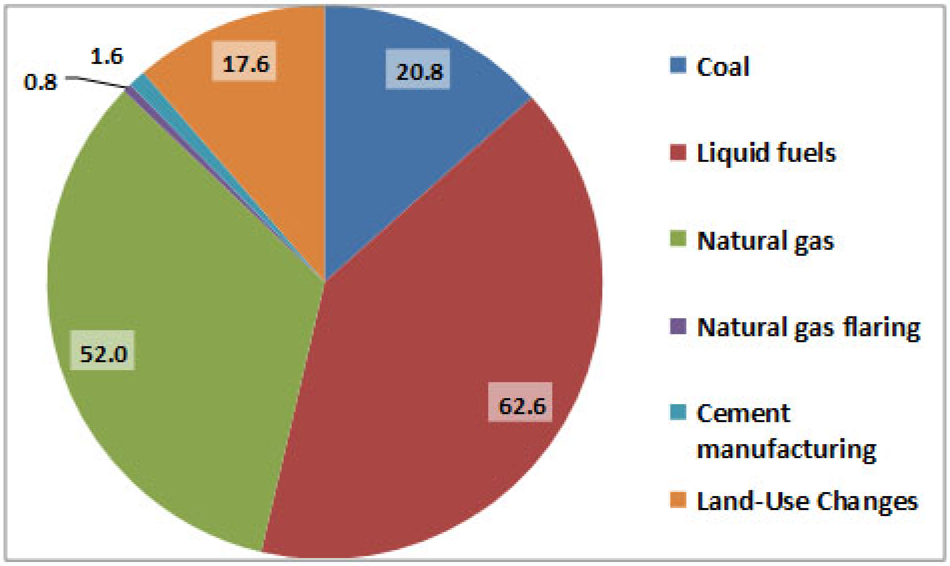


Table 17.2. Global and North American Emissions of Carbon Dioxide and Methane. Source: CDIAC (2015).

Source of Emissions (10^6 tC/y)	Emissions (10^6 t/y)		
	U.S.A	Canada	Global
Emissions of CO_2 (2012)			
Combustion of fossil fuels			
Coal	443	20.8	4137
Liquid fuels	569	62.6	3185
Natural gas	372	52	1776
Natural gas flaring	2.4	0.8	59
Cement manufacturing	10.1	1.6	509
TOTAL	1397	137.8	9666
Land-Use Changes (2005)	-31.9	17.6	1467
TOTAL	1365	155.4	11133
Methane Emissions (2002)			
Solid-waste disposal	8.4	1.14	32
Coal mining	4.6	0.54	29
Oil and gas production	6.2	2.36	34
Wet rice agriculture	0.5	0	77
Livestock	7	1.33	87
TOTAL	26.7	5.37	259

Figure 17.4. Major Sources of CO_2 Emissions to the Atmosphere in Canada. Data are for 2004 and are in 10^6 tC/y. Data for coal, petroleum, and natural gas are related to combustion sources, while land-use changes are

mostly disturbances of natural ecosystems. Source: Data from CDIAC (2015)



The global commercial emissions are equivalent to about 1.3 tCO_2/person•year (in 2010; Table 17.3). Of course, per-capita use of fossil fuels differs greatly among countries, depending on their kind and degree of industrialization, types of energy sources, climate, and other factors. The largest per-capita emissions are in several countries that flare large amounts of fossil fuels at wellheads and refiners, such as Qatar and Trinidad & Tobago. Other than those cases, the greatest emissions are in wealthy, energy-intensive countries, such as Canada, Australia, the United States, Japan, and most of Western Europe. The smallest emissions are in the poorest, least-developed countries, where there is relatively little use of fossil fuels because of the expense to purchase them.

Table 17.3. Per-Capita Emissions of CO_2 by Selected Countries. Data are for commercial sources of emission (mostly fossil fuels), in units of tonnes of CO_2-C per person•year in 2010. Source: Data from Boden et al. (2014).

Country	Per-Capita Emissions
Global Average	*1.33*
Qatar	10.9
Trinidad & Tobago	10.3
Kuwait	9.34
United States	4.71
Australia	4.57
Canada	4
Russia	3.32
South Korea	3.21
Norway	3.19
Japan	2.52
Germany	2.47
United Kingdom	2.16
France	1.57
Mexico	1.07
Italy	1.83
China	1.68
Brazil	0.59
India	0.45
Bolivia	0.42
Guatemala	0.21
Bangladesh	0.1
Congo	0.14
Haiti	0.06
Ethiopia	0.02
Nepal	0.03
Tanzania	0.04
Rwanda	0.02
Burundi	0.01
Chad	0.01

Future emissions of CO_2 from fossil-fuel combustion are predicted to be much larger than those occurring today, mainly because of the anticipated industrialization of poorer countries as they develop economically. One prediction suggests that global emissions by the middle of the twenty-first century could be up to 55 billion tonnes of CO_2 per year, about double the current releases.

CO_2 from Clearing Forest

Mature forest stores large amounts of organic carbon in vegetation and the dead organic matter of soil. All other kinds of ecosystems, including younger forests that are regenerating from a disturbance, store much less organic carbon than occurs in older forests. This observation suggests that whenever an area of mature forest is disturbed by timber harvesting, or is cleared to provide land for agricultural or urbanized use, much less organic carbon will be stored on the land.

If a harvested stand is allowed to regenerate to another mature forest, then the depletion of stored carbon will be a medium-term phenomenon. However, if forest is converted into an anthropogenic land-use, such as for agriculture or urbanization, there is a permanent loss of carbon stored on the land. In either case, the difference in the average quantity of organic carbon stored in the ecosystem is balanced by an emission of CO_2 to the atmosphere. The CO_2 release mostly occurs by decomposition of the forest biomass or by burning. To a lesser degree, and for similar reasons, a carbon loss also occurs when natural grassland is converted into cultivated agriculture.

It is well known that humans have caused enormous reductions in the area of mature forest in most regions of the world (Chapters 12 and 14). These changes began slowly, initially perhaps with the domestication of fire and its widespread use to improve the habitat of hunted animals. Deforestation proceeded more rapidly when it was discovered that fertile agricultural land could be developed by removing the natural cover of forest or grassland. (The harvested trees were also valuable commodities.) Deforestation has proceeded especially quickly during the past several centuries because of population growth, agricultural expansion, and industrialization.

Prior to any substantial clearing of Earth's natural forests, the global terrestrial vegetation stored an estimated 900-billion tonnes of organic carbon (Figure 17.5). About 90% of that carbon was stored in forest, of which half was in tropical forest. Now, only about 560-billion tonnes of carbon are stored in terrestrial vegetation, a 38% decrease. Moreover, the stocks of global biomass are diminishing further as more-and-more natural ecosystems are converted into agricultural and urban ones that store much less carbon.

During the 143-year period from 1870 to 2013, changes in land-use (mostly conversions of forest into agricultural land) resulted in the emission of about 145-billion tonnes of CO_2-C. This quantity is about 45% of the emissions due to fossil fuel combustion during the same period (320-billion tonnes of CO_2). More recently, in 2013, the combustion of fossil fuels emitted about 9.9-billion tonnes of CO_2-C into the atmosphere, while deforestation accounted for another 0.9-billion tonnes.

As was previously noted previously, forest and grassland ecosystems store large amounts of carbon in the biomass of their vegetation and soil. When these "high-carbon" ecosystems are converted into agricultural or urban ones, there is a large emission of their organic carbon to the atmosphere (mostly as CO_2 from decomposition and fires).

The disturbance of forests by harvesting timber also results in a large emission of CO_2, because mature stands support much more biomass than younger ones (old-growth forest stores the most). However, the carbon emission scenario is complicated by what is done with the harvested timber. For example, if the tree biomass is burned as a fuel, the release of CO_2 to the atmosphere occurs rapidly. On the other hand, if the harvested wood is used to manufacture lumber, furniture, or violins, all of which are "enduring" products with an extended lifespan, the release of CO_2 to the atmosphere occurs slowly. It must also be remembered that much of the initial release of CO_2 may eventually be offset by regeneration of the harvested forest (unless this is prevented, as happens when deforestation occurs to develop agricultural or urban land-use).

Table 17.4 shows large differences between regions in their emissions of CO_2 from changes in land-use. In North America, extensive forest clearing began when the continent was colonized by Europeans and continued until the 1920s. Since then, however, large areas of marginally economical agricultural land have been returned to forest. Overall, the net emission of CO_2 by changes in forest area has recently been close to zero—that is, agricultural land is regenerating back to forest about as quickly as forest elsewhere in North America is being converted into agricultural and urban land-uses. The European situation is similar, and forest biomass (and carbon storage) there has also increased since the 1920s.

However, in relatively poor, less-developed, tropical countries of Africa, Asia, and Latin America, forests are being cleared rapidly. This is being dome mostly to develop agricultural land to provide livelihoods and grow food for increasing numbers of people, and also to provide agriculture commodities for export. This is a serious problem not only because of the large emissions of CO_2, but also because of the consequences for biodiversity (Chapter 26).

Fortunately, there are signs that the rate of global deforestation may be slowing down. It appears to have reached a peak in the 1990s, when the resulting carbon emissions from deforestation and other land-use changes was about 1.6 x 10^9 tC/y, and has slowed to 0.9 x 10^9 tC/y from 2004-2013 (Global Carbon Budget (2014).

Image 17.2. The conversion of carbon-dense ecosystems, such as forest, into agricultural and urban ecosystems that store much less carbon is an important source of CO_2 emissions. This site on Sumatra has had its tree cover felled and the woody debris burned. The land will be planted with a variety of crops. Deforestation is proceeding rapidly in this region of Indonesia, and in most tropical countries. Source: B. Freedman.

Table 17.4. Net Emissions of CO_2 to the Atmosphere as a Result of Land-Use Changes. Negative numbers indicate that carbon stored in ecosystem biomass is increasing. Source: Data from Houghton (2008).

Country/Region	Emissions of CO_2 (10^6 tC/y)			
	1850	**1900**	**1950**	**2005**
Canada	5.5	11.3	32.4	17.6
United States	164.1	286.3	-11.4	-31.9
Europe	55	45.2	24.7	-18.1
Developed Pacific Region	2	21.7	34	3.9
Russia	58.6	57.8	13.1	20.1
China	101.8	64.4	290.1	-12.9
North Africa & Middle East	4	17.6	43.2	23.2
South & Central America	23.5	60.3	192.8	606.4
South & Southeast Asia	87.3	163.1	313.4	619.7
Tropical Africa	-1.3	-0.7	105.2	239.2
Global	501	727	1037	1467

Overall, in modern times, most CO_2 emissions associated with deforestation have been occurring in less-developed tropical countries. In contrast, most CO_2 emissions from the combustion of fossil fuels have been occurring in relatively wealthy, industrialized, higher-latitude countries, of which Canada is a leading example.

Global Carbon Geochemistry

Key anthropogenic influences on the global carbon budget are summarized in Figure 17.5, which shows the major compartments in which carbon is stored as well as transfers between them. Although Figure 17.5 simplifies the complex nature of the global carbon cycle, some important inferences can be made that are relevant to the greenhouse effect.

Anthropogenic emissions have caused a 43% increase to occur in the amount of CO_2 stored in the atmosphere, from about 580 x 10^9 t of CO_2-C in pre-industrial times to 844 x 10^9 t in 2015. The atmospheric concentration of CO_2 has accordingly increased during the same period, from about 280 ppm to 400 ppm.

Before humans began to modify the character of Earth's ecosystems, especially by extensive deforestation, the global emission and fixation of atmospheric CO_2 were approximately in balance. In other words, on a global basis, the gross primary production (GPP) was about equal to ecosystem respiration (ER), and biologically fixed carbon was not changing over time. However, deforestation is now resulting in huge emissions of CO_2, amounting to about 2.0 x 10^9 t/y of CO_2-C. Overall, modern terrestrial ecosystems are storing about 38% less carbon in their vegetation and 12% less in soil compared with pre-industrial times.

Ultimately, the oceans are the most important sink for CO_2 emitted through human activities. The oceans have a net absorption of about 3.1 x 10^9 t/y of CO_2-C from the atmosphere. However, this is much less than the anthropogenic emissions of 8.6 × 10^9 t/y of CO_2-C, and so the amount of CO_2 stored in the atmosphere is increasing. The oceans have an enormous capacity for absorbing atmospheric CO_2, which is ultimately deposited as calcium carbonate ($CaCO_3$), a mineral that accumulates in sediment (mostly as the shells of molluscs, foraminifera, and other invertebrates). However, the rate of formation of $CaCO_3$ is affected by various factors, including the concentration of inorganic carbon in seawater as well as acidity. This concentration is determined by the rate at which CO_2 enters the oceans from the atmosphere, minus its biological uptake (mostly by phytoplankton during photosynthesis). Although anthropogenic CO_2eventually ends up as $CaCO_3$ in oceanic sediment, there is a substantial time-lag in the response of oceanic sinks to increasing concentrations of CO_2 in the atmosphere. This lag allows atmospheric CO_2concentrations to increase because of anthropogenic emissions.

Acidification of the ocean is an additional issue. In actual fact, the ocean is maintained as a non-acidic environment by carbon dynamics and a variety of other influences, with a typical pH between about 7.5 and 8.4 (Chester and Jickells, 2012). In this case, acidification would be represented oceanic water becoming less alkaline over time. The acidification is caused by atmospheric CO_2 dissolving into oceanic water, a process that forms carbonic acid (H_2CO_3), a weak acid, according to this equation:

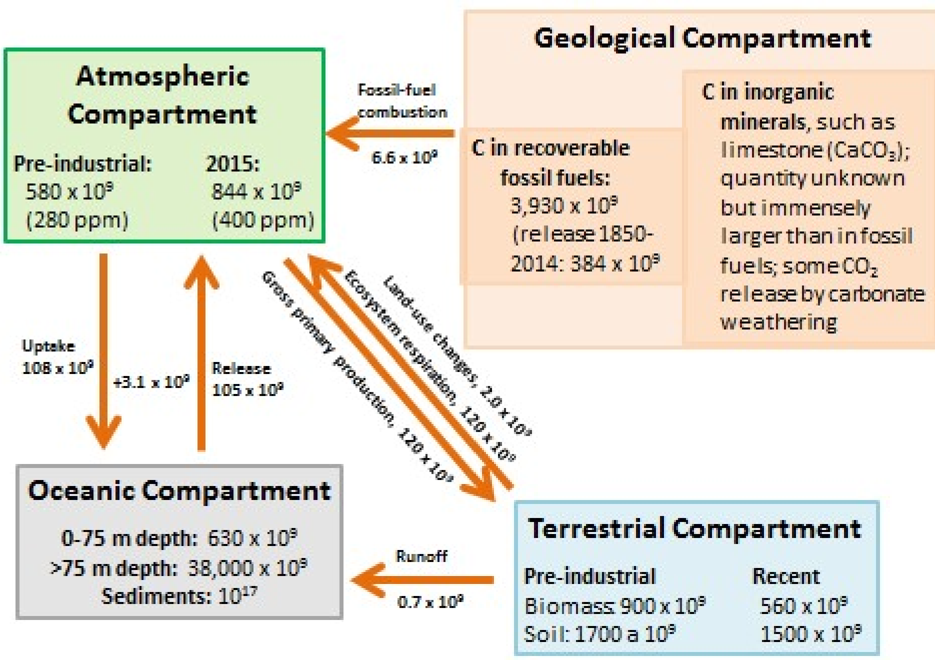
$$CO_2 + H_2O \rightleftharpoons H_2CO_3$$

The carbonic acid may then dissociate to form bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}), as follows:

$$H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{-2} + H^+$$

The rate at which CO_2 can dissolve into the ocean is in equilibrium with its atmospheric concentration. As a result, the rapid increases of atmospheric CO_2 (to 400 ppm in 2015) has resulted in more dissolving, more production of carbonic acid, and the apparent beginning of acidification of that vast aquatic ecosystem. One estimate is that the average pH of the global oceans has decreased from 8.25 to about 0.1 unit less (still non-acidic, but nevertheless representing a degree of acidification; Jacobson, 2005). Ocean acidification is a potentially serious problem, because many marine organisms can only live within a narrow range of tolerance of this aspect of water chemistry.

Figure 17.5. Key Compartments and Fluxes of the Global Carbon Cycle. Amounts stored in the compartments are in units of tonnes of carbon, while transfers are in tonnes of carbon per year. Sources: Data from Blasing (1985), Solomon et al. (1985), Schlesinger (1995), and Global Carbon Budget (2014).



Climate Change

As was previously examined, Earth has a naturally occurring greenhouse effect, the physical mechanism of which is relatively simple and understood by scientists (Chapter 4). Moreover, the greenhouse effect helps to maintain the surface temperature within a range that is comfortable for organisms – averaging about 15°C, or 33° warmer than it would be with a non-greenhouse atmosphere. It is also well documented that the concentrations of CO_2 and other radiatively active gases are increasing in the atmosphere. It is reasonable, therefore, to hypothesize that this increase will intensify the natural greenhouse effect.

Although this potential intensification of the greenhouse effect remains a hypothesis, it is an extremely important one. If this environmental change does happen, it would have many climatic and ecological consequences, some of which would be catastrophic for both economically important and natural ecosystems.

Climate change refers to long-term variations of the weather that are experiences in a region. One of the most important indicators of climate change is the temperature of the surface atmosphere. Air temperature is measured routinely in many places throughout the world. These data can be used to calculate estimates of the average surface temperature of Earth and to detect changes over time. However, the air-temperature records suffer from some important problems:

- Air temperature is extremely variable over time and space, and the unfavourable signal : noise ratio makes it difficult to detect long-term trends.
- Most of the older data are less reliable than modern records (accurate recordings of surface air temperatures began around 1880).
- Many weather-monitoring stations are located in urbanized areas, and their data are influenced by the so-called "urban heat island", which is characterized by typically warmer conditions than occurs in surrounding, rural places. Moreover, a large number of initially rural weather stations have become surrounded by urban land-uses, resulting in a "contamination" of their air-temperature records.
- Global temperatures can respond to influences other than changes in the greenhouse effect, such as the cooling effects of volcanic eruptions that inject great masses of highly reflective aerosols into the upper atmosphere, as well as variations in the intensity of solar output.

In spite of the various difficulties with data used to estimate Earth's average surface temperature, recent analyses suggest that there has been a definite warming trend since the mid-nineteenth century. The average global surface temperature has increased by more than 0.8°C over the past 150 years (Figure 17.6). The warmest years since 1850 have all occurred since about 1990. This warming partly reflects the end of a 400-year period of climate cooling, known as the Little Ice Age, which lasted until the mid-1800s (Figure 17.7). However, there appears to have been a particular intensification of warming during the most recent several decades. Note also that the recent warming trend is not without precedent – even warmer periods have occurred during the past 10-12-thousand years.

Figure 17.6. Recent Changes in Global Surface Temperature. The data are the global annual temperature anomaly (°C), calculated relative to the average for 1961-1990. A negative value means a year was relatively cool,

while a positive number means it was warmer. Source: Data from Jones et al. (2013).

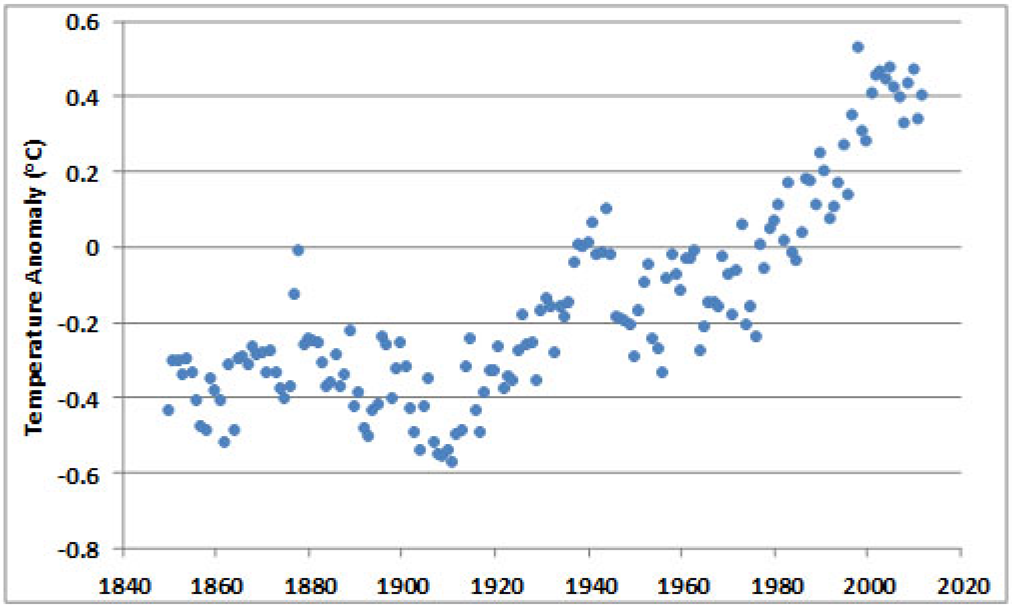
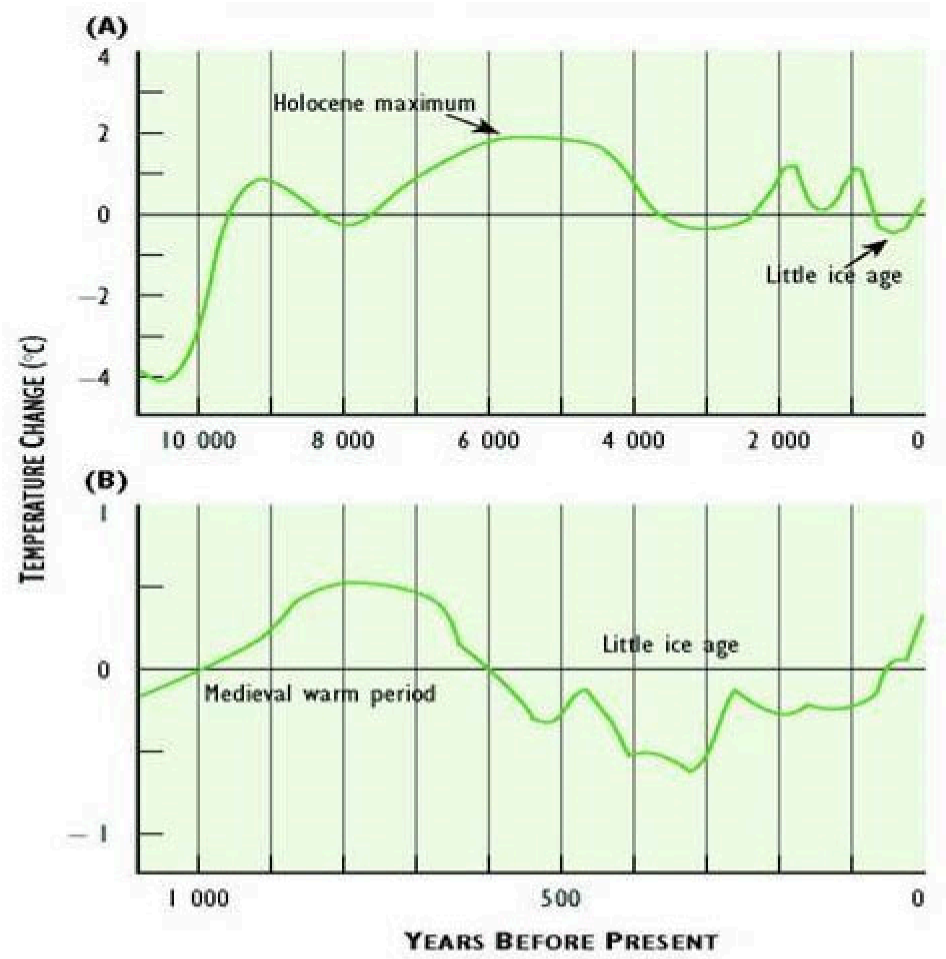


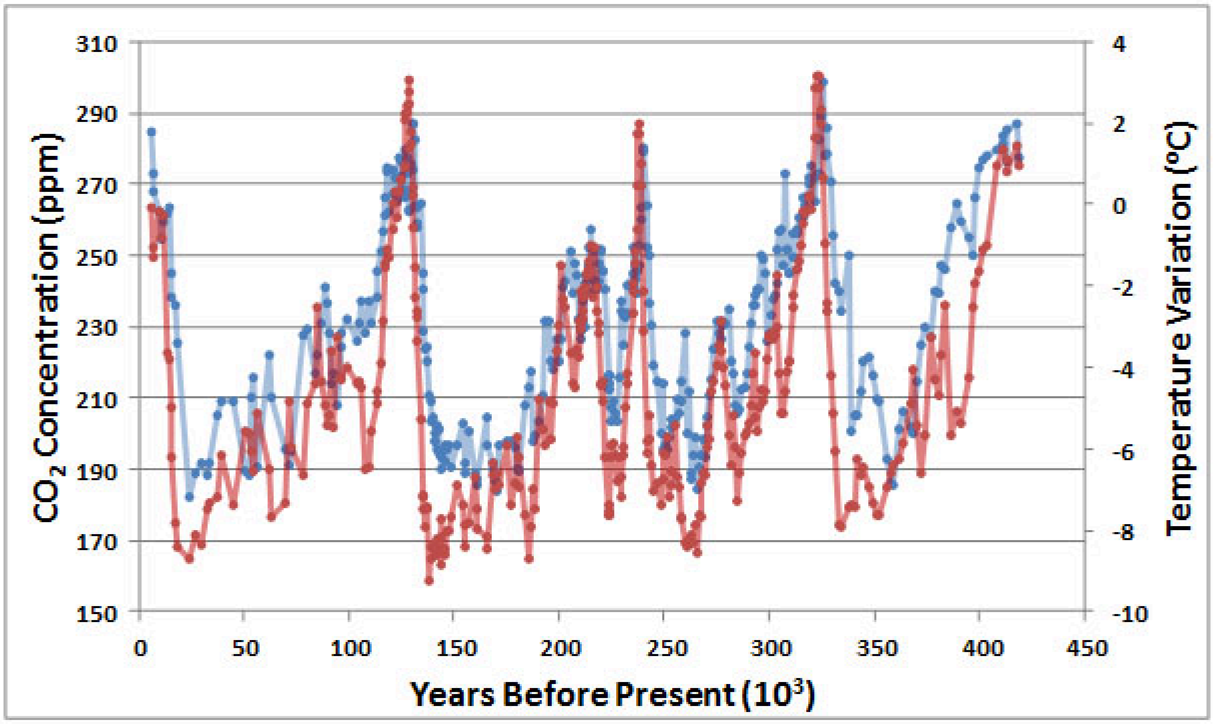
Figure 17.7. Deviation of Global Average Surface Temperature from Present Conditions. Curve (a) shows long-term trends since the end of the most recent ice age. Curve (b) shows the past millennium. Note that a value of “zero” means that no temperature change (deviation) has occurred. Sources: Modified from Environment

Canada (1995).



Moreover, paleoclimatic studies of long-term changes have provided rather convincing evidence of a link between concentrations of atmospheric CO_2 and climatic warming. Especially valuable data come from a core of glacial ice taken in Antarctica, representing a record of 417-thousand years (Figure 17.8). Results of this important study suggest a strong correlation between CO_2 concentration and air temperature, implying a possible causal relationship. It is not clear, however, whether increased concentrations of CO_2caused warming via an intensified greenhouse effect, or possibly the opposite. An increase in CO_2emissions from ecosystems could have been a result of climatic warming, perhaps because the rate of biomass decomposition increased or because of the warming of frozen soil in polar latitudes (which would release biomass in permafrost for decomposition and methane release). Clearly, Figure 17.8 suggests a strong relationship between CO_2 and temperature change, but the possible interpretations are ambiguous because of "chicken or egg" considerations – it is unclear which came first.

Figure 17.8. Variations in Atmospheric CO_2 and Surface Temperature. These data were obtained by studying a 417,000-year glacial-core record from Vostok, Antarctica. The red data are the temperature deviation and the blue are CO_2 concentration. The two data sets are strongly correlated, with a coefficient of 0.82. Sources: Data from Petit et al. (2000) and Barnola et al. (2003).



Other valuable insights have been obtained by running sophisticated mathematical models of global climate processes on high-powered supercomputers. These "virtual experiments" examine the potential climatic responses to increases in atmospheric CO_2. The computer simulations are known as three-dimensional general circulation models (GCMs). The models simulate the complex movements of energy and mass in the global circulation of the atmosphere. They also examine the interactions of these processes with physical variables that are important aspects of climate, such as temperature and precipitation. Many simulation experiments have been run using various GCMs, and the results are variable. Nevertheless, a strong tendency that emerges from these virtual experiments is that global warming and associated climate changes are a likely consequence of the well-documented increases of CO_2 and other GHGs in the atmosphere.

Many such simulation experiments have examined the scenario of a doubling of CO_2 concentration from its recent concentration of about 400 ppm. These experiments suggest that such a doubling would result in an increase of 1°C to 4°C in the average temperature of the surface atmosphere. The intensity of warming is predicted to be greatest in high-latitude regions, where the temperature increases might be two to three times greater than in the tropics.

Warming of the lower atmosphere will be one likely change that will be caused by an increased intensity of the greenhouse effect. However, there could also be important effects that occur indirectly, in response to changes in the distribution of heat in the atmosphere. The most important of the indirect changes would include large-scale shifts in the patterns of atmospheric circulation. Such shifts would likely result in changes in the amounts, spatial distribution, and seasonality of precipitation. Changes in precipitation regimes would influence soil moisture, which would greatly affect the distribution and productivity of vegetation, both natural and managed. These changes in precipitation regime would likely have much greater effects on agricultural and wild ecosystems than would any direct influence of a warmed atmosphere.

Global Focus 17.1. The 2014 IPCC Report

The Intergovernmental Panel on Climate Change (IPCC) is mandated by the United Nations to review the accumulating body of scientific evidence related to climate change. The IPCC also helps to formulate policies to reduce emissions of greenhouse gases and to deal with the economic and ecological consequences of climate change. The IPCC is considered by many people to offer authoritative evidence and opinions relevant to climate change and its consequences. Still, the field is highly controversial, and some other people believe that some of the work of the IPCC is flawed by political processes and social pressures that are involved in its consensus-building processes.

The IPCC has released an influential series of research reports—in 1990, 1995, 2001, 2007, and 2014. Each of the IPCC report was the most detailed syntheses ever done, up to their time. The 2014 IPCC report (IPCC, 2014a). The reports made strong statements about the reality of global warming, its potential consequences, and the anthropogenic role in its causation. Some highlights include the following statements (from IPCC, 2014b; text in italics is directly quoted):

- Human interference with the climate system is occurring, and climate change poses risks for human and natural systems.
- In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. The evidence of impacts is strongest for natural systems, but effects on human systems have also been attributed.
- In many regions, changing precipitation or melting snow and ice are altering hydrological systems. This is affecting water resources, with glaciers shrinking almost worldwide, affecting runoff and water resources downstream, and permafrost warming and thawing in both high-latitude and high-elevation regions.
- Many terrestrial, freshwater, and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances, and species interactions in response to ongoing climate change.
- Based on many studies covering a wide range of regions and crops, negative impacts of climate change on crop yields have been more common than positive impacts.
- Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability.
- Climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty. Poor people are affected by effects on livelihood, reduced crop yields, or destruction of homes, as well as indirectly by increased food prices and insecurity.

The IPCC (2014b) report also noted that society was now routinely incorporating climate-related adaptations into planning and social policies:

- Adaptation is becoming embedded in some planning processes, with more limited implementation of responses. Recognition is increasing of the value of social, institutional, and ecosystem-based measures, and of the limits to adaptation . So far, technological and engineered options are the most commonly implemented adaptive responses, often within existing programs such as disaster risk management and water management.

It must be recognized that these and other IPCC projections and policy suggestions are based on imperfect scientific and economic models. Nevertheless, although the IPCC predictions suffer from some degree of inaccuracy, the likelihood of errors was addressed in the many component studies (and is indicated by qualifiers such as “very likely” and “high confidence”). The field of anthropogenic climate change remains highly controversial, but the IPCC (2014) reports are by far the most reliable sources of credible information that we have to advise our individual and societal responses to this important problem.

In terrestrial ecosystems, the direct effects of global warming and associated climatic changes would be restricted mainly to plants. Animals and microorganisms would also be affected, but only through secondary responses to changes in their habitat caused by any effects on vegetation.

The predicted increases in air temperature might not affect plants much because those changes would probably not be sufficient to increase heat-related stress. Much more important would be any substantial changes in the amounts and seasonal patterns of precipitation. Soil moisture is often a key environmental influence on the distribution and productivity of vegetation. For instance, a decrease in the amounts of precipitation or soil moisture in the Canadian Prairies would likely cause the natural mixed-grass prairie to change into short-grass prairie, or even to semi-desert. Decreased soil moisture would also affect the kinds of crops that could be grown in many regions, as well as their productivity. That could make present agricultural systems more difficult or even impossible unless irrigation was practised.

About 14-thousand years ago, the continental glaciers started to melt back, and they were about 80% gone by 8-10-thousand years ago. Vegetation in the regions of Canada changed substantially during the warming climates that followed this deglaciation. One of the paleoecological tools that have been used to study the changes involves the examination of fossil pollen grains extracted from dated sections of cores of lake sediment (these studies are known as palynology). This kind of analysis has provided a record of vegetation changes extending as far back as early deglaciation.

The research in Canada and elsewhere suggests that plants responded to post-glacial warming in a species-specific manner. This occurred because of the different abilities of species to migrate to and colonize newly available habitats released by the melting of glacial ice. As a result, the species composition of early post-glacial plant communities was different from that occurring today under similar climatic regimes. We can expect the responses of natural vegetation to future climate changes to also be species-specific. This will result in the development of plant communities that are different from those that occur now. If climate change results in substantial modifications in the character of plant communities, there will also be adjustments in the species of animals, microbes, and other organisms that can be supported on the landscape. Challenges to native biodiversity will be an important consequence of climate change in Canada and everywhere else in the world.

Image 17.3. This is a small "island" of trees in the midst of tundra near Tuktoyaktuk in the Northwest Territories. These short individuals of white spruce (Picea glauca) are remnants of a more widespread population that established during a period of warmer climate more than about six centuries ago. If an anthropogenic intensification of Earth's greenhouse effect were to result in a warming climate, as has been predicted, then these tree-islands may be focal points from which trees could colonize the tundra. If this kind of change occurs over large area, there would be profound consequences for the biota and for human interests. Source: B.

Freedman.

Climate change in tropical countries, which support much larger numbers of species than Canada does, would have great ecological consequences. For example, most of northern and central South America is now characterized by a warm and humid, tropical climate. However, this region is thought to have been considerably drier during the past glacial period, which ended 10-14-thouand years ago. During that time, much of the tropical region was covered by an open-canopied savannah, while rainforest occurred only in isolated regions with relatively high rainfall, known as refugia. In terms of the landscape, the refugia of tropical forest occurred as "islands" within a more extensive matrix of savannah, which is an inhospitable habitat for species of moist forest. The restructuring of tropical ecosystems during the Pleistocene Ice Age, which was driven by climate changes of the time, must have had enormous impacts on the multitudes of rare species of the rainforest. It is likely that many of those species became extinct as a result of the habitat changes. In modern times, an anthropogenic intensification of the greenhouse effect would also cause substantial changes to occur in the character of tropical habitats over enormous areas, and similar ecological calamities would again result.

It is important to acknowledge that scientists do not fully understand the probable dynamics of impending changes in climate. As a result, they are not able to make reliable predictions about the changes in surface temperature, precipitation, evapotranspiration, and other climatic factors that may occur in the regions of Canada or elsewhere. Nevertheless, it can be reasonably suggested that any large changes in climate, and especially in precipitation, would result in fundamental alterations of the structure and productivity of both natural ecosystems and agroecosystems. Those changes would have important consequences for the flows of resources that are required by people, as well as for the habitats of other species.

As was just noted, changes in climate would influence the ability of landscapes to support agricultural production. In Canada, this would be particularly true of the great expanses of agricultural land in the Prairie Provinces. Much of this terrain is already marginal from a rainfall perspective, and is vulnerable to years of severe drought. Wheat, for example, is a vital crop that is grown extensively in areas that were originally short-grass prairie. In North America, as much as 40% of this 400-million hectare, semi-arid region has already been desertified to some degree as a consequence of ecological changes associated with agricultural practices. Sporadic crop-threatening droughts occur widely. If the land is irrigated, the limitations of sparse precipitation in this region can be alleviated. However, insufficient water is available for this purpose, and secondary problems, such as salinization, can be caused by irrigation. Clearly, any further losses of soil moisture in this important agricultural region would be extremely damaging to agricultural production and to food security.

The extent and severity of forest fires would also likely be affected by changes in the amount and distribution of precipitation and evapotranspiration, and to their secondary effects, such as soil moisture. In a typical year, 1-2-million hectares of forest burns in Canada, but this is variable – in some years more than 10-million hectares may be consumed. Modelling experiments have suggested that an increased intensity of the greenhouse effect would cause a drier climate to occur over much of the boreal region, and this could result in a 50% increase in the annual burned area (Flannigan and Van Wagner, 1991).

In marine ecosystems, increases in water temperature would adversely affect some biota. Prolonged warming may cause corals to lose their symbiotic algae (known as zooxanthellae), sometimes resulting in death of the coral. This syndrome of damage, known as coral bleaching, can be induced by unusually high or low temperature, changes in salinity, and other stresses. Coral reefs are the world's most biodiverse marine ecosystems, and they are already threatened by many stressors associated with human activities, including coastal pollution, mining of the coral, and overly intensive fisheries.

Another predicted consequence of global warming is the accelerated melting and retreat of glaciers. There is widespread evidence that this change is already occurring. In Canada, most glaciers in Alberta, British Columbia, Nunavut, and the Yukon are in rapid retreat. This will have consequences for the flow of rivers that are substantially dependent on glacial meltwater, including large ones that provide water for some of the largest cities and towns in Alberta and Saskatchewan, including Calgary, Edmonton, Regina, and Saskatoon. Rapid glacial retreat is also well documented in the Alps of Europe and on Mount Kilimanjaro in Kenya, the top of which may be ice-free by 2050. It is also affecting the world's most massive glaciers, in Greenland and Antarctica.

An additional predicted effect of global warming is an increase in sea level. This change would be caused mostly by a thermal expansion of seawater, because as water warms, its volume increases. There would also be an influence on sea level from the melting of massive glaciers, particularly those in Antarctica and Greenland, which would release some of their enormous mass to the oceans. Even an increase of sea level of a metre or so would have massive implications for low-lying populated regions, such as the Netherlands in Europe and the Maldives and other archipelagos in the Indian and Pacific Oceans. These low coastal places would become much more vulnerable to the devastating effects of storm surges. There would also be risks for shallow-water marine ecosystems, such as coral reefs.

It is also predicted that global warming might increase the frequency, and perhaps the severity, of events of severe weather. This means that hurricanes, tornadoes, and even El Niño events could become more frequent, and perhaps also more intense. These extremes of weather have well known, devastating effects on economic and ecological systems. Most of the climate-modelling studies suggest that the intensity of warming will be much greater at higher latitudes. This means that changes in countries like Canada, where the climate ranges from temperate to polar, would be much greater than in tropical regions. Therefore, relatively wealthy, well-developed countries like Canada and the United States may be exposed to much of the damage associated with climate change. Less-developed, equatorial countries may be less directly affected. These predictions are, however, highly uncertain.

Global Focus 17.2. The Kyoto Protocol

Scientists agree that the Earth has a naturally occurring greenhouse effect that helps to keep the planet habitable. They also agree that this key function is due to greenhouse gases (GHGs) in the atmosphere, whose concentrations are increasing rapidly, particularly carbon dioxide. Although there is some controversy as to whether the increased GHGs will intensify the greenhouse effect, scientists are rapidly moving toward a broad consensus that considerable warming is likely to occur. Because global warming would have great consequences for the human economy and the natural world, mitigative actions are being proposed, and in some cases taken, by governments.

On the international front, key initiatives related to research and planning are being led by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), which in 1988 established the Intergovernmental Panel on Climate Change (IPCC). The IPCC undertakes comprehensive reviews of the science of global warming, with a focus on likely scenarios of climatic, ecological, and economic consequences. The IPCC also does research on ways to slow or prevent the increases in GHGs and on how economic and ecological systems might adapt to predicted climate change. At the international level, the IPCC is the most credible source of information about climate change. In 2014, the IPCC released its fifth round of technical and policy reports (IPCC, 2014a).

Because of concerns about the potentially disastrous consequences of global warming, in 1990 the IPCC and other groups of climate specialists recommended that the United Nations (UN) mobilize global leadership to negotiate an international agreement to reduce emissions of GHGs. The UN then established an Intergovernmental Negotiating Committee to draft the terms of a UN Framework Convention on Climate Change (UNFCCC). After a series of difficult international negotiations, the UNFCCC was drafted and then adopted in 1992 at the UN Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil.

The objective of the UNFCCC is to stabilize atmospheric GHGs at concentrations that would prevent a dangerous intensification of the planetary greenhouse effect. Signatory nations to the UNFCCC, known as “parties to the convention,” have agreed to undertake certain actions to compile information on emissions of GHGs, develop policies to decrease emissions, prepare strategies to adapt to anticipated effects of climate change, and provide financial and scientific support to developing countries. Moreover, the 140 countries that signed the UNFCCC in Rio agreed to discuss its implementation at a global forum, which was held in Berlin in 1995. At that meeting, it was agreed that global emissions of GHGs should be reduced and a further series of international negotiations was needed to reach consensus on an implementation strategy. Those negotiations were completed at another meeting, held in Kyoto, Japan, in 1997. The outcome of that key meeting was the Kyoto Protocol.

According to the terms of the Kyoto Protocol, the world’s nations are divided into three groups:

- Annex I consists of developed and rapidly developing countries, including the United States, Canada, those of the European Union, Japan, Russia, and Australia. It also includes rapidly developing countries that are major emitters of GHGs, such as China and India, but these were excluded from the CO_2-reduction obligations of the wealthier countries.
- Annex II consists of the same developed countries as in Annex I (38 countries), but not the rapidly developing ones (also known as economies in transition). The Annex II countries have special obligations to reduce their emissions (overall by 5.2% compared with 1990 levels), and they must also help developing countries by providing financial and technological resources to reduce emissions and adapt to any adverse effects of climate change.
- Annex III consists of the world's least-developed countries – these have ratified the Kyoto Protocol but have no immediate obligations to reduce their emissions of GHGs.

In addition, many organizations have "observer" status, including about 50 inter-governmental and 650 non-governmental organizations (NGOs) that represent the business, environment interests, industry, labour, indigenous cultures, and research and academic bodies. For the Kyoto Protocol to become legally binding, it had to be ratified by at least 55 parties to the UNFCCC, including enough Annex I countries to account for at least 55% of the CO_2 emissions of all developed countries (in 1990). Canada, the European Union, and Japan ratified in 2002, and when Russia did so in 2004, the 55% criterion was reached and the Kyoto Protocol because a legal treaty. Unfortunately, the United States had not ratified the Protocol, although it is nevertheless making progress with actions to reduce its emissions of GHGs.

Key aspects of the Kyoto Protocol are the binding targets that it sets for the reduction of GHG emissions by developed countries. It is important to understand, however, that the Protocol is only a first step toward reducing global emissions of GHGs – the intent is to negotiate additional protocols that will include reductions by rapidly developing countries such as China and India, and further efforts by developed ones. For example, in 2015, the global community met in Paris to review and improve upon the existing Kyoto-related targets to reduce emissions of GHGs.

The commitments of Canada are typical of countries of Annex II. When Canada ratified in 2002, it committed to reduce its emissions of CO_2 by 6% below the levels in 1990, and to achieve that goal by 2008-2012. To accomplish such a large reduction was, however, a formidable challenge. In fact, by the target date, Canadian emissions of CO_2 had increased by about 33% since 1990. That had occurred mostly because of rapid economic developments in Alberta, especially great increases in the amount of mining and processing of oil-sand. Moreover, even today, Canada has not developed an effective strategy for meeting its legal obligations under the Protocol, largely because of the intense political and economic controversies associated with the actions that would be necessary. Moreover, the governments of Canada and some other jurisdictions, notably Alberta, are focusing on intensity-based targets, which encourage improved technological efficiencies but do not necessarily reduce the aggregate emissions of GHGs. Such tactics do little to reduce the rapid increase of emissions from new fossil-fuel enterprises, such as the aggressively growing oil-sand industry.

In 2012, Canada formally withdrew from its ratification of the Kyoto Protocol. This was done by the Harper Government of the day because of the certainty that Canada would badly miss its Kyoto targets, coupled with a political philosophy that economic growth should not be sacrificed to meet environmental targets of this sort.

At about the same time, the Harper Government announced its new target to reduce emissions of greenhouse gases – to have emissions in 2020 that would be 17% below those in 2005. At the time of this writing, the most recent emissions data (for 2010) showed that our national emissions had actually increased by 13% (Boden et al., 2014). The most important reason for that increase was a rapid expansion in large industrial facilities to mine and process oil-sand in northern Alberta, a development for which much further aggressive growth is planned for the next decade or more. As a consequence, it is extremely unlikely that Canada`s presently avowed emissions reductions will be met.

However, many other developed countries will have little difficulty in meeting their obligations. For instance, since 1990, many countries of Western Europe have extensively replaced coal-burning industrial utilities with ones that use natural gas, which results in a large reduction of CO_2 emissions. Also, most countries of the former Soviet Union, including Russia, have suffered a downsizing of their industrial sectors since 1990, making it easy for them to meet their Kyoto targets. These economic restructurings, which had no direct linkage to the Kyoto Protocol, did not occur in North America. The only ways for countries like Canada and the United States to reduce their emissions of GHGs is to rapidly change the ways that energy is used by aggressively enacting conservation measures while also moving away from a heavy reliance on fossil fuels. It will take a high level of political fortitude if they are to achieve such changes, and without such determination, countries like Canada will fail to meet their international obligations to collaborate with other countries in reducing global emissions of CO_2 and other greenhouse gases.

Effects of CO_2 on Plants

Carbon dioxide is an important nutrient for plants. As a result, increased concentrations of CO_2 can stimulate the productivity of some plants, especially if moisture and nutrients are abundant.

Many laboratory experiments have shown that agricultural plants can be more productive when fertilized by CO_2. In fact, some commercial greenhouses increase the productivity of crops such as cucumber, tomato, and ornamental plants by fertilizing the air with CO_2 at concentrations of 600-2000 ppm.

Usually, however, the productivity of crops grown under field conditions is limited by an inadequate supply of nutrients other than CO_2, usually nitrogen, phosphorus, or potassium, and often the availability of water is also a constraint. Under these kinds of conditions, the responses of plants to CO_2 fertilization are small and short term, or non-existent.

Increased concentrations of CO_2 can also affect many plants by decreasing their rate of water loss by transpiration. Most water loss occurs through tiny pores, known as stomata, on the leaf surfaces. The size of the stomatal opening is controlled by specialized guard cells. Activity of the guard cells is influenced by CO_2, and stomata tend to close partially or entirely when its concentrations are high. Because the availability of moisture is an important factor affecting plant productivity in agricultural and forest ecosystems, decreased water losses from lessened transpiration could be a beneficial effect.

It appears that some benefits might be realized from CO_2 fertilization and decreased transpiration, especially in intensively managed agricultural systems. It is important to recognize, however, that these gains are likely to be minor. Moreover, the possible benefits would probably be overwhelmed by the negative consequences of anthropogenic climate change. The distribution and composition of natural and managed ecosystems could be greatly affected by effects on precipitation and other climatic factors, and that could result in enormous damage being caused to economic resources in agriculture, forestry, and fisheries, and also to natural biodiversity.

Environmental Issues 17.1. Carbon Credits

Carbon credits (or carbon offsets) are a way to achieve a net reduction of emissions of greenhouse gases (GHGs). For example, a person might want to offset emissions of CO_2 associated with the driving a gasoline-powered vehicle. To do this, CO_2 credits might be purchased from an organization that commits to plant trees to fix an offsetting amount of atmospheric CO_2 into biomass. In essence, carbon credits gained from one activity (such as planting trees) are traded against another that emits greenhouse gases (such as driving a car).

Carbon credits are related to systems of emissions trading, which were first applied to releases of SO2. For instance, in the United States, governmental regulators assigned companies an amount of SO2 that they were permitted to emit. If a company exceeded its limit, it could be fined, which provided an economic incentive to meet its target. Alternatively, a company could purchase unused credits from another company that had not reached its SO2 limit. In effect, this system established a "marketplace" for SO2-emission credits.

Although the trading of carbon credits is not yet regulated or certified in Canada, they are still being acquired by many individuals and companies who are seeking to reduce their net emissions of GHGs or to achieve a carbon-neutral lifestyle or business. Carbon credits can be generated in various ways:

- Afforestation is the establishment of forest on land in a low-carbon area, such as pasture or cropland. As the forest grows, the carbon stored on the land increases, resulting in less CO_2 in the atmosphere, plus additional benefits such as habitat for biodiversity. If the intent of a project is to develop an older forest and maintain it, then the carbon-storage benefits are larger than any other ecological offset scheme.
- Reforestation is the regeneration of a new forest on land where timber has been harvested. Although the harvest reduces the carbon stored on the site, reforestation ensures that forest biomass is regenerated. Compared with a post-harvest conversion of the land to agricultural or urbanized uses, reforestation provides carbon credits.
- Conservation agriculture involves practices that increase soil biomass. This is done by leaving crop residues to enhance soil organic matter, by planting seeds directly into the soil without ploughing, and by using a crop rotation instead of continuously planting a single species.
- Geological carbon storage involves trapping CO_2 produced by fossil-fuel combustion and then concentrating it as a liquid or gas that can be injected into an underground reservoir. For instance, CO_2 produced by a coal-fired power plant in North Dakota is being concentrated, transported by pipeline to Weyburn in southern Saskatchewan, and injected into a geological formation to enhance pressure and petroleum recovery. Carbon offsets are also generated – up to 40-million tonnes of CO_2 over 30 years.
- Replacing some fossil fuel use by non-GHG energy sources also generates carbon credits. This could involve renewable energy sources or nuclear-derived electricity. For example, an investment in the development of wind-turbine energy, photovoltaics, passive solar, or biomass fuels result in less use of fossil fuels. So does improved insulation and wind-proofing of buildings and the installation of higher-efficiency technologies, such as fluorescent lighting and hybrid gasoline-electric vehicles.

It is clear that any of these options results in a reduced amount of CO_2 in the atmosphere. Nevertheless, some kinds of carbon credits are controversial, and critics refer to them as "hot air." Here are the key objections to trading in carbon credits:

- Genuine decreases in CO_2 emissions may be avoided by the purchase of carbon credits. Ultimately, dealing with climate change will require that large reductions occur in the emissions of GHGs. In this context, carbon credits may be viewed as a modern form of the archaic Catholic tradition of "indulgences", or the forgiveness of sins, the purchase of which allowed people to sin without great consequence.
- Fictitious carbon credits have been marketed by disreputable people or organizations, Examples include trees not being planted as contracted or not being tended, so they did not survive. Because carbon trading is not yet regulated or audited, there is potential for fraudulent or incompetent schemes.
- Downsized economies also represent a carbon credit, in that less industrial activity results in reduced emissions of GHGs. Examples include the down-sized economies of post-1990 Russia and other countries of Eastern Europe. These post-Cold War economies became smaller because of inefficiencies of their social and industrial systems, which had nothing to do with actions to reduce emissions of GHGs. It is not sensible to reward a necessary economic restructuring with carbon-credit monies.
- Ecological carbon credits must be maintained against natural disturbances, timber harvesting, and other influences that would reduce the carbon stored in biomass. Moreover, older forests do not forever increase

in biomass. Once the maximum is reached, management should maintain the accumulated carbon or convert some of it into "enduring consumer products" such as the wood of buildings or furniture.

Clearly, there are a number of ways to generate reliable carbon offsets, and their implementation will reduce the net emissions of GHGs. However, it is important that these schemes be properly audited and regulated. It is also crucial to understand that any effective, societal-level plan to deal with emissions of GHGs will require large reductions in the use of fossil fuels.

Reducing Carbon Dioxide

Because of the potential consequences of anthropogenic climate change, governments are considering actions to reduce the emissions of CO_2 and other GHGs in the atmosphere, or at least to slow their rates of increase. This goal could be achieved in two ways: (1) by reducing the emissions of GHGs, and (2) by increasing the rates at which they are removed from the atmosphere. The latter tactic is especially relevant to CO_2, the most abundant of the anthropogenic GHGs.

Ultimately, large decreases in the emissions of GHGs, particularly CO_2, must be the major tactic of any strategy to deal with an intensification of the greenhouse effect. However, it is extremely difficult to rapidly reduce emissions of CO_2 because they are associated with so many economically important activities. As we previously examined, the major CO_2-emitting activities include the use of fossil fuels in industry, transportation, and space heating; the manufacturing of cement; and ecological conversions, particularly of forest to agriculture. Politicians, economists, and environmental specialists all worry about the shorter-term economic consequences of actions necessary to rapidly reduce the emissions of CO_2 to the atmosphere. In general, they believe it is more prudent to reduce those emissions through more protracted actions.

Planting large numbers of trees is an option that would contribute to reducing the CO_2 concentration in the atmosphere. As trees and other plants grow, they fix CO_2 into the organic carbon of their accumulating biomass. Depending on the species and growing conditions, that biomass can eventually reach several tonnes of dry weight per large tree, about half of which is carbon.

Studies have shown that substantial carbon credits can be gained by planting large numbers of trees in urban and rural environments. The carbon credits are especially large if the tree-planting involves afforestation, or the creation of forest on disused agricultural land. (Afforestation converts non-forested land into a forest, while reforestation ensures that another forest regrows on a site from which timber was harvested.) Agroecosystems typically store small amounts of carbon in biomass, while forests store much more. The carbon-storage function would be optimized if mature or old-growth forest is established, and if that ecosystem were maintained in its high-carbon condition for as long as possible. (Harvesting of mature trees would detract from the carbon-storage function.) Moreover, the afforestation of extensive areas would achieve many additional, non-carbon benefits, such as the enhancement of biodiversity.

Although tree-planting and afforestation are attractive options toward reducing CO_2 in the atmosphere, these tactics cannot offset more than a portion of the CO_2 emitted by fossil-fuel combustion and deforestation. An enormous area of land would have to be afforested to achieve full offsets. For example, to fully offset the CO_2 emissions from one 200 MW coal-fired generating station (which would emit about 0.34-million tonnes of CO_2-C per year), the carbon-fixing services of about 500,000 ha of natural forest of the kind typical of eastern Canada would be required. If the forest productivity were increased by silvicultural management on a fertile site, as little as one-tenth of that area might be required, but that would still be a huge area (Freedman et al., 1992). Only a limited amount of land is available, in

Canada or elsewhere, for afforestation to provide carbon offsets. The use of larger areas would withdraw too much land from other productive uses, especially agriculture.

In any event, dealing effectively with an anthropogenic climate change will require a comprehensive, integrated strategy, of which reduced emissions of GHGs must be the major component. Carbon offsets such as tree-planting will be a useful element, but they will not be sufficient.

The most important means of reducing CO_2 emissions would potentially involve the following:

- aggressive conservation of energy through more efficient use, which would result in a decreased demand for fossil fuels
- increased use of non-carbon energy (such as solar, wind, tidal, hydro, biomass, and nuclear) to displace many uses of fossil fuels
- prevention of further conversions of forest into agricultural and other land-uses, to avoid CO_2emissions that are associated with deforestation
- afforestation, which would increase carbon stored in ecosystems

However, it must be recognized that the implementation of an effective strategy involving these actions would be politically and economically difficult. Industrialized nations depend heavily on fossil fuels, and changes in this reliance will have huge implications for economic systems, industrial capitalization, resource use, and citizens' expectations of lifestyle. Similarly, deforestation in tropical countries is a primary means by which impoverished people gain access to opportunities and livelihoods, and harvested timber helps to earn the foreign exchange that is necessary to fund development activities.

The societal changes that would be necessary to effectively deal with an intensified greenhouse effect are revolutionary in their nature and magnitude. Designing the required economic and energy systems will be a tremendous challenge, and implementing them will require enlightened and forceful leadership. Unfortunately, there are no easy solutions to an environmental problem as potentially damaging as anthropogenic climate change. Moreover, it appears that it will be necessary and precautionary to implement effective actions as soon as possible, even before it is definitely known that many of the damages are occurring.

> Environmental Issues 17.2. Politics and Climate Change
> It is reasonable to conclude that not much of the scientific debate about climate change is actually about whether the climate is changing! In fact, there is a broad consensus among scientists that global climates have always changed, that this is also occurring now, and there has been a substantial warming since about 1850 when the Little Ice Age ended. Rather, the ongoing dispute is about the role of human influences on the recent trend of global warming – whether the recent changes in climate are anthropogenic. Although a robust consensus of scientists has concluded that anthropogenic climate change is a clear and present reality, as witnessed by the increasingly strong statements of the IPCC and related organizations, there is still a dissenting minority.
>
> In general, the climate-change skeptics do acknowledge that there has been a recent trend of global warming, because it is well evidenced by melting glaciers, a lengthening ice-free period in polar waters, climate-related changes of the distribution of many species, and an increase in mean global surface temperature. Nevertheless, the skeptics believe that natural causes may be responsible for these effects – such as variations in the emission of energy by the Sun or in the absorptive capacity of Earth's atmosphere (perhaps related to changes in reflective aerosols emitted by volcanoes).
>
> Because there is not yet scientific unanimity about anthropogenic climate warming, there is room for political and economic interests to deny that the problem is real or important. This allows them to avoid taking

expensive actions to mitigate the problem, such as reducing the emissions of greenhouse gases. To further build their dissenting case, vested economic interests (such as companies in the fossil-fuel sector) may provide funding to climate-change skeptics or their organizations to help marshal dissenting evidence and engage in the public debate. Furthermore, climate-change skeptics often give prominence to environmental research that runs contrary to mainstream observations of climate warming, such as expanding glaciers in a particular area, which are exceptions to the much more frequent observations of mountain glaciers and polar ice that are retreating at rates unprecedented in recorded history.

Arguably, these are legitimate actions for the vested interests to take, because effective societal responses to anthropogenic climate change have such large economic implications. Nevertheless, it is possible to view such actions with a cynical eye, because these kinds of tactics have been used before with other public controversies related to health and environment, such as thalidomide, cigarette smoking, acid rain, and others. In fact, some environmental advocates suggest that it is possible to establish a predictable framework for the response of vested industrial / economic / political interests to public controversies, such as anthropogenic climate change:

- Step 1. Deny that the problem exists, or claim that the scientific evidence is weak or inconsistent.
- Step 2. If possible, suppress the conduct or release of new scientific research that is likely to produce results that are contrary to the views of the vested interest. This is possible if scientific agencies are under their political or economic control.
- Step 3. If possible, blame "external" influences or interests for the damage, particularly "natural" factors.
- Step 4. Insist that an especially large burden of well-validated scientific evidence must be in place before agreeing that environmental change has been substantial enough for the vested interest to accept a measure of responsibility and so to take mitigative action.
- Step 5. Finally, claim that despite any resulting environmental damage, the instigating economic activity is too important to the regional/national/global economy to bear significant regulation – in the sense that any slowing of economic activity is viewed as being contrary to vital national interests and therefore unacceptable to society at large.

However, there are also cases where people and organizations that believe in anthropogenic climate change have mocked or denigrated the views of skeptics. Moreover, some climate-change proponents "oversell" some of the evidence. For example, some proponents claim that hurricane Katrina (2005) and similar events of extreme weather were somehow caused by global warming. In fact, this is just an idea and there is no convincing scientific evidence to back it up (although modelling research does suggest that over the medium- and longer-term, the Gulf of Mexico and other tropical waters will become warmer and this might be expected to spawn more and stronger hurricanes). These non-objective positions are particularly worrisome if scientists are involved, because the conduct and communication of their knowledge should remain objective and apolitical and not stray into the emotional realm of advocacy.

Moreover, environmental scientists have a limited ability to provide convincing evidence of an anthropogenic influence. Climatic systems are extremely large, open, and complex, and science is not able to make watertight predictions about these sorts of systems. In fact, uncertainty about outcomes is the basis of a precautionary orientation: scientists may advocate action in the absence of complete proof, because the consequences of no action might be too great for society to absorb. This is the reason why so many scientists are advocates of taking action to deal with climate change, even though they may not yet be fully convinced, in a strictly scientific sense, of the degree to which recent global warming is due to anthropogenic influences.

Strident advocacy positions by either skeptics or believers of anthropogenic climate change are not particularly helpful. Ideally, environmental controversies should be resolved by a continuous and objective review of the emerging scientific evidence, and by a consensual development of political and economic policies that would effectively mitigate the problem.

Conclusions

Earth's natural greenhouse effect is caused by the activity of radiatively active gases in the atmosphere, and it helps make the planet habitable. The concentrations of key GHGs are increasing rapidly, particularly carbon dioxide, and this is predicted to intensify the greenhouse effect. This could result in global warming and many other climatic effects, such as changes in precipitation regimes and in the frequency of severe weather events. These changes would have severe consequences for agroecosystems and the human economy in general, and also for natural ecosystems (notwithstanding that, in some places, there might be improvements in agriculture and new opportunities for some species and ecological communities). At the international level, the Kyoto Protocol is the key first action being taken to reduce the emissions of GHGs that threaten to cause global warming. Many countries have ratified this treaty and are taking steps to reduce their emissions of GHGs (unfortunately, Canada withdrew its ratification in 2012 because of an imminent failure to meet its targets for reduced emissions). However, the Kyoto-related actions are highly controversial and are not in themselves sufficient to achieve their intended goal of preventing or slowing global warming – future actions will have to be more decisive.

Questions for Review

1. Describe Earth's natural greenhouse effect and the factors that create it.
2. How may human influences be making the greenhouse effect more intense?
3. What is a greenhouse gas (GHG)? What are the most important GHGs in the atmosphere, and how are human actions affecting their concentrations?
4. What are the likely climatic and ecological consequences of an intensification of the greenhouse effect?

Questions for Discussion

1. How might the Canadian economy and the lifestyles of typical Canadians be affected if serious actions are taken to reduce the emissions of greenhouse gases?
2. Despite repeated commitments since the Conservative Party of Canada assumed control of the Government of Canada, our country has not yet announced a comprehensive strategy to reduce our national emissions of greenhouse gases. Especially problematic are a lack of regulations for the fossil-fuel industries, whose rising emissions are the key reason that Canada has missed its avowed Kyoto targets. Do you think that these actions by the Harper Government are prudent and justified, or do you disagree with them? Explain your answer.
3. Mostly because of the potential economic effects, the Kyoto Protocol has been highly controversial in Canada and other countries. But even if the provisions of the treaty are fully implemented, there would only be a slowing of the rate of increase of greenhouse gas concentrations in the atmosphere. This is because the rates of emission of CO_2 and other GHGs would still be larger than can be absorbed by the planetary sinks. Should the reductions of emissions of GHGs be even larger than required by the Kyoto Protocol? How would you convince politicians, industrial interests, and other concerned parties that it must be done?

Exploring Issues

1. Your provincial government has struck a committee of politicians and citizens to recommend actions to reduce the net emissions of greenhouse gases. As the principal science advisor to the committee, you have been asked to develop a list of practical options that should be undertaken. What actions would you recommend for implementation immediately, and which more gradually (that is, progressively during the next 10 years)? Justify each of your recommendations.
2. For one day, make a list of your activities that result in emissions of carbon dioxide or methane to the atmosphere. These should include direct emissions (for example, by breathing or driving a vehicle) and indirect ones (as when trees must be harvested to provide you with paper, or when organic garbage is disposed into a landfill). Estimate the percentage reduction in emissions that you think you could make without suffering an unacceptable degree of change in your lifestyle.

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Chapter 18 ~Toxic Elements

Key Concepts

After completing this chapter, you will be able to:

1. Describe the ubiquitous distribution of elements in the environment and explain this phenomenon in terms of the difference between pollution and contamination.
2. Outline cases of natural pollution by toxic elements and explain how they provide insight into the effects of anthropogenic pollution.
3. Describe cases of anthropogenic pollution by metals and outline the resulting ecological damage.

Introduction

All of the naturally occurring metals and other elements are ubiquitous (found everywhere) in at least trace concentrations in soil, water, air, and organisms. As long as the detection limits of the available analytical chemistry are low enough, this universal contamination can always be demonstrated.

Organisms require some of the trace elements as essential micronutrients, including copper, iron, molybdenum, zinc, and in some cases aluminum, nickel, and selenium. Under certain conditions, however, these same elements can accumulate to high concentrations in organisms and cause ecological damage (see In Detail 18.1). Trace elements that are most often associated with environmental toxicity are the heavy metals cadmium, chromium, cobalt, copper, iron, lead, mercury, nickel, silver, tin, and zinc, as well as the lighter elements aluminum, arsenic, and selenium.

Some cases of elemental pollution are natural in origin. This usually involves metal-rich minerals being exposed at the surface and causing local ecological changes. However, human activities have caused additional examples of pollution by toxic elements, particularly in the vicinity of industrial sources such as smelters. In addition, emissions of mercury and lead from power plants and automobiles have caused widespread contamination of remote environments, although it is not yet certain that this is causing ecological damage.

There are cases of people having been poisoned by exposure to toxic elements in their environment. Some historians believe that the decline of the Roman Empire may have been hastened by neurotoxicity caused by chronic lead poisoning. The Romans had significant exposure to lead because they stored acidic beverages (such as wine) in pottery treated with pigments and glazes that contained lead. As well, their water piping was made of lead (the word "plumbing" is based on the Latin word for lead – plumbum). In nineteenth-century Britain, many people who made felt top-hats developed neurological damage because of their exposure to mercury compounds used to give a shiny finish to the hats – hence Lewis Carroll's character in Alice in Wonderland, the "Mad Hatter," and the expression "mad as a hatter."

More recently, thousands of people suffered mercury poisoning during the 1960s after they ate grain that had been treated with mercuric fungicide. In one disastrous case in Iraq in 1971, more than 6,500 people were poisoned (about 500 died) when they ate food prepared from mercury-treated grain. The grain had been donated by a foreign aid program and was intended only for planting. Although the sacks of grain were labelled to indicate that the seeds were poisonous, many of the victims were illiterate or did not understand or ignored the implications of the message. About the same time, similar poisonings occurred when people ate mercury-treated grain in Guatemala, Iran, and Pakistan.

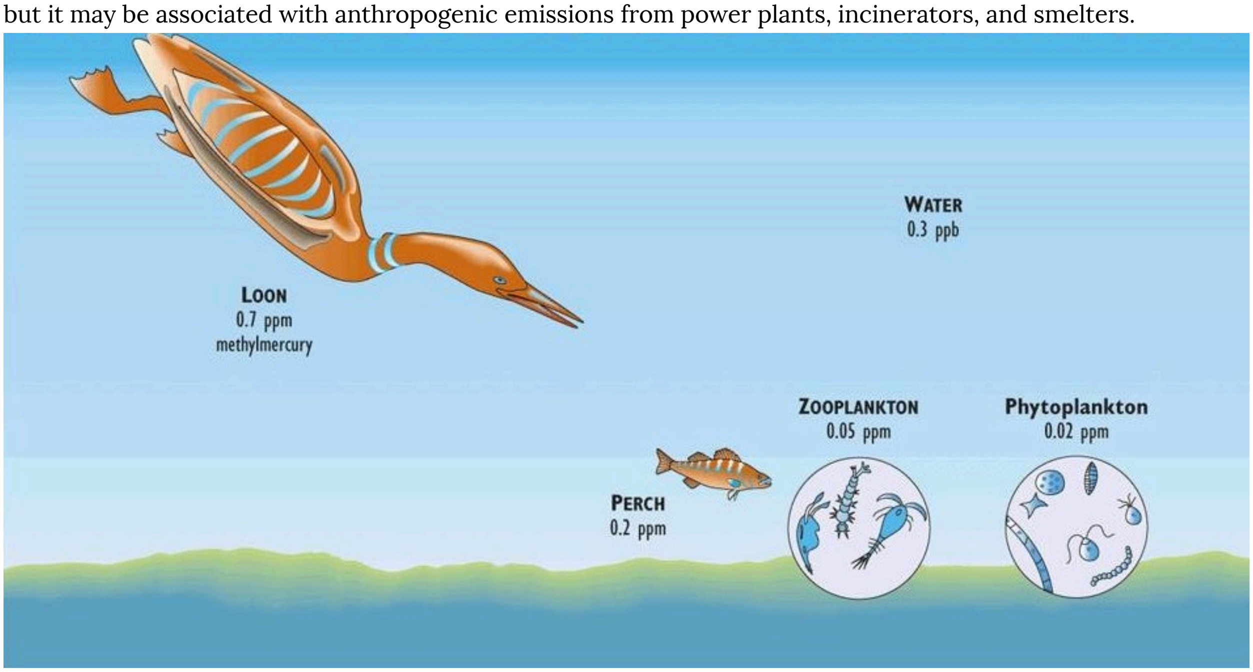
To avoid these problems today, fungicide-treated seed-grain is usually dyed red, which warns people not to use it as food.

Mercury also caused thousands of cases of poisoning at Minamata, Japan. A factory there had discharged elemental mercury into Minamata Bay. In that form mercury is not very poisonous, but microbes in the sediment transformed the metal into methylmercury, which is extremely toxic and bio-accumulates in organisms in preference to the water of their aquatic environment. The methylmercury further biomagnified up the food web and caused extensive poisoning of fish-eating birds, domestic cats, and people (see In Detail 18,1 and Global Focus 18.1). In this chapter, we examine natural and anthropogenic pollution with toxic elements and the resulting ecological consequences.

In Detail 18.1. Bioaccumulation and Biomagnification
Certain metals or their organic compounds, such as methylmercury, tend to occur in much higher concentrations in organisms than in the ambient, non-living environment. This phenomenon is known as bioaccumulation (also called bioconcentration). Similar tendencies are shown by chlorinated hydrocarbons, such as DDT, PCBs, and dioxins (see Chapter 21). Bioaccumulation occurs because certain substances have a strong affinity for organisms and therefore concentrate within them in preference to their non-living environment. Many of these chemicals dissolve in biological fluids and tissues, such as lipid (fat), in preference to ambient water or soil.

Another phenomenon, known as biomagnification (or food-web magnification), is the tendency for top predators to have the highest concentrations of these chemicals. Organisms are highly efficient at assimilating methylmercury and organochlorines from their food. Therefore, these chemicals become stored in organisms, rather than being excreted. This means that predators at the top of the food web develop the highest concentrations (residues) of these chemicals. Usually, bioaccumulation and food-web magnification progress with age, so the oldest individuals in any population are the most contaminated.

Figure 18.1. Biomagnification leads to progressively higher concentrations of methylmercury and chlorinated hydrocarbons in organisms higher in the food web. The common loon (Gavia immer) is a top predator in many lakes. In some regions of Canada, these birds can harbour concentrations of methylmercury that are high enough to impair their reproduction. The source of the environmental mercury is not yet known for certain, but it may be associated with anthropogenic emissions from power plants, incinerators, and smelters.



Concentration and Availability

All of the naturally occurring elements are present in at least trace concentrations in all samples of water, soil and rocks, air, and organisms. The term background concentration refers to a presence that is not significantly influenced by either anthropogenic emissions or unusual natural exposures. The background concentration in soil and rocks is usually much higher than in water, and also generally higher than in the tissues of organisms (Table 18.1).

However, elements that are dissolved in water often occur in chemical forms (such as ions) that are relatively easily absorbed by organisms. For this reason, even a trace aqueous concentration may be toxic. In contrast, the much higher concentrations that commonly occur in soil and rocks are mostly insoluble, and therefore are not particularly bioavailable. Scientists determine the total concentration of metals in a component of the environment (such as soil, sediment, or rock) by digesting a sample in a hot mixture of strong acid. In contrast, the "available" concentration is determined from an aqueous (water) extract of a sample. In general, the available concentration of toxic elements in soil are much smaller than the total concentrations (generally less than 1% of the total value), and it is also much more relevant to potential toxicity.

Most elements are found in only trace concentrations in the environment (Table 18.1). In contrast, aluminum and iron are prominent constituents of rocks and soil, with concentrations typically about 8% and 3-4%, respectively. However, almost all of the aluminum and iron in soil and rocks occurs as insoluble minerals that are not readily available for uptake by organisms. For example, virtually all aluminum in soil occurs as insoluble silicate and clay minerals. Although aluminum in these forms comprises about 8% of the soil mass, it is not available for uptake by plants and is therefore non-toxic. However, much smaller concentrations of aluminum, typically only a few parts per million (ppm), are found as ions, either bound to organic matter and clay surfaces or freely dissolved in soil water. The ionic forms of aluminum are readily available for biological uptake and may cause toxicity to species that are sensitive to this metal.

Much higher concentrations of soluble available aluminum occur in strongly acidic environments, especially when the pH is less than about 5.5. (In fact, almost all metals are much more soluble under acidic conditions.) Aluminum solubility is also greater in strongly alkaline environments, with pH higher than about 8. Moreover, different ionic species of aluminum occur at different pH levels:

- Al^{3+} is dominant in strongly acidic environments with a pH less than about 5.0
- $AlOH^{2+}$ and $Al(OH)_2+$ are important under less acidic conditions of pH 4.5–5.5
- $Al(OH)_3$ from pH 5.2–9.0
- and $AlOH_4-$ in alkaline environments with pH greater than 8.5.

Aluminum toxicity is a common problem for organisms that live in highly acidic or alkaline environments. This is because of the combined influences of greater solubility and the presence of relatively toxic ions under those conditions.

Table 18.1. Background Concentration of Elements in Selected Components of the Environment. Source: Data

from Bowen (1979).

Element	Rocks (ppm)			Soil	Water (ppb)		Organisms (ppm)		
	Granite	Basalt	Limestone	(ppm)	Oceanic	Fresh	Plants	Mammals	Fish
Aluminum	77,000	87,600	9,000	71,000	2	300	90-530	0.7-28	20
Arsenic	1.5	1.5	1	6	3.7	0.5	0.2-7	0.007-0.09	0.2-10
Cadmium	0.1	0.13	0.03	0.35	0.1	0.1	0.1-2.4	0.1-3.2	0.1-3
Chromium	4	90	11	70	0.3	1	0.03-10	<0.002-0.8	0.03-2
Cobalt	1	35	0.1	8	0.02	0.2	0.005-1	0.005-1	0.006-0.05
Copper	13	90	5.5	30	0.3	3	5-15	10	0.7-15
Fluoride	1,400	510	220	200	1,300	100	0.02-24	0.05	1,400
Iron	27,000	56,000	17,000	40,000	2	500	70-700	180	9-98
Lead	24	3	5.7	35	0.03	3	1-13	0.2-3.3	0.001-15
Manganese	400	1,500	620	1,000	0.2	8	20-700	0.2-2.3	0.3-4.6
Mercury	0.1	0.01	0.18	0.06	0.3	0.1	0.005-0.02	0.02-0.7	0.4
Molybdenum	2	1	0.16	1.2	10	0.5	0.06-3	0.02-0.07	1
Nickel	0.5	150	7	50	0.6	0.5	1-5	1.2	0.1-4
Selenium	0.05	0.05	0.03	0.4	0.2	0.2	0.03	0.4-1.9	0.2
Silver	0.04	0.1	0.12	0.05	0.04	0.3	0.01-0.8	0.009-0.28	0.04-0.1
Tin	3.5	1	0.5	4	0.004	0.01	0.2-2	0.01-2	0
Uranium	4.4	0.43	2.2	2	3.2	0.4	0.005-0.04	0.001-0.003	0.04-0.08
Vanadium	72	250	45	90	2.5	0.5	0.001-0.5	0.002-0.02	0.3
Zinc	52	100	20	90	5	1.5	20-400	240	9-80

Toxicity

The toxicity of elements and other chemicals is related to two factors: (1) the exposure (dose) and (2) the vulnerability of an organism to the particular substance. The dose received is influenced by the available concentration in the environment and the period of exposure. Therefore, a long-term exposure to only a minute available concentration may cause toxicity, especially if the element is able to bioaccumulate and then biomagnify in the food web until it exceeds a threshold of biological tolerance.

Organisms vary greatly in their tolerance of exposures to toxic elements (and to all other poisons). Consequently, an intense exposure to a potentially toxic chemical may result in some species being poisoned, while tolerant ones may not be damaged and may even benefit from the demise of sensitive species in their community. In addition, there is usually genetically based variation for tolerance within a species. This can lead to the evolution of populations (known as ecotypes) that are relatively tolerant of toxic exposures (we examine this topic in the next section).

The most common mechanism of poisoning by toxic elements is damage to an enzyme system. (Organisms have a huge diversity of enzymes, which are proteins that catalyze specific biochemical reactions and are critical to healthy metabolism.) The poisoning occurs because metal ions bind to specific enzymes, which changes their shape and results in a loss of their unique catalytic function. Toxic elements may also cause poisoning by binding to DNA or RNA, thereby disrupting transcription and translation, the processes by which genetic information is used to produce specific proteins (including enzymes; see In Detail 6.1). Toxic metals can also disrupt DNA replication and hence cell division.

Typical symptoms of acute poisoning caused by toxic elements in plants include abnormal patterns of growth, decreased productivity, impaired reproduction, the occurrence of disease, and ultimately death. Symptoms of chronic toxicity are harder to detect and may include a "hidden injury" such as a decrease in productivity that occurs without signs of acute damage. Animals can show a variety of symptoms associated with enzyme disruption, often including neurotoxicity and impaired functioning of the kidneys, liver, and other organs.

Natural Pollution

Localized natural pollution sometimes occurs when metal-rich minerals are present at the surface and are prominent in the chemistry of soil, surface water, and vegetation. These conditions can often be identified by a distinctive, stunted growth form of the vegetation, and sometimes by the presence of particular indicator plant species. In combination with chemical analyses, these biological indicators can be used to explore for metal-rich deposits, a technique known as biogeochemical prospecting.

In some cases, natural pollution by metals can be quite intense. For example, soil containing up to 3% lead plus zinc was found at a site on Baffin Island. In another case, peat filtering a spring of metal-rich groundwater in New Brunswick accumulated as much as 10% copper. High concentrations of metals in soil are also reflected in the chemistry of plants, especially in certain genetically adapted hyperaccumulator species that may occur in metal-rich habitats. For example, nickel concentrations as high as 10% have been measured in plants in the genus Alyssum growing in Russia, and up to 25% in the blue-coloured latex of Sebertia acuminata from New Caledonia in the South Pacific. These hyperaccumulator plants grow on naturally metal-polluted sites.

Serpentine Soil and Vegetation

Some well-studied cases of natural pollution involve soil influenced by serpentine minerals, which are rich in nickel, chromium, and cobalt and are associated with asbestos deposits. Soil containing serpentine minerals is toxic to non-adapted plants because of the high concentrations of these metals, in combination with an imbalance of the nutrients calcium and magnesium. Serpentine soil typically contains several thousand parts per million of nickel, but can have as much as 25-thousand ppm (or 2.5%) of this metal.

The natural vegetation on serpentine sites is often distinctively stunted. Extensive serpentine “barrens” occur in eastern Quebec and western Newfoundland. Those habitats support tundra-like ecosystems in a landscape that is otherwise covered by boreal forest.

In some places, serpentine areas support plant species that occur only in that kind of habitat, a narrow distribution that ecologists refer to as endemic. In other cases, widespread species have evolved locally adapted populations that can cope with the toxic and nutritional stresses of serpentine soil – these are known as ecotypes. On non-serpentine sites, the specifically adapted endemics and ecotypes are quickly eliminated by competition with plants that are better competitors in less-stressful habitats.

Serpentine sites in northern California support relatively ancient vegetation, because the area was not glaciated. These habitats contain at least 215 endemic species or subspecies of plants. Some of the endemics occur only on particular serpentine sites in California and nowhere else in the world. In contrast, the serpentine barrens in eastern Canada are relatively young, being released from glaciation only about 10-thousand or fewer years ago. Consequently, not enough time has passed to allow many serpentine endemics or ecotypes to evolve.

> Image 18.1. An extensive area of serpentine-rich rock occurs in Gros Morne National Park in western Newfoundland. Soil rich in serpentine has high concentrations of toxic nickel and cobalt and is poor in nutrients. These conditions are stressful to plants and result in the development of stunted vegetation of limited species diversity, as in this scene. The typical vegetation on non-serpentine soil in this region is a

conifer-dominated boreal forest. Source: B. Freedman.

Seleniferous Soil and Vegetation

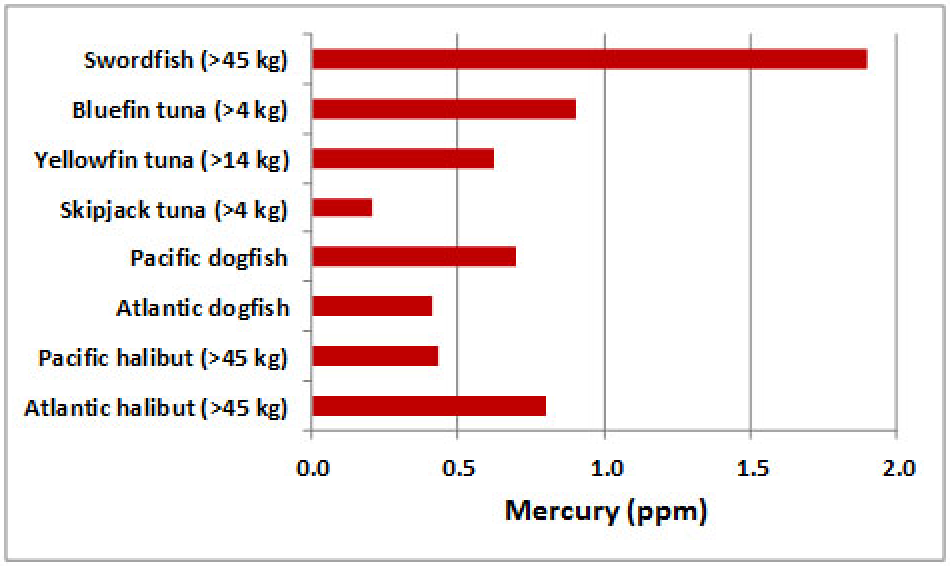
Semi-arid regions in various parts of the world often have areas with soil that contains high concentrations of selenium. These seleniferous habitats may support plants that hyperaccumulate selenium, such as species in the genus Astragalus (locoweeds). About 25 North American species of Astragalus are hyperaccumulators of selenium. They may contain up to 1.5% of selenium in their tissues, storing it in unique amino-acid-like biochemicals, such as selenomethionine. The Astragalus species also emit dimethyl selenide and dimethyl diselenide to the atmosphere, giving them a distinctive, unpleasant odour. Livestock that feed on these plants are poisoned by a toxic syndrome known as alkali disease or blind staggers.

Mercury in Aquatic Environments

Even in remote oceanic habitats, mercury often accumulates in high concentrations (as methylmercury, CH_3Hg) in fish, birds, and sea mammals. In marine waters off eastern and western Canada, large fish may have mercury concentrations in their flesh that exceed the limit considered acceptable for human consumption (more than 0.5 ppm mercury on a fresh-weight basis; Figure 18.1). Analysis of old specimens of fish and seabirds in museums has revealed levels of mercury contamination similar to those in modern samples, which suggests that the phenomenon may be natural. The contamination of marine animals represents a substantial biomagnification from ambient seawater, which has a trace concentration of mercury of less than 0.1 ppb.

Figure 18.2. Mercury Contamination of Fish Captured Offshore of North America. The data show the average mercury concentration in the muscle of species of marine fishes. The data are in ppm, measured on a fresh-

weight basis. Source: Data from Armstrong (1979)



The biomagnification occur because of the progressive accumulation of mercury up the trophic web. Algae initially absorb mercury from the water (as methylmercury), and zooplankton accumulate even larger residues as they graze on the algae. Zooplankton-eating fish accumulate still larger quantities, but the largest residues occur in long-lived top predators, such as big fish and marine mammals (see In Detail 18.1).

Within any particular species of fish, larger (and older) individuals generally have higher mercury concentrations than smaller (and younger) ones. A study of swordfish caught off eastern Canada found that animals heavier than 45 kg had an average mercury concentration of 1.1 ppm, while those weighing 23-45 kg had 0.86 ppm, and those smaller than 23 kg had 0.55 ppm (Armstrong, 1979). It appears that mercury residues become more intense as the animals age and grow larger.

High concentrations of mercury also occur in fish-eating marine mammals and birds, which are top predators in their ecosystem. Studies of adult harp seals (Phoca groenlandica) in eastern Canada found an average mercury concentration of 0.34 ppm in muscle and 5.1 ppm in the liver (Armstrong, 1979). High mercury residues also occur in North Atlantic seabirds, with an average of 7 ppm found in feathers of northern skua (Catharacta skua), 5 ppm in puffin (Fratercula arctica), and 1-2 ppm in fulmar (Fulmarus glacialis), kittiwake (Rissa tridactyla), razorbill (Alca torda), and common murre (Uria aalge) (Thompson et al., 1991).

Mercury contamination of fish has also been observed in many remote lakes. For example, about three-quarters of 1,700 lakes monitored in Ontario have fish with mercury exceeding 0.5 ppm fresh weight in their flesh. In a remote lake in northern Manitoba, the average mercury concentration in muscle of 53 northern pike (Esox lucius) was 2 ppm fresh weight and one animal had 5 ppm (McKay, 1985). In general, freshwater fish that are top predators have the highest residues of mercury, and larger or older individuals are the most contaminated.

Federal, provincial, and territorial governments in Canada issue advisories about eating fish taken from particular lakes and rivers where mercury residues are known to be a problem; the advisories may also have information about other contaminants, such as PCBs and dioxins. In Ontario, for example, more than 2,200 waterbodies are monitored for this purpose (MOEE, 2014). The advisories tell people how many fish of particular species and sizes they can eat. The general threshold is 0.61 ppm, but it is as low as 0.26 ppm for pregnant women and children, and no fish with more than 1.84 ppm should be consumed. About one-third of the advisories given for sportfish taken from Ontario lakes result in some level of consumption restriction. In Sweden, about half of the lakes have some fish with mercury exceeding the health advisory limit (0.5 ppm), and hundreds of lakes have been blacklisted because their fish are considered unfit for human consumption.

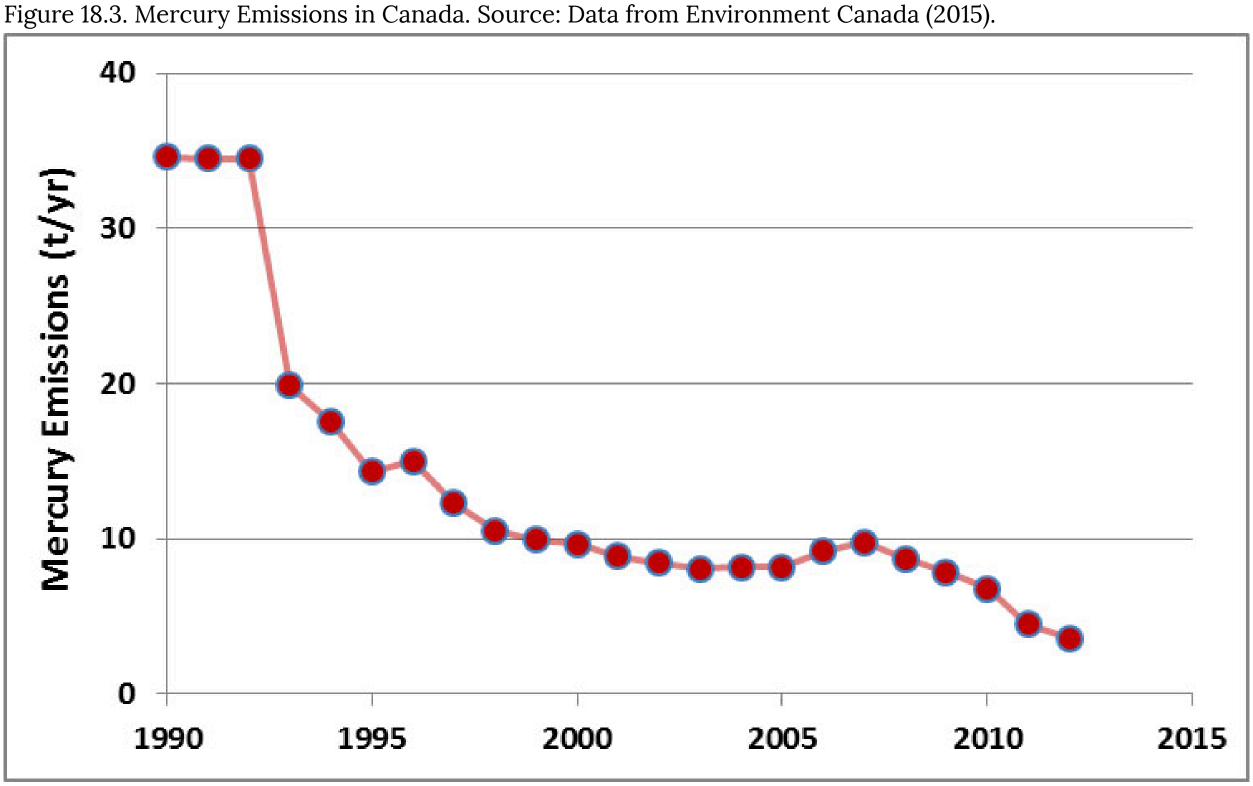
The causes of mercury contamination of lakes are not known for certain. It seems likely that the phenomenon may be natural in regions that are remote from sources of emission. However, anthropogenic mercury is contributing to the problem closer to large emissions sources, such as coal-fired generating stations, municipal incinerators, and smelters. For example, Harp Lake in Ontario is located relatively close to municipal and industrial sources of emissions. Studies found that atmospheric deposition accounted for 57% of the mercury input to that lake, suggesting a significant anthropogenic influence (Mierle, 1990).

The above discussion of mercury in lakes refers to the many situations in which there are no direct anthropogenic inputs of the metal. However, there are well known cases of pollution caused directly by industrial releases. For example, discharges from chlor-alkali and acetaldehyde factories and some older pulp mills have caused local mercury pollution, resulting in high residues of methylmercury in fish and other animals. The case of Minamata Bay, Japan, involved an acetaldehyde plant (Global Focus 18.1). A less severe case in Canada, which affected parts of the English and Wabigoon Rivers in northwestern Ontario, involved a pulp mill.

Significant bioaccumulation of mercury also occurs when hydroelectric reservoirs are developed (see Chapter 20). Flooding leaches naturally occurring soil mercury into the reservoir, where bacteria in oxygen-poor sediment transform it into methylmercury that is biomagnified by fish. This process occurs more rapidly in acidic lakes because that condition favours the production of methylmercury in the sediment, compared with less available dimethylmercury in non-acidic waterbodies.

Although there is some controversy about the relative importance of natural and anthropogenic sources of mercury to remote lakes, it is reassuring to know that the overall emissions have been greatly reduced in recent decades (Figure 18.3). This occurred because of improved emissions controls at industrial facilities, including the closing of several metal smelters and coal-fired power plants.

Figure 18.3. Mercury Emissions in Canada. Source: Data from Environment Canada (2015).



Global Focus 18.1. Mercury in Minamata Bay

Minamata is a city in Japan where industrial emissions from a factory caused a famous example of toxic pollution, beginning in the 1950s. The factory produced acetaldehyde, which is used to make plastics. The industrial process used inorganic mercury as a catalyst, and between 1932 and 1968, about 25 tonnes of the metal was dumped into Minamata Bay with wastewater discharges. Bacteria in anaerobic sediment transformed the mercury into methylmercury, which became biomagnified in fish to resides as high as 20 ppm. The fish were eaten by predatory birds, causing toxicity and reproductive failure. Fish and shellfish were also harvested and eaten by people living around the bay, which has a long-standing, traditional fishing economy. This caused an episode of toxicity that became known as "Minamata Disease."

It took several years for the complex of symptoms caused by methylmercury poisoning to be recognized as being ultimately due to emissions from the acetaldehyde factory. Initially, in the mid-1950s, doctors noticed that people were displaying a novel and strange neurological syndrome, characterized by progressive degeneration of the nervous system. Symptoms intensified from numbness in the limb extremities, to slurred speech, loss of peripheral vision, convulsions, unconsciousness, and ultimately the death of many victims. There was also a congenital syndrome caused by toxicity to fetuses by methylmercury passed across the placental barrier. Afflicted children suffered from deformity, mental retardation, and impaired motor control. At the same time, fish-fed cats were killed by a neurological disease, as were fish-eating birds.

It soon became apparent that the disease was being caused by eating fish harvested from Minamata Bay. Although industrial waste being dumped into the bay was an early suspect, not much was initially done to either reduce the discharges or to prevent people from eating seafood caught in the polluted area. Then, in 1959, scientists from Kumamoto University concluded that an organo-mercurial compound was the cause of the toxic syndrome. Soon after, it was realized that its origin was inorganic mercury of industrial origin that was being naturally methylated in the bay. The company that caused the pollution challenged these conclusions, although it began to pay compensation to some of the most severely afflicted people (but only if a release was signed that absolved the company of responsibility and eliminated the possibility of future lawsuits; moreover, many affected people were denied compensation). Despite intense controversy, the company continued to release mercury to the aquatic environment until 1968, when a change in technology eliminated it from the manufacturing process.

Ultimately, about 2,200 people were officially diagnosed as having Minamata Disease as a result of exposure to methylmercury in seafood harvested from the bay. Of these, about 100 died of their poisoning. In addition, at least 12-thousand people may have suffered milder forms of the disease but were not officially diagnosed. In 1973, a court found the chemical company to have behaved in a negligent manner and to be liable for the damages. Many people suffering from mercury-caused disease were awarded compensation, although the amounts paid were disputed as being insufficient and many people received nothing. The bottom line, however, is that people died of avoidable methylmercury poisoning, and many survivors experienced terrible physical and mental disabilities.

Important lessons can be learned from this environmental catastrophe. One is that unanticipated consequences may result from human activities that are thought to be environmentally safe. In the Minamata case, it was believed that the dumping of wastewater containing inorganic mercury would not cause serious damage to the marine environment. At the time, it was not known that bacteria in sediment are capable of transforming mercury into bio-magnifying and toxic methylmercury. Moreover, even when it was recognized that this was happening, and that people and wildlife were being poisoned, business interests and regulatory and political authorities did not act decisively to ensure that people were no longer exposed to the toxic threat. This negligence greatly compounded the problem.

In any event, the tragic case of Minamata Bay has improved our understanding of the consequences of discharging mercury into an aquatic environment. However, the broader lesson about unintended consequences of poorly considered economic activities is not yet firmly enshrined in our planning and regulatory systems.

Anthropogenic Sources

Industrial processes used to mine, process, and use metals can result in the pollution of air, water, and land (refer to Figure 13.1).

Mining Residues

Areas near mine sites may be badly damaged by the dumping of metal-rich excavation waste (rocks whose metal concentration is not high enough to be considered commercial ore). Because these materials may be toxic, vegetation development can be restricted to early successional communities, such as sparse grassland. In some cases, soil toxicity is severe enough that few plants manage to establish even after hundreds of years. This can be seen on mine wastes from 2000-year-old Roman lead workings in England and Wales.

Ecologists studying British sites polluted by mine wastes have found that these habitats often support plant ecotypes that are genetically tolerant of the metals that are present. The locally adapted ecotypes can grow in metal-polluted soils, where non-tolerant plants are eliminated by the toxic stress. Conversely, the tolerant ecotypes are poor competitors in non-polluted environments, and so are rare in habitats unaffected by metal toxicity.

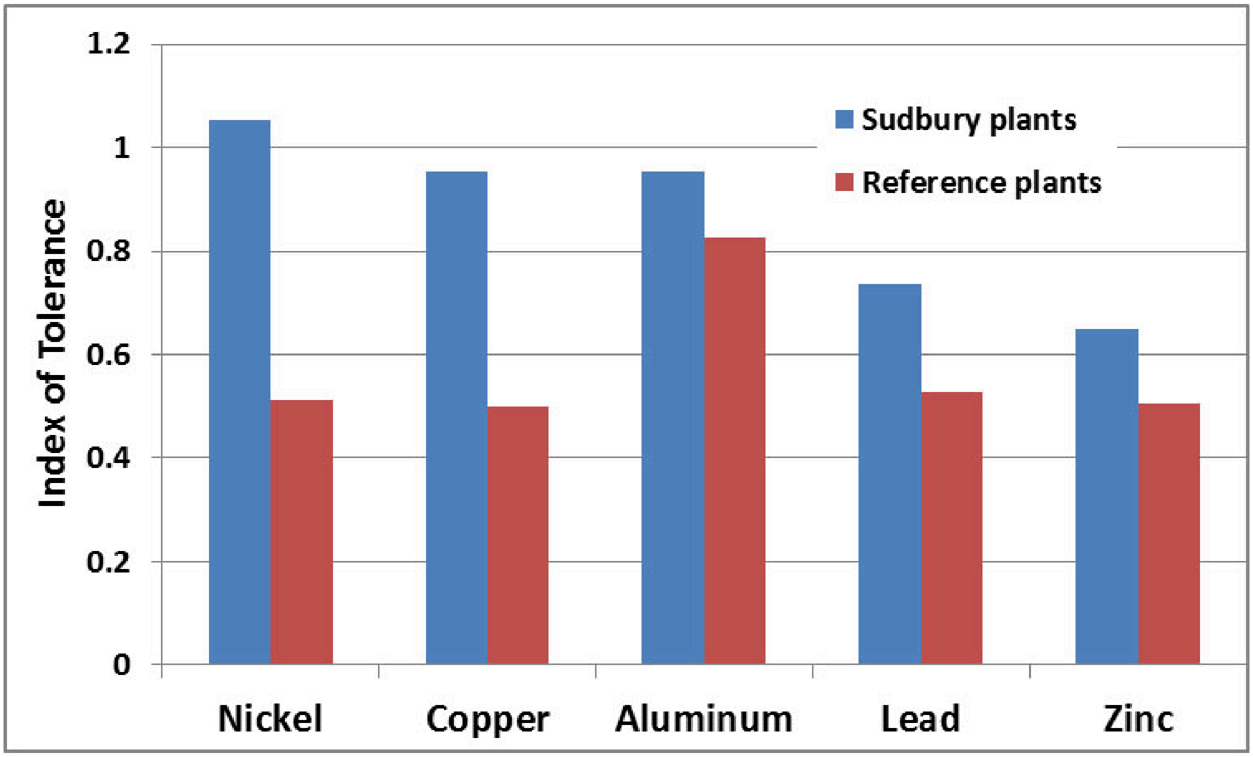
Research into metal-tolerant ecotypes has provided insights into the process of evolution (Chapter 6). Metal-tolerant individuals do occur in populations growing on non-polluted sites, but they are rare. However, the frequency of tolerant genotypes increases quickly after metal pollution occurs. In places with sharp boundaries between polluted and non-polluted soils, a tolerant population can maintain itself over a distance of only a few metres. This is possible because the intense toxicity of polluted soil strongly favours the survival and reproduction of tolerant individuals. Such a population-level change in genetically based characters, occurring in response to an agent of natural selection (in this case, metal pollution), is a demonstration of evolution (more specifically, microevolution).

Metal-tolerant ecotypes have been studied near Sudbury, where pollution by nickel and copper has been caused by emissions from smelters and roast beds (see Chapter 16). Plant communities of polluted sites are dominated by metal-tolerant ecotypes of several grasses, particularly Agrostis gigantea and Deschampsia caespitosa. Meadows of these grasses developed soon after the extremely tall "superstack" was commissioned in 1972. Because it dispersed emissions widely, the superstack greatly reduced ground-level SO_2 pollution. However, soil in the area remained acidic and polluted with metals. The local ecotypes of these grasses can tolerate toxic stress from acidity and metals, but are intolerant of SO_2, which is why the grasslands did not develop until after the superstack began to operate.

The metal tolerance of the grass Deschampsia caespitosa has been studied. Plants were grown in solutions containing the metals of interest, and were compared with controls (Figure 18.3). The data show that the Sudbury population is tolerant of nickel and copper, which occur in their native soil at concentrations of about 400 ppm, compared with 20 ppm at non-polluted reference sites. The Sudbury population is also more tolerant of aluminum. This is a response to the greater solubility and toxicity of aluminum in acidic soil near the smelters (which had a pH of 3.5-3.9, compared with pH 6.8-7.2 at reference sites).

Figure 18.4. Tolerance of a Grass to Metals. Populations of the hairgrass (Deschampsia caespitose) were collected from metal-polluted places near Sudbury and from reference sites where metals are not a problem. The index of metal tolerance is based on the root growth that occurs when plants are grown in solutions

containing metals, compared with a no-metal control. The larger the index number, the greater the tolerance. In all comparisons presented here, the two populations had statistically significant differences in tolerance to the metal tested, with a probability level of <0.001, except for aluminum ($p < 0.05$; note: a probability value of <0.001 means that there is less than a 0.1% (or 1/1000) likelihood that the difference between the two populations is due to chance alone; $p <0.05$ means there is less than a 5% chance). Source: Data from Cox and Hutchinson (1979).



Metal-Containing Tailings

Once ore is mined, it is ground to a fine powder in a process called milling. The powder is then separated into a valuable metal-rich fraction, which is roasted and smelted, plus large quantities of waste tailings. In most cases, the tailings are dumped into a low-lying contained area, which when full is covered with vegetation as a stabilization measure. Although the tailings are a waste product, they still contain high concentrations of metals, and that can make it difficult to establish vegetation after a dump is filled. In addition, if sulphide minerals are present, acidity is generated when they become oxidized by bacteria, and that makes the toxicity worse. Chemical analyses of tailings from several Canadian mines are shown in Table 18.2. The tailings contain high concentrations of various metals, depending on the ore being processed. The acidic tailings are especially toxic, because metals are much more soluble and bioavailable under acidic conditions.

Table 18.2. Chemical Analyses of Metal-Contaminated Tailings. Samples were taken from sites in the Yukon and northern Ontario. Metal data are in ppm, sulphur in %. Data modified from Kuja (1980).

Site	pH	Arsenic	Cadmium	Copper	Nickel	Lead	Zinc	Sulphur
Gold mine A	1.9	5200	18	140	13	952	2400	1.1
Gold mine B	3.2	400	15	613	14	130	9600	44.4
Gold mine C	6	1350	102	172	15	3600	6200	5.7
Gold mine D	6.9	50000	114	330	20	2300	18000	13.5
Gold mine E	7.1	7	3	33	21	1130	1060	4
Tungsten mine	7	–	< 1	1420	22	12	288	6.5
Copper mine	9	15	1	1710	21	9	178	0.1

Canadian regulators require that tailings-disposal areas be covered with vegetation once they are full of waste or after their associated mine closes. This is done because tailings dumps have poor aesthetics and can be sources of wind-borne dust. These environmental problems can be substantially mitigated if an abandoned tailings dump is covered with a stable cover of vegetation. In addition, if their associated dams and berms are not structurally sound and become breached by high water flows during severely rainy weather, tailings-disposal areas can be a source of massive water pollution.

One such disaster occurred in 2014 in the Cariboo region of central British Columbia, when an accidental breach occurred at the tailings disposal area of a copper- gold mine at Mount Polley. The massive spill involved about 10-million cubic metres of water and 4.5-million cubic metres of slurry (a fluid mixture of tailings particles and water) (Allen and Voiland, 2014). The great scouring flow eroded banks and uprooted trees and much of the volume eventually deposited into nearby Polley Lake, whose surface rose by 1.5 metres. Some of the flow then continued via Hazeltine Creek into the much larger Quesnel Lake, which had been famous as a deep, pristine waterbody. By the end of the day of the breach, the 4-km2 tailings pond was almost empty. In this case, the cause of the breach appears to have been over-filling of an under-engineered tailings disposal area.

Image 18.2. A catastrophic release of tailings occurred at the Mount Polley mine in 2014. The top image shows the tailings-disposal area prior to the breach, with the light-blue colour representing the area where wastes were being dumped. The bottom image shows conditions after the breach, with almost all of the volume of the dump site having escaped to Polley Lake and some also to Quesnel Lake. Source: NASA (2014).


Mount Polley
Mine
Polley
Lake
retention
basin
Quesnel
Lake
Hazeltine Creek
N
1 km
Mount Polley
Mine
Polley
Lake
Quesnel
Lake
Hazeltine Creek
N
1 km

If a filled-up tailings-disposal area is to have a stable cover of vegetation established on top, its contents must be treated to reduce the toxicity. If the tailings are acidic, a liming treatment is needed to raise the pH to a neutral level and so reduce the availability of metals. Fertilizer may also be used to alleviate nutrient deficiency and organic matter added to improve soil structure and water-holding capacity, and then plants are sown. Sometimes, novel techniques are used, such as the use of acid- or metal-tolerant ecotypes in the planting mixture. If the tailings are extremely toxic or acid-generating, they may have to be covered with a locally available overburden, such as glacial till, which is then vegetated. Canadian Focus 18.1 describes the reclamation of tailings-disposal areas in the vicinity of Sudbury.

Image 18.3. Tailings are the fine waste that remains after ore is ground and processed to remove metal-rich minerals. Tailings contain high concentrations of metals and can generate acidity when exposed to the atmosphere. These conditions make it difficult to establish vegetation after disposal sites are filled. This is a view of a reclaimed area of tailings near Sudbury. Most of the vegetation was sown, but native shrubs and trees are also becoming established. Source: B. Freedman.

Canadian Focus 18.1. Tailings Reclamation at Copper Cliff
A large smelter at Copper Cliff, near Sudbury, is serviced by a mill that produces large amounts of tailings (54-thousand tonnes per day at the time the case study of Peters (1984) was written). The tailings are mixed with water and piped as a slurry to be disposed in natural basins whose capacity is increased by the construction of earthen dikes. In 2005, the tailings dumps covered about 3,025 ha, of which 1,425 ha had been stabilized by a cover of perennial vegetation. The vegetation prevents fine dust from blowing into the atmosphere and improves aesthetics and environmental quality. The re-vegetated tailings areas have a central pond, which is surrounded by gradually sloping grassland.

The tailings are a finely ground material, composed mainly of minerals that are not particularly toxic. However, the tailings contain pyrites that oxidize when exposed to atmospheric oxygen, and generate acidity as low as pH 3.7. These extremely acidic conditions result in metals becoming available for plant uptake, which greatly increases the toxicity of the tailings. Plant-available metals were analyzed by extracting tailings with acetic acid, and very high levels of available metals were found, with nickel up to 87 ppm, copper 81 ppm, and iron 440 ppm.

The reclamation procedures result in a stable grassland being established, which is then invaded by native shrubs, trees, and other plants. The methods include the following:

1. application of 900 kg/ha of limestone ($CaCO_3$), which raises the pH of the tailings to 4.5-5.5 and reduces the availability of metals
2. several applications of fertilizer during the initial stages of grassland establishment, with nitrogen being especially important
3. application of an organic mulch to improve the water-holding and aeration characteristics of the surface tailings
4. sowing with a mixture of long-lived pasture grasses and legumes, as well as annual rye (Secale cereale), which provides a short-lived nurse crop that helps mitigate the stressful microclimate for tender seedlings of the perennial grasses and legumes

As vegetation establishes and develops on the reclaimed tailings-disposal areas, some animals begin to use the habitat. Birds that breed in the grassy habitat and its central pond include mallard and black ducks (Anas platyrhynchos and A. rubripes), American kestrel (Falco sparverius), killdeer (Charadrius vociferus), and savannah sparrow (Passerculus sandwichensis). At least 90 species of birds have been observed to use the reclaimed tailings dump and its pond during migration.

Smelters

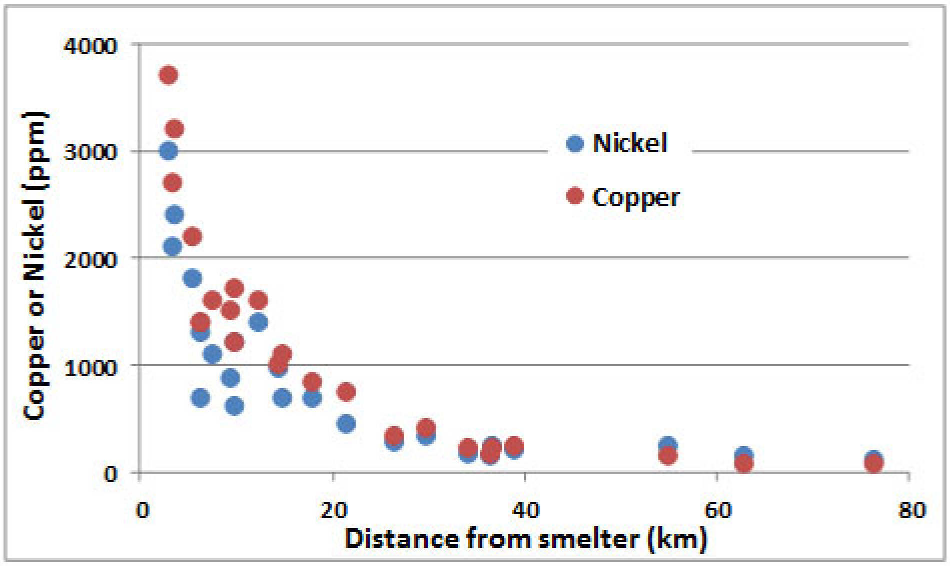
A smelter is a large industrial facility where ore is roasted. This is done to oxidize sulphide minerals, a process that results in large amounts of waste SO_2 and metallic particulates. In most cases today, pollution-control technologies are used to recover much of the SO_2 and particulates before the flue-gases are vented to the atmosphere. In the past, however, those wastes were emitted into the environment, causing intense pollution and ecological damage. As recently as several decades ago this was a common practice, and it still is for some older smelters. Newer smelters operate much more cleanly.

A smelter is a point source of toxic stress to surrounding ecosystems. Emissions may result in well-defined spatial gradients of both pollution and its resulting ecological damage, which diminish with increasing distance. Studies of damage near smelters indicate the following generalizations:

- Close to the point source, pollution by atmospheric SO_2 and metals in soil is most severe
- The intensity of pollution decreases rapidly (more or less exponentially) with increasing distance from the smelter.
- Damage to vegetation varies with the intensity of toxic stress and includes decreases in biomass, productivity, and species diversity, with only a few low-growing species occurring in the most polluted habitats
- Ecological processes such as nutrient cycling and decomposition are disrupted by toxic metals, gases, and acidity

The pattern of metal pollution around a point source can be illustrated by the Copper Cliff smelter near Sudbury. Figure 18.4 shows that metal concentrations in the environment decline rapidly with increasing distance from that smelter. These data specifically refer to the forest floor, but similar observations are seen in soil, vegetation, lakewater, and other components of the ecosystem.

Figure 18.5. Metal Pollution near Sudbury. Decades of emissions of metals from the Copper Cliff smelter caused an accumulation of nickel and copper in the environment. The most intense pollution occurs close to the point source. These data are for metals in the forest floor, which is the organic-rich layer that overlies the mineral soil. The forest floor binds metals in organic complexes and accumulates higher residues than the underlying soil. The samples were collected along a transect running south from the smelter. The spatial patterns of copper and nickel are highly correlated, with a coefficient of 0.98. Source: Data from Freedman and Hutchinson (1980)



As we examined in Chapter 16, SO_2 has also been an important pollutant in the Sudbury area. Consequently, it is difficult to determine the specific role of toxic metals in causing ecological damage. One way to investigate the influence of metals is to grow plants in polluted soil in a greenhouse, where SO_2 is not present. These bioassay experiments have demonstrated that soil collected near the smelters is toxic, mainly because of its high concentrations of metals. To a substantial degree, the toxicity persists even after the soil acidity is neutralized by adding lime.

Not all smelters emit both SO_2 and metals. The ecological damage that results from those that emit only metallic particulates has consequently been caused by metal pollution. One well-studied smelter, at Gusum, Sweden, has operated since 1661 (Tyler, 1984). Zinc is an important pollutant there, reaching concentrations as high as 2% (20-thousand ppm) in surface organic matter close to the point source, compared with less than 200 ppm farther than 6 km away. Copper pollution is similar, reaching 1.7% within 0.3 km, compared with 20 ppm beyond 6 km. The zinc and copper pollution has caused local ecological damage. Pine and birch trees have died or declined close to the source, and understorey plants, mosses, lichens, and soil-dwelling invertebrates have been damaged. Rates of decomposition and nutrient cycling are also impaired in the most polluted sites. Some plants, however, are tolerant of the metal pollution at Gusum. They include the grass Deschampsia flexuosa and the moss Pohlia nutans, which do relatively well in sites that are toxic to other plants.

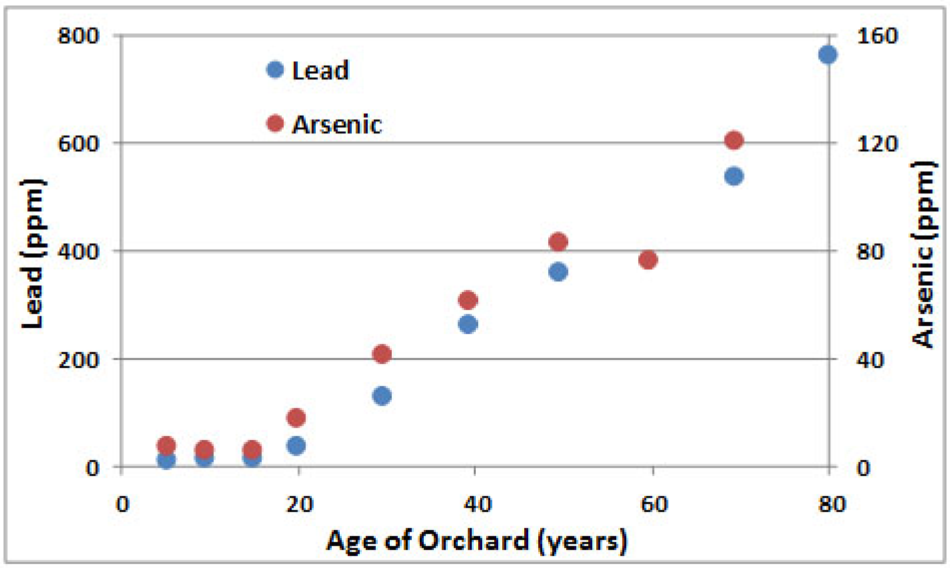
Use of Inorganic Pesticides

Until the 1970s, inorganic chemicals were widely used as pesticides in agriculture (see also Chapter 22). This was especially true in fruit orchards, where pesticides based on lead arsenate, calcium arsenate, copper sulphate, and related compounds were used to control fungal diseases and arthropod pests. These compounds have now been largely displaced by synthetic organic pesticides.

However, until the mid-1970s, annual spray rates of lead in Ontario orchards were as high as 8.7 kg/ha, while arsenic treatments reached 2.7 kg/ha, zinc 7.5 kg/ha, and copper 3.0 kg/ha (Frank et al., 1976). The spray rates depended on the crop being grown, the pest being managed, and the pesticide used, but in some cases all of these toxic elements were applied in the same orchards.

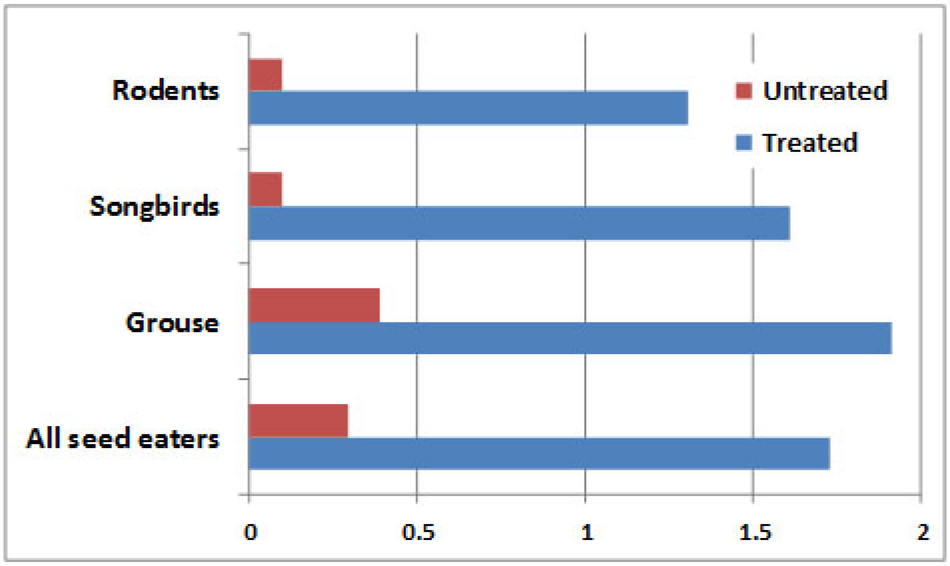
Residues of these chemicals accumulated in the soil of treated orchards. Studies of apple orchards found residues as high as 890 ppm of lead and 126 ppm of arsenic in surface soil, compared with background levels of <25 ppm lead and <10 ppm arsenic (Figure 18.5). The accumulations were caused by up to 70 years of spraying lead arsenate as an insecticide, mostly against the codling moth (Laspeyresia pomonella), a pest that causes “wormy” apples.

Figure 18.6. Accumulation of Arsenic and Lead in Orchards. Lead arsenate was used as an insecticide to combat infestations of apple orchards with codling moth. These data show the progressive accumulation of arsenic and lead in soils of orchards in southern Ontario. The largest residues are in the oldest orchards, which had been sprayed for many years. The background concentration for lead is 20 ppm, and for arsenic it is 10 ppm. Source: Data from Frank et al. (1976).



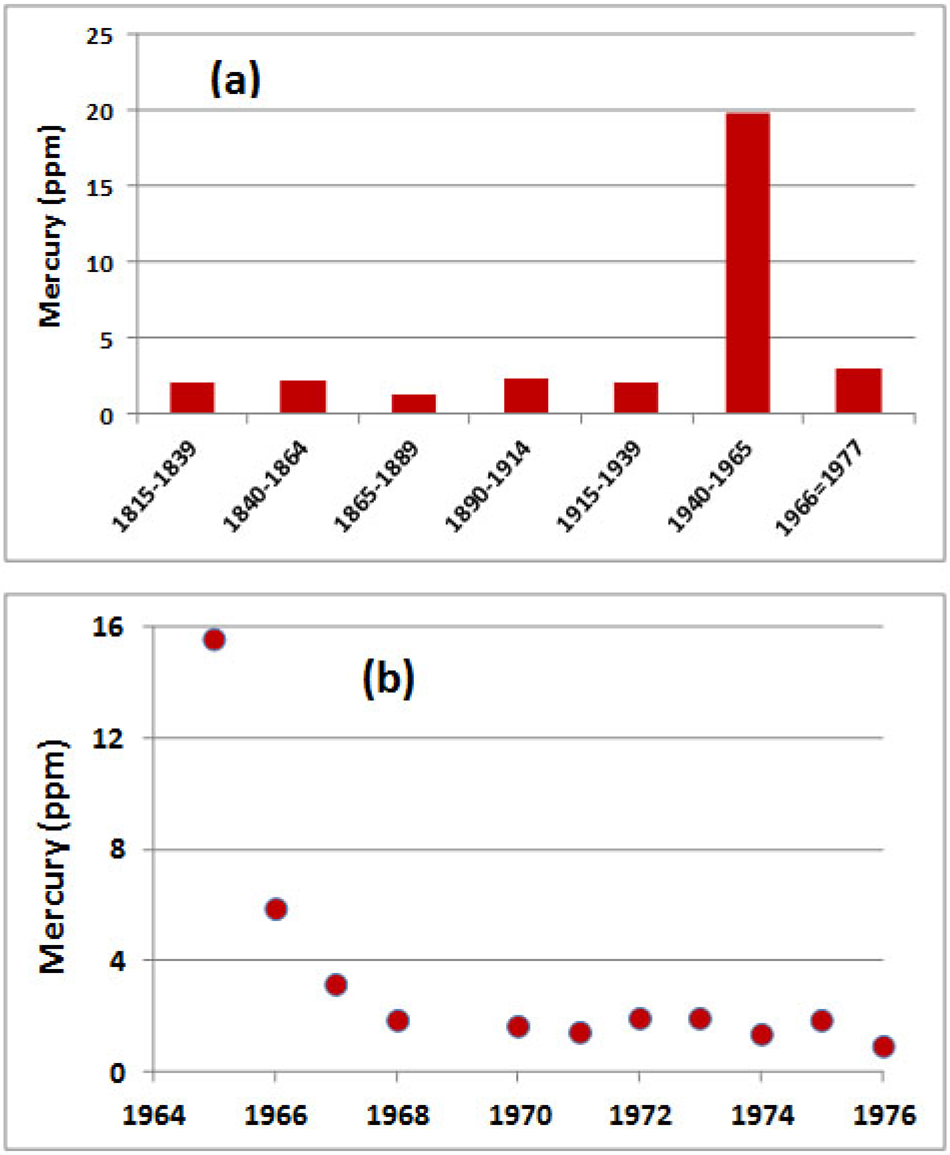
Agricultural soil can also be contaminated by the use of mercury-containing fungicides, especially those that protect newly germinated seedlings from a fungal infection known as damping-off. This pathogen attacks seedlings at the soil-air interface and causes the weakened plant to fall over and die. Mercury-containing pesticides are also used to control turfgrass diseases on golf-course putting greens. Mercury residues ranging from 24-120 ppm have been measured in the soil of putting greens in Ontario, while up to 9 ppm was found in Nova Scotia. The sowing of seed coated with mercuric fungicide has caused poisoning of wild animals that consumed the planted grain or ate herbivores that did so. Alkyl-mercury compounds such as methylmercury are especially hazardous in this respect because this form is extremely toxic and readily assimilated by animals from their food. Figure 18.6 shows the mercury contamination of seed-eating wildlife in regions of Alberta where treated seed was used, compared with areas where that exposure did not occur. Use of these fungicides was common until the early 1970s.

Figure 18.7. Mercury in Animals Feeding on Treated Seed. Seed-eating rodents and birds were exposed to alkyl-mercury fungicide by feeding on treated seed in agricultural areas in Alberta. Data are also presented for an area where mercury-treated seed was not used (labelled as untreated). The data are average data for liver and are in ppm dry weight. Source: Data from Fimreite et al. (1970).



Beginning in the late 1960s, most developed countries prohibited the use of alkyl-mercury fungicides as seed dressings. This ban resulted from the recognition of ecological problems associated with use of these chemicals, especially the poisoning of wild animals. Sweden, for example, prohibited the use of these pesticides in 1966, while approving the use of alkoxyl-alkyl-mercury compounds, which are much less toxic, as replacements. This action rapidly led to decreased mercury contamination of wildlife, such as predatory birds (Figure 18.7). Canada took similar action, although several years later.

Figure 18.8. Mercury Contamination of Swedish Hawks. (a) Mercury in feathers of goshawks (Accipiter gentilis), during various time periods; (b) Mercury in feathers of marsh harriers (Circus aeruginosus). Note the large increase in contamination caused by the use of alkyl-mercury fungicides and the rapid decrease that followed the banning of these chemicals in 1966. Source: Data from Johnels et al. (1979).



As was noted in the introduction to this chapter, humans have also been poisoned by inadvertently eating mercury-treated seed grain.

Birds and Lead

Millions of birds have suffered lead poisoning in North America each year because they ate spent shotgun pellets. Most of the spent shot was associated with hunting. In Canada, for example, about 2000 tonnes of lead shot were used by hunters each year in the early 1990s. Although more localized, skeet shooting was also a problem because of the large amount of shot deposited, up to tonnes of lead each year.

After being ingested by a seed-eating bird, lead shot may be retained in the gizzard, a muscular forepouch of the stomach. Hard grit is normally retained in the gizzard and used to grind tough-coated seeds, aiding in their digestion. Unfortunately, shotgun pellets are similar in size and weight to the grit that many birds select for this purpose. The shot becomes abraded in the gizzard, and the bits are swallowed and dissolved by acidic stomach fluid. The lead is then absorbed into the bloodstream, allowing it to poison the nervous system of the bird, leading to death.

Waterfowl have been especially widely affected, with 2-3 million individuals, or 2-3% of the North American population, dying each year from lead-shot poisoning in the early 1990s. The retention of just one or two pellets in its gizzard can poison a duck, causing a wasting away of 30-50% of its body weight, neurological toxicity, and ultimately death. Typically, about 10% of the waterfowl surveyed in North America had one or more shotgun pellets in their gizzard. Larger aquatic birds, such as swans, are known to retain lead fishing weights in their gizzard. Lead sinkers or shot were cited as the cause of 20-50% of the mortality of trumpeter swans (Cygnus buccinator) in western North America. Lead sinkers are also known to poison tundra swans (C. columbianus) wintering in the eastern United States, mute swans (C. olor) in Europe, and common loons (Gavia immer) in Canada and the United States. In Canada, about 500 t/y of lead fishing sinkers and jigs were lost in the early 1990s.

A related syndrome, caused by ingesting lead shot and bullets, afflicts birds that scavenge dead carcasses. Although the numbers are not well documented, this poisoning is known to kill vultures, eagles, and other scavenging birds. The critically endangered California condor (Gymnogyps californianus) has been relatively well studied – about 60% of its known deaths in the wild between 1980 and 1986 were caused by toxicity from ingested bullets in carrion. Because of the widespread poisoning of birds by lead shot, regulators have now restricted its use. Lead shot is banned over most of the United States. In Canada, the use of non-toxic shot has been required in all wetland areas since 1997 and in all other hunting areas since 1999. The use of lead shot for hunting is being replaced mostly by steel shot, and to a lesser degree by bismuth shot. The restricted use of lead shot has caused some controversy because many hunters believe that the alternative shot types might cause more crippling deaths. However, field tests have shown this effect to be marginal, as long as the inferior ballistic qualities of the alternatives are compensated for by shooting at closer distances or by using a larger size of shot.

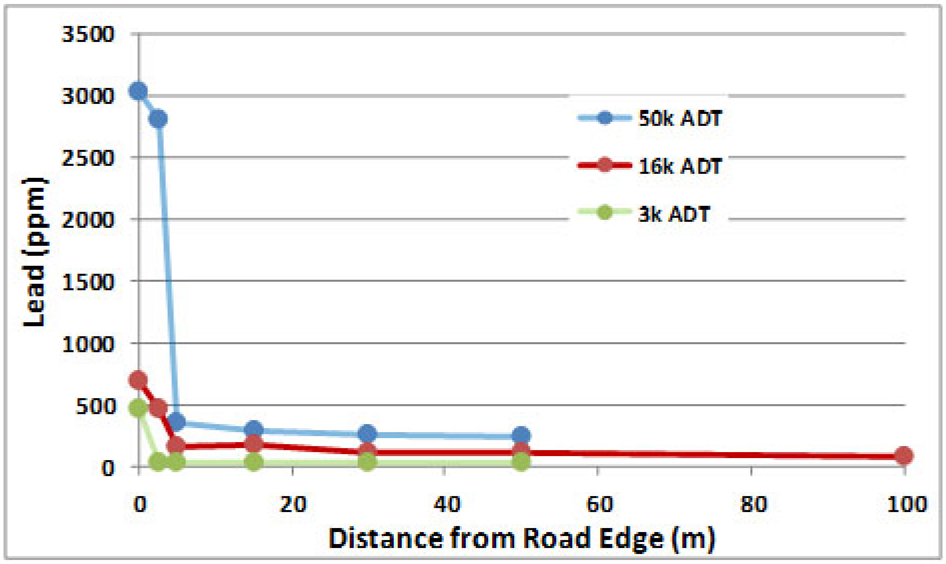
Automobile Emissions of Lead

Lead emitted by automobiles has contributed to a general contamination of urban environments. From 1923, but particularly after 1945, tetraethyl lead was added to gasoline as a so-called “anti-knock” compound. The lead increases mechanical efficiency and gasoline economy, while decreasing engine wear. In 1975, about 95% of the gasoline used in North America was leaded at concentrations as high as 770 ppm. In 1987, only 35% of the gasoline was leaded, and the maximum permitted then was 290 mg/L. The decreased use of lead between 1975 and 1987 was mostly due to the increased use of catalytic converters to reduce emissions of other automobile pollutants, especially carbon monoxide and hydrocarbons. Automobiles equipped with a catalytic converter can only use unleaded gasoline, because the catalysts, usually platinum, are rendered inactive by lead. The increasing use of unleaded fuels resulted in a 93% decrease in lead particulates in the air of Canadian cities between 1977 and 1989.

After 1990, the use of leaded gasoline was banned in Canada and the United States (the only exceptions were low-lead fuels [up to 30 ppm] for use in some farm vehicles, marine engines, and large trucks). Consequently, emissions of lead from automobiles in Canada decreased from about 9,500 t in 1978 to less than 100 t/y since 1995. However, many other countries, particularly in the less-developed world, continue to allow the use of leaded fuels.

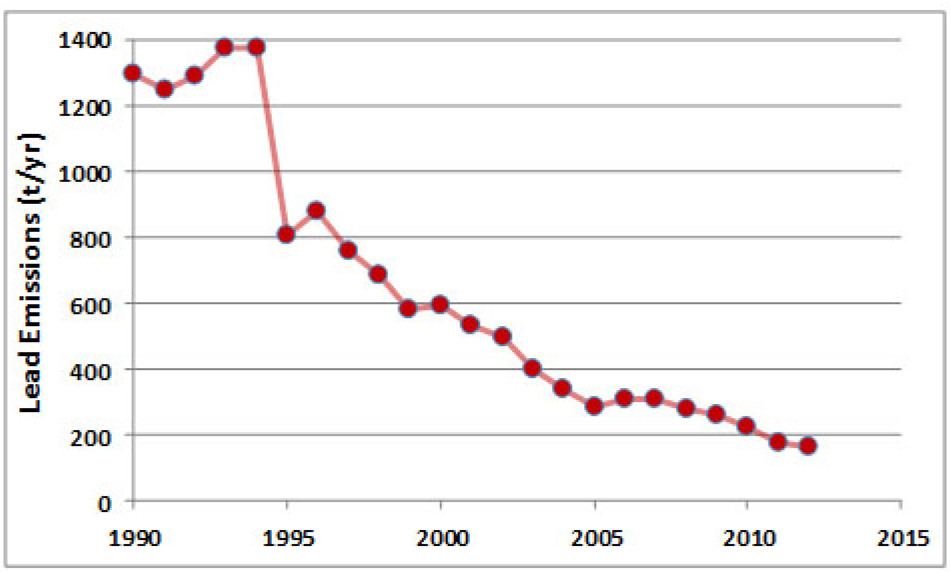
Almost all of the lead in gasoline is emitted as particulates through the vehicle tailpipe. The larger particulates settle out close to the roadway. This results in the buildup of a well-defined gradient of lead pollution, the intensity of which is related to traffic volume. This pattern of roadside pollution is illustrated in Figure 18.8 (this study was made prior to the banning of leaded fuels). Finer lead particulates are more widely dispersed in the atmosphere and contribute to the general contamination that occurs in cities. Not surprisingly, studies have shown some effects of lead on urban wildlife. For example, pigeons (Columba livia) living in cities can have significant residues of lead and may exhibit symptoms of acute poisoning.

Figure 18.9. Lead Pollution and Vehicular Traffic. Soil was collected near roads of different traffic density in Halifax, and was analyzed for its lead content. Metal data are in ppm dry weight, while average daily traffic (ADT) is in vehicles per day. The background concentration in soil is 14 ppm. Source: Data from Dale and Freedman (1982).



Overall, there have been large reductions in the emissions of lead in Canada, and also in other developed countries (Figure 18.9). This improvement in environmental conditions has occurred because of the banning of leaded gasoline as well as improved emissions controls at smelters and other industrial facilities.

Figure 18.10. Lead Emissions in Canada. The especially large decrease in 1995 was due to the banning of leaded gasoline, and much of the continuing reduction was due to improvements of industrial practices. Source: Data from Environment Canada (2015).



Conclusions

All of the naturally occurring elements are present in at least a trace level of contamination in all components of the environment – in the air, water, soil, and organisms. Sometimes their concentration is naturally elevated, as occurs when an ore body is present at the surface of the ground. Increasingly, however, anthropogenic activities are responsible for large emissions of toxic elements to the environment, and in some cases this has resulted in serious damage to ecosystems and in toxicity to people. The worst cases of pollution involve industrial practices that are no longer allowed in Canada or other wealthy countries, such as uncontrolled emissions of metals from smelters, the dumping of mercury into aquatic environments, the use of leaded gasoline, and the use of lead shot for hunting. Nevertheless, pollution by toxic elements is still an important problem. Damage is still being caused to ecosystems and organisms by releases of lead, mercury, and other toxic elements. This is true of all parts of the world, although pollution by toxic elements in poorer countries is much less controlled than in wealthier ones.

Questions for Review

1. How can we identify normal (or reference) levels, contamination, and pollution by metals and other elements given that these substances are ubiquitous in the environment?
2. What are the important sources of metal emissions to the environment?
3. What is the difference between the total and available concentrations of metals?
4. Describe the spatial pattern of metal pollution around a large point source of emissions, such as a smelter.

Questions for Discussion

1. Do you think that environmental damage similar to that near Sudbury is likely to be caused if a new smelter is constructed to process the ore mined at the ore deposit at Voisey's Bay, Labrador? (Note that the ores in both cases are similar – they contain sulphide minerals of nickel and copper.)
2. Important environmental benefits have been gained by banning the use of leaded gasoline in Canada. Why were there long delays in taking similarly vigorous actions against the use of lead shot in hunting and skeet shooting and lead weights in fishing?
3. Pick an element that was examined in this chapter and research its benefits, toxicity, effects on the environment, control, and mitigation.
4. Explain the principles of bioaccumulation and biomagnification using the case of methylmercury in aquatic ecosystems. Why do you think these phenomena were unanticipated "surprises" to environmental scientists?

Exploring Issues

1. Assume that Canada and the United States are negotiating a treaty to govern their emissions of mercury to the environment. You are a science advisor to the Canadian team. Some members of the team want to press for a "zero emissions" policy, believing that no emissions of mercury to the environment are acceptable. They ask for your advice on this issue. What kinds of information about the toxicity of mercury, to humans and to wild ecosystems, do you need in order to give the team objective advice about the proposed zero-emissions policy? Also, is it

physically possible to have zero emissions?

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Chapter 19 ~ Acidification

Key Concepts

After completing this chapter, you will be able to:

1. Describe the most important chemical ingredients of precipitation and explain which ones may cause acidity to develop.
2. Outline the spatial patterns of acidic precipitation in North America, and identify factors influencing this distribution.
3. Explain the difference between the wet and dry deposition of acidifying substances and how their rates vary.
4. Describe how water chemistry is affected as precipitation interacts with vegetation and soil, and explain the implications for surface waters.
5. Identify factors that make fresh waters vulnerable to acidification.
6. Describe the effects of acidification on freshwater organisms.
7. Discuss the roles of liming and fertilization in the reclamation of acidified lakes.
8. Explain the importance of reducing emissions of sulphur and nitrogen gases to mitigating the acidification of surface waters.

Introduction

Acidification is a process that is characterized by increasing concentrations of hydrogen ions (H^+) in soil or water. It can cause metals and their compounds to ionize, producing ions (such as Al^{3+}) in concentrations high enough to be toxic to plants, animals, and microorganisms. Consequently, increasing acidification is usually interpreted as a degradation of environmental quality. Acidification is caused by many influences, both natural and anthropogenic, but the most widespread problems are associated with a phenomenon commonly referred to as acid rain.

Acid rain has been an important problem in parts of North America since at least the 1950s, but it did not become a high-profile issue until the early 1970s. This rather sudden attention resulted from the discovery that acid rain was a widespread problem in Western Europe, and the realization that the same conditions likely occurred in North America. This awareness stimulated research in Canada and the United States, which demonstrated that acid rain was causing a widespread acidification of lakes and streams, and possibly of soil. The acidification of aquatic ecosystems was resulting in important ecological damage, including the loss of many fish populations. Buildings and other materials were also being damaged because acidity erodes metals, paint, and some kinds of quarried stone.

Strictly speaking, the term “acid rain” refers only to acidic rainfall, which along with snowfall accounts for wet deposition. However, acidifying chemicals are also deposited from the atmosphere when it is not raining or snowing, through the dry deposition of certain gases and particulates. A suitable phrase to define this complex of processes is “the deposition of acidifying substances from the atmosphere”, or more simply, acidifying deposition. In this chapter we examine natural and anthropogenic causes of the acidification of ecosystems. We focus on the chemical qualities of acidic precipitation and dry deposition, their effects on terrestrial and aquatic ecosystems, and how acidification can be avoided or mitigated.

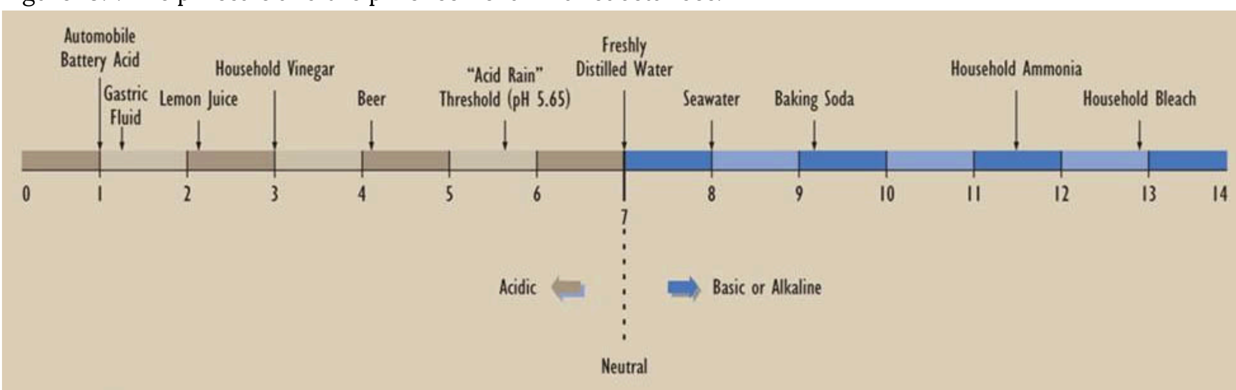
In Detail 19.1. Acids and Bases

An acid is defined as a substance that donates protons (hydrogen ions, H^+) during a chemical reactions. An aqueous solution is acidic if its concentration of H^+ is more than 1×10^{-7}moles per litre. In contrast, a base (alkali) donates hydroxyl ions (OH−) in chemical reactions. A solution is basic if its concentration of OH^- exceeds 1×10^{-7}mol/L. (A mole is a fundamental unit that measures the amount of a substance and is equal to 6.02×10^{23} molecules, atoms, or ions. This number is known as Avogadro's constant and it is derived from the number of carbon atoms contained in 12 g (1 mole) of carbon-12.)

Acids and bases react together to form water and a neutral salt. If equal numbers of moles of each are present, the solution has both zero acidity and zero alkalinity – the concentrations of H^+ and $OH^-$are both exactly 1×10^{-7}mol/L. Such a solution is said to be neutral.

Because extremely wide ranges of H^+ and OH^- concentrations are encountered in nature and in laboratories, acidity is measured in logarithmic units, which are referred to as pH (an abbreviation for "potential of hydrogen"). pH is defined as $-\log_{10}H^+]$, or the negative logarithm to base 10 of the aqueous concentration of hydrogen ion, expressed in units of moles per litre. Acidic solutions have a pH less than 7.0, while alkaline solutions have a pH greater than 7.0. Note that a one-unit difference in pH implies a 10-fold difference in the concentration of hydrogen or hydroxyl ions. The scale illustrated below shows the pH of some commonly encountered substances.

Figure 19.1. The pH scale and the pH of some familiar substances.



Chemistry of Precipitation

Scientists have adopted a functional definition of acidic precipitation as having a pH less than 5.65. This was chosen as the cut-off because at pH 5.65, an aqueous solution of carbonic acid (H_2CO_3) is in equilibrium with atmospheric CO_2, as follows: $CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3- \rightleftharpoons 2H^+ + CO_3^{2-}$

This definition assumes that "non-acidic" precipitation is essentially distilled water, in which the acidity is determined only by the atmospheric concentration of CO_2 and the amount of carbonic acid that subsequently develops. This is why the threshold below which precipitation is deemed "acidic" is set at the slightly acidic pH of 5.65, rather than at the strict zero-acidity pH of 7.0 (see In Detail 19.1).

It is, however, too simplistic to consider atmospheric moisture as consisting merely of distilled water in a pH equilibrium with gaseous CO_2. Additional chemicals are also present in trace concentrations in precipitation. For example, on windy days, dust containing calcium and magnesium is blown into the atmosphere, and precipitation containing these elements may develop a pH higher than 5.65. This is especially true of agricultural and prairie landscapes, where the ground surface is often bare of plant cover and soil particles may be easily eroded into the atmosphere. In some other regions, a relatively high concentration of naturally occurring sulphate in the atmosphere may result in precipitation having a pH less than 5.65.

The most abundant cations (positively charged ions) in precipitation are hydrogen ion (H^+), ammonium (NH_4+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+). The most abundant anions (negatively charged ions) are sulphate (SO_4^{2-}), chloride (Cl^-), and nitrate (NO_3-). Other ions are also present, but only in trace amounts that have little influence on the pH (see In Detail 19.2).

In Detail 19.2. Conservation of Electrochemical Neutrality
The principle of conservation of electrochemical neutrality states that in any electrically neutral solution (one that does not carry an electrical charge), the total number of positive charges associated with cations must equal the total number of negative charges of anions. For the purposes of calculating a charge balance, the concentrations of ions are measured in units known as equivalents. These are calculated as the molar concentration multiplied by the number of charges on the ion. (When dealing with precipitation or surface waters, microequivalents, or μeq, are generally the units reported.)

This principle is relevant to the acidification of water. The concentration of H^+ can be determined as the difference in concentrations of the sum of all anion equivalents minus the sum of all cations other than H^+. Therefore, if the total equivalents of anions exceed the total equivalents of cations other than hydrogen ion, then H^+ must go into solution to balance the cation "deficit," as follows: $H^+ = (SO_4^{2-} + NO_3^- + Cl^-) - (Na^+ + NH_4^+ + Ca^{2+} + Mg^{2+})$

The above equation has proven to be useful in studies of acidic precipitation. Prior to about 1955, the measurement of pH was somewhat inaccurate. There were, however, reliable analyses of other important ions in surface waters and precipitation. In such cases, the equation can be used to calculate pre-1955 pH values, providing important data for studies of the historical pH in waters sensitive to acidification.

One of the longest-running records of precipitation chemistry is from a research site at Hubbard Brook, New Hampshire, in a region exposed to intense acidifying deposition. During 1967-1971, when acid rain was relatively severe, the average pH of precipitation at Hubbard Brook was 4.1. This level of acidity then relaxed somewhat to pH 4.9 in 1991-1995 because of decreased industrial emissions, particularly of the acid-forming gas SO_2, and then even more so in 2009-2013 because of further decreases in SO_2emissions (Table 19.1; see In Detail 19.2 for an explanation of equivalents). Sulphate and nitrate are the most important anions in precipitation, and from 1967-1971 they occurred accounted for 88% of the anion equivalents. During 2009-2013 these two still contributed 87% of the anion equivalents, although their total amounts were considerable smaller. These data suggest that most of the acidity in the precipitation occurs as dilute solutions of sulphuric and nitric acids. The precipitation events at Hubbard Brook that are most acidic are associated with storms that have passed over the large metropolitan regions of Boston, New York, and New Jersey. These areas have enormous emissions of SO_2 and NO_x, which are the precursor gases of much of the SO_4^{2-} and NO_3^- in acidic precipitation.

Table 19.1. Chemistry of Precipitation at Hubbard Brook. The data represent the average concentration (in microequivalents per litre, or μeq/L) of various ions in precipitation during three 5-year periods. The small difference between the sums of cation and anion equivalents is due to analytical inaccuracies, which are inevitable in even the best chemical data. Source: Data from Buso et al. (2003).

Constituent	1967-71	1991–95	2006-10
	µeq/L	µeq/L	µeq/L
Cations			
H^+	76.6	50.4	22.2
NH_4^+	13.9	11.9	7.5
Ca^{2+}	7.2	3.8	3.2
Na^+	5.2	5.2	3
Mg^{2+}	3.3	2	5.7
Al^{3+}	0.4	0.4	0.4
K^+	1.5	1.1	1
Anions			
SO_4^{2-}	57.4	39.1	26.2
NO_3^-	25.3	26.3	12.8
Cl^-	10.9	6.6	3.8
PO_4^{3-}	0.1	0.1	1.2
HCO_3^-	<0.1	<0.1	<0.1
Sum Cations	108.1	74.8	44
Sum Anions	93.7	72.1	44.6
pH	4.12	4.3	4.69

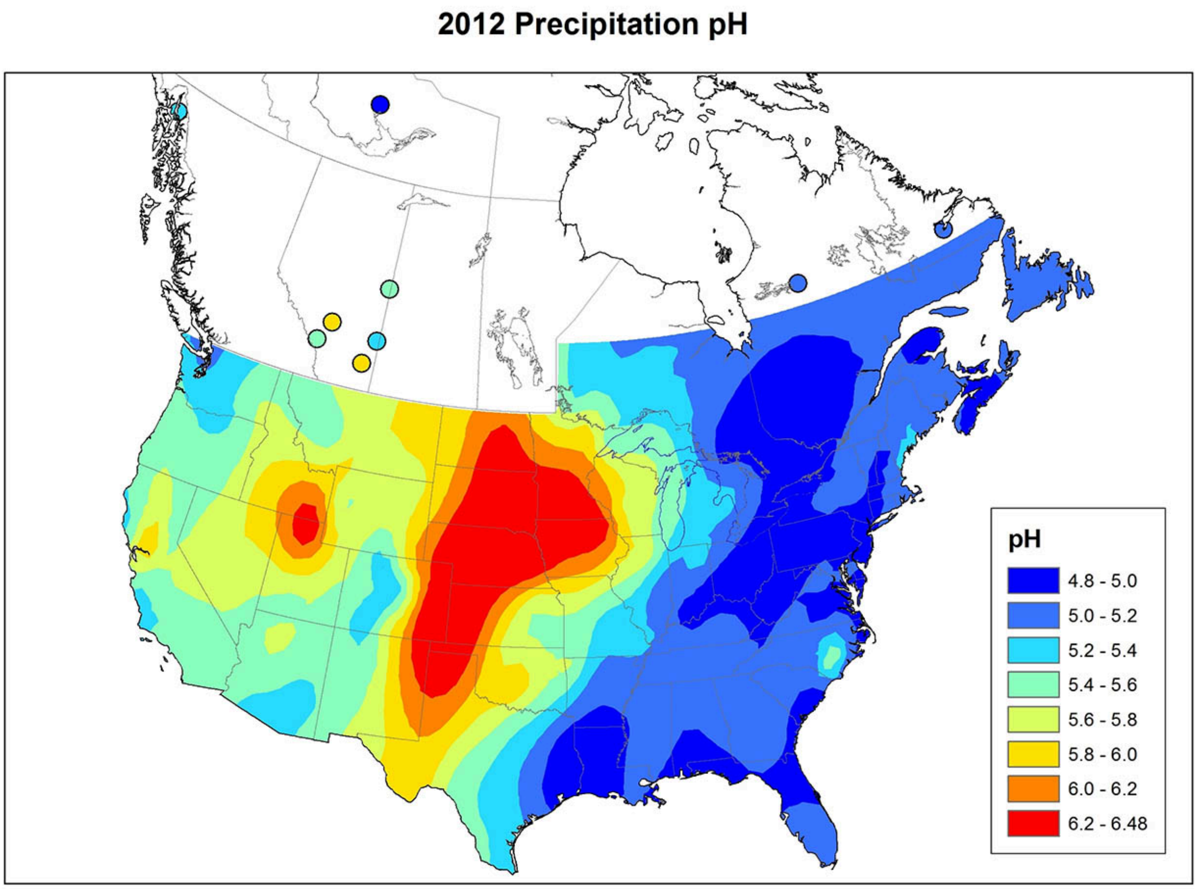
Spatial Patterns

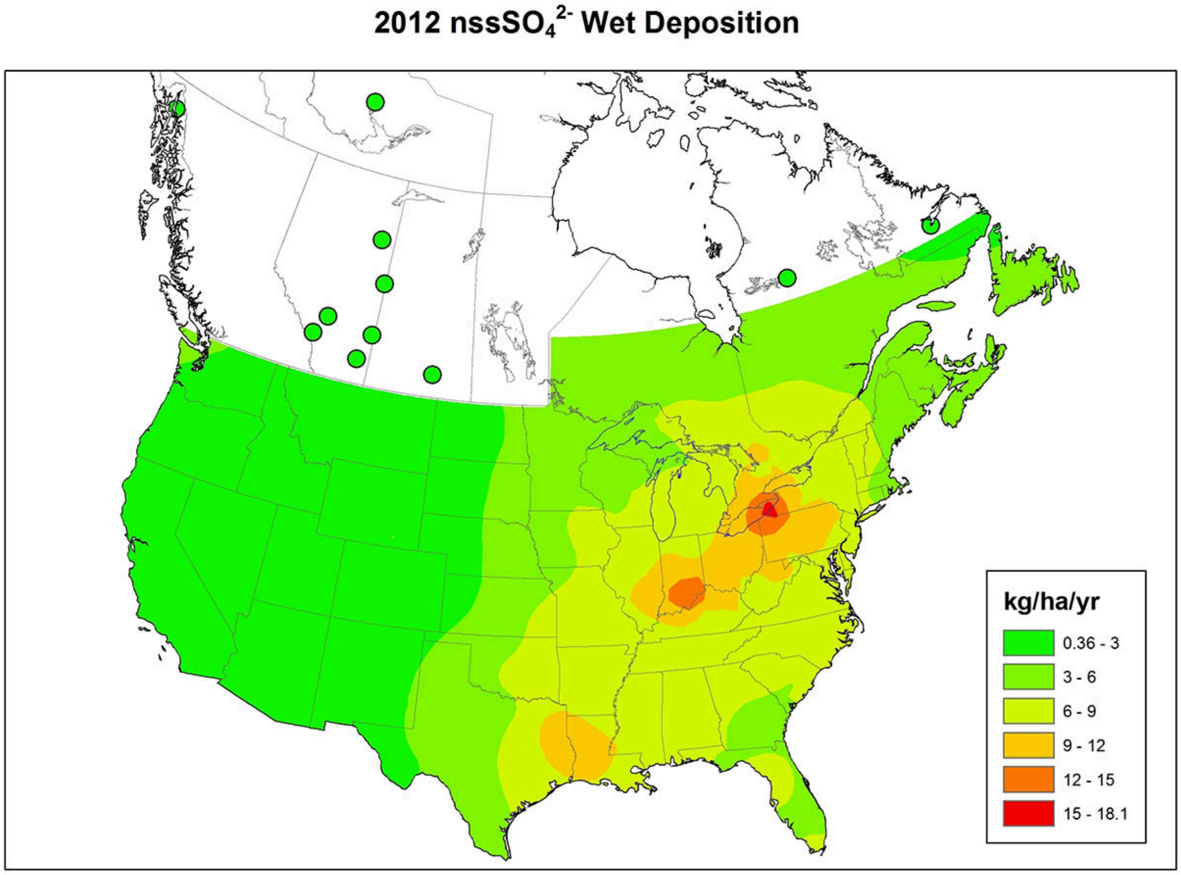
Acidic precipitation is a widespread phenomenon in eastern North America (Figure 19.1), Europe, eastern Asia, and elsewhere. In eastern North America prior to the mid-1950s, precipitation with pH below 4.6 affected only relatively local areas, mostly in southern Ontario, New York, Pennsylvania, and New England. Since then, however, this area has expanded considerably. At present, most of southeastern Canada and the eastern United States experiences acidic precipitation. It appears that the spatial pattern in North America existed before the 1950s, but the phenomenon has since become more widespread and its intensity has increased. One of the most important aspects of acidic precipitation is the vast size of the areas it affects.

Precipitation chemistry varies greatly between regions (Figure 19.1). The variation reflects the patterns of emission of SO_2 and NO_x, the degree of oxidation of those gases to SO_4^{2-} and NO_3-, the prevailing direction travelled by polluted air masses, and the amount of acid-neutralizing dust in the atmosphere. Atmospheric dust is particularly important where vegetation cover is sparse, such as in agricultural regions where tiny soil particles are easily eroded into the atmosphere by strong winds blowing over bare fields. Unpaved roads are also an important source of atmospheric dust.

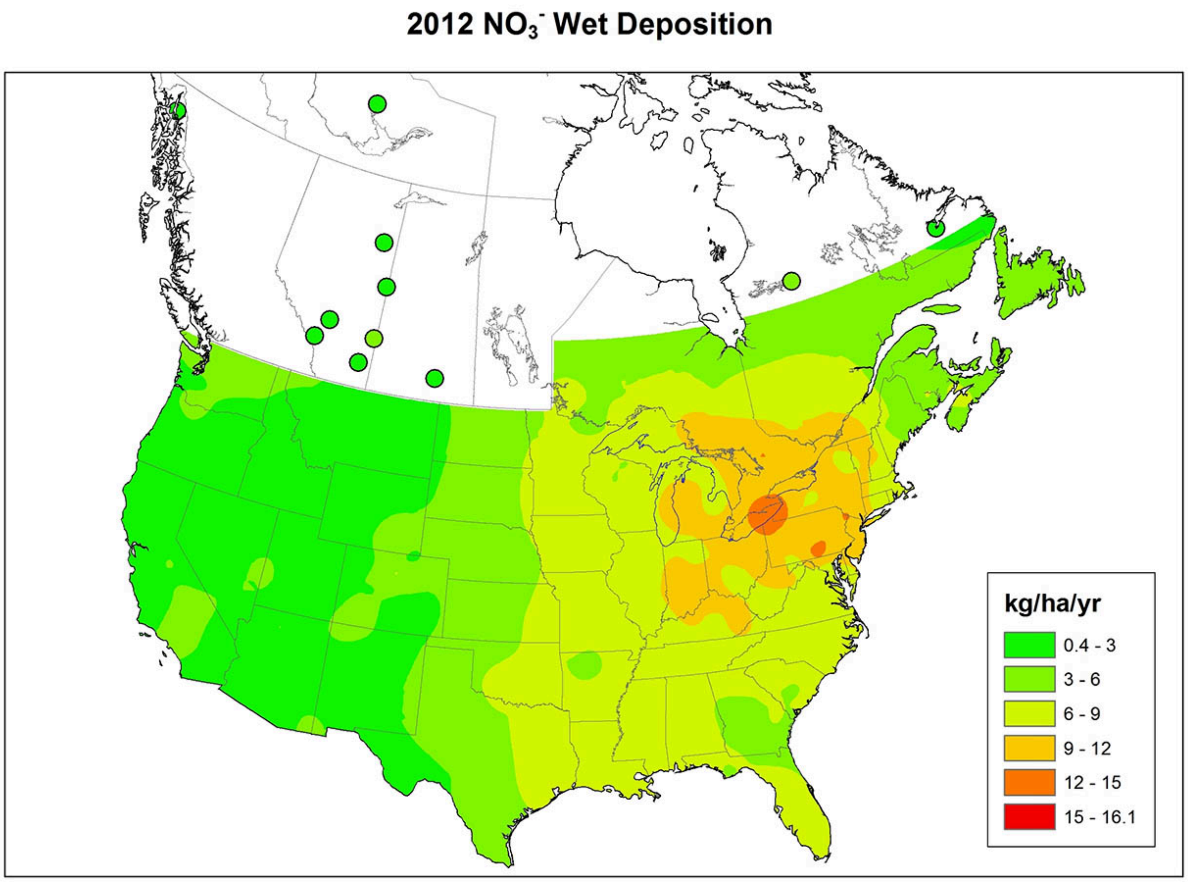
Figure 19.2. Characteristics of Precipitation in Eastern North America. Points on the curved lines (known as isopleths) have equal annual average values of (a) pH in precipitation; (b) sulphate deposition in precipitation (in kg/ha•y; this is excess sulphate, which is corrected for sulphate of marine origin); and (c) nitrate deposition (in

kg/ha•y). Maps are for 2012. Source: Ro (2014).


2012 Precipitation pH
pH
4.8 - 5.0
5.0 - 5.2
5.2 - 5.4
5.4 - 5.6
5.6 - 5.8
5.8 - 6.0
6.0 - 6.2
6.2 - 6.48



2012 nssSO4 2- Wet Deposition
kg/ha/yr
0.36 - 3
3 - 6
6 - 9
9 - 12
12 - 15
15 - 18.1



Information on the chemistry of precipitation at four widely separated Canadian sites is summarized in Table 19.2. Dorset is located in a rural area south-central Ontario, but not far north of the densely populated region of Greater Toronto (noted as "populated continental" in the table because it is an inland site close to large population centres to the south). The terrain is underlain by hard rocks of the Precambrian Shield, such as granite, gneiss, and quartzite, and the vegetation cover is mostly forest. The precipitation is highly acidic in the Dorset region, with an average pH of 4.1 and high concentrations of SO_4^{2-} and NO_3-, which suggests that the acidity is due mainly to dilute sulphuric and nitric acids. Much of the sulphate and nitrate in precipitation is derived from SO_2 and NO_x emitted by industries and automobiles to the south, which are then transported in the atmosphere before being deposited as acidifying deposition in the Dorset region.

Table 19.2. Precipitation Chemistry in Various Places in Canada. The data (in μeq/L) are average concentrations in wet-only precipitation, meaning the collector was open to the atmosphere only during rain or snow events.

ELA refers to the Experimental Lakes Area. Source: Modified from Freedman (1995).

Constituent	Dorset, ON (Populated Continental)	ELA, ON (Remote Continental)	Kejimkujik, NS (Coastal Maritime)	Lethbridge, AB (Prairie)
Cations				
H^+	73.6	18.6	25.1	1
Ca^{2+}	10	12	4.3	112.8
Mg^{2+}	2.4	2.4	2.9	25.5
Na^+	3.9	4.3	26.1	9.6
K^+	1	2	1.1	2.3
NH_4^+	15.6	18.9	4.2	22.2
Anions				
SO_4^{2-}	58.3	27.1	27.5	43.5
NO_3^-	35.5	16.4	9.7	20.8
Cl^-	4.2	5.4	29.5	9.9
pH	4.1	4.7	4.6	6

The ELA (Experimental Lakes Area) site is in a remote area of northwestern Ontario near Kenora (see Canadian Focus 20.1). Like Dorset, the ELA is in a largely forested landscape of Precambrian Shield, where bedrock and soil are composed of hard minerals such as granite and gneiss. However, the ELA site is much less influenced by air masses affected by anthropogenic emissions (labelled as "remote continental"), so its precipitation is not as acidic (average pH 4.7) than at Dorset and has less nitrate and sulphate.

The Kejimkujik site in western Nova Scotia is also underlain by hard granitic bedrock and the nearby terrain is forested. This site is distant from large sources of emissions of SO_2 and NO_x, but it often receives air masses that have passed over densely populated areas in the northeastern United States and eastern Canada. However, by the time the storm systems reach Kejimkujik, much of their acidic material has rained out, so the local precipitation is only moderately acidic (average pH 4.6). Kejimkujik is also influenced by oceanic weather systems, so its precipitation has high concentrations of sodium and chloride that are derived from sea spray. Oceanic salt water has a pH of about 8.0 because of the presence of chemicals such as bicarbonate, so marine aerosols have an acid-neutralizing influence on the precipitation in coastal regions.

Lethbridge is located in a landscape of mixed-grass prairie in southern Alberta. Precipitation there is non-acidic (average pH 6.0) because of the neutralizing influence of calcium- and magnesium-rich particulates that are relatively abundant in the atmosphere. These originate with dust blown up from agricultural fields and roads. This dust also accounts for the abundant Ca^{2+} and Mg^{2+} in the precipitation.

Rapid changes in precipitation chemistry may occur at the border between a forested landscape and areas dominated by prairie or agricultural land. A study in southern Ontario examined precipitation at eight places in a forested area with thin soil and Precambrian bedrock, and at three sites just south of the Shield in agricultural terrain with calcium-rich soil (Dillon et al., 1977). The average pH of precipitation among the Shield sites was 4.1-4.2, while at sites to the south it was 4.8-5.8. Precipitation was less acidic in the agricultural area because of the local neutralizing influence of dust blown up from fields and roads.

Image 19.1. Terrain in the La Cloche highlands of Ontario is sensitive to acidification because of the presence of thin soil and hard quartzitic bedrock (whitish colour in the photo). Lakes in this terrain have very little capability for neutralizing inputs of acidifying substances from the atmosphere. Source: B. Freedman.

Another important characteristic of acidic precipitation is that, unlike SO_2 and metal particulates, its intensity does not increase closer to large point sources of emissions, such as a coal-fired power plant or a smelter. For instance, precipitation is no more acidic close to the superstack at Sudbury than in the larger region, yet that is Canada's largest point sources of SO_2. Moreover, when that smelter was closed by a strike in 1979, the acidity of local precipitation did not change – it averaged pH 4.49 during the seven-month strike, compared with pH 4.52 during the prior seven months when there were large SO_2 emissions (Scheider et al., 1980).

Fog moisture may also be quite acidic in eastern North America and elsewhere. Fogwater collected at high elevations and at coastal locations is commonly more acidic than pH 4.0, and it can be as acidic as pH 2.5-3.0. At forested sites where fog is a common occurrence, large amounts of acidity and other chemicals are filtered out of the atmosphere by trees. This occurs because tiny suspended water droplets coalesce on the surface of foliage and bark as fog passes through a forest canopy, a process that removes much of the fogwater from the atmosphere. This phenomenon is illustrated in Table 19.3 for a conifer forest on a mountain that often experiences foggy conditions. The total input of atmospheric moisture to that forest was 264 cm/year, with rain and snow accounting for 68% and fogwater 32% (fog was present 40% of the time). However, the concentrations of many chemicals are much higher in fogwater than in precipitation – because the suspended water droplets are tiny, the dissolved chemicals are less "diluted" by their aqueous matrix. As a result, the rates of deposition of dissolved substances to the forest can be higher than from precipitation. At this particular location, fog water accounted for 62% of the H^+ deposition and 81% of the inputs of SO_4^{2-} and NO^{3-}.

Table 19.3. Chemistry and Deposition of Fogwater. The deposition of water and ions was studied in a conifer forest at a high-elevation site on Mount Moosilauke, New Hampshire. Fogwater deposition occurs when

suspended water droplets are "filtered" from the atmosphere by trees. The concentrations are average values, in microequivalents per litre. Precipitation refers to rain plus snow, while percent fogwater refers to the deposition that was due to that source. Source: Modified from Lovett et al. (1982)

	Concentration	Deposition (kg/ha•y)			Percent Fogwater
	(μeq/L)	Cloud	Precipitation	Total	
H^+	288	2.4	1.5	3.9	62
NH_4^+	108	16.3	4.2	20.5	80
Na^+	30	5.8	1.7	7.5	77
K^+	10	3.3	2.1	5.4	61
SO_4^{2-}	342	275.8	64.8	340.6	81
NO_3^-	195	101.5	23.4	124.9	81
H_2O (cm/y)		84	180	264	32

Transboundary Air Pollution

Acidifying substances and their gaseous precursors are often transported over long distances in the atmosphere, far from their sources of emission. The acidifying chemicals do not respect political boundaries, so emissions occurring in one country can degrade ecosystems and valuable resources in other countries. This transboundary context has helped to focus the attention of governments on the problem of acidifying deposition from the atmosphere.

In Western Europe, for example, Scandinavians justifiably argued that most of the acidifying deposition that has affected extensive regions of their landscape has resulted from emissions of SO_2 and NO_x in Germany and England. This international European context was the first well-demonstrated case of so-called LRTAP, an acronym for the long-range transport of atmospheric pollutants.

Similar transboundary circumstances occur elsewhere. In eastern North America, there are large populations and industrial centres in the northeastern United States. Emissions of SO_2 and NO_x from those areas often waft into eastern Canada, worsening damage caused there by local emissions. U.S. emissions are responsible for about 90% of the wet deposition of acidifying nitrogen compounds in eastern Canada, along with 63% of the wet deposition of sulphur compounds, 43% of the dry deposition of nitrogen, and 24% of the dry deposition of sulphur (Shannon and Lecht, 1986). Canada also exports some of its emissions to the United States, although Canadian emissions account for less than 5% of the total deposition of sulphur and nitrogen compounds in the eastern states. In total, Canada receives about 4 million tonnes of SO_2 per year from the United States (Environment Canada, 1999).

Dry Deposition

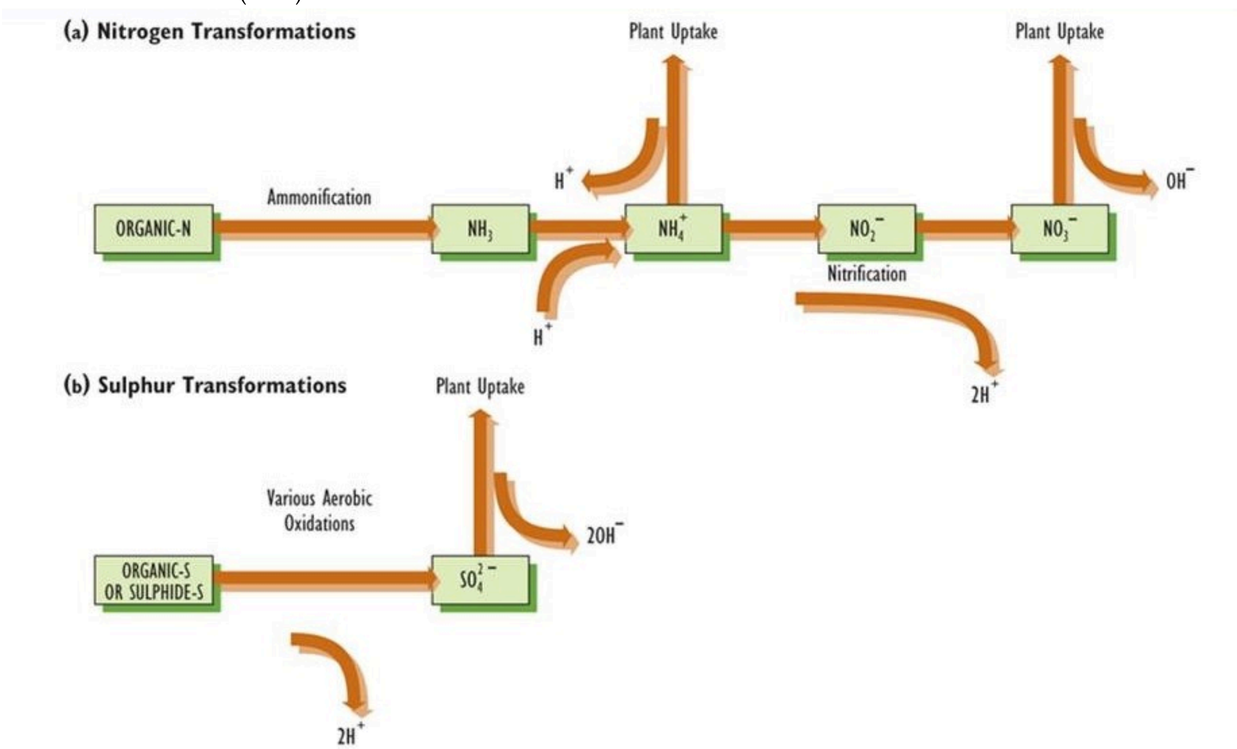
Dry deposition occurs during intervals between precipitation events, and it includes the following:

- the direct uptake of gaseous SO_2 and NO_x by vegetation, soil, and water
- gravitational settling of larger particles
- the filtering of suspended particulates by vegetation

Dry deposition occurs to all kinds of habitat, but forest is particularly effective at absorbing gases and particles from the atmosphere. This is because trees have such a large and complex surface area of foliage and bark, which greatly enhances the rate of dry deposition.

Dry deposition can result in large inputs of substances from the atmosphere, including some that generate acidity when they are chemically transformed within the ecosystem. For instance, atmospheric SO_2 readily dissolves into the surface water of lakes and streams. This gas is also freely absorbed by plants – it enters foliage through tiny abundant pores on the surface known as stomata, and then dissolves into the moist film of water that covers the surface of cells in a sub-stomatal cavity. In this sense, the SO_2 behaves just like CO_2, a vital nutrient, which is also absorbed by plants in this manner. The absorbed SO_2 becomes oxidized to the anion sulphite (SO_3^{2-}), which is rapidly oxidized to sulphate (SO_4^{2-}). Because the sulphate is balanced electrochemically mostly by hydrogen ions, acidity is generated by the transformation of SO_2 gas into the SO_4^{2-} ion (see Figure 19.2).

Figure 19.3. Acidification Caused by Transformations of Sulphur and Nitrogen. This diagram describes the acidifying effects of important transformations of nitrogen and sulphur compounds in soil or water. Source: Modified from Reuss (1985).



NO_x gas may be similarly dry-deposited and then oxidized to nitrate (NO_3-), which also generates an equivalent amount of H^+. The gas ammonia (NH_3) and the cation ammonium (NH_4+) can also be dry-deposited to soil or water, where they can be oxidized by bacteria to nitrate plus equivalent quantities of H^+.

The rates of dry deposition of sulphur and nitrogen compounds are greatest when there are high concentrations of gaseous NO_x and SO_2 in the atmosphere. Such conditions typically occur in urban areas and close to large industrial sources of emissions. In those places, dry deposition accounts for much larger inputs of acidifying substances than does wet deposition. In more remote, less-contaminated environments, far from sources of emission, inputs with precipitation are typically larger than dry deposition.

Within 40 km of the largest smelter at Sudbury, about 55% of the atmospheric sulphur deposition occurs as dry deposition (Chan et al., 1984). About 91% of the dry deposition involves gaseous SO_2, while the rest is sulphate particulates. However, the superstack at that smelter, being extremely tall (380 m), is effective at dispersing its emissions of SO_2. Consequently, less than 1% of the SO_2 emitted by that point-source is deposited nearby (in this case, within 40 km). Rather, almost all of the SO_2 is transported much farther away before it is deposited to the landscape.

Soil Acidity

Soil acidity is an important factor that affects the growth of plants. Soil acidification is a natural process that has been demonstrated by studies of succession in ecosystems.

One well-known study was done at Glacier Bay in Alaska. The melting of a glacier in a long fiord is exposing a mineral substrate of till that has a pH of about 8.0 and contains up to 10% carbonate minerals of calcium and magnesium (Crocker and Major, 1955). Once exposed, this material becomes modified by colonizing plants and climatic factors. Rainfall is especially important, because much of it percolates through the soil and leaches dissolved chemicals to beyond the rooting depth of the plants. These influences result in an increased acidity of the soil, which reaches about pH 4.8 after 70 years of succession, by which time a conifer forest is established. The acidification is accompanied by large and progressive declines in the amounts of Ca, Mg, and carbonates in the soil during the succession.

In part, the acidification is caused by the uptake of the nutrients Ca, Mg, and K by trees and other plants, a process that is accompanied by the excretion of H^+ and a decrease in the buffering capacity of the soil (this is related to the ability of the soil to resist further acidification). The leaching of calcium and other cations out of the soil by rainwater also contributes to acidification.

Various chemical changes occur as rainwater percolates through the soil and interacts with minerals, organic matter, microbes, and roots:

- Roots and microorganisms selectively absorb, release, and transform chemicals
- Ions are exchanged at the surfaces of clay particles, minerals, and organic matter
- Insoluble minerals are made soluble by so-called weathering processes, including reactions with acids
- Secondary minerals are formed, such as certain clays and insoluble precipitates of iron and aluminum oxides

These reactions cause important changes to occur in the soil, such as acidification, the leaching of calcium and magnesium, and the solubilization of metals, particularly toxic ions of aluminum (such as Al^{3+}; see Chapter 18). All of these processes occur naturally wherever the input of water from precipitation exceeds the amount returned to the atmosphere by evapotranspiration, so there is a surplus to percolate downward through the soil. These reactions are also influenced by the kind of vegetation growing on the site. For instance, pines, spruces, and oaks tend to cause soil to acidify. In addition, the deposition of acidifying substances from the atmosphere can potentially increase the rates of some of these processes in soil, and thereby increase the leaching of toxic Al^{3+} and H^+ into streams and lakes.

Factors Affecting Soil Acidity

Soil acidity is influenced by numerous chemical transformations and ion exchanges. Some are carried out by organisms, while others are non-biological reactions. The following are the most important factors affecting soil acidity.

- **Carbonic Acid**. In many terrestrial ecosystems, such as grassland and forest, the surface litter and upper soil are rich in organic matter and roots. Decomposition and respiration result in high concentrations of CO_2 (often exceeding 1%) in the atmosphere within the soil. The high CO_2concentrations result in carbonic acid (H_2CO_3) forming in the soil water, which contributes to its acidification. This effect is strongest in soil with a pH greater than about 6.0, and it is unimportant in acidic soil with pH less than about 5.5.

- **The Nitrogen Cycle**. Soil acidity can also be affected by microbial transformations of nitrogen compounds and by their uptake and release by plants (Figure 19.2). Ammonium (NH_4+) and nitrate (NO_3-) are especially important because plants must take up one or both of these essential nutrients, the choice depending largely on soil acidity. In soil with pH less than about 5.5, almost all inorganic nitrogen occurs as NH_4+. The NH_4+ may originate from the ammonification of organic nitrogen to form ammonia (NH_3), a process carried out by many species of microorganisms (see Chapter 5). The ammonia absorbs one H^+ to form ammonium. If the NH_4+ ion is absorbed by a plant root, one H^+ is excreted into the soil to maintain electrochemical neutrality, so there is no net change in acidity. However, if NH_4+ is added directly to soil (such as by atmospheric deposition or by the application of a fertilizer), then plant uptake of NH_4+, accompanied by the release of H^+, has an acidifying effect. In soils with pH greater than 5.5, most of the inorganic nitrogen occurs as NO_3-, which is produced by the oxidation of NH_4+ through the process of nitrification (Chapter 5). Nitrification is carried out by the bacteria Nitrosomonas and Nitrobacter, which are intolerant of acidity. The oxidation of NH_4+ to NO_3– generates two H^+ (Figure 19.2). If the NH_4+ originated from ammonification of organic nitrogen (which consumes one H^+ for each NH_4+ produced), the net effect is the release of one H^+ for each NO_3– produced from organic nitrogen. However, if the NO_3– is then absorbed by a root, one OH^- is excreted to the soil to maintain electrochemical neutrality, which is equivalent to the consumption of one H^+. In that case, the net effect on soil acidity is zero. It is well known to farmers and agronomists that the addition of ammonium to soil can have a severely acidifying influence. This happens because the NH_4+ becomes nitrified into NO_3-, which generates large amounts of acidity. There are two main types of ammonium inputs: the treatment of agricultural fields with fertilizer containing inorganic nitrogen (such as urea or ammonium nitrate), and the deposition of NH_3 gas and NH_4+ from the atmosphere.

- **The Sulphur Cycle**. Much of the sulphur in soil occurs in organically bound forms. Microbial processes can transform this organic sulphur into more highly oxidized compounds, including sulphides and elemental sulphur, but if oxygen is abundant, these become further oxidized to sulphate. Overall, the oxidation of organic sulphur to SO_4^{2-} releases one equivalent of H^+ per equivalent of SO_4^{2-} produced (this is the same as two H^+ per SO_4^{2-} SO_4^{2-} is absorbed by a root, an equivalent quantity of OH^- is excreted to conserve electrochemical neutrality, so there is no net effect on acidity. However, if atmospheric deposition causes a direct input of SO_4^{2-} to the soil, followed by uptake by plant roots, the net effect is a reduction of acidity. In addition, if the soil is deficient in oxygen (anaerobic), as commonly occurs in wet sites, then the SO_4^{2-} can be transformed by microbes into a sulphide compound, which results in the consumption of an equivalent amount of H^+ and a reduction in acidity.

  Reactions associated with the sulphur cycle usually have a smaller effect on soil acidity than those involving the nitrogen cycle. In certain situations, however, the sulphur cycle is dominant. For instance, when a wetland is drained, its previously anaerobic sediment becomes aerobic. This allows bacteria to oxidize reduced sulphide compounds into sulphate. Some drained wetlands develop an extremely acidic condition known as acid sulphate soil. For 10 or more years after drainage occurs, usually to develop agricultural land, the pH can be lower than 3.0. This severely impairs crop growth, although the acidity can be neutralized by adding calcium carbonate (lime) to the soil.

  Sometimes, sulphide minerals such as pyrite (iron sulphides) become exposed to atmospheric oxygen. This allows specialized Thiobacillus bacteria to oxidize the sulphides, a process that produces sulphate and oxidized iron ions, according to the following reaction: $4\ FeS_2 + 15\ O_2 + 14\ H_2O \rightarrow 4\ Fe(OH)_3 + 16\ H^+ + 8\ SO_4^{2-}$

  This phenomenon, known as acid-mine drainage (or as acid-rock drainage), causes severe acidification of soil and surface waters. It can cause a pH less than 2.0 to develop, with high concentrations of sulphate and toxic ions of aluminum and iron. Acid-mine drainage is an important problem where coal and metal mining have exposed mineral sulphides to the atmosphere (see In Detail 19.3).

- **Uptake of Basic Cations by Plants**. Terrestrial plants obtain many of their nutrients by absorbing ions from the soil in which they are growing. (A few nutrients, however, are absorbed mainly from the atmosphere, particularly CO_2.) Calcium, magnesium, and potassium are important nutrients that are absorbed from soil as cations (Ca^{2+}, Mg^{2+}, and K+), whose absorption is offset by a release of H^+. In natural ecosystems, the absorbed Ca^{2+}, Mg^{2+}, and K+ are eventually returned to the soil with plant litter, so there is no long-term effect on soil acidity. However, if biomass is removed from the site, as occurs in agriculture and forestry, these cations are removed, resulting in acidification of the soil.
- **Leaching of Ions**. In most soils, the anions nitrate and chloride readily leach downward into the groundwater. They do this because they are highly soluble in water, and are only weakly retained at anion-exchange sites on organic matter and clays. The leached anions may eventually reach surface waters such as streams and lakes. This is also true of sulphate, especially in relatively young soils of glaciated regions, including most of Canada (older soils of more southern regions often have a greater capacity to retain sulphate). In areas with large inputs of acidifying substances, the amounts of NO_3– and SO_4^{2-} in soil may be high enough to result in substantial rates of leaching. As these anions leach from the soil, they are accompanied by cations such as Ca^{2+}, Mg^{2+}, H^+, and Al^{3+}, which results in acidification, nutrient loss, and toxicity (associated with the Al^{3+}) in terrestrial and aquatic ecosystems. For instance, one monitored watershed in south-central Ontario was found to have lost 30% of its soil calcium between 1983 and 1999 (Watmough and Dillon, 2004).

Atmospheric Deposition and Soil

The potential effects of atmospheric deposition on soil acidity have been studied in experiments in which simulated rainwater solutions was added to soil contained in plastic cylinders, known as lysimeters. These experiments have shown that extremely acidic solutions can cause these changes in soil chemistry:

- an increase in acidity
- increased leaching of calcium, magnesium, and potassium, resulting in their depletion and greater vulnerability of the soil to acidification
- increased solubilization of toxic metal ions, especially of aluminum, but also iron, manganese, and others
- an overwhelming of the ability of soil to absorb sulphate, after which this ion leaches freely, at a rate similar to its input (because SO_4^{2-} is an anion, its leaching is accompanied by base cations and toxic Al^{3+} and H^+, which may contribute to the acidification and toxicity of surface waters.)

One experiment involved the treatment of a sandy soil from jack pine stands with simulated rainwater, adjusted with sulphuric acid to a pH of 5.7, 4.0, 3.0, or 2.0 (Table 19.4). Even treatment with the extremely acidic pH 2.0 had little effect on soil acidity, and the percolating solutions had a pH higher than 6.5 in all treatments. However, the leaching of Ca, Mg, total bases (Ca + Mg + K + Na), and sulphate were much higher in the pH 2.0 treatment. Overall, this experiment found that the soil was quite resistant to effects of acid loading. Eventually, however, the resistance could be overcome by treatment with highly acidic solutions, and perhaps by long-term exposure to more moderate acidities. Keep in mind that experiments such as these are short-term investigations, whereas soil acidification in nature is a slow, long-term process.

Table 19.4. Experimental Leaching of Soil by Acidic Solutions. The data are concentrations of chemicals in water that drained from lysimeters containing sandy soil collected from two jack pine (Pinus banksiana) stands in northern Ontario. The experiment ran for three years, with simulated rainfall of various pH levels added at 100 cm/year as weekly 1-2 hour events. The data are averages of three replicates. Source: Modified from Morrison

(1983).

	Solution pH	Concentration in Percolate (meq/L)			
		Ca	Mg	All Bases	SO_4
Soil A	5.7	0.74	0.05	0.99	0.23
	4	0.67	0.05	0.99	0.22
	3	0.75	0.07	1.1	0.15
	2	0.87	0.2	1.35	0.53
Soil B	5.7	0.42	0.17	0.73	0.15
	4	0.45	0.18	0.77	0.15
	3	0.4	0.17	0.7	0.28
	2	3.72	1.47	5.5	5.43

Researchers monitoring soil chemistry at particular places in the field can determine whether acidification has occurred, although such studies do not necessarily identify the causes of the change. For instance, the conversion of agricultural land into conifer forest usually results in acidification of the soil. In southern Ontario, the afforestation of abandoned farmland with pine or spruce caused the soil to acidify from pH 5.7 to pH 4.7 after 46 years of forest development (Brand et al., 1986). It is less understood whether already-forested sites will become more acidic because of atmospheric inputs of acidifying substances. A study in southern Ontario re-sampled forest soils after a 16-year interval, in a region where the average pH of precipitation is about 4.1, but no further soil acidification was observed (Linzon and Temple, 1980).

Overall, studies conducted elsewhere in Canada, and in the United States and Europe, have also come to ambiguous conclusions about the effects of atmospheric deposition on soil acidification. Except for cases where the atmosphere is severely polluted by SO_2, such as near a metal smelter, there is no convincing evidence that atmospheric deposition has acidified soil on a wide scale. It appears that soil acidification is a potential long-term risk associated with this type of pollution.

Terrestrial Vegetation

Numerous studies have demonstrated that plants may be injured by treatment with simulated "acid rain." In almost all of the studies, however, the pH that caused acute injuries was more acidic than is normally found in ambient precipitation.

For example, experiments in Norway exposed young conifer stands to simulated acid rain for three years (Tveite, 1980). The control treatment was pH 5.6-6.1, while the acidified treatments used pH 4.0 or 3.0. On average, control saplings of lodgepole pine (Pinus contorta) grew 15–20% less than plants receiving the acidic treatments. Growth of Scotch pine (P. sylvestris) and birch (Betula pendula) was also stimulated by the acidic treatments, while spruce (Picea abies) was unaffected. However, the moss-dominated ground vegetation was severely damaged by the most acidic treatment (pH 3.0).

Laboratory experiments are also useful for determining the effects of rainwater pH on plants, because the environmental conditions can be well controlled. In general, such experiments do not find reductions of growth until the pH becomes more acidic than about 3.0 (for comparison, the average acidity of precipitation is about pH 4.0 in regions where acid rain is considered a severe problem). Moreover, the productivity of some tolerant species may be stimulated by rainwater even more acidic than pH 3.0. For example, seedlings of white pine (Pinus strobus) grew more quickly when exposed to acidic mist ranging from pH 2.3 to 4.0 than at pH 5.6 (Wood and Bormann, 1976). In another experiment, seedlings of 11 tree species were treated with solutions of various pHs, but acute injury to foliage was caused only after a week of treatment at pH 2.6, which is an unnaturally acidic exposure (Percy, 1986).

In general, it appears that trees and other vascular plants have little risk of suffering acute injury from exposure to ambient acid rain. However, stresses associated with acidic precipitation could possibly decrease plant growth, even in the absence of acute injuries. These “hidden injuries” (see Chapter 16) might be caused by a subtle disruption of plant metabolism, or indirectly by changes in soil chemistry. Because acidic precipitation affects extensive regions, even a small decrease in plant productivity could have important economic and ecological consequences.

Hidden injuries, if they do occur, are most relevant to forest and other kinds of natural vegetation. Agricultural land becomes acidified mostly through management practices, such as cropping and the use of nitrogen fertilizer. Moreover, agricultural soil is routinely treated with liming agents to reduce its acidity.

Image 19.2. During the 1980s, many stands of sugar maple (Acer saccharum) in Ontario and Quebec suffered a severe thinning of their canopy. In some places, many trees died. Some scientists believe this damage was caused by acid rain, or by other types of air pollution, such as ozone. Alternative explanations include climate change, severe winter weather, nutrient imbalance, and a history of insect infestation. The controversy over the causes of the phenomenon has not been resolved, but fortunately, much of the damage disappeared by the mid-1990s. This photo was taken in a declining stand in southern Ontario. Source: R. Vinebrooke.

A number of studies in eastern North America and Europe have examined the potential effects of acidic precipitation on forest productivity. Although species of trees in some regions have shown recent decreases in productivity, it has not been conclusively demonstrated that these changes were caused by acidic precipitation or other kinds of atmospheric pollution. Forest productivity decreases naturally as a stand matures, mainly because canopy closure intensifies competition among the trees. Forest productivity is also influenced by such factors as climate change and management practices. So far, field research has not clearly separated any influences of acidic precipitation on forest productivity from effects related to succession, climate change, insect defoliation, or other factors. However, some growth-modelling studies have suggested that productivity could decrease by 10% in eastern Canada if critical deposition rates of sulphate and nitrate are exceeded (Natural Resources Canada, 1998).

Clearly, the effects of acidifying depositions on soil and vegetation are somewhat ambiguous. However, as the following sections will show, the effects on vulnerable freshwater ecosystems can be severe.

Surface Waters

Surface waters include streams, rivers, lakes, and ponds. Their chemistry is influenced by the types of soil and vegetation in the watershed, climatic factors, and the deposition of chemicals from the atmosphere.

In regions where the winters are cold and a snowpack accumulates, the springtime meltwater that flows into streams and lakes tends to be relatively acidic. This so-called acid shock phenomenon occurs partly because snowmelt cannot percolate into the frozen soil, so its acidity does not become neutralized by interaction with minerals there. In addition, the initial meltwaters are considerably more acidic than the later fractions. The relatively intense acidity of snowmelt is responsible for much of the toxicity of affected surface waters.

The water chemistry of two lakes in a region of Nova Scotia that is subject to acidic precipitation is described in Table 19.5. These lakes are more dilute than most fresh waters, in the sense of having a low concentration of dissolved ions, and their nutrient supply is sparse, so they are unproductive (oligotrophic). Nevertheless, these lakes have higher concentrations of dissolved substances than the precipitation that falls on them –their total ions average 440 μeq/L, compared with 135 μeq/L in precipitation. The higher concentrations are due to substances that leach from terrestrial soil and eventually migrate into the lakewater. In contrast, the concentrations of ammonium and nitrate are higher in precipitation than in the lakes, suggesting that the atmospheric inputs of these nutrients are “consumed” by biological uptake within the watershed.

Table 19.5. Chemistry of Two Lakes in Nova Scotia Lakes. The data are the average concentration (μeq/L) of chemicals in precipitation and in water of two lakes. Beaverskin Lake has clear water while Pebbleloggitch has brown water because of drainage from a bog in its watershed. Both are headwater lakes, meaning they do not receive drainage from lakes higher in altitude. Source: Data from Kerekes and Freedman (1988) and Freedman

and Clair (1987).

Constituent	Precipitation	Beaverskin	Pebbleloggitch
Cations			
Ca^{2+}	4.3	20	18
Mg^{2+}	2.9	32	30
Na^{+}	26.1	126	126
K^{+}	1.1	8	6
Fe^{3+}	<0.1	1	4
Al^{3+}	<0.1	2.2	23.4
NH_4^{+}	4.2	1	2.4
H^{+}	29.9	5	33
Anions			
SO_4^{-2}	27.5	48.7	57.9
Cl^{-}	29.5	124	111
NO_3^{-}	9.7	1	0.9
Organic anions	<0.1	32	66
Total cations	68.5	195.2	242.8
Total anions	66.7	205.7	235.8
Total Carbon (mg/L)	0	4.5	13.8
Colour (Hazen units)	0	6	87
pH	4.6	5.3	4.5

Beaverskin Lake is slightly acidic (pH 5.3) and oligotrophic, with very transparent water. In comparison, Pebbleloggitch Lake is influenced by drainage from an adjacent bog. Dissolved organic compounds (known as fulvic acids) drain from the bog into the lake, giving the lakewater a dark-brown colour and an acidity (pH 4.5) that is similar to the precipitation. Although these two lakes are located only 1 km apart, they differ markedly in acidity because of the organic acids in tea-coloured Pebbleloggitch Lake. In general, bog-influenced waters are naturally acidic, commonly with an acidity of pH 4.0-5.0.

Image 19.3. About a third of the watershed of Pebbleloggitch Lake, Nova Scotia, is an acidic bog (the fine, light texture in the upper part of the image). The rest is covered by forest. The boggy area leaches organic acids to the lake, giving it a dark-brown colour and making it naturally acidic, with a pH of about 4.5. Source: J. Kerekes.

Acidification of Surface Waters

A widespread acidification of surface waters in eastern Canada has been attributed to the deposition of acidifying substances from the atmosphere. The eastern United States and Scandinavia have also been affected in this way.

A survey of surface waters was conducted by the Environmental Protection Agency in the United States (Baker et al., 1991). In a national sample of 28,300 lakes, 1,180 were acidic, most of which are in eastern states. Atmospheric deposition was thought to have acidified 75% of the acidic lakes, while 3% were affected by acid-mine drainage and 22% by acidity from bogs. Of 64,300 streams that were sampled, 4,670 were acidic, of which 47% were acidified by atmospheric deposition, 26% by acid-mine drainage, and 27% by bogs. Florida has the highest frequency of acidic lakes, mostly because of organic acids from natural wetlands. The influence of atmospheric deposition is most important in the northeastern states, particularly in the Adirondack Mountains, where 10% of the lakes have a pH ≤5.0, and 20% have a pH ≤5.5.

Although such a comprehensive survey of the status of lakes and streams has not been carried out in Canada, acidified surface waters are known to be common, particularly in the eastern provinces. It has been estimated that there are more than 14,000 acidic lakes in Ontario, Quebec, and the Atlantic Provinces (Environment Canada, 1996). The sensitivity of surface waters to acidification is related to the amount of alkalinity in their water, which itself is associated with the amounts of calcium and magnesium in soil and rocks of the watershed (see the following section).

Surface waters on 46% of Canada's land area (about 4.0-million square kilometers) are considered highly sensitive to acidifying deposition, and another 21% (1.8-million km^2) are moderately sensitive.

The chemical and biological changes that occur as surface waters become acidified have been examined in important studies in which sulphuric acid was deliberately added to lakes (Schindler, 1990). These whole-lake experiments were conducted in the Experimental Lakes Area (ELA) of northwestern Ontario. The most intensively studied lake, named Lake 223, is a 279 ha, oligotrophic waterbody. Lake 223 was studied for two years before it was experimentally acidified, and then for a number of years afterward. Beginning in 1976, sulphuric acid was added to acidify the lake, which reduced its pH from 6.5 initially to 5.0-5.1 during 1981-1983. Its acidity was then allowed to decrease to pH 5.5-5.8 during 1984-1988.

As expected, the concentrations of sulphate and hydrogen ions increased in Lake 223, because these were added to the lake. Sulphate averaged 35 μmol/L in 1975, compared with 115 μmol/L in 1979. Increased concentrations of manganese (a 980% increase by 1980), zinc (550%), and aluminum (155%) occurred because these chemicals dissolved out of sediment under the acidified conditions. Acidification also caused the water to become more transparent, which allowed increased light penetration and deeper heating during the summer. Many biological changes also occurred; these are described later in this chapter.

In Detail 19.3. Acid-rock Drainage.
Acid-rock drainage (ARD; also known as acid-mine drainage) refers to flows of water that have been severely acidified by the oxidation of pyrite and other reduced-sulphur minerals. ARD usually involves pollution associated with coal mining, but it may also be associated with metal mining. The acidity is produced by the exposure of pyritic minerals, usually iron sulphide, to atmospheric oxygen, which allows specialized Thiobacillus bacteria to oxidize the sulphides and produce sulphate and oxidized iron ions, as follows: $4\ FeS_2 + 15\ O_2 + 14\ H_2O \rightarrow 4\ Fe(OH)_3 + 16\ H^+ + 8\ SO_4^{2-}$

Note the large numbers of H^+ that are produced – these can lead to severely acidic conditions in water draining from the substrates where the reactions are occurring. In fact, acid-mine drainage commonly results in a pH less than 2.0, along with high concentrations of sulphate and toxic aluminum, iron, and manganese. If the ARD is associated with rock or tailings from metal mining, it may also be rich in toxic copper, nickel, or other heavy metals.

As a stream flows away from a source of ARD, it interacts with neutralizing minerals and may also receive inflows of non-acidic water. These cause the acidity to be reduced, so the pH gradually increases. Once the pH recovers beyond about 3.0, dissolved iron comes out of solution as a yellow-orange precipitate of $Fe(OH)_3$, sometimes known as "yellow-boy." As the yellow-boy settles over the streambed, it can smother bottom-dwelling organisms.

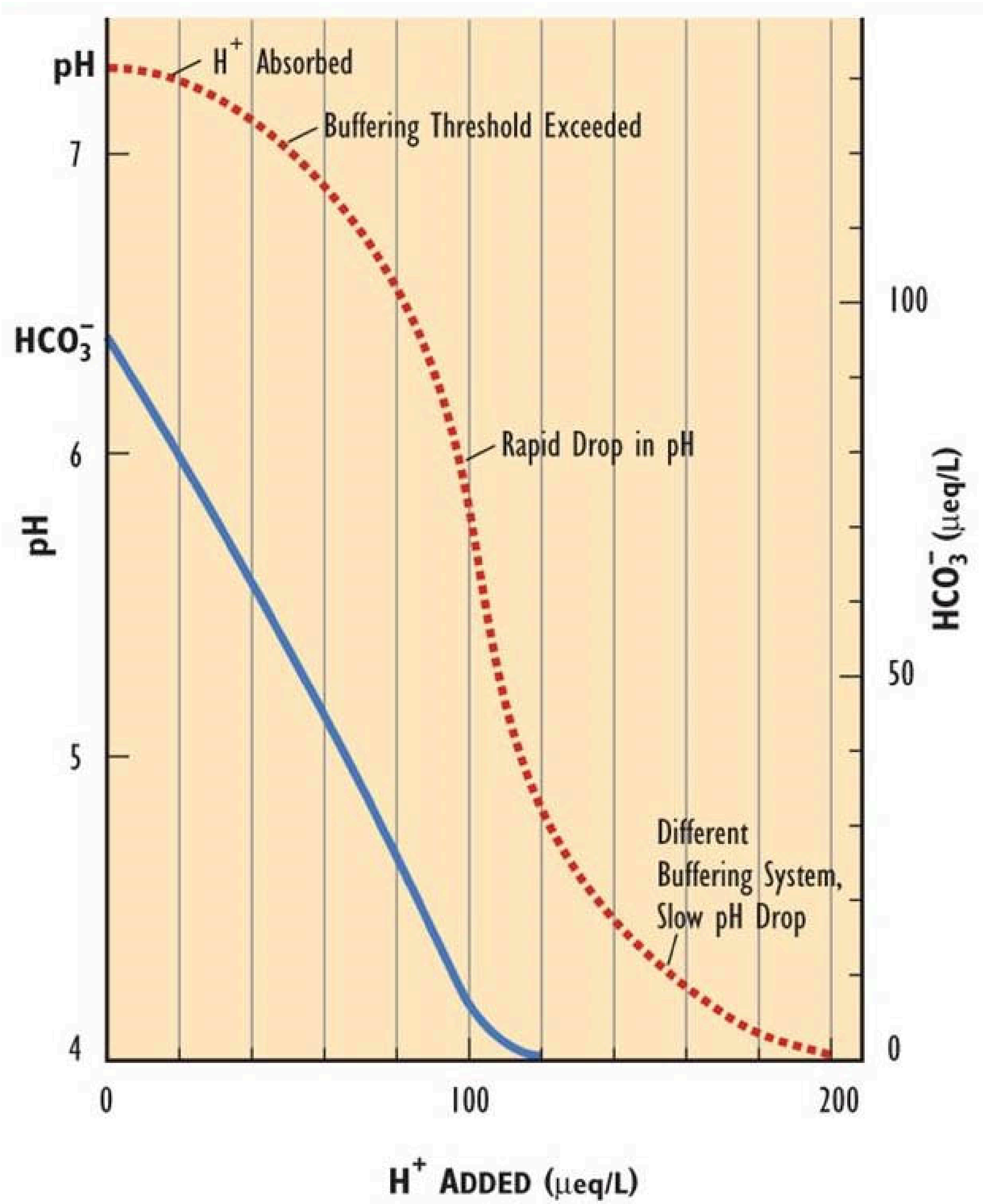
Wherever it occurs, acid-rock drainage is a severe environmental problem, mostly because it is so toxic to aquatic life. Consequently, efforts are made to prevent ARD at the source, or to treat it once it has occurred. In Canada, work to address ARD is concentrated under the Mine Environment Neutral Drainage (MEND) program of Natural Resources Canada. It has been estimated that the total "liability" from ARD is equivalent to $2-5 billion if problems are not treated.

Where possible, it is prudent to avoid ARD by preventing the exposure of sulphide-bearing rocks to the atmosphere. Metal mines and construction industries often accomplish this by storing sulphide tailings under water. However, there are still many cases where they cause ARD and need to treat it to reduce its toxicity. The usual way to mitigate ARD is to add a liming agent, such as limestone ($CaCO_3$) or lime ($Ca(OH)_2$), which neutralizes the acid content. In a few cases, "artificial wetlands" have been constructed to deal with the problem: the ARD is input at one end of the wetland and exits at the other, with much of its acidic content having been consumed by microbes living in anaerobic sediment. This happens because the sulphate ions (SO_4^{2-}) become chemically reduced to sulphides, such as iron sulphide (FeS_2) or hydrogen sulphide (H_2S). These reactions consume acidity, while also causing toxic metal ions to precipitate from solution.

Vulnerability to Acidification

Surface waters that are vulnerable to acidification have a low alkalinity, or acid-neutralizing capacity. As H^+ is added to water, it is absorbed by acid-neutralizing reactions until the capacity to neutralize the acid is exceeded. After that point, there is a rapid decrease in pH, until a different buffering system comes into play (Figure 19.3). Bicarbonate (HCO_3^-) alkalinity is the critical buffering system within the circumneutral pH range of 6.0-8.0. When the buffering capacity of the available HCO_3^- is depleted, the water acidifies rapidly. Bicarbonate reacts with H^+ to form $H_2O + CO_2$. Because this reaction neutralizes added H^+, the pH does not change until the alkalinity is exhausted.

Figure 19.4. Titration Curves for Fresh Water. This diagram shows a titration curve for water from a typical freshwater lake. The initial concentration of alkalinity (HCO_3^-; lower curve) was 100 μeq/L. These curves are similar to what is observed when dilute acid is slowly added to clear lakewater with little alkalinity. Once the alkalinity is exhausted, the water acidifies rapidly. Source: Modified from Henriksen (1980).



The concentration of bicarbonate in natural waters is influenced by geochemical factors, especially by the presence of limestone ($CaCO_3$) or dolomite (Ca, $MgCO_3$) in soil or bedrock of the watershed or in the aquatic sediment. As these minerals dissolve, they create bicarbonate alkalinity and give the water a degree of acid-neutralizing capacity. If carbonate-rich minerals are abundant in a watershed they can generate enough alkalinity to neutralize acidifying inputs from the atmosphere. As a result, surface waters in these kinds of watersheds are not sensitive to acidification, even in a region where the atmosphere and precipitation are polluted (except perhaps in cases of extremely high rates of dry deposition of SO_2).

The situation is different, however, in watersheds in which the bedrock, soil, and sediment are derived from hard, poorly soluble rocks such as granite, gneiss, and quartzite, which contain few carbonate minerals. Watersheds of this type have little capacity for generating alkalinity and so they are easily acidified by wet and dry depositions from the atmosphere. Vulnerable watersheds are especially common in eastern Canada, where thin soils derived from carbonate-poor glacial till commonly overlie hard granitic bedrock.

Headwater lakes and streams are at particular risk of acidification. These systems receive no drainage from waterbodies at higher elevation, and their watersheds are usually small. Consequently, there is little opportunity for rainwater to interact with soil and bedrock, and much of the acidity in precipitation does not become neutralized before the water reaches headwater lakes and streams.

At high elevation in many mountainous regions, crustal granite is exposed by erosion and the terrain in such regions may also be vulnerable to acidification. This is the case in parts of the Rocky Mountains of western North America and in the Appalachians of the eastern United States. Again, the vulnerability occurs because granite contributes little alkalinity to surface waters.

Within a vulnerable region, however, even a small pocket of calcium-rich soil in the watershed can provide enough alkalinity to allow a waterbody to resist acidification. For example, 15 lakes were surveyed in an area of Precambrian Shield in southern Ontario where precipitation is quite acidic (Dillon et al., 1977). Fourteen of the lakes had little alkalinity (95-175 μeq/L), were slightly acidic (pH 5.8–6.7), and were considered highly vulnerable to acidification. One lake, however, had some calcium-rich till in its watershed. That lake had a high alkalinity (1,200 μeq/L) and high pH (7.1), and it is unlikely to acidify.

A related issue is the gradual loss of calcium and magnesium from terrestrial watershed due to long periods of leaching by acidic groundwater. Eventually, the supply of those cations also becomes depleted in oligotrophic streams and lakes with naturally dilute concentrations of ions, which are common in regions of granitic bedrock, such on the Precambrian Shield. The depletion of calcium and magnesium represents a depletion of the acid-neutralizing capacity of a waterbody, and it is a physiological issue for organisms that need large amounts of those cations to form their shells of calcium carbonate (such as mussels) or chitin (a glucose-derived polysaccharide that needs calcium to harden). The occurrence of aquatic osteoporosis has been demonstrated in lakes in eastern Canada, and additional research will likely show that it is widespread problem (Jeziorski et al., 2008).

Freshwater Organisms

Many changes occur in the biota as freshwater ecosystems become acidified. In general, freshwater organisms are considerably more sensitive to the acidification of their habitat than are terrestrial plants.

Freshwater Algae

Many species of microscopic, single-celled algae (phytoplankton) live in lakes. The water chemistry greatly influences the particular species that are present. Because species of diatoms (family Bacilliarophyceae) and golden-brown algae (Chrysophyceae) are particularly sensitive, they are useful indicators of water chemistry. For example, a study of 72 lakes in the Sudbury area found that certain diatom species were indicators of particular aspects of water chemistry (Dixit et al., 1991):

1. indicators of acidic water: Eunotia pectinatus, Fragilaria acidobiontica, Pinnularia subcapitata, Tabellaria

quadriseptata
2. indicators of acidic water with high metals (Cu, Ni): Eunotia exigua, E. tenella, Frustulina rhomboides saxonica, Pinnularia hilseana
3. indicators of non-acidic water: Achnanthes lewisiana, Cyclotella meneghiniana, Fragilaria construens, F. crotonensis The silica-rich cell walls of diatoms differ in shape for each species, and they persist in lake sediment after death of the cell. As well, the water-chemistry requirements of many diatom species are known. Consequently, the abundance of diatom fossils in dated layers of lake-sediment cores can be used to infer historical communities and water chemistry. This technique has been used to demonstrate that some presently acidic lakes in eastern Canada were not acidic as recently as several decades ago.

The phytoplankton community changed markedly during the acidification of Lake 223 in the Experimental Lakes Area (Findlay and Kasian, 1986). Initially, it was dominated by species of golden-brown algae, but with acidification this changed to green algae (Chlorophyceae). Although species composition changed substantially, there was little difference in the diversity of species. A small increase in algal biomass occurred as a result of the acidification, likely caused by increased water clarity, which allowed more productivity to occur. When Lake 223 was allowed to become less acidic, algal species typical of the pre-acidification community quickly reappeared.

However, the phytoplankton community is much more sensitive to fertility of the water than to changes in its acidity, being especially responsive to phosphorus (see Chapter 20). In fact, the productivity of almost all fresh waters increases if they are fertilized with phosphorus. This ecological change, known as eutrophication, also occurs in acidic waterbodies. This is illustrated by studies of two adjacent lakes in Nova Scotia, Little Springfield and Drain. After construction activity in their watersheds exposed pyrite-containing minerals to the atmosphere, both lakes became highly acidic through a process similar to acid-mine drainage (Kerekes et al., 1984). Little Springfield Lake had a pH of 3.7 and supported little algal productivity – it was oligotrophic. However, Drain Lake (pH 4.0) received phosphorus-rich sewage, and it became eutrophic and highly productive in spite of its acidity.

Periphytes are microscopic algae that live on the surface of sediment, rocks, woody debris, and aquatic plants. The periphyton community can include hundreds of species, even in acidic lakes. Periphytes are especially abundant in lakes with clear water, including acidic ones, where their late-summer biomass may develop cloudy or felt-like mats. During the acidification of Lake 223, a benthic mat of the filamentous green alga Mougeotia developed in shallow water after the pH decreased below 5.6. The reasons for the growth of algal mats are not known, but they could be due to reduced grazing by invertebrates.

Aquatic Plants

Aquatic plants (or macrophytes) can be abundant in shallow lakes and ponds. The acidification of some lakes has resulted in an increase of aquatic mosses, especially species of Sphagnum. In some cases, this was accompanied by declines of other plants, such as reed (Phragmites communis), water lobelia (Lobelia dortmanna), and quillwort (Isoetes spp.). Moreover, the invasion by Sphagnum may intensity acidification, because these mosses are highly efficient at absorbing Ca^{2+}, Mg^{2+}, and other cations from the water, which they exchange for H^+. Mats of Sphagnum also interfere with chemical reactions at the sediment/water interface, which hinders the neutralization of acidity that occurs there.

Communities of aquatic plants differ greatly between clear-water acidic lakes and those with organically stained water. For example, Pebbleloggitch Lake (Table 19.5) has dark-brown, acidic (pH 4.5) water, which prevents light penetration into deeper habitats. Consequently, aquatic plants can grow only within a shallow fringe around the edge of the lake, and only 15% of the bottom is vegetated (Stewart and Freedman, 1989). The most abundant macrophytes, such as the yellow water-lily (Nuphar variegatum), have floating leaves. In comparison, nearby Beaverskin Lake has extremely clear water and virtually the entire bottom receives enough light to support aquatic plants, even to a depth of 6.5 m. Many of the macrophytes, including mats of Sphagnum, maintain all of their foliage underwater.

Even in acidic lakes, the productivity of macrophytes is stimulated by the addition of nutrients. Drain Lake (mentioned above) is an extremely acidic (pH 4.0) but eutrophic lake, with a lush productivity of aquatic plants. As with phytoplankton, the fertility of the water has a much greater effect on the productivity of aquatic plants than acidity does.

Zooplankton

Zooplankton are tiny animals, mostly crustaceans, that live in the water column. Most zooplankters filter-feed on phytoplankton cells, but a few are predators. Some species are tolerant of acidity and may occur in water of pH 4.0 or less. The effects of acidification on zooplankton are complex because several factors are involved:

- the toxicity of H^+ and metals, such as Al^{3+}
- changes in the availability of phytoplankton as food
- changes in predation, especially if zooplankton-eating fish are eliminated

A survey of 47 lakes in Ontario found that certain zooplankton are good indicators of water chemistry (Sprules, 1975). Indicator species of acidic lakes with pH < 5.0 were *Daphnia catawba*, *D. pulicaria* and *Polyphemus pediculus*. Others occurred only at pH > 5.0: *Daphnia ambigua*, *D. galeata mendotae*, *D. longiremis*, *D. retrocurva*, *Diaptomus oregonensis*, *Epischura lacustris*, *Leptodora kindtii*, and *Tropocyclops prasinus mexicanus*. However, some zooplankters were indifferent to acidity and occurred over a wide range of pH. For example, *Diaptomus minutus* was the most frequently observed species, occurring over pH 3.8 to 7.0. Acidic lakes had a somewhat depauperate community of zooplankters – those with pH < 5.0 had 1-7 species with only one or two dominant being dominant, while lakes with a pH > 5.0 had 9-16 species with three or four being dominant.

The experimental acidification of Lake 223 resulted in an increased abundance of zooplankton, an effect that was attributed to an increase in their food of phytoplankton biomass (Malley et al., 1982). Throughout the acidification, Diaptomus minutus and Cyclops bicuspidatus remained the most abundant zooplankters, but some other species were intolerant. This included the opossum shrimp (Mysis relicta), a large predator that disappeared when the pH decreased below 5.6.

Benthic Invertebrates

Benthic invertebrates live on or in the sediment of waterbodies. The number of species tends to be lower in acidic waters, but they can still be abundant, especially it predatory fish have disappeared. The most common benthic invertebrates in acidic lakes are species of insects and crustaceans (although other species of these groups are intolerant of acidity). Molluscs do not occur in strongly acidic conditions because it is difficult for them to maintain their shell of calcium carbonate. A study of more than a thousand lakes in Norway found that no species of clams could tolerate a pH below 6.0, and no snails below 5.2 (Okland and Okland, 1986).

Because sediment is more strongly buffered than its overlying water, it is much less vulnerable to acidification. For instance, the acidity of sediment did not change much during the experimental acidification of Lake 223 (Kelly et al., 1984). When the pH of water just above the sediment was 5.3, at 0.5 cm into the sediment it was 6.0, and at 2.0 cm it was 6.7, unchanged from the pre-acidification condition. Because the habitat of benthic invertebrates is well buffered, some of them are not much affected by acidification of the overlying lakewater. During the acidification of Lake 223, the abundance of chironomid midges increased and peaked at a water pH of about 5.6 (Mills, 1984). However, the initially abundant mayfly larvae disappeared at pH 5.0, and the crayfish Orconectes virilis became extirpated because of reproductive failure after the pH fell below 5.6.

Fish

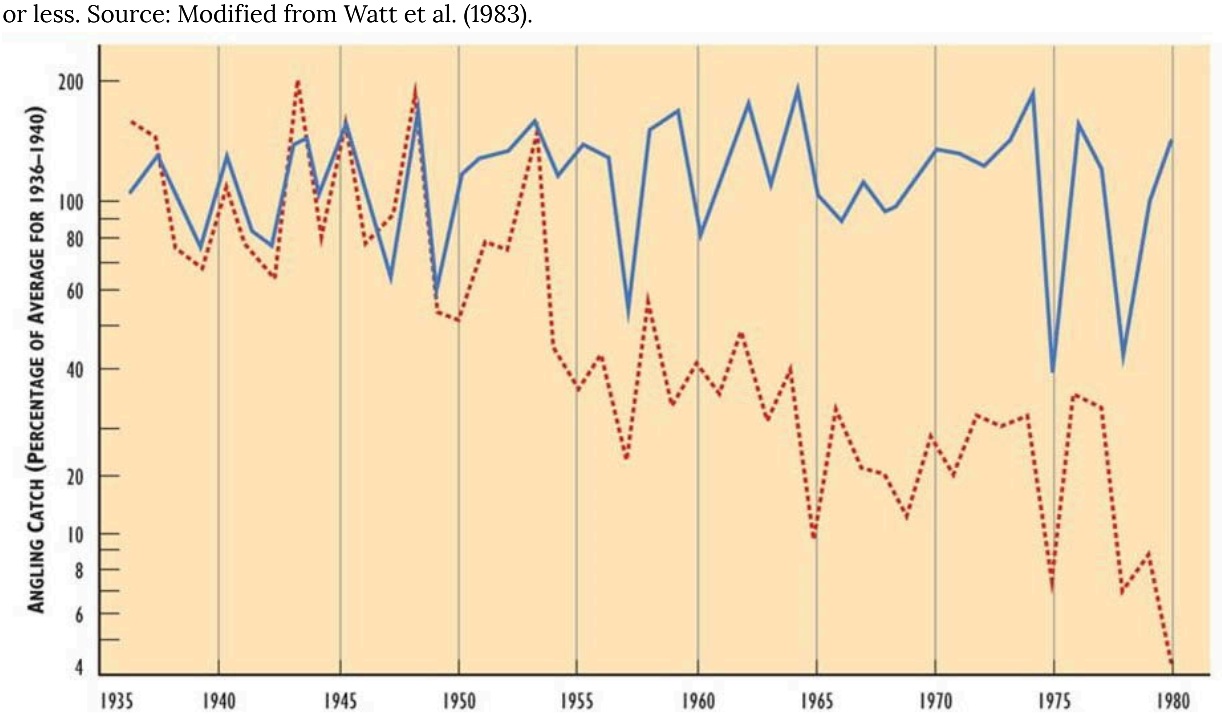
Fish populations are the best-known victims of acidification. Many losses of trout, salmon, and other economically important fish have occurred in acidified waters in Canada, the United States, and Eurasia.

Studies in Ontario have documented the loss of fish populations from acidified lakes in the Killarney region (Beamish and Harvey, 1972; Harvey and Lee, 1982). That area is subject to severely acidic precipitation (pH 4.0-4.5) and to dry deposition of acidifying SO_2 because of its proximity to the smelters at Sudbury. A survey in the 1970s found that 33 of 150 lakes in the Killarney area had a pH below 4.5. These ecologists actually monitored the local extirpation of several fishes in Lumsden and George Lakes. There was also anecdotal evidence for losses of other populations, because local people had a memory of historical sport fisheries in currently fishless lakes. The Killarney area has had 17 extirpations of lake trout (Salvelinus namaycush), an important sportfish that cannot breed at pH <5.5. There are also extirpations of smallmouth bass (Micropterus dolomieiu) from 12 lakes, of largemouth bass (M. salmoides) and walleye (Stizostedion vitreum) from four lakes, and yellow perch (Perca flavescens) and rock bass (Ambloplites rupestris) from two lakes.

Lumsden Lake acidified from pH 6.8 in 1961 to 4.4 in 1971. That acidification resulted in a reproductive failure and extirpation of lake trout, lake herring (Coregonus artedii), and white sucker (Catostomus commersoni). When George Lake reached pH 4.8-5.3, lake trout, walleye, burbot (Lota lota), and smallmouth bass disappeared. As acidification progressed further, there were losses of northern pike (Esox lucius), rock bass, pumpkinseed sunfish (Lepomis gibbosus), brown bullhead (Ictalurus nebulosus), and white sucker. These extirpations resulted from persistent failures of these fishes to reproduce in acidified lakes.

Losses of sportfish populations have also occurred in Nova Scotia, where Atlantic salmon (Salmo salar) has been lost from acidic (pH below 4.7) rivers, but not from those with higher pH (Figure 19.4). Lacroix and Townsend (1987) penned juvenile salmon in four acidic streams in Nova Scotia – none survived in pH below 4.7, but all did at higher pHs.

Figure 19.5. Catch of Atlantic Salmon in Nova Scotia Rivers. These sport-fishing data are standardized to facilitate comparison among rivers. The top line is rivers with pH greater than 5.0, and the bottom one is pH 5.0 or less. Source: Modified from Watt et al. (1983).



Elsewhere, early surveys (from the 1930s) in the Adirondack Mountains of New York State found that brook trout

(Salvelinus fontinalis) were present in 82% of the lakes. However, in the 1970s, that species was absent in 43% of 215 lakes in the same region (Schofield, 1982).

An extensive survey of 700 Norwegian lakes in the 1970s found that brown trout (Salmo trutta) was absent from 40% of the waterbodies and sparse in another 40% (Wright and Snekvik, 1978). Almost all of those lakes had supported trout before the 1950s. The extirpation of trout populations was most extensive in southern Norway, where acidifying deposition is most intense.

In eastern North America, the fish that are most tolerant of acidification are yellow perch, rock bass, central mudminnow (Umbra limni), largemouth bass, bluegill (Lepomis macrochirus), black bullhead (Ictalurus melas), brown bullhead, golden shiner (Notemigonus crysoleucas), and American eel (Anguilla rostrata). These species occur in some waterbodies with pH more acidic than 4.6. Other species are more sensitive to acidification and generally need a pH >6.0 to survive.

Prior to its experimental acidification, Lake 223 supported lake trout, white sucker, fathead minnow (Pimephales promelas), pearl dace (Semotilus margarita), and slimy sculpin (Cottus cognatus) (Mills et al., 1987). The fathead minnow was most sensitive to acidification, and it rapidly declined when the pH reached 5.6. Reproductive failure of lake trout began at pH 5.4, and of white sucker at pH 5.1, resulting in population declines as older fish died.

In general, younger life-history stages (fry and juveniles) are more sensitive to acidity than are adult fishes. This is why most losses of populations are attributed to reproductive failure rather than to mortality of adults. There are, however, many observations of adult fish being killed by exposure to acid-shock events during snowmelt in the springtime.

As surface waters acidify, the concentration of dissolved metals increases, especially of Al^{3+} and $AlOH^{2+}$, which are toxic ions of aluminum. In many acidic waters, aluminum toxicity is sufficient to kill fish, regardless of any direct effects of H^+. In general, the survival and growth of fish larvae and older life-history stages become reduced when the concentration of dissolved ionic aluminum exceeds 0.1 ppm, an exposure that is common in acidic waters. In brown-coloured water, however, almost all dissolved aluminum and other metals is present as organometallic complexes. Metals in that state are much less toxic than the free-ionic forms that occur in clear water with a similar acidity.

Amphibians

Amphibians depend on aquatic habitat during at least part of their life cycle. Most Canadian species lay their eggs in water, which their larvae inhabit until metamorphosis occurs, after which the adults utilize nearby terrestrial habitat. Research suggests that some species of amphibians are vulnerable to acidification of their aquatic habitat, while others appear to be indifferent.

A study of amphibian breeding sites in Nova Scotia, covering a pH range from 3.9 to 9.0, found that some species were not obviously influenced by acidity (Dale et al., 1985):

- the bullfrog (Rana catesbeiana) occurred from pH 4.0 to 9.0
- spring peeper (Hyla crucifer) and yellow-spotted salamander (Ambystoma maculatum) from pH 3.9 to 7.8
- green frog (R. clamitans) from pH 3.9 to 7.3
- and wood frog (R. sylvatica), from pH 4.3 to 7.8.

Yellow-spotted salamander and green, bull, wood, and pickerel (R. palustris) frogs all had eggs, developing larvae, and adults present in some habitats at pH 4.0, suggesting that reproduction was occurring at that extreme acidity. Studies in other regions, however, have shown that some species of amphibians are intolerant of acidity.

Laboratory experiments with 14 species of amphibians found that exposing eggs to pH 3.7-3.9 caused more than 85% embryonic mortality, while prolonged exposure to pH 4.0 caused a rate of mortality >50% (Freda et al., 1991). It must be borne in mind, however, that an aquatic pH as acidic as 4.0 is uncommon in nature. Moreover, such acidic conditions are usually associated with acid-mine drainage or natural bogs, rather than with acidification caused by atmospheric deposition (which has an acidification threshold of about pH 4.5 or higher). Overall, it appears that most species of amphibians are less vulnerable than fish to suffering population declines caused by acidification.

Aquatic Birds

Directly toxic effects of acidification on waterfowl and other aquatic birds have not been documented and probably do not occur. However, acidification causes aquatic habitats to change, and this has indirect consequences for bird populations. For instance, if acidification eliminates populations of smaller fishes, then fish-eating waterfowl such as the common loon (Gavia immer) and merganser (Mergus merganser) will suffer, as will piscivorous raptors such as osprey (Pandion haliaetus). At the same time, however, the extirpation of predatory fish could result in an increased abundance of aquatic insects and zooplankton, which improves the food resource for other waterfowl, such as mallard (Anas platyrhynchos), black duck (A. rubripes), ring-necked duck (Aythya collaris), and goldeneye (Bucephala clangula).

The breeding success of common loons was studied on 84 lakes in Ontario (Alvo et al., 1988). Only 9% of breeding attempts were successful on low-alkalinity lakes (< 40 μeq/L), which are either acidic or vulnerable to acidification. In contrast, 57% of breeding attempts were successful on lakes with alkalinity of 40-200 μeq/L, and 59% if > 200 μeq/L. These observations likely reflect the size of the fish populations in these lakes.

A study of 79 small lakes and ponds in New Brunswick found a larger biomass of aquatic invertebrates in the littoral zone (shallow, near-shore) in acidic waterbodies with pH 4.5-4.9 than in those with pH >5.5 (Parker et al., 1992). Five species of ducks that feed on invertebrates had an average of 3.5 broods/ha on waterbodies with pH 5.5, compared with 0.65 broods/ha at higher pHs. The greater biomass of invertebrates in the acidic waterbodies was likely due to decreased predation because of a reduced fish community.

Drain Lake in Nova Scotia was previously described as a highly acidic (pH 4.0) but eutrophic lake. Drain Lake is fishless but it has large populations of aquatic invertebrates and plants. This habitat allows black ducks and ring-necked ducks to be more productive than is typical for lakes in the region (Kerekes et al., 1984).

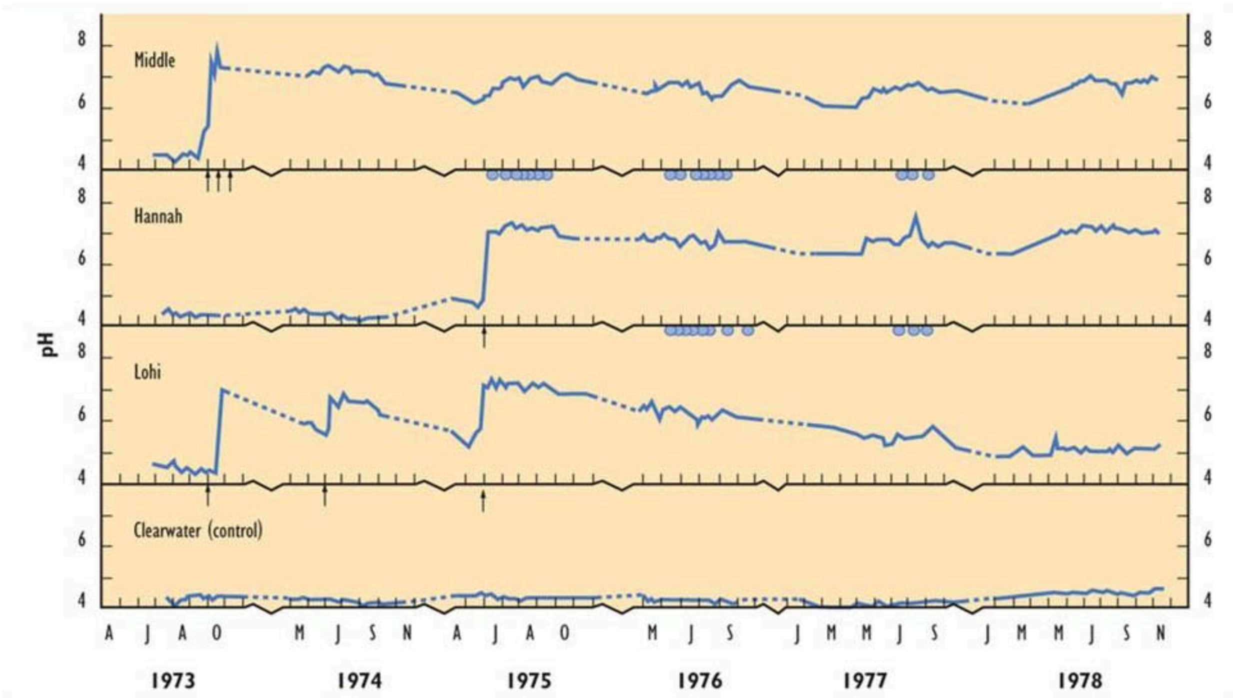
Reclamation

Even before acidification became a high-profile issue, wildlife managers in some regions were "improving" habitat for sportfish in brown-coloured lakes by treating the acidic water with powdered limestone (calcium carbonate, $CaCO_3$) or lime (calcium hydroxide, $Ca(OH)_2$). These treatments, known as liming, serve to reduce acidity, clarify the water, and improve the productivity of fish such as trout. Not surprisingly, considerable research has also been done on the use of liming treatments to improve the condition of lakes and other surface waters that have been acidified by atmospheric deposition.

Effects of liming on pH are illustrated in Figure 19.5 for three limed lakes and one reference (non-limed but acidic) lake in Ontario (Dillon et al., 1979; Yan et al., 1979). Initially, the treated lakes had a pH of 4.0-5.0, but this was increased to pH 7.0-8.0 by the whole-lake liming treatment. Middle and Hannah Lakes had a fairly stable pH after treatment, but Lohi quickly drifted back to an acidic condition. This difference reflects the sizes of the watersheds of the lakes – Lohi drains a relatively large area and flushes quickly, so its neutralization results are shorter lived. Note that fertilizing the lakes with phosphate, which stimulates the productivity of phytoplankton, also has an acid-neutralizing effect, although it is much smaller than what resulted from liming.

Figure 19.6. Effects of Liming Lakes. These lakes are located in the Sudbury region, and they were acidified by a

combination of dry and wet atmospheric depositions. The times of treatment with neutralizing agents ($CaCO_3$ or $Ca(OH)_2$) are indicated by arrows, and the addition of phosphate by solid dots. Source: Modified from Dillon et al. (1979).



Initially, the treated lakes had a large decline in the productivity of phytoplankton and zooplankton. However, the phytoplankton biomass soon returned to the pre-liming condition, but with lingering changes in species composition. The zooplankton recovered more slowly, and even after three years had not returned to the pre-liming abundance. In addition, fish kept in cages in the limed lakes suffered high rates of mortality. This was likely due to metal toxicity, because the lakes had been affected by fallout from the Sudbury smelters. Although the aqueous concentrations of Al, Cu, Ni, and Zn all decreased after liming, because their solubility is greater in acidic water, they still remained high enough to stress fish and other biota.

In some regions of Scandinavia, liming is routinely used to treat large numbers of acidified lakes and rivers. This is done to mitigate the damage caused by acidification, especially to fish populations. Sweden, for example, has the world's largest liming programs (Stensdotter et al., 2005). By the late 1970s, about 17-thousand lakes in Sweden had been acidified by atmospheric deposition (out of a total of 90-thousand lakes), as had many streams and rivers. Of the acidified waterbodies, more than 7,500 lakes and 14,000 km of flowing water are being treated with liming agents; about 200-thousand tonnes of powdered limestone is used each year. Typically, the liming treatment must be repeated on a three-year rotation. In Norway, about 3,000 waterbodies have been limed (State of the Environment Norway, 2008). Liming has been conducted much less extensively in North America, largely because the programs are expensive and environmental priorities are different from Scandinavia.

Research on liming has shown that acidified surface waters can be neutralized. Nevertheless, it must be understood that liming treats the symptoms of damage in acidified ecosystems, but not the causes of the acidification. Moreover, liming itself represents an environmental stress that transforms a waterbody from one polluted condition to another that is still damaged, but less toxic. Liming causes a large change in acid-adapted ecosystems, which is followed by changes in species abundances as new communities develop. In general, the most important benefit of liming is that less-acidic waters can support fish, whereas acidic waters cannot. However, liming is not a long-term solution to the acidification of fresh waters. In part, this is because waterbodies must be periodically re-treated as the liming materials are consumed or flushed out of the system.

To some degree, acidified waterbodies may also be managed by treating them with fertilizer to stimulate their productivity, as was previously examined for Drain Lake. Fertilized acidic lakes can sustain a large biomass of phytoplankton, macrophytes, and invertebrates. Waterfowl may thrive in this habitat, even if fish cannot be sustained because of the acidic conditions. However, it is not necessarily appropriate to create large numbers of highly productive lakes. For example, where recreational swimming is an important activity, abundant algae and macrophytes are considered a nuisance.

Image 19.4. This lake near a smelter at Sudbury was acidified to a pH less than 4.0, mostly by the dry deposition of SO_2. Since this photo was taken in 1972, SO_2 pollution in the vicinity has been greatly abated, and that has allowing the lake to become less acidic. Today, it again provides habitat for species that are intolerant of severe acidity. Source: B. Freedman.

Reducing Emissions

Ultimately, the extensive damage caused by acidifying deposition from the atmosphere can only be resolved by reducing the emissions of acid-forming gases. Although this fact is intuitively clear, the issue of emissions reduction remains controversial for the following reasons:

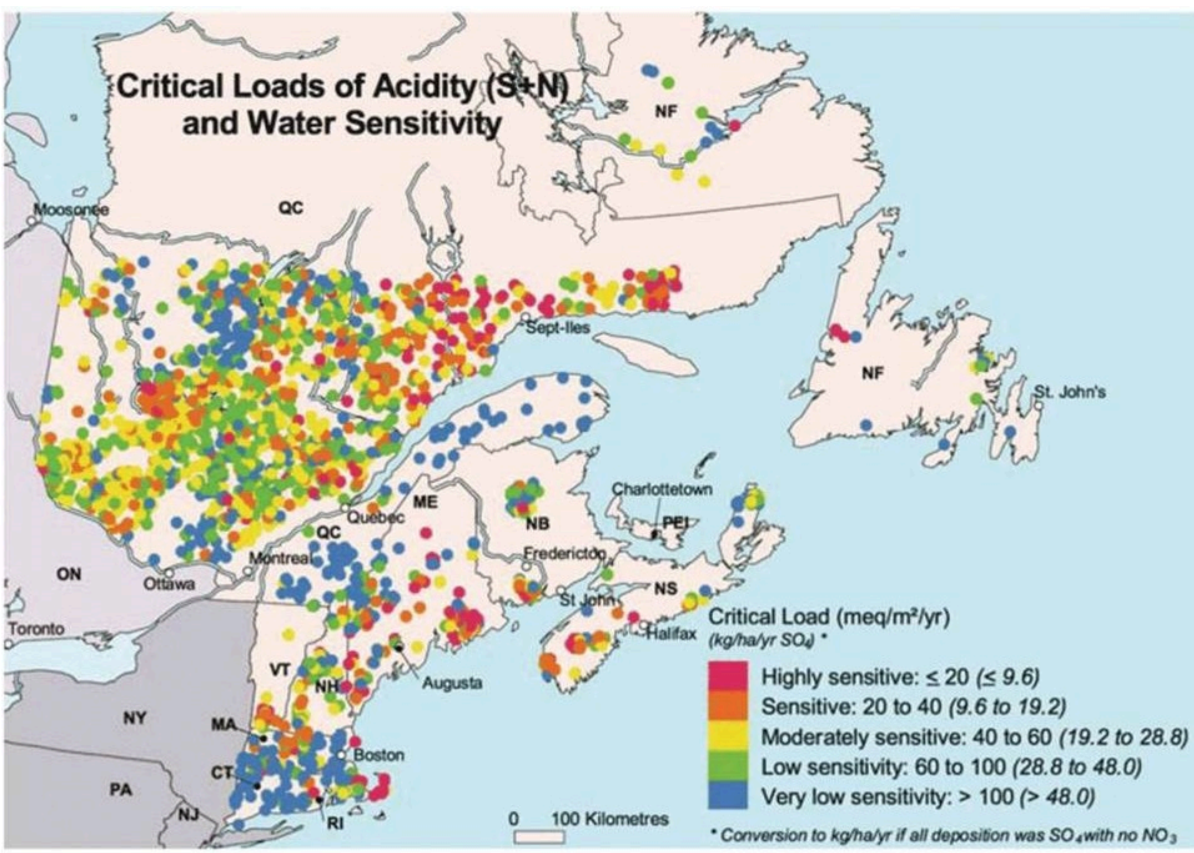
- Scientists do not know exactly how much the emissions of SO_2 and/or NO_x must be reduced to prevent damage by acidifying deposition.
- Various emission-reduction strategies are possible, and they vary in their economic consequences. Would it be more effective to target large point-sources of emissions, such as power plants and smelters, while paying less attention to smaller but numerous sources, such as automobiles and oil-burning home furnaces? Or should both large and small sources be aggressively curtailed?

- To be effective, emissions reductions must be coordinated among neighbouring countries. For example, what would happen if the government of one country (perhaps with large emissions of $SO_2$and NO_x) does not regard acidifying deposition to be a high-priority problem, but neighbouring countries do?

Not surprisingly, industries and regions that are responsible for large emissions of acid-forming gases have tended to resist the imposition of substantial legislated reductions of their releases. In general, they argue that the scientific justification for the reductions is not yet convincing, while the costs of controls are known to be large and potentially disruptive of the economy.

In addition, how low should the rates of atmospheric deposition of sulphur and nitrogen compounds be, in order to avoid further acidification of sensitive surface waters or to allow their recovery? The critical rates of deposition of acidifying compounds are influenced, in part, by the vulnerability of the receiving ecosystems – areas with shallow, nutrient-poor soil can sustain much lower inputs of acidifying substances than areas rich in calcium. Highly sensitive lakes in eastern Canada are considered to have critical-load thresholds of <20 meq/ha•y of sulphur and nitrogen deposition (Figure 19.6).

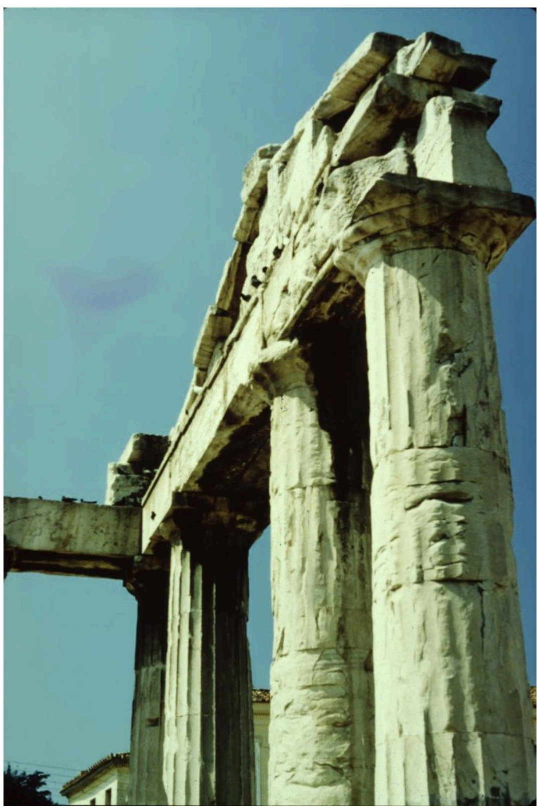
Figure 19.7. Critical Loads of Sulphur and Nitrogen and Sensitivity of Surface Waters in Eastern Canada. A critical load is the wet and dry deposition of sulphur and nitrogen compounds that can be tolerated without causing acidification. The data are in meq/ha•yr. The values in parentheses are for sulphur only (kg SO_4/ha•yr). Source: Environment Canada (2005).



Although there are many uncertainties about the specific causes and magnitude of the damage caused by the atmospheric deposition of acidifying substances, it is obvious that what goes up (emissions of acid-precursor gases) must eventually come down (as acidifying deposition). This common sense idea is supported by a great deal of scientific evidence. This knowledge, combined with public awareness and concern about acidification in many countries, has spurred politicians to begin to take effective action. This is resulting in reduced emissions of SO_2 and NO_x, particularly in relatively wealthy countries in North America and Western Europe.

In 1992, the governments of Canada and the United States signed a binational treaty aimed at reducing acidifying deposition in both countries. This agreement, known as the Canada–U.S. Air Quality Agreement, calls for large expenditures by industries and governments to substantially reduce the emissions of air pollutants, especially SO_2. These cutbacks are on top of reductions of emissions that both countries had already achieved during the 1980s. In the United States, emissions of SO_2 have decreased from 23.1 Mt in 1980 to 16.9 Mt in 1995 and to 6.0 Mt in 2011, while emissions of NO_xincreased slightly from 20.7 Mt in 1980 to 21.8 Mt in 1995 and then decreased to 13.6 Mt in 2011 (EPA, 2014; see also Table 16.2). For comparison, the Canadian emissions of SO_2 decreased from 4.7 Mt in 1980 to 2.5 Mt in 1995 and to 1.3 Mt in 2012, while emissions of NO_x remained about the same during 1980 to 1995 at 2.4–2.6 Mt/y, and then declined to 1.9 Mt/y in 2012 (Environment Canada, 2014).

Image 19.5. The built environment may also be damaged by acidifying deposition from the atmosphere. For example, structures made of limestone, marble, or sandstone become chemically destabilized and eroded by the dry deposition of SO_2 and NO_x and by acidic precipitation. These pollutants are seriously damaging many famous artifacts of cultural heritage, such as this ancient citadel known as the Acropolis in Athens, Greece. Source: B. Freedman.



A major component of the U.S. initiatives to reduce emissions of SO_2, established under the 1990 Clean Air Act Amendments, is the creation of a marketplace for emissions trading. In essence, any company that is emitting SO_2 at a rate less than it has been permitted by the Environmental Protection Agency (EPA) has a right to sell (or trade) those non-used “credits” to another business that is exceeding its emissions target. This is an important initiative because it helps to set a “market value” for emissions of certain pollutants, and also for investments to reduce their release. From the environmental perspective, this marketplace for emissions is a logical instrument because the atmosphere is a common-property resource that is owned and affected by everyone, so any changes in the release of pollutants (whether increases or decreases) have a global effect. In essence, a company whose emissions are smaller than its allowance can realize a profit by selling its credits, while another that has exceeded its target incurs costs. Those costs may be paid either by purchasing emissions credits or by taking action to reduce the emissions, such as installing SO_2-removal technology, switching to a low-sulphur fuel, or in extreme cases, shutting down particularly dirty facilities.

The flexibility associated with these options is considered by many economists and politicians to have been an important benefit of the system of emissions trading. Nevertheless, the establishment of a marketplace that commodifies the release of SO_2 does liberate many companies from the expensive investments that would be required to achieve tangible reductions of their emissions. This fact has engendered controversy, as has the potential establishment of a global marketplace for tradable emissions of greenhouse gases under the Kyoto Protocol (Chapter 17).

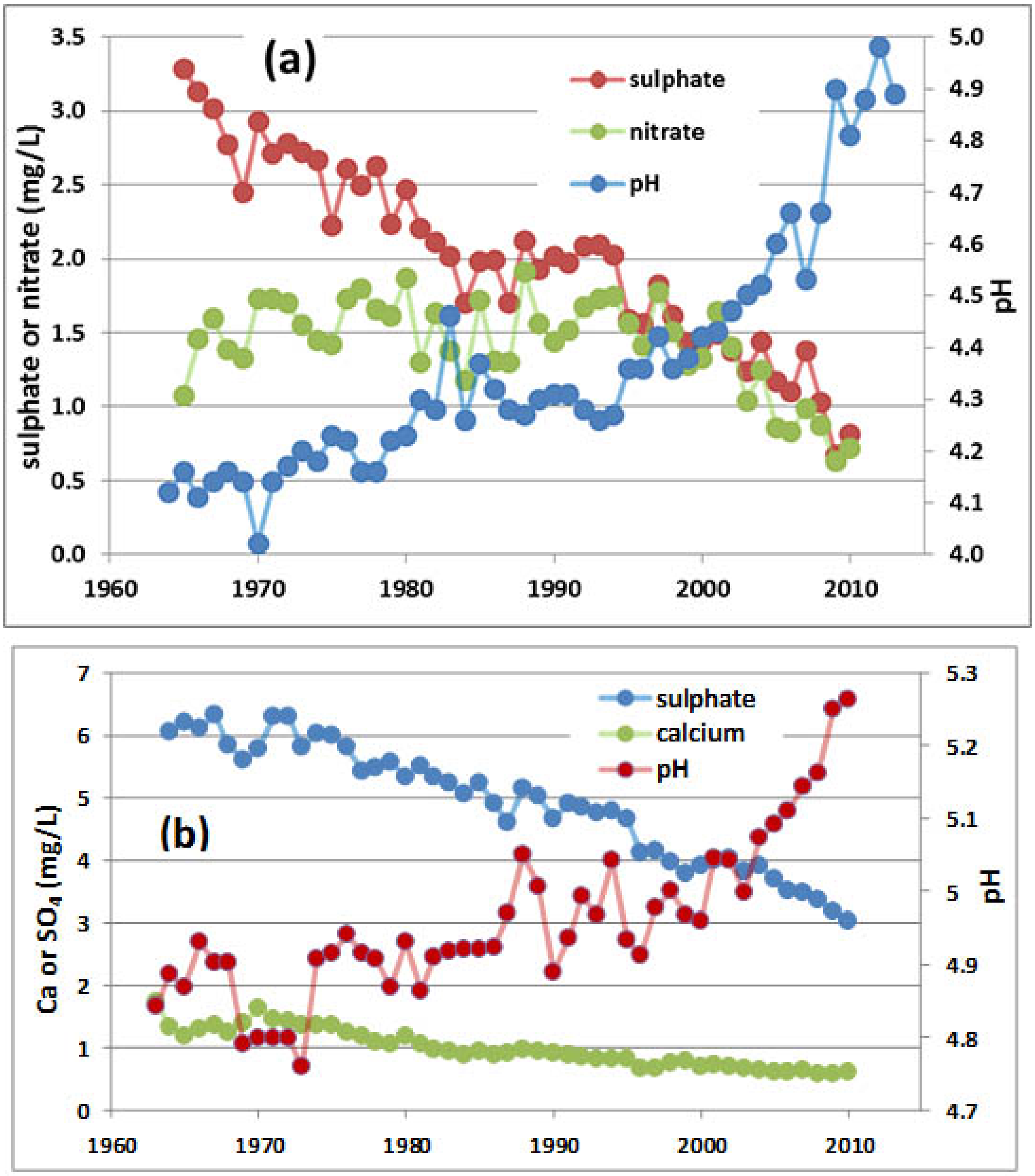
In any event, are the cuts in emissions large enough to achieve their intended effect of preventing and repairing the acidification of ecosystems? According to a science assessment carried out by Environment Canada, the reductions of SO_2 emissions have resulted in lower rates of acidifying deposition in Canada (based on a comparison of data for 1990–1994 and 1996–2000; Environment Canada, 2005). Nevertheless, an estimated 21-75% of eastern Canada still receives amounts of acidifying deposition that exceed the critical loads (the smaller numbers correspond to a best-case scenario, and the larger to a worst-case one). Environment Canada also suggests that, to protect ecosystems from further damage caused by acidifying deposition, a further 75% reduction of SO_2 emissions will be required by Canada and the United States beyond those agreed to under the existing Air Quality Agreement. A similar conclusion was reached by the U.S. Environmental Protection Agency in its own science assessment of the issue (2011).

Furthermore, not much action has been taken to reduce the emissions of NO_x, and this appears to be working against the environmental benefits associated with increased control of SO_2. It is crucial that future regulatory actions include reduced emissions of both SO_2 and NO_x and that acid rain and its environmental damage continues to be monitored.

The 1992 air-pollution treaty between Canada and the United States is a helpful accomplishment. Although there have been reductions in the acidity of precipitation and surface waters in some areas, it appears that the reductions of SO_2 emissions are not large enough to fully mitigate many of the damages caused by acidifying deposition. So far, extremely large areas of terrain continue to be affected by acidification caused by Atmospheric deposition.

Improving trends in the chemistry of precipitation and streamwater at Hubbard Brook, NH, a monitoring location with outstanding longer-term data of this sort of data, are shown in Figure 19.7. The precipitation data show that the acidity of precipitation is decreasing (the pH is increasing), and that the concentrations of sulphate and nitrate are also decreasing. The reduction of sulphate concentrations is especially large, and likely reflects the fact that regulatory controls have concentrated on SO_2 emissions (the main precursor of sulphate) more so that on NO_x (the precusors of nitrate). The streamwater data also show decreasing acidity and sulphate concentration, as well as a steady decrease in the concentrations of calcium. The latter observation may reflect a progressive loss of calcium from these watersheds, which represents a degradation of the ability of the system to provide acid-neutralizing capability agains future inputs of acidifying substances. John Smol (2008) of Queen's University refers to the phenomenon of progressive calcium losses as a kind of "osteoporosis" that affects and degrades many watersheds whose soil and bedrock are low in calcium.

Figure 19.8. Trends in the chemistry of (a) precipitation and (b) streamwater chemistry at Hubbard Brook, NH. Source: data obtained from Gene E. Likens, Hubbard Brook Eco system Study, with funding from the National Science Foundation and The A.W. Mellon Foundation. http://www.hubbardbrook.org/data/dataset_search.php



Some lakes are also benefiting from reduced sulphate loading. A survey of 202 lakes monitored in eastern Canada since the early 1980s found that the acidity of 33% had decreased, while 56% were unchanged, and 11% became more acidic (Environment Canada, 1998. Overall, about 80% of recently sampled lakes in Nova Scotia had a pH <6.0, as did 40% of those in Ontario and 25% in New Brunswick (note that pH <6.0 is considered a critical threshold of tolerance for sensitive fish and other aquatic animals; Environment Canada, 2005). Many of these lakes are naturally acidic because of organic substances leaching from bogs, particularly in Nova Scotia, where brown-waters comprise about 40% of the acidic lakes. Across eastern Canada, however, 0.5-0.6 million lakes are thought to still be vulnerable to acidification under an atmospheric-deposition regime similar to that in recent years.

It must be recognized that pollution control is extremely expensive. For example, it could cost $600 million annually to further reduce the SO_2 emissions by 50% below the current targets for eastern Canada and the eastern United States. Because of this cost, policies that favour reduced emissions of SO_2 and NO_xmay not be able to survive the frequent challenges mounted by politicians, economists, and business people who do not believe that such actions are necessary.

So far, actions to reduce the emissions of SO_2 and NO_x have been vigorous only in relatively wealthy regions of North America and Western Europe. In less-wealthy countries, the political focus is mostly on industrial and economic growth. However, air pollution and other environmental damages "subsidize" that economic growth and are often paid little heed. As soon as possible, much more political and scientific attention must be devoted to the problems of acidifying deposition and other kinds of pollution in eastern Europe, Russia, China, India, Southeast Asia, Mexico, and other rapidly growing economies. In those countries, emissions of SO_2, NO_x, and other important airborne pollutants are galloping out of control.

Conclusions

Acidification is a natural process that occurs as ecosystems interact with climatic and biological influences, for example in bogs and coniferous forest. Acidification is also caused by anthropogenic influences, particularly emissions of SO_2 and NO_x, which oxidize to form acids while in the atmosphere or after they are dry-deposited to ecosystems. Aquatic and terrestrial ecosystems that are vulnerable to acidification have little acid-neutralizing capacity, largely because of small amounts of calcium and magnesium carbonates in their soil, sediment, or rocks. Low-alkalinity freshwaters are particularly at risk of acidification by atmospheric deposition. When a waterbody acidifies to a pH less than about 6.0, it begins to lose its populations of vulnerable fish species and other sensitive biota. Acidifying influences also damage the built environment by eroding materials made of limestone, marble, and certain metals such as copper. Although some of the ecological damage caused by acidification to surface waters can be mitigated by liming, this treatment has to be repeated, typically on about a three-year rotation. The best way to avoid the environmental problems associated with acidifying deposition is to reduce the emissions of the key acid-precursor gases (SO_2 and NO_x). To a substantial degree, this is being done in wealthy countries, including Canada. However, rapidly growing economies, such as China and India, are not paying much attention to this environmental problem, and it is rapidly becoming worse as they aggressively increase their supply of commercial energy by burning sulphurous fossil fuels, particularly coal.

Questions for Review

1. Explain the principle of conservation of electrochemical neutrality? How is it relevant to the chemistry of precipitation and surface waters?
2. What environmental influences cause soil to become acidic? How can this problem be mitigated?
3. How does the acidification of freshwater habitat affect the aquatic biota, including phytoplankton, macrophytes, zooplankton, benthic invertebrates, fish, and birds?
4. Define critical load, and explain factors that influence its value for particular kinds of terrain and surface waters.

Questions for Discussion

1. Compare the chemistry of rainwater and lakewater in a region that is vulnerable to acidification. What are the reasons for the differences?
2. How do wet and dry depositions of acidifying substances contribute to acidification? Why do their rates and relative importance differ between urban and rural areas?
3. Are surface waters in the area where you live acidic or likely to become so? Explain your answer in terms of terrain

factors that influence vulnerability to acidification.
4. Explain why wealthy countries have been taking action to reduce their emissions of acid-precursor gases, but rapidly growing economies such as China and India have not. What are likely consequences of these policies?

Exploring Issues

1. There are two broad options for dealing with acidifying deposition: (1) reduced emissions to prevent the problem and (2) liming of water and soil to treat the symptoms. Some people have called emissions reductions the "billion dollar solution," and liming the "million dollar solution." This is because of the potentially greater capital costs associated with technologies for reducing SO_2 and NO_x emissions. Which of these options (or both) do you think is most appropriate for dealing with acidification as an environmental problem? Explain your answer.
2. Canada and the United States have negotiated a treaty concerning the transboundary movements of air pollutants, with a focus on acidifying deposition from the atmosphere. Major aspects of the treaty are reductions in the emissions of SO_2, and to a lesser degree, NO_x to the atmosphere. You are a scientist working for Environment Canada and have been given the responsibility of monitoring whether the negotiated emissions reductions have been successful in improving conditions in the province where you live – is acidification becoming less of a problem? How would you design a program of environmental monitoring and research to answer this important question? What ecological and human health questions would you examine?

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Chapter 20 ~ Additional Problems of Surface Waters

Key Concepts

After completing this chapter, you will be able to:

1. Compare the causes of eutrophication in fresh and marine waters.
2. Explain the evidence that phosphorus is usually the limiting nutrient for eutrophication of fresh waters.
3. Describe the objectives and technologies used in sewage treatment.
4. Explain the role of eutrophication and other stressors in damage caused to the ecosystem of Lake Erie.
5. Compare the effects of hydroelectric developments involving reservoirs and run-of-the-river facilities.
6. Describe the environmental damage caused by dams and reservoirs.

Introduction

Aquatic ecosystems are affected by many environmental stressors, both natural and anthropogenic. All levels of the aquatic food web are affected, as are ecological processes such as productivity and nutrient cycling. In previous chapters, we examined the use of aquatic resources (Chapter 14) and damage caused by pollution by metals and acidification (Chapters 18 and 19). Here, we look at the effects of eutrophication caused by nutrient enrichment, and caused by hydroelectric developments. Effects on aquatic ecosystems of oil spills, pesticides, forestry, agricultural activities, and urbanization are examined in later chapters.

Eutrophication

Eutrophic waters are well supplied with nutrients, and as a result they are highly productive. In contrast, oligotrophic waters are much less productive because of a restricted availability of nutrients. Mesotrophic waters are intermediate between these two conditions.

Some waterbodies occur in inherently fertile watersheds and are naturally eutrophic. So-called cultural eutrophication, however, is caused by anthropogenic nutrient inputs, usually by the dumping of sewage or runoff of fertilizer from agricultural land. Both inland and marine waters can become eutrophic through increases in their nutrient supply, although the problem is more common in fresh waters.

The most conspicuous symptom of eutrophication is a large increase in primary productivity, especially of phytoplankton, which can develop extremely dense populations known as an algal bloom. Shallow waterbodies may also experience a vigorous growth of aquatic plants (macrophytes). Because the increased productivity of algae and macrophytes can allow higher trophic levels to be more productive, aquatic invertebrates, fish, and waterfowl may also be abundant in eutrophic waterbodies.

However, extremely eutrophic (hypertrophic) waters may become severely degraded. These waterbodies develop noxious blooms of cyanobacteria (blue-green bacteria) and algae during the summer, which may cause an off-flavour in water used for drinking, and may also release toxic organic compounds. In addition, decomposition of the algal biomass consumes a large amount of oxygen, which causes anoxic conditions that are extremely stressful and even lethal to aquatic animals.

Because cultural eutrophication degrades water quality and ecological conditions, it is an important problem in many areas. Severe eutrophication may impair the use of a waterbody as a source of drinking water, to support a fishery, or for recreation, and it degrades the ecological qualities of natural waters.

Causes of Eutrophication

Most lakes in Canada are geologically "young" because they occur on landscapes that were released from glacial ice only about 8-12-thousand years ago (depending on the region). Many lakes are relatively deep, having had little time to accumulate much sediment in their basins. They also tend to have low rates of nutrient input. Over the millennia, however, oligotrophic lakes of this sort gradually increase in productivity as they accumulate nutrients. They also become shallower due to sedimentation, which results in increased rates of nutrient cycling. The slowly increasing productivity of many lakes over time is a natural expression of the eutrophication as a longer-term process.

Surface waters may also be naturally eutrophic if they occur in a watershed with fertile soil. This is the case of many lakes and ponds in the prairie region, where there is an abundance of shallow waterbodies that recycle their nutrients quickly.

Anthropogenic (cultural) eutrophication involves more rapid increases in aquatic productivity. This is most often caused by nutrient loading associated with sewage dumping or runoff contaminated by agricultural fertilizer. Wherever humans live in dense populations or engage in intensive agriculture, there are large inputs of nutrients into lakes and rivers. In coastal areas, estuaries and shallow near-shore areas may also be affected by anthropogenic nutrient inputs and eutrophication.

A theory called the Principle of Limiting Factors states that certain ecological processes are controlled by whichever environmental factor is present in the least supply relative to demand. According to this idea, the primary production of waterbodies is limited by the nutrient that is present in least supply relative to its demand (assuming that light, temperature, and oxygen supply are all adequate). Research has shown that, in almost all fresh waters, primary production is limited by the availability of phosphorus, occurring as the phosphate ion (PO_4^{3-}. In contrast, marine waters are usually limited by the availability of inorganic nitrogen, particularly in the form of nitrate (NO_3^-).

Phosphorus as the Limiting Nutrient

During the 1960s and early 1970s, eutrophication was a topic of intense environmental controversy, part of which focused on the question of which nutrients were the limiting factors to primary production in lakes. Many scientists believed that phosphorus was most important in this regard. Others, however, suggested that dissolved nitrogen, in the form of nitrate or ammonium, was the critical limiting nutrient in many fresh waters. Plants and algae have relatively large demands for all of those nutrients, which typically occur in low concentrations in water.

It was also suggested that dissolved inorganic carbon (as bicarbonate, HCO_3^-) could be a limiting factor. Inorganic carbon is needed in large amounts by autotrophs, but in aquatic systems HCO_3^- is replenished mainly by the diffusion of atmospheric CO_2 into the surface water, which is a slow process.

Eventually, research convincingly demonstrated that phosphorus is the key nutrient that limits primary production in most fresh waters. Consequently, controlling the rate of phosphorus supply is now known to be a crucial action if eutrophication is to be avoided.

The vital role of phosphorus is suggested in Table 20.1, which shows its typical concentration in fresh water (an index of supply) and its concentration in plants (an index of demand). Because the ratio of demand to supply for phosphorus is considerably larger than for other nutrients, it is a likely candidate to be the primary limiting factor for the productivity of algae and plants. The data also suggest that the next-most important nutrient is inorganic nitrogen, in the form of nitrate or ammonium.

Table 20.1. Demand and Supply of Essential Nutrients in Water. These are indexed by the typical concentrations in freshwater plants and in fresh water. Source: Data from Vallentyne (1974).

Nutrient	Plants (%)	Water (%)	Ratio Plants:Water
Carbon	45	0.012	3,750
Silicon	1.3	0.00065	2,000
Nitrogen	0.7	0.000023	30,000
Potassium	0.3	0.00023	1,300
Phosphoru:	0.08	0.000001	80,000

Other studies confirm that phosphorus is the usual controlling nutrient for eutrophication. Perhaps the most convincing data come from a famous series of experiments conducted in the Experimental Lakes Area (ELA; see Canadian Focus 20.1). Most of the research at the ELA involved the addition of nutrients at various rates and in different combinations to selected lakes, followed by monitoring of the ecological responses. The most important whole-lake experiments were the following (Schindler, 1978, 1990; Levine and Schindler, 1989):

- For two years, Lake 304 was fertilized with phosphorus, nitrogen, and carbon. It responded by becoming eutrophic. After the addition of phosphorus was stopped, the lake returned to its original oligotrophic condition, even though nitrogen and carbon were still being added.
- The two basins of Lake 226, an hourglass-shaped lake, were isolated with a vinyl curtain. One basin was fertilized with carbon, nitrogen, and phosphorus in a weight ratio of 10:5:1, while the other received only carbon and nitrogen at 10:5. Only the basin receiving phosphorus developed algal blooms. After five years, the nutrient additions were stopped, and the original oligotrophic condition returned within just one year. A similarly rapid recovery was observed in another experiment, involving Lake 303, after fertilization with P was stopped.
- Lake 302N was fertilized with phosphorus, nitrogen, and carbon. However, the nutrients were injected directly into deep water during the summer, at a time when lakes develop a thermal stratification (see In Detail 20.1). Because the nutrients were injected deeply, primary production in the surface water was not affected and eutrophication did not occur. Research at the ELA also showed that when phosphorus was added to lakes, the supply of nitrogen and carbon already present was capable of supporting phosphorus-induced eutrophication. In part, this occurred because eutrophication induced an increased rate of fixation of atmospheric dinitrogen (N2) by blue-green bacteria and a faster diffusion of atmospheric CO_2 into the lakewater.

Eutrophication also causes pronounced changes to occur in the species composition, relative abundance, and biomass of phytoplankton, which are the most important primary producers in the ELA lakes. Changes in the phytoplankton resulted in effects on organisms at higher levels of the food web, such as zooplankton and fish. For example, the productivity of whitefish (Coregonus clupeaformis) in hourglass-shaped Lake 226 was greater in the eutrophied basin than in the oligotrophic one. This occurred in response to the greater abundance of their prey of zooplankton and aquatic insects, which itself a trophic response to increased algae productivity.

In Detail 20.1. Lake Stratification
During most of the year, lakes have a rather uniform distribution of temperature throughout their depth. This allows their bottom and surface waters to mix easily under the influence of strong winds. During the summer, however, lakes often develop a persistent stratified condition. This is characterized by a surface layer of

relatively warm water, several metres thick in most lakes (but thicker in some large lakes), lying above deeper, cooler water. Because the density of warm water is less than that of cool water, the two layers remain discrete and do not mix.

The relatively warm, upper water of a stratified lake is known as the epilimnion, while the cooler, deeper water is the hypolimnion. These layers are separated by a narrow zone of rapid change, known as the thermocline. During the autumn, as the epilimnion cools, the stratification diminishes and the two layers become mixed by strong winds.

During stratification, oxygen and other dissolved substances can enter the hypolimnion, but mainly by diffusion across the thermocline. Because diffusion is a slow process, hypolimnetic oxygen becomes depleted in stratified lakes whose deeper water receives large inputs of organic material. The organic input may be associated with sewage, agricultural runoff, or algal biomass sinking from the epilimnion. The development of anoxic (no oxygen) conditions represents an important degradation of water quality because fish and most other animals cannot live in such an environment.

Sometimes, density gradients associated with dissolved salts may also cause lakes to become stratified. In these cases, a surface layer of fresh water sits on top of more saline, deeper water, with the layers separated by a steep chemical and density gradient known as a halocline.

Canadian Focus 20.1. The Experimental Lakes Area

Some of the most famous Canadian research in ecology and environmental science has been conducted in the Experimental Lakes Area (ELA). Research at the ELA, funded mainly by the Federal Department of Fisheries and Oceans (DFO), began during the late 1960s. The first two decades of work are closely identified with David Schindler, but hundreds of other Canadian and international scientists from governments and universities have been involved in research in the area. Several of the leading scientists working at the ELA, notably Schindler, have won international awards for their outstanding contributions.

The ELA is located in a remote region of northwestern Ontario near Kenora. The area contains many lakes and wetlands. The watersheds are largely forested, with thin soil that overlies hard quartzitic bedrock of the Canadian Shield. The ELA is not a protected area, so forestry is pursued, as are mining exploration and tourism. However, there is an understanding among the various interests in the ELA that some of the lakes and their watersheds are being used for research and should not be disturbed.

> Image 20.1. Lake 226 in the Experimental Lakes Area was divided into two separate basins with a heavy vinyl curtain. The upper basin in the photograph was fertilized with phosphorus, nitrogen, and carbon, while the lower one received nitrogen and carbon. Only the basin that received phosphorus became eutrophic and developed blooms of phytoplankton, which are discernible as a whitish hue in the photo.

Source: Michael Paterson.

One of the most important experimental procedures used at the ELA has been the controlled perturbation of entire lakes or wetlands. This is done to investigate the ecological effects of certain anthropogenic stressors, such as eutrophication, acidification, metal pollution, and flooding of wetlands. These are known as whole-lake experiments (and some as whole-wetland experiments). The experimental procedure includes an initial study of the lake or wetland for several years to determine the baseline conditions. The system is then perturbed in some way, for example, by causing it to become eutrophic by adding nutrients. The experimental lakes are monitored for a range of ecological responses, such as changes in the abundance and productivity of species and communities, in nutrient cycling, and in chemical and physical factors.

The experimental lakes are paired with reference (non-perturbed) ones, which provide information on natural changes that are unrelated to the manipulation. Because the reference lakes are monitored for a long time, they also provide extremely useful information relevant to changes in the ambient environment, such as climate warming.

Unfortunately, research at the ELA has been periodically threatened by cutbacks in funding, and the future of this world-class facility and its programs has been subjected to bouts of uncertainty. Throughout the history of the ELA, the DFO provided most of the funding to maintain its research infrastructure. Most of the experiments were also funded by DFO and conducted by its personnel or by university scientists working with them. However, during the early 1990s, DFO focused its activities more so on marine issues, and for several years it looked as if cutbacks might result in the ELA facility closing down. In fact, despite an international outcry from aquatic scientists and environmentalists, the ELA was essentially closed for about a year. During that time several buildings were taken down and extremely important research projects were curtailed or abandoned. Fortunately, however, the provinces of Ontario and Manitoba provided funding that has allowed the International Institute for Sustainable Development to manage and operate the ELA facility, so this vital location for whole-ecosystem science is now operating again to support world-class ecological research.

Sources of Nutrient Loading

In North America, eutrophication was most severe as an environmental problem during the 1960s and 1970s. At that time, the average discharge of phosphorus to inland waters was about 2 kg/person•year. About 84% of the phosphorus loading was associated with the dumping of municipal sewage, and the rest was due to agricultural fertilizer and sewage (from livestock). In addition, the nitrogen discharge at the time was about 12.5 kg/person•year, of which 36% was from municipal and 64% from agricultural sources.

Because scientists have convincingly demonstrated that phosphorus is the primary limiting nutrient for eutrophication in fresh water, control strategies have focused on reducing the input of that nutrient to surface waters.

Phosphorus in Detergent

One of the first targets was domestic detergents. During the 1960s and early 1970s, detergents contained large amounts of sodium tripolyphosphate (STP), which typically accounted for 50-65% of the weight of the product (12-16% as phosphorus). The STP was added as a so-called “builder” to reduce the activity of calcium and other cations in the wash water, thereby allowing the cleaning agents in the detergent (the surfactants) to work more efficiently. During the 1960s and early 1970s, as much as 3-million kilograms of high-phosphate detergents were used in North America each year, and virtually all was eventually flushed into surface waters through the sewage system. Detergent use accounted for about half of the phosphorus content of wastewater discharges during the early 1970s.

Fortunately, the domestic use of detergent is a discrete activity, and good substitutes are available to replace STP in the builder function. Consequently, it was relatively easy to achieve a rapid decrease in phosphorus loading by regulating the use of high-phosphate detergent. In 1970, detergents sold in Canada could contain as much as 16% phosphorus; this was decreased to 2.2% by 1973, and in 2010 the limit was reduced to 0.5%. Some areas have already banned the sale and use of detergents containing any phosphorus.

Sewage Treatment

The production of livestock manure in Canada is about 181×10^6 t/y, with a phosphorus content of 0.30×10^6 t/y and nitrogen content of 1.10×10^6 t/y (in 2006; Statistics Canada, 2008). Not much of the livestock manure is treated before being released to the environment – it is mostly disposed onto fields or into a nearby waterbody. The production of human sewage is about 10×10^9 t/y (most of this is water, equivalent to 10×10^{12} L/y; because municipal sewage is flushed away in toilets, it is much more diluted by water than is livestock manure; Environment Canada, 2010). Most of the human sewage in Canada is treated before it is released to the environment (see Chapter 25 for notable exceptions).

In most places, the principal objectives of sewage treatment are to reduce inputs of pathogenic microorganisms and oxygen-consuming organic matter to receiving waters. However, in places where surface waters are vulnerable to eutrophication, sewage may also be treated to reduce the quantity of phosphorus in the effluent.

All sizeable towns and cities in Canada have facilities to collect the sewage effluent from homes, businesses, institutions, and factories (Chapter 25). This infrastructure consists of complex webs of underground sewage pipes and other collection devices. Some municipalities have separate systems to collect domestic and industrial wastes, because the latter often contains toxic and hazardous chemicals that should be treated separately. Some municipalities also have a separate system to handle the large volumes of storm flows, which result from the runoff of rain and snow meltwater. Eventually, these large quantities of wastewater must be discharged into the ambient environment, usually into a nearby lake, river, or ocean. Wherever possible, it is highly desirable – and environmentally responsible – to treat the wastewater to reduce its pollutant load before discharging it into an aquatic ecosystem.

Regrettably, however, some municipalities in Canada continue to dump their raw, untreated sewage into a nearby aquatic environment. This practice is more common for cities and towns that are located beside an ocean, because well-flushed marine environments have a huge capacity for diluting and biodegrading organic pollutants. Cities that dump raw sewage into the ocean include Saint John and St. John's on the Atlantic coast, and Victoria on the Pacific coast. Consequently, some of their coastal habitats have become degraded by the aesthetic, hygiene-related, and ecological damage associated with the dumping of untreated sewage. Although the worst damage is restricted to the vicinity of the sewage outfalls, it is still an important problem that should be responsibly addressed by constructing sewage-treatment facilities.

Image 20.2. Even acidic lakes can become eutrophic if fertilized. Drain Lake near Halifax became extremely acidic (pH 4.0) after pyritic minerals in its watershed were exposed to the atmosphere by construction activity, which resulted in their oxidation and the production of sulphuric acid. However, the lake also received inputs of sewage, which caused it to become eutrophic and to support a lush productivity of aquatic plants, algae, zooplankton, insects, and waterfowl. The lake was too acidic, however, to support fish (see also Chapter 19). Source: B. Freedman.

Compared with many oceanic environments, inland waters such as lakes and rivers have a much smaller capacity for diluting and biodegrading sewage waste. Consequently, most municipalities located beside an inland waterbody treat their sewage before discharging the effluent. Sewage treatment can, however, vary greatly in degree and in the technology used, as we examine below (Freedman, 1995; Sierra Legal Defence, 2004, 2006).

- Primary sewage treatment is relatively simple. It usually involves the screening of raw sewage to remove larger materials, and then allowing the remainder to settle to reduce the amount of suspended organic matter. The resulting effluent is then discharged into the environment, although it may first be treated with a disinfectant (usually a chlorine compound) to kill pathogens, especially bacteria. Primary treatment typically removes 40-60% of the suspended solids of raw sewage and 5-15% of the phosphorus, while reducing the biological oxygen demand (BOD) by 25-40%. (BOD is the capacity of the organic material in wastewater to consume oxygen during decomposition.) More advanced primary systems can reduce the suspended solids by 90% and the BOD by 50%. In addition, they can reduce fecal coliforms by 45-55%.
- Secondary sewage treatment may be applied to the effluent of primary treatment, mostly to further reduce the BOD. Secondary treatment usually involves the use of a biological technology that enhances aerobic decomposition of organic waste by stimulating the microbial community in an engineered environment. Two such biotechnologies in common use are (1) activated sludge, which involves a vigorous aeration of sewage water to enhance the decomposition of its organic content, and (2) trickling filters, in which the wastewater passes slowly through a complex physical matrix that supports a large population of microorganisms. These biotechnologies, along with primary treatment, produce large quantities of a humus-like product known as sludge, which can be composted and then spread onto agricultural land as an organic-rich conditioner. Sludge may also be less-usefully incinerated or dumped in a landfill (see Chapter 18). Primary and secondary treatments together remove 30-50% of the phosphorus from sewage, and reduce the BOD and suspended solids by 85-90% and coliforms by 90-99%.
- Tertiary sewage treatment includes processes to remove most of the remaining dissolved nutrients from the effluent. Phosphorus removal may be achieved by adding aluminum, iron, calcium, or other chemicals that develop insoluble precipitates with phosphate, which then settle out of the water, removing 90% or more of the phosphorus. Other tertiary processes may be used to remove ammonium and nitrate.
- Artificial wetlands are sometimes constructed to provide advanced treatment of sewage. The wetlands are engineered to develop a highly productive ecosystem, in which vigorous microbial activity decomposes organic waste while algae and macrophytes decrease nutrient concentrations in the water. Most sewage-treatment wetlands are constructed outdoors, but some are developed inside of a greenhouse, which allows the system to work during the winter. The efficiency of these systems depends on climate, the rate of flow-through of the sewage, and the nature of the engineered wetland. Typically, artificial wetlands remove up to 30% of the phosphorus from raw sewage, while reducing BOD by as much as 90%.

Tertiary treatment to reduce phosphorus in municipal effluents requires expensive investments in technology and operating costs. Consequently, this practice is pursued only under certain conditions. Tertiary treatment is mostly used by communities located beside rivers and around the Great Lakes. Moreover, because the Great Lakes are affected by effluents originating from sources in both Canada and the United States, bilateral agreements have been negotiated concerning the loading of phosphorus and other pollutants. To meet the target loadings, municipalities in both countries must use tertiary systems to achieve a high degree of phosphorus removal from sewage.

Elsewhere in Canada, less attention is generally paid to the removal of phosphorus from municipal effluents. Although municipalities may treat their sewage, only primary or secondary systems are generally used, mostly to reduce the abundance of pathogens and to lower BOD in the effluent (Chapter 25).

As previously noted, agricultural livestock produce enormous amounts of fecal materials. However, their manure is rarely treated before it is disposed into the environment. Treatment facilities for agricultural sewage are considered too expensive and are not often required by regulators. This happens even though some intensive rearing facilities, such as agro-industrial feedlots and factory farms, may produce huge amounts of concentrated manure, equivalent to the sewage of a small city.

Eutrophication of an Arctic Lake

Meretta and Char Lakes are two small lakes that are located on Cornwallis Island in northern Canada. Because of the severe climate in the High Arctic, tundra lakes are relatively simple ecosystems. Moreover, nutrient inputs are sparse and cycling is slow, so tundra lakes are naturally oligotrophic. Char Lake is a typical oligotrophic, polar lake, with extremely clear water and low rates of productivity of algae, zooplankton, and fish. Meretta Lake, in contrast, received sewage from a small community. Because of the nutrient input, it became moderately eutrophic (Schindler et al., 1974).

The sewage dumping resulted in phosphorus loading about 13 times larger in Meretta than in Char Lake, while the nitrogen input was 19 times higher. Consequently, during the growing season, Meretta Lake developed a phytoplankton biomass averaging 12-times greater than in Char, and up to 40-times higher during the summer algal bloom. In the winter, these lakes are covered with ice, which restricts the rate at which atmospheric oxygen can enter the water. During this time, the decomposition of organic material, mostly sewage waste but also algal biomass, exerts a great demand for oxygen in the bottom water of Meretta Lake, resulting in anoxic conditions. The oxygen depletion causes severe stress to aquatic animals and impairs the reproduction of Arctic char (Salvelinus alpinus), a type of trout.

This case demonstrates that even polar lakes, which are relatively simple ecosystems because of their severe climatic environment, can exhibit a strong eutrophication response to fertilization with limiting nutrients.

Lake Erie: Eutrophication and Other Stressors

The Great Lakes are one of the world's outstanding fresh water systems, holding about one-fifth of global surface fresh water (excluding glaciers). Lake Superior sits at the top of this chain, with Lakes Michigan, Huron, Erie, and Ontario located below. The lakes and their watersheds drain to the Atlantic Ocean through the St. Lawrence River, itself a great waterway (there is also some flow to the Mississippi River, through a canal in Chicago). The aggregate surface area of the Great Lakes is 245-thousand km^2, and the watershed is 539-thousand km^2 (Table 20.2). About 35 million people live in the watershed, of which 10-million are in Canada.

All of the Great Lakes except Lake Michigan form part of the border between Canada and the United States. Consequently, issues concerning resources and water quality are binational: waters in Canadian jurisdiction are affected by actions in the United States and vice versa. Especially important issues are the dumping of sewage and industrial waste, the conversion of forest and wetlands into agricultural and residential land-uses, and commercial and sport fishing. Recognizing this context, the governments of Canada and the United States have entered into a number of co-operative agreements regarding the management of resources, emissions of pollutants, and research and monitoring of their shared Great Lakes ecosystem. Much of the integrated binational activity is coordinated by the International Joint Commission, a body with equal representation from both countries. The Great Lakes Water Quality Agreement, implemented in 1972 and modified in 1978, 1983, 1989, and 2012, commits Canada and the United States to maintain and restore the chemical, physical, and ecological integrity of the Great Lakes and their watershed.

Lake Erie has a relatively small volume and is located in a watershed with fertile soil. Consequently, Lake Erie has always been the most productive of the Great Lakes. However, its productivity has been greatly increased as a result of nutrient inputs associated with urban sewage and agricultural drainage. This has created eutrophic conditions in shallower regions of the lake. The western basin of Lake Erie is particularly vulnerable to eutrophication because it is relatively shallow and warm and receives large inputs of sewage and agricultural runoff. In addition to nutrient loading, Lake Erie has been affected by other important stressors. These include contamination by potentially toxic chemicals, large commercial and recreational fisheries, conversion of most of the natural ecosystems in its watershed into agricultural and urban land-uses, and introductions of alien plants and animals. This complex of stressors has degraded the water quality and ecosystem of Lake Erie. The damage was particularly acute during the late 1960s and early 1970s, when pollution was relatively uncontrolled. Although some of the earlier problems have been alleviated, Lake Erie is still in a degraded condition. The following sections examine the most important ecological changes in Lake Erie, as a case study of the effects of eutrophication occurring in combination with other stressors (Freedman, 1995).

Table 20.2. Size and Watershed Characteristics of the Great Lakes of North America. Sources: Data from Gregor and Johnson (1980), Neilson et al. (1994), Environment Canada (1996, 2013), Dolan et al. (2010), and EPA (2012).

	Superior	Michigan	Huron	Erie	Ontario
Surface area (km^2)	82,100	57,800	59,600	25,700	18,960
Average depth (m)	147	85	59	19	86
Water retention time (y)	191	99	22	2.6	6
Watershed area (km^2)	127,700	118,000	134,100	78,000	64,030
Land-use in watershed (%)					
forest	95	50	66	17	56
agriculture	1	23	22	59	32
urban	<1	4	2	9	4
wetland, other	4	23	10	15	8
Population in watershed ($\times 10^3$)	607	10,057	2,694	11,875	8,151
Population density (persons/km^2)	4.8	85.2	20.1	152.2	127.3
Phosphorus loading (10^3 t P/y)					
1976-1978	4	6	5	10	17
1988-1990	2	4	3	7	18
target loading	3.4	5.6	4.3	11	7
Phosphorus in open water (µg/L)					
1983-1985	2	6	4	13	7.5
2005-2008	3	3	2	15	6
guideline	5	7	5	10-15	10

Oxygen Depletion

Lake Erie develops a stratified condition during the summer, making it difficult for oxygen to penetrate to deep-water habitat (see In Detail 20.1). If the deeper water is subject to large demands for oxygen to decompose organic materials, deoxygenation can result. During most summers from the 1950s to 1970s, this condition occurred widely in Lake Erie, especially in its shallow western end. Sewage dumping and algal biomass sinking from the surface water resulted in an intense demand for oxygen, causing extensive deoxygenation of bottom water.

Deoxygenation is harmful to aquatic animals, most of which require free access to oxygen in order to live. The episodes of anoxia in Lake Erie caused great changes to occur in the community of invertebrates living in the sediment (benthos). The benthic community was dominated by larvae of mayflies (aquatic insects in the order Ephemeroptera). The most common species were Hexagenia rigida and H. limbata, which lived in surface mud in an abundance of about 400/m^2. However, following a series of severe oxygen depletions in the 1950s, these insects decreased to about 40/m^2, and by 1961 they had almost disappeared, occurring at less than 1/m^2.

The collapse of benthic mayflies was widely reported by the popular media, which sensationalized the phenomenon by suggesting that Lake Erie was "dead." This was by no means the case, because the mayflies had been replaced by a benthic fauna that is tolerant of deoxygenation. These included aquatic worms known as tubificids (Limnodrilus spp.), insect larvae of the midge family (order Diptera, family Chironomidae), and small molluscs (snails in the order

Gastropoda and clams in the family Sphaeriidae). The worm-dominated benthos, however, is considered an indication of great degradation of ecological integrity compared with the mayfly-dominated community of well-oxygenated sediment.

Algal Blooms

Because Lake Erie has a greater supply of nutrients, it supports a much larger biomass of phytoplankton than the other Great Lakes. When its eutrophication was most severe, its western basin supported about twice as much algal biomass as Lake Ontario (per unit of surface area), and 11 times more than oligotrophic Lake Superior.

The communities of phytoplankton vary greatly among the sub-basins of Lake Erie and also between its nearshore and offshore waters. The eastern and central basins are relatively deep and unproductive, while the shallower western basin is more productive. In all three basins, however, shallow nearshore habitat is more productive than offshore water. The algal bloom that occurs during the spring in eutrophic water is typically dominated by diatoms of the genus Melosira, while the bloom in late summer is dominated by the blue-green bacteria Anabaena, Microcystis, and Aphanizomenon, the diatom Fragilaria, and the green alga Pediastrum.

In addition, the colonial green alga Cladophora glomerata can occur as filamentous mats attached to rocks in shallow habitats. This alga grows in locally fertile habitats in Lake Erie and some of the other Great Lakes. It was especially abundant during the 1960s and 1970s, when storms caused mats of its biomass to detach from rocky substrates, eventually washing ashore as a malodorous mass or sinking to deeper water to contribute to the development of anoxic conditions.

Studies have shown that the western basin of Lake Erie has always been relatively productive, sustaining a lush growth of aquatic plants and algae and large populations of fish. However, the huge nutrient inputs associated with sewage dumping and agricultural runoff increased the intensity of eutrophication. Fortunately, these problems have been alleviated substantially since the 1970s. This is because inputs of phosphorus to the lake have decreased, mainly through a ban on high-phosphate detergent and the construction of tertiary sewage-treatment plants to service cities and towns.

Changes in Zooplankton

The zooplankton of Lake Erie used to be dominated by relatively large species, such as Limnocalanus macrurus and species of Daphnia. By the 1960s, however, these had mainly been replaced by smaller, previously rare species, such as Diaptomus siciloides, which is considered to be an indicator of eutrophic conditions. The greatest changes occurred in the shallow western basin, where the midsummer zooplankton density increased from less than about 7-thousand/m^3 prior to 1940, to as much as 110-thousand/m^3 in 1959. However, even at that time, zooplankton species typical of oligotrophic conditions survived in the deeper eastern basin.

Changes in the zooplankton community were caused partly by the increasing primary productivity, because single-celled phytoplankton are the food-base of these tiny crustaceans. In addition, at about the same time that Lake Erie was becoming more eutrophic, its commercial fishery was over-exploiting larger species of fish, which are typically piscivorous (they eat other fish). After the demise of the piscivorous species, the fish community became dominated by smaller species that feed on zooplankton (known as planktivorous fish), which selectively feed on larger zooplankton. Therefore, smaller species of zooplankton were favoured and their abundance increased.

Changes in the Fishery

Lake Erie has long supported a large fishery, which typically exceeds the combined landings of all the other Great

Lakes. Remarkably, the total catch by the commercial fishery has been quite stable over the years. This has occurred despite enormous changes in the species of fish present, fishing technology, intensity of eutrophication, pollution by toxic chemicals, habitat damage caused by damming rivers required for spawning, and sedimentation of shallow habitat by soil eroded from deforested parts of the watershed.

Although the catch of the fishery on Lake Erie has not declined, the nature of the fish community has changed greatly. These changes illustrate a severe degradation of the fishery resource and of the natural ecosystem. When the commercial fishery on Lake Erie began in the nineteenth century, the prime targets were the largest, most valuable species – these were whitefish (Coregonus clupeaformis), lake trout (Salvelinus namaycush), and herring (Leucichthys artedi). This is a common pattern whenever a previously unexploited fishery or forest resource is initially harvested – take the best and leave the rest (see Chapter 14).

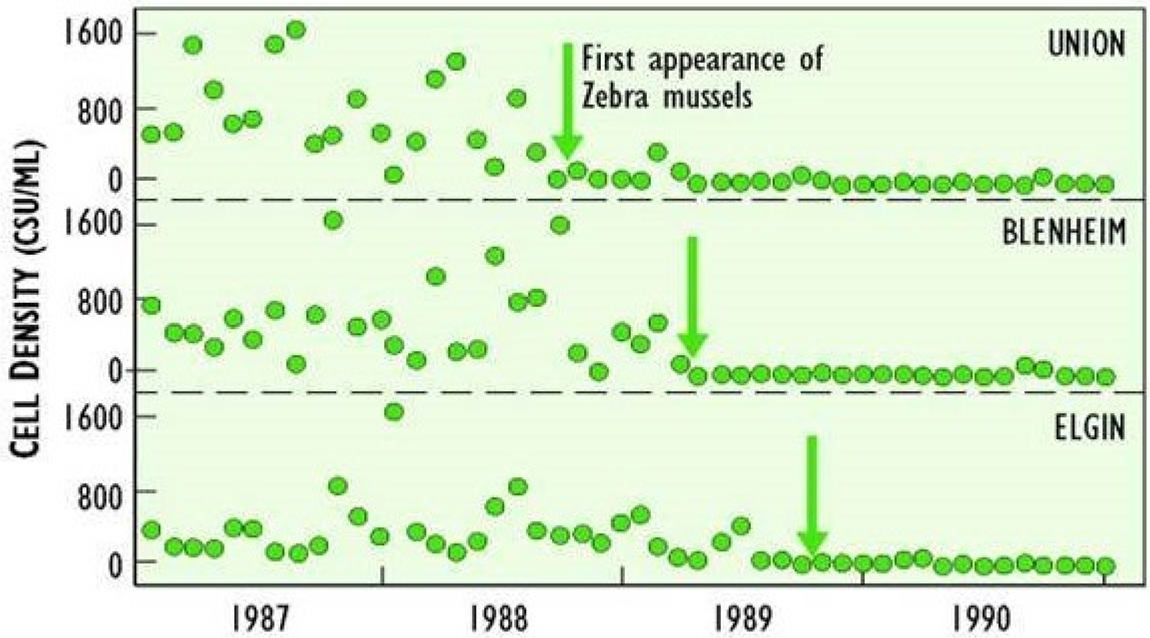
Unfortunately, populations of the most desirable species were rapidly depleted. This happened because the fishing pressure was excessive and could not be sustained. Also, severe habitat degradation occurred in the lake, caused mainly by erosion and siltation associated with extensive deforestation of its watershed. As the most desirable species disappeared, the fishing industry switched to "second-choice" species, such as blue pike (Stizostedion vitreum glaucum), walleye (S. v. vitreum), sauger (S. canadense), and yellow perch (Perca flavescens). Because of over-exploitation and habitat degradation, the species of Stizostedion became extirpated or rare by the early 1970s. The fishery was then dominated by smaller, low-value species such as yellow perch, and by alien fish such as rainbow smelt (Osmerus mordax), freshwater drum (Aplodinotus grunniens), and carp (Cyprinus carpio). Therefore, although the total yield of fish caught has remained fairly large and consistent over time, the quality of the economic resource and the integrity of the fish community have been badly degraded.

Recent Changes in Environmental Quality: For a number of reasons, ecological conditions have improved markedly in Lake Erie since the late 1970s. This has largely been achieved by the construction of sewage-treatment facilities in lakeside cities and towns in Canada and the United States (as well as upstream, especially on the Detroit River and Lake St. Clair). Many of these facilities include technology to reduce phosphorus inputs. The annual loading of phosphorus to Lake Erie has been reduced from about 28-thousand tonnes in 1968, to 20-thousand t in 1974, and 6-17-thousand t during 1981-2008 (average 9-thousand t; Richards, 2012; Figure 20.1). Whereas in the 1960s most of the phosphorus loading was from point-sources (primarily discharges of sewage from towns and cities), it is now mostly non-point discharges associated with agricultural runoff.

The reduction of phosphorus input has alleviated eutrophication in Lake Erie (Makarewicz and Bertram, 1991). The average biomass of phytoplankton decreased from 3.4 g/m^3 in 1970 to 1.2 g/m^3 during 1983-1985. The largest biomass still occurs in the western basin, where it averaged 1.9 g/m^3 during 1983-1987, compared with 1.0 g/m^3 in the central basin and 0.6 g/m^3 in the deepest, eastern basin. Blooms of nuisance algae have also decreased in intensity. For example, the blue-green alga Aphanizomenon flos-aquae had a standing crop as high as 2.0 g/m^3 in 1970, but only 0.22 g/m^3 during 1983-1985. Similarly, diatoms that indicate eutrophic conditions have decreased in abundance, by 85% in the case of Stephanodiscus binderanus in the western basin, and by 94% for Fragilaria capucina. At the same time, diatoms indicative of mesotrophic or oligotrophic conditions have become more abundant, notably Asterionella formosa and Rhizosolenia eriensis. The open water of the previously eutrophic western basin is now considered to be in a mesotrophic condition, while the eastern basin is now oligotrophic.

Figure 20.1. Phytoplankton Density in Lake Erie. This figure shows how filter-feeding on phytoplankton by zebra mussels has helped to clarify the water of Lake Erie (along with the influence of reduced phosphorus loading). The sampling site at Union is at the western end of the lake, while Blenheim and Elgin are progressively east. The zebra mussel invaded from west to east, and there was a lag in the development of its

dense shoals along this gradient. Source: Modified from Edsall and Charlton (1997).



The animal communities have also changed since the 1970s. Species of zooplankton that indicate oligotrophic conditions have become more abundant, while indicators of eutrophication are fewer and mostly restricted to the western basin. Since 1972, the populations of relatively large fishes have increased greatly, particularly walleye and introduced Pacific salmon (Oncorhynchus spp.). These are fish-eating species, and their predation has decreased the abundance of smaller, zooplankton-eating fish such as smelt, alewife (Alosa pseudoharengus), and shiners (Notropis spp.). The decrease of planktivorous fishes has allowed secondary increases of larger-bodied zooplankton, such as the waterflea Daphnia pulicaria.

The zebra mussel (Dreissena polymorpha) is another cause of important ecological change. This bivalve mollusc, a native of Eurasia, was accidentally introduced to the Great Lakes by the discharge of ballast water from transoceanic ships. The mussel can rapidly attain an extremely dense population (up to 50-thousand/m^2) on hard underwater surfaces such as rock, metal, and concrete. It is a filter-feeder, and its huge populations have an enormous capability for removing algal cells from water. Consequently, they may be responsible for some of the recent clarification of Lake Erie and eutrophic parts of other Great Lakes (Figure 20.1). In addition, their dense populations have benefited some species of ducks that winter on the lakes and feed on benthic molluscs and other invertebrates. However, the invasion of the Great Lakes by zebra mussels has also caused serious damage, including a reduction in filter-feeding zooplankton (with secondary effects on planktivorous fish), and the displacement of native molluscs that cannot compete with the dense shoals of this non-native mussel. Industries and water utilities have also suffered damage from the clogging of their water-intake pipes.

Overview of the Lake Erie Case Study

Lake Erie is an important example of the cumulative, detrimental effects of a variety of anthropogenic stressors on the ecological health of a large lake. The stressors that have degraded Lake Erie include eutrophication caused by nutrient loading, habitat damage through siltation resulting from deforestation of the watershed, over-exploitation of a potentially renewable fishery, pollution by oxygen-consuming sewage and toxic chemicals, and introductions of alien species. Fortunately, Lake Erie is also beginning to demonstrate that a highly degraded ecosystem can be induced to recover somewhat, assuming that the causes of the damage can be mitigated effectively. Still, there is much that should yet be done to improve environmental conditions in Lake Erie and the other Great Lakes, particularly with respect to the continued dumping of incompletely treated and even raw sewage.

Dams and Impoundments

A dam is a structure that is used to contain flowing water, which backs up to form a lake-like impoundment. Some dams are immense. The world's first "very large" dam was the 221 m Hoover Dam, built in 1935. The tallest is the Jinping-I Dam at 305 m, on the Yalong River in China. Dams may be built for various useful purposes: as components of a hydroelectric development, as a flood-control structure, and to store water for use in irrigated agriculture or to supply municipal water. The International Commission on Large Dams (2014) reports that there are 58.3-thousand dams taller than 15 m in the world (these are referred to as "large dams"), and perhaps 800-thousand shorter ones. About 49% of the dams have a single use, of which 49% are for irrigation, 20% for hydroelectricity, 13% for municipal water supply, 9% for flood control, and 10% for other purposes. Of the multi-use dams, 24% are for irrigation, 19% for flood control, 17% for municipal water supply, 16% for hydroelectricity, 12% for recreation, and 12% for other purposes.

Canada has 1,166 large dams (>15 m) and also many smaller ones. About 64% of the large dams are primarily used for hydroelectricity, 11% for water supply, 9% to containing tailings from mines, 6% for municipal water supply, 6% for irrigation, 2% for flood control, and 4% for other purposes, while 9% are multi-purpose (Environment Canada, 2010).

The construction of dams and impoundments always causes environmental damage and affects local people in various ways. For these reasons, these developments are always controversial at the local scale, and often at national and international levels as well. Such controversy has been sufficient to halt some proposals (often in concert with concerns about economic and energy-supply issues). A high-profile Canadian example of this is the Great Whale development, which was suspended in 1994. This was to be the second phase of a series of hydro megadevelopments proposed by Hydro-Québec in waterways east of James Bay and Hudson Bay. An international example is the Three Gorges Project in China (see Global Focus 20.1).

Moreover, if today's criteria for acceptable environmental and socio-economic impacts had been applied to earlier proposals, many of the existing dams and impoundments would not have been constructed. For example, the World Bank has progressively upgraded its environmental and socio-economic criteria for funding large dam projects. In 1996, it re-evaluated proposals it had considered during the period of 1960 to 1995 (Dorcey et al., 1997) and found that under the older evaluation criteria, about 10% of the proposals had been considered "unacceptable" for funding. Under the new criteria, however, 26% would have been considered unacceptable and another 48% only "potentially acceptable" (the latter could become acceptable if modified to take account of certain environmental and/or socio-economic concerns).

In the next sections we examine the most important environmental effects of dams and impoundments, with an emphasis on those occurring in Canada.

> Global Focus 20.1. The Three Gorges Project
> China is the most populous country in the world, with a population of 1.4 billion people in 2014. It is also a rapidly developing country – during the 25-year period from 1991 to 2014, the Chinese economy grew by an impressive 24-fold, or an average rate of 9.6% per year to a gross domestic product (GDP) of US$2,410 billion in 2015 (for comparison, the Canadian GDP was $1,873 billion in that year and that of the United States was $17,416; IMF, 2015). The impressive economic growth of China has greatly increased its need for massive and reliable sources of commercial energy. Much of this demand is being met through the use of fossil fuels, especially coal and petroleum, the latter being mostly imported at great expense. Because of the huge drain on finances that is

associated with importing fuels, and the pollution caused by their use, the government of China has placed a high priority on developing hydroelectric resources, which are a renewable source of energy (see Chapter 13).

The highest-profile hydroelectric development in China, and the second-largest in the world, is the Three Gorges Project (the largest is the Itaipú Dam in Brazil and Paraguay) (China Three Gorges Project, 2011; International Rivers, 2008; Wikipedia, 2015). Construction began in 1993 and was completed in 2012, with a total expenditure equivalent to US$26 billion. The project has flooded an enormous reservoir in the canyon of the Yangzi River in southeastern China. The main dam is 0.94 km wide and 182 m high, and the reservoir extends for 640 km and covers 632 km^2. The project has 32 generating units each of 700 MW of installed capacity, which will provide an enormous amount of power (the aggregate capacity is 22,400 MW, or about 12% of the national total). The power will be used in southern and central regions of China, where the economy is growing most quickly.

The Three Gorges Project is expected to provide the following key benefits to China:

- a huge amount of electricity, from a renewable source
- some relief from the expense of importing fossil fuels
- mitigation of damage from periodic disastrous flooding of the Yangzi River, which killed more than 1 million people in the past century
- improved access for commercial shipping into the interior, extending up to 2400 km through a series of locks
- stimulation of economic growth because of relatively inexpensive energy and improved transportation
- a proclamation of Chinese greatness and accomplishment

However, the massive Three Gorges project is also extremely controversial for many reasons:

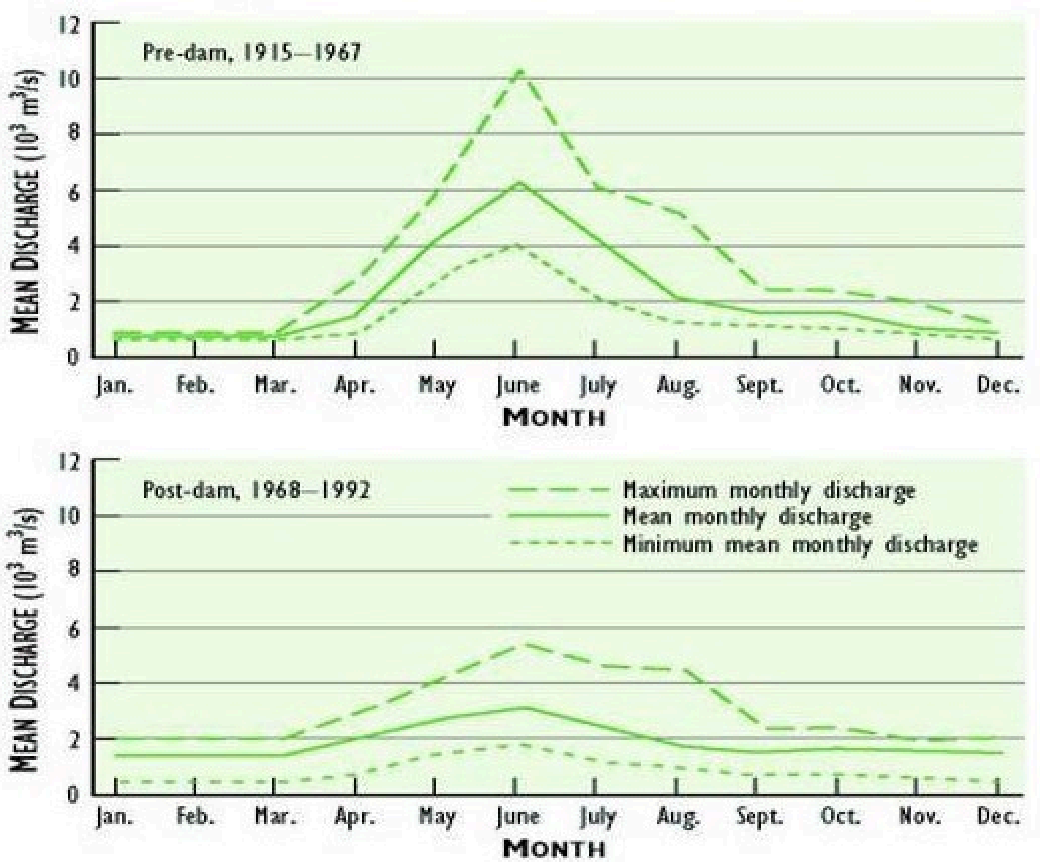
- it has dammed the flow of a great river – at 6,300 km, the Yangzi is the third-longest river in the world (after the Nile and Amazon)
- its associated reservoir inundated land where many people lived – about 1.3 million people had to be relocated to higher ground, many of whom were dispossessed of fertile land and built-upon developed property and ended up in worsened financial circumstances.
- there are fears about the safety of the dam and its enormous reservoir, partly based on risks of inferior design and construction fostered by corruption in the awarding of some contracts; an engineering failure could be a massive catastrophe
- pollutants are likely to accumulate in the reservoir (at present, they are mostly carried by the river to the ocean), including massive amounts of chemicals released from flooded industrial sites that were not properly cleaned up
- the reservoir may silt up rather quickly, because of erosion caused by extensive deforestation of the Yangzi watershed
- about 1,300 sites of cultural and historical importance were destroyed by inundation; only some of their artefacts and structures were salvaged

Clearly, the Three Gorges Project is a monumental undertaking of human ingenuity and engineering. It has transformed a significant part of the surface of the planet and is having gigantic economic and environmental impacts. It is a sobering thought that the extreme benefits and risks of such a colossal endeavour were made necessary by the astonishing increases in the economic scale of the human enterprise. As enormous as this project is, we can expect proposals for others of similar or larger magnitude if the energy and material demands of the burgeoning human economy are to be met.

Hydroelectricity is produced by using the kinetic energy of flowing water to turn a turbine, which connects to a generator that produces electricity, which is distributed to consumers through a complex network of transmission lines (see Chapter 13). The global use of hydroelectricity was 3,782 terawatt-hours of electricity (in 2013; this is equivalent to 856 x 10^6 tonnes of oil equivalent; BP, 2015). About 56% of the global use of hydroelectricity occurs in developed countries, and 23% in North America. Canada has invested relatively heavily in the development of hydroelectric resources and accounts for 10% of the global use of this energy source (for comparison, Canada constitutes 0.5% of the global population). Hydroelectricity accounts for about 6.7% of all commercial energy use, but 75% of the use of renewable sources (others include wind, solar, geothermal, and biomass).

There are three basic ways to harness flows of surface water to generate hydroelectricity:

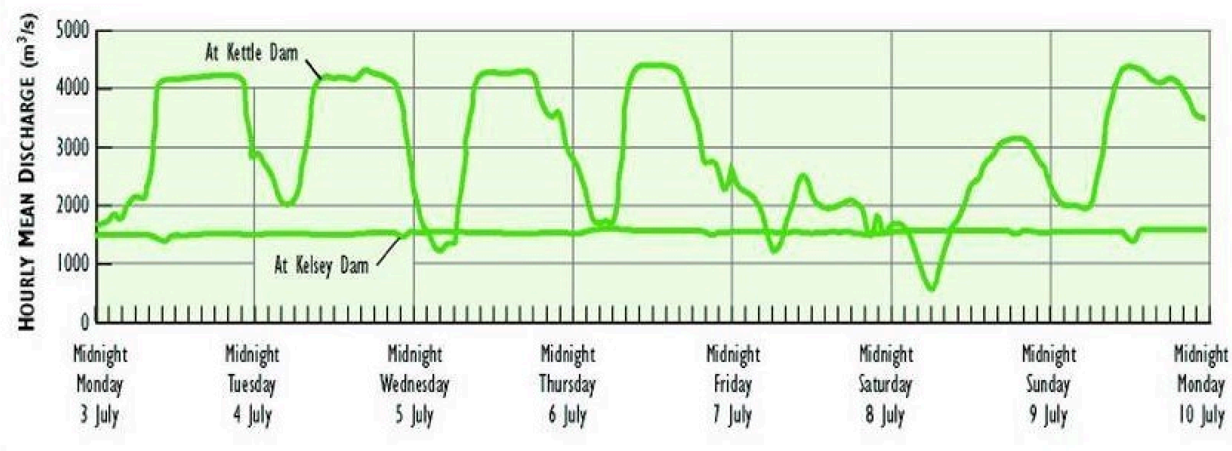
1. A large impoundment can accumulate riverflow and flood an extensive area of land. This stores water from the spring high-flow period so that electricity can be generated according to demand throughout the year. This kind of facility has a large effect on the seasonal variation of below-dam riverflow, because it greatly reduces the spring peak flow while increasing the flow during the summer, fall, and winter (Figure 20.2). Large impoundments are the most common type of major hydroelectric facility in Canada.
   Figure 20.2. Effects of Reservoir Development on Seasonal Flow of the Peace River. The Bennett Dam and its associated reservoir were built in 1968, so the upper curves (for 1915–1967) represent pre-impoundment conditions. The flows were measured at the town of Peace River, Alberta. The most notable changes are (1) an overall reduction in the annual variation of riverflow; (2) a large reduction in peak flow during mid-April to mid-July; and (3) an increase during the low-flow period of September to March. Source: Modified from Rosenberg et al. (1997).



2. A run-of-the-river development directly harnesses the flow of a river to drive turbines, without creating a large impoundment for storage. This kind of facility utilizes riverflow according to its seasonal availability. A run-of-the-river development has little or no capacity to store part of the spring peak flow, or to coordinate the timing of electricity generation with peaks of consumer demand. However, this kind of hydro development causes much less environmental damage than one involving a large reservoir.

3. A combined system incorporates elements of both run-of-the-river and the development of a large impoundment. These so-called peaking systems will store water during part of the day and release it during the time of highest demand for electricity, which is generally between 08:00 and 22:00 (Figure 20.4). One variation is the pumped-storage system, in which electricity generated during low-demand times of the day is used to pump water into an elevated reservoir; the stored water is later used to generate electricity at the peak-demand time. If the peak-flow system causes large flow variations downriver, important ecological damage may be caused. Other combined systems have run-of-the-river generators installed on rivers draining into a central reservoir or installed downriver of a reservoir.

Figure 20.3. Effects of Peaking Discharges on Hourly Mean Discharge to the Nelson River. The data are for a one-week period in July 1984. This figure illustrates the changes in hydrology that occur downstream if the generation of electricity is timed to meet the peak daily demand. Note the relatively low demand during the weekend. Kelsey Dam is not subject to these peaking discharges, so it represents the background pattern of low flow in the summer. Source: Modified from Rosenberg et al. (1997).



Environmental Effects

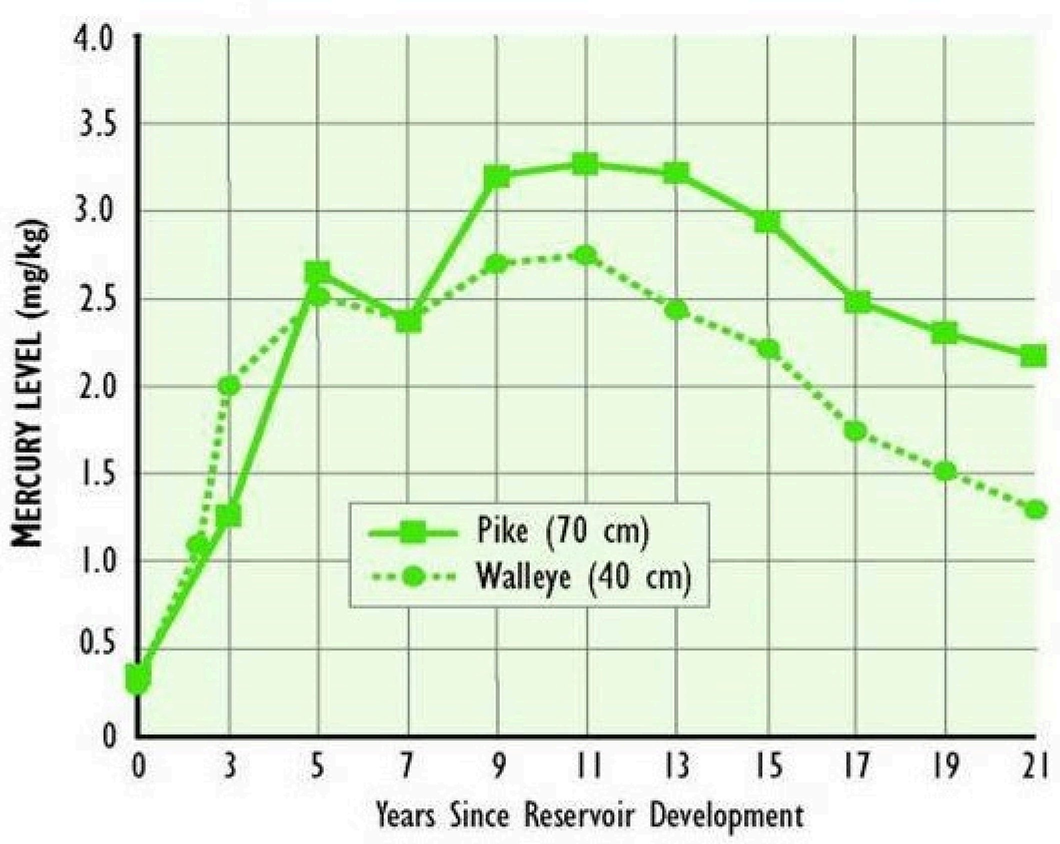
Important environmental benefits are associated with the use of hydroelectricity:

- Because the energy source (flowing water) is renewed through the hydrologic cycle, hydroelectricity is a renewable source of power.
- The emissions of greenhouse gases are much smaller than those associated with the use of fossil fuels to generate electricity.
- Unlike fossil fuels, there are no direct emissions of SO_2 or NO_x, which are important causes of acid rain.
- In some regions, impoundments help control downstream flooding, which might otherwise cause economic damage and risks to people living in flood plains (described later).
- Substantial recreational or commercial fisheries may develop in reservoirs.

However, to a degree these advantages are rather simplistic, particularly because large quantities of fossil fuels, metals, and other non-renewable resources are used to construct hydroelectric facilities. Moreover, the dams and impoundments cause some important environmental damages (Dorcey et al., 1997; Rosenberg et al., 1997; International Rivers Network, 2005).

- Flooding of Natural Habitat: Large reservoirs flood extensive areas of terrestrial and wetland habitat. This causes ecological damage, including the displacement of plants and animals that had utilized the original habitats. In some cases, uncommon or rare species may be affected, particularly if unusual habitats such as waterfall spray zones or special wetlands are destroyed. Of course, even while flooding destroys terrestrial and wetland areas, it also develops new aquatic habitats, which provide opportunities for certain fish, waterfowl, and other aquatic species. The productivity of algae, zooplankton, and fish is usually relatively high for several years after the creation of a new reservoir because of nutrients leached from flooded soil.
- Methylmercury: High concentrations of methylmercury commonly occur in fish in reservoirs. This happens because inorganic mercury that is naturally present in soil becomes methylated by bacteria under the anoxic conditions that develop in sediment after flooding. As we learned in Chapter 18, methylmercury is readily bioaccumulated by organisms and then magnifies up the food web to occur in particularly high concentrations in top predators. It also tends to occur in higher concentrations in older individuals within a fish population. Mercury concentrations in the flesh of predatory fish in reservoirs are often higher than 1.0 ppm and can reach 3 ppm, which significantly exceeds the 0.5 ppm limit for fish intended for human consumption. Fish with high concentrations of methylmercury are also a toxic hazard to natural predators such as osprey (Pandion haliaetus), bald eagle (Haliaeetus leucocephalus), and river otter (Lutra canadensis). In the boreal region of Canada, the concentration of mercury in fish increases after the initial development of a reservoir and persists for 10-30 years or longer (Figure 20.5). In general, this phenomenon is most intense in large, new reservoirs. It is less of a problem in reservoirs that are created by raising the water level of a steep-sided lake or river valley with shorter-term storage, or in older impoundments.

  Figure 20.4. Mercury in Fish in the Robert Bourassa Reservoir, Quebec. The data are for mercury in the muscle of fish, expressed in mg/kg (or ppm) on a fresh-weight basis. The data are standardized to fish size; those for pike are for individuals 70 cm long, while those for walleye are for animals 40 cm long. The reservoir was first filled in 1979. Source: Data from Schetagne et al. (2002).

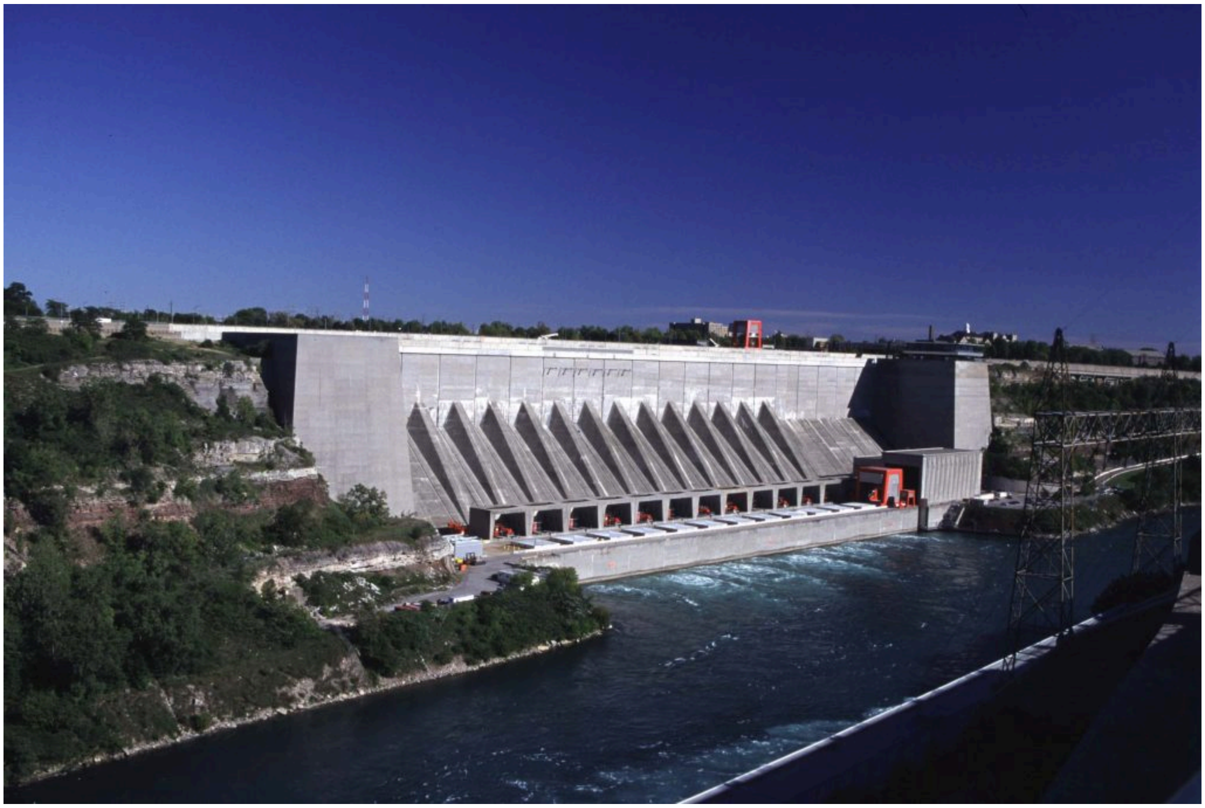


- Altered Flows and Obstructions: Many downstream effects result from the construction of dams, other flow-control structures, and diversions of rivers to increase the flow into reservoirs. Changes in the timing and amounts of flow affect the sedimentation regime: decreased flow results in silt deposition and the infilling of gravel beds used by spawning fish, while scouring by increased flow causes other kinds of habitat damage. Large changes in the flow also affect the productivity of algae and macrophytes, in part by affecting the flux of nutrients. These effects can be particularly acute in riverine marshes, deltas, and estuarine habitat. The resulting changes in productivity and other habitat characteristics may secondarily affect aquatic invertebrates, fish, migratory birds, and aquatic mammals. In one rare case in 1984, a torrential flow on the Caniapiscau River in northern Quebec, partly caused by the release of water from an overly full reservoir (due to a week of unusually heavy rain), drowned about 10-thousand migrating caribou (Rangifer tarandus).

Image 20.3. Two views of Churchill Falls, Labrador: (left) the 75 m tall falls prior to the completion of the 5429 MW generating station in 1974; and (right) the greatly reduced flow in 1988 due to the diversion of riverflow to generate electricity. Source: A. Luttermann.

- Effects of Obstructions: A high dam can be an insurmountable obstruction to the up-river passage of migratory fish. However, this blockage can sometimes be partially mitigated by installing a fish ladder, by catching migrating fish and transporting them above the dam, or by releasing young fish raised at a hatchery. In addition, juvenile fish migrating to the ocean may be killed or injured during passage through the turbines of a hydroelectric facility. Some of this damage can be avoided by installing screens or deflectors, while also providing an alternative passageway for the migrating fish.

  Image 20.4. This hydroelectric generating station is located on the Niagara River in southern Ontario. It generates electricity mostly at night, using river flow that has been diverted to a storage reservoir (not visible in the photograph). During the day, however, the riverflow passes over Niagara Falls, a popular tourist destination. Source: B. Freedman.



- Emissions of Greenhouse Gases: The development of a large reservoir results in conditions suitable for the emission of large amounts of carbon dioxide and methane to the atmosphere (see Chapter 17). The production of methane, which is about 28 times more potent as a greenhouse gas than carbon dioxide, may occur if flooding results in anaerobic conditions through the decomposition of large amounts of biomass – the dead trees and litter of drowned forests and the organic matter of inundated wetlands, especially peaty bogs and fens. Such oxygen-poor conditions favour the production of methane during decomposition, which out-gasses into the atmosphere. The emission of greenhouse gases is greatest during the first several decades after flooding and then slows to a rate similar to that of natural lakes. Experimental flooding of a wetland at the Experimental Lakes Area resulted in a twenty-fold increase in the rate of methane emission to the atmosphere. Under conditions that are particularly favourable for methane generation, the rate of emission of greenhouse gases (standardized as greenhouse warming potential because CH_4 has greater radiative activity than CO_2) can exceed that of a coal-fired power plant (although this is more characteristic of tropical reservoirs than cooler ones; Rosenberg et al., 1997).

- Effects on Biodiversity: Some hydroelectric developments have destroyed the habitat of threatened species or unusual ecosystems. The proliferation of dams on rivers has greatly reduced or extirpated many populations of Atlantic salmon (Salmo salar) and Pacific salmon (Oncorhynchus spp.). At least 142 stocks of Pacific salmon in western Canada have been lost partly because of hydroelectric dams (in combination with logging, over-fishing, and other stressors), and many others are threatened. Hydroelectric developments also threaten the breeding habitat of the harlequin duck (Histrionicus histrionicus) in both eastern and western Canada (it is endangered in the eastern part of its range). Construction of the Churchill Falls hydro project in Labrador destroyed the habitat of rare species of ferns, mosses, and liverworts in the misty spray zone of the original natural waterfall. Undoubtedly, numerous undocumented losses of rare species and their habitat occurred during the construction of hydroelectric developments in Canada and elsewhere prior to the early 1970s, when biodiversity surveys became a routine component of environmental impact assessments for these projects.

- Effects on Local People: The lifestyle of local people can be greatly affected by a hydroelectric development. This is particularly true if a large reservoir is developed in a heavily populated area, which is often the case in less-developed countries. For example, in China alone, the Three Gorges Dam displaced about 1.3-million people; the Danjiangkou Dam (completed in 1974) displaced 383-thousand people; the Sanmenxia (1960), 319-thousand; the Xinjiang (1961), 306-thousand; and in India, the Dongpinghu Dam (1958) displaced 278-thousand people (Goodland, 1994). In such crowded countries, suitable land for relocation of these displaced people is often unavailable. People are also displaced by reservoirs in northern Canada, although typically several hundred or fewer. Almost all of the displaced people are Aboriginal, who may have to be relocated from traditionally used areas if their villages become flooded. They are also deprived of opportunities to hunt mammals and birds in part of their traditional foraging area, and they may not be able to eat fish from the reservoir or downstream for several decades after its creation (because of health hazards associated with methylmercury). Of course, local economic opportunities exist for some of these people, such as jobs associated with the construction and maintenance of the hydro facility and its related infrastructure of transmission lines and roads. However, entry into wage employment can be extremely disruptive to traditional subsistence lifestyles, for both individuals and the community. There are also many social and economic disruptions caused by the influx of people from elsewhere in Canada and from the construction of new roads and towns. For these and other reasons, local people often bitterly resist the development of large hydroelectric facilities (and other large industrial projects) in the areas where they live.

Canadian Focus 20.2. Hydro Development in Labrador

Hydroelectric power is an economically attractive and renewable source of energy. In the past, areas with a high potential for hydroelectricity were often developed without much consultation with local people, who also may not have received many economic benefits from the project. Local people generally did, however, bear the brunt of the environmental damage, which typically included extensive flooding, changes in the hydrology of rivers used for transportation or for fishing, and sometimes harmful influences on traditional lifestyles and culture.

One example of insensitive hydro development was the Churchill Falls Project in Labrador, for which construction began in 1967. In 1969, the government of Newfoundland entered into a contract with Hydro-Québec (a Crown Corporation of Québec) to supply power for 65 years, but at a price that (incredibly, in retrospect) took no account of monetary inflation or the future value of hydroelectricity. In 1971, flooding of the Smallwood Reservoir began, and it eventually covered an immense 6,700 km^2. In 1974, a generating station with a capacity of 5429 MW was completed and electricity began to flow to markets in Québec and the northeastern United States.

It is astonishing by the standards of today, but the Churchill Falls Project was developed with only a few studies of its potential environmental impacts. For instance, there was little understanding of how the local and regional ecology might be affected by the enormous changes in the hydrology of the Churchill River, one of the great watercourses of eastern Canada. Inevitably, the huge reservoir caused extensive damage through flooding, other habitat changes, and the mobilization of bioavailable methylmercury.

It is also remarkable that this immense industrial development occurred without much consultation with the local people, particularly those of the Innu culture, who are the original inhabitants of that region of Labrador. The local Innu had long engaged in subsistence hunting and commercial trapping in the project region, undertaking seasonal movements to traditional areas where they obtained wild meat as food and furs to sell. Most of these people were completely unaware of the proposed hydroelectric development or its likely consequences for their traditional activities. Some of them lost their canoes, cabins, and other possessions to flooding, for which they were not compensated. Many archaeological sites, such as burying grounds, were also lost.

In 1975, planning and construction began for a subsequent hydroelectric development, this time to harness the lower Churchill River by building a dam and power plant at Gull Island, about 200 km downriver of Churchill Falls. Although the project was not completed at the time, the development potential remained attractive in terms of industrial and economic considerations. In 1990, and several times since, new proposals were brought forward to develop the hydroelectric potential of the lower Churchill River, and as of 2015 (when this case study was written), it looked certain that the project would proceed. Although these plans have generally been supported by business interests in nearby Goose Bay, many of the Innu have been opposed to the proposed new hydro project. Their governing organization, known as Innu Nation, has demanded the following features in any development agreement they would consider signing:

- compensation for damage suffered by Innu during the initial development at Churchill Falls
- a full assessment of the environmental and socio-economic impacts of the proposed new development
- royalties and other compensation, such as specified job and contract opportunities, for Innu persons and companies during the new development
- the settlement of a comprehensive land claim, in view of the assertion of the Innu Nation of Aboriginal title for almost all of that region of Labrador

To reinforce their position, the Innu have at various times held public protests in the project area and on Newfoundland. They have also petitioned their case to environmental organizations, power companies, and state governments in the northeastern United States, where much of the power would likely be sold. A particularly high-profile demonstration was held to confront a press conference staged by the governments of Québec and Newfoundland in March of 1998, near the village of Churchill Falls, where their premiers jointly announced a new plan for a hydro development on the Lower Churchill River. This protest by the Innu garnered front-page attention throughout Canada and internationally. The project envisioned at that time would have cost about $10 billion. It would have constructed a new reservoir, dam, and generating facility of 2,264 MW at Gull Island, while also increasing the capacity of the existing Upper Churchill Falls station by 1000 MW.

Since then, the government of Newfoundland & Labrador has enetered into an agreement with Nova Scotia to develop a hydro facility on the Lower Churchill River and a transmission corridor through to New England. However, at the time of writing (2015), full consensus had not yet been obtained from the Innu people, and a land settlement had not been achieved. However, many detailed or environmental and socio-economic impact assessments had been completed. Although this hydroelectric development in Labrador remains contentious, its construction is likely to begin in the summer of 2015.

A Case Study: La Grande Complex

The La Grande Complex in Québec was developed between 1973 and 1996 (Messier, 1998). The development is centred on the La Grande River, but the river's natural flow has been augmented by diversions of the Caniapiscau River (48% of its flow) and the linked Eastmain and Opinaca Rivers (90% of their flow). The first phase of the development occurred between 1973 and 1985 and resulted in five reservoirs with a total impoundment area of 11,335 km^2 (including 10,400 km^2 of newly flooded land). Three powerhouses were built, with a total generating capacity of 10,282 MW. The second phase of the development, between 1987 and 1996, added five powerhouses (capacity 4,962 MW) and three new reservoirs (1,618 km^2, including 1,134 km^2 of flooded land). During the planning, construction, and operating phases of the development, Hydro-Québec undertook extensive studies of hydrology, climate, ecology, socio-economics, and other issues related to potential environmental impacts.

For several years after the new impoundments were flooded, there was a relatively high productivity of phytoplankton and zooplankton. This occurred because of the high concentrations of nutrients, especially phosphorus, that were leached from flooded soil. The resulting abundance of invertebrates and small fish allowed a relatively high productivity of lake whitefish (Coregonus clupeaformis) and northern pike (Esox lucius) for several years. However, mercury concentrations up to 3 ppm developed in these and other predatory fishes. The maximum concentrations in whitefish occurred five years after impoundment and subsequently declined, while those in pike peaked after 10 years. The mercury concentrations are expected to return to background levels after 10-25 years for fish that feed on invertebrates, and after 20-30 years for fish that feed on other fish.

Image 20.5. Hydroelectric developments in relatively flat terrain can result in the flooding of enormous areas as reservoirs. This view shows a small part of one of the reservoirs behind the LG-1 Dam on the La Grande River. The first phase of this immense hydroelectric development resulted in five reservoirs with a total area exceeding 11,000 km^2. Source: A. Luttermann.

Erosion associated with high-water discharges threatened the village of Fort George on the estuary of the La Grande River, forcing the relocation of its inhabitants to a new settlement upstream at Chisasibi. The relocation resulted in considerable social and lifestyle disruptions for the people, almost all of whom were Cree. The immense impoundments also affected the patterns of land-use by local hunters and trappers, some of whom no longer had access to their traditional areas. Greatly increased winter flows associated with hydroelectricity production have also created unstable ice conditions on the river. Consequently, some former winter travel routes are no longer safe to use.

Local people and their communities were also greatly affected by the diverse economic effects of the land-claim settlement and seven project-related agreements. (A total of $555 million was allocated for compensation and remedial work on Cree, Inuit, and Naskapi lands associated with the development of the La Grande Complex.) They were also greatly affected by the entry into wage employment, the construction of a network of roads and other infrastructure, the influx of many non-local people working on the hydro facilities, and by other rapid socio-economic changes. Some of the changes have been viewed favourably but others have not, particularly if they are considered to have degraded the traditional elements of Cree, Inuit, or Naskapi culture.

Some areas are highly vulnerable to flooding in the springtime, especially if the yield of water from the watershed due to rapid snowmelt or a severe rain event exceeds the capacity of a river channel, which may cause massive spillover onto normally terrestrial habitat. An area that is vulnerable to this kind of hydrological influence is known as a flood plain, and they are common in many parts of Canada (see Canadian Focus 20.3). Such flooding may occur regularly or it may happen only in years with unusually high water yield from the watershed. To prevent or reduce the damage caused by flooding, control structures such as dams, reservoirs, and channelled spillways may be constructed.

Some Canadian proposals to develop impoundments for flood control and irrigation have been extremely controversial. Two of the most notable have been the Rafferty-Alameda project in southeastern Saskatchewan and the Oldman Dam in southwestern Alberta.

The Rafferty-Alameda project consists of the Rafferty Dam and Reservoir on the main branch of the Souris River, the Alameda Dam and Reservoir on Moose Mountain Creek, and associated channelizations and diversions. This project was undertaken to provide the following benefits: water for the irrigation of about 4,800 ha of land, regional flood control, storage of municipal water, cooling water for a thermal power plant, and reservoir-based recreation. However, opponents of the project objected to some of its environmental impacts, which included the displacement of 75 farm families by flooding of the reservoirs, the destruction of habitat of rare prairie plants and animals as well as fish, a degradation of downstream water quality and quantity, and damage to cultural and historical sites. Intense controversy was engendered by this proposal, and a legal challenge forced it to undergo a full-scale environmental impact assessment (EIA). This was done, even though construction activities were already at an advanced stage and had to be temporarily halted. The Rafferty Dam was completed in 1992 and the Alameda, in 1994.

It should be noted that the Rafferty-Alameda Project was the subject of a landmark decision in Canadian law, known as the Rafferty Decision. The project was initially issued a permit by the provincial government, but its opponents initiated legal action based on the need for a full EIA under the requirements of federal law. In 1989, the Federal Court of Canada ruled that the Department of the Environment (a federal agency) must conduct a comprehensive EIA of the proposed project under the Environmental Assessment and Review Process (EARP). That legal decision gave the federal EARP guidelines the force of law, making it mandatory to do such assessments for any development proposals involving the federal government. This includes any federally funded proposal, even if the development is to be undertaken by another (non-federal) organization, or if there is a risk of an environmental effect on an area of federal responsibility. Much of the political controversy in this case was associated with disagreements between the provincial and federal governments over jurisdictional issues.

The Oldman project consists of a dam, a reservoir, and associated structures on the Oldman River. The project was undertaken to provide the following benefits: water for irrigation of 68,850 ha of land, regional flood control, storage of municipal water for Lethbridge and Fort McLeod, enhancement of downstream fish populations through flow regulation, and reservoir-based recreation. However, opponents of the project, including members of the local Peigan Aboriginal Nation, objected to some of its likely environmental impacts, which are similar to those described for the Rafferty-Alameda case. Opponents of the Oldman Dam were successful in a legal action to force the proponents to undertake a full EIA (this was the first application of the Rafferty decision of 1989; it was eventually resolved by the Supreme Court of Canada). The EIA was conducted, even though the development was already about 40% completed. Construction of the dam was completed in 1993. However, much controversy remained because some concerns of the environmental review panel were not fully addressed before the permit was granted for completion.

Canadian Focus 20.3. Disastrous Floods

Severe flooding is a natural catastrophe that can disrupt the lives of many people, even killing them, and causing expensive damage to homes, agriculture, and industry. Flood-control structures, such as dams, reservoirs, and levees, can help to prevent overflowing into vulnerable low-lying areas, but they are not fail-safe. Three famous episodes of recent catastrophic flooding in Canada occurred in the Saguenay region of Quebec, in southeastern Manitoba, and in southern Alberta.

The Saguenay disaster, in 1996, was caused by an intense July rainstorm that delivered 15.5 cm of precipitation during a 50-hour period. The resulting flooding caused the deaths of 10 people and forced about 16-thousand others from their homes. About 1,350 houses were destroyed or badly damaged, and one-thousand families had to be permanently relocated. There was also a devastating impact on commercial, industrial, and tourism operations. The total economic damage was more than $800 million. Although some of the rivers feeding into the Saguenay region had flood-control dams and reservoirs in place, these were not adequate to deal with the enormous volume of water generated by the extreme rain event.

A much-more extensive event affected the flood plain of the Red River in 1997, as a result of a high volume of spring runoff from an unusually deep snowpack that had accumulated from several storms. The flooding affected more than 2-thousand km^2 of flat low-lying terrain, and it caused 24-thousand people to be evacuated from their homes in southeastern Manitoba and more than 50-thousand in North Dakota and Minnesota, including almost all of the population of the city of Grand Forks. The total cost of the damage from this flood exceeded $1 billion. The destruction in Manitoba would have been much worse, but an extensive network of temporary dikes was hurriedly built by local residents, volunteers, and the Canadian army. Along with an existing system of permanent dikes and diversion channels, these protected most of the city of Winnipeg, which otherwise would have been devastated by flooding (although these same dikes did exacerbate some of the flooding that occurred south of Winnipeg). Crucial to saving the city was the Red River Floodway, built in 1968 to give protection from just this kind of severe flooding. Until the great flood of 1997, many people somewhat derisively referred to this floodway as “Duff’s Ditch,” after Duff Roblin, the premier who had authorized construction of the project against intense political opposition because of its high capital costs.

The third case occurred in the early summer of 2013, when heavy rains triggered the worst flooding ever recorded in southern Alberta. The rainfall reached 32.5 cm over two days in some places on the eastern slope of the Rocky Mountains, and the massive downward flow from large watershed then inundated low-lying floodplains of the Bow, Elbow, Highwood, Red Deer, Sheep, Little Bow, and South Saskatchewan rivers and their various tributaries. More than 100-thousand people were displaced from their homes, four people died of drowning, and the economic damage was estimated to exceed $5 billion.

Image 20.6. A view of flooding in Calgary, looking towards the East Village neighbourhood during the Great Alberta Flood of 2013. Source: Ryan L.C. Quan, Wikimedia Commons, http://en.wikipedia.org/wiki/

2013_Alberta_floods#mediaviewer/File:East_Village_Calgary_Flood_2013.jpg

Conclusions

Eutrophication is a natural process in many waterbodies, in which it is characterized by increasing productivity resulting from an enhanced nutrient supply. In addition, “cultural eutrophication” is a widespread problem caused by anthropogenic influences, most commonly the dumping of inadequately treated sewage of humans or livestock, which deposits large amounts of nutrients into waterbodies. Eutrophication causes severe environmental damage, but it can be controlled by responsibly treating sewage and other nutrient-rich materials before wastewater is released into the environment. Severe environmental damage is also caused by dams and reservoirs, which may be developed for various purposes, such as to generate hydroelectricity, control flooding, or provide a reliable supply of water for irrigation or municipal needs. The environmental damage may include the flooding of natural habitat, increased mercury concentrations in fish, and the disruption of local people. To a large degree, these damages are an inevitable consequence of any decision to develop a dam and reservoir, and that is the reason why such proposals are always controversial.

Questions for Review

1. Outline the evidence that phosphorus is the limiting nutrient for algal productivity in lakes.
2. Lake Erie has been affected by a variety of environmental stressors. Which of them have caused the most damage to the lake?

3. What are the major environmental impacts of hydroelectric developments? Briefly describe each of them.
4. Why is methylmercury contamination of fish such a common occurrence after the development of a reservoir?

Questions for Discussion

1. How is sewage treated in the community where you live? Describe the environmental benefits of treating your community's sewage, and the damages of not doing so.
2. Compare the major environmental effects of large impoundments and run-of-the-river hydroelectric developments.
3. Are there any dams or reservoirs close to where you live? Identify one and prepare a list of the "benefits" and "damages" that it brings to society and the environment.
4. Why do large hydroelectric proposals always engender such intense local controversy?

Exploring Issues

1. A proposal is being made to develop a hydroelectric facility on a large river. There are two development options: (a) a run-of-the-river facility, and (b) a larger dam that would develop an extensive reservoir. Option (b) would generate considerably more electricity. You are an environmental scientist and have been asked to compare the potential environmental impacts of the two proposals. What major topics would you examine in your impact assessment? What do you think the likely results would be (in terms of the relative impacts of the two development options)?

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Chapter 21 ~ Oil Spills

Key Concepts

After completing this chapter, you will be able to:

1. Outline the most common causes of oil spills on land and at sea.
2. Describe how spilled oil becomes dispersed in the environment.
3. Explain how hydrocarbons cause toxicity to organisms.
4. Explain how petroleum kills birds and how they may be rehabilitated.
5. Describe case studies of the ecological effects of oil spills at sea and on land.
6. Discuss the potential consequences of petroleum resource development in the Arctic.

Introduction

Petroleum (crude oil) is a non-renewable natural resource (Chapter 13) used mainly as a source of energy. It is also used to manufacture a diverse array of petrochemicals, including synthetic materials such as plastics. Petroleum is mined in huge quantities. Pipelines, ships, and trains transport most of this volume, plus its refined products, around the globe. The risks of spillage are always present, and oil spills may cause severe ecological damage. Petroleum accounts for about 33% of the global production of commercial energy (in 2013; 31% in Canada) (Table 13.9). Moreover, the global use of petroleum is still increasing – by 8% from 2004 to 2013 (Table 21.1). The fastest increases are in rapidly growing economies, such as China (59%) and India (75%). Relatively wealthy, developed countries support about 20% of the human population, but account for 48% of the global use of petroleum – 22% in North America, 21% in Europe, and 5% in Japan.

Table 21.1. Petroleum Production and Use in Selected Countries in 2013. Data are in 10^6 t/year, with percentage change since 2004 (10-year period) given in brackets. Positive values for net export means the country

produces more petroleum than it uses, so the rest is exported. Source: Data from British Petroleum (2015).

Country	Production	Consumption	Net Export
Canada	193 (+33)	104 (+3)	89
China	208 (+20)	507 (+59)	-299
Germany	<1	112 (-10)	-112
India	42 (+10)	175 (+75)	-133
Iran	166 (-20)	93 (+27)	73
Japan	<1	209 (-15)	-209
Mexico	142 (-25)	90 (+1)	52
Norway	83 (-45)	11 (+6)	72
Russia	531 (+15)	153 (+21)	378
Saudi Arabia	542 (+8)	135 (+53)	407
United Kingdom	41 (-57)	70 (-15)	-29
United States	446 (+37)	831 (-11)	-385
Venezuela	135 (-21)	36 (+8)	99
World	4130 (+6)	4185 (+8)	-55

The global reserves of petroleum are about 238-billion tonnes, of which 48% occurs in the Middle East, 13% in North America, and 6% in Russia (2013 data; BP, 2014). Almost all mining of petroleum occurs far from the places where it is consumed. The Middle East, for example, is a huge exporter of petroleum and its refined products; the amount shipped abroad is about 3.5 times larger than domestic usage in that region. In contrast, Europe (minus the former USSR) produces about 22% of the petroleum it consumes, while Asia produces 28%, and the United States 54%.

Canada produces about 87% more petroleum than it consumes (in 2013; CAPP, 2014). About 42% of the production is conventional crude oil, and the other 58% is synthetic petroleum manufactured from oil-sand bitumen. About 76% of the Canadian production occurs in Alberta, 15% in Saskatchewan, and 7% offshore of Newfoundland.

Most of the production occurs in remote areas, while most consumption is in densely populated areas of the country. Consequently, enormous quantities of petroleum and its refined products are transported over great distances, mostly by overland pipelines, railroads, and trucks. In addition, western Canada exports large amounts of petroleum and refined products to the United States and to Asia, and eastern Canada exports to the eastern United States and imports from the Middle East and Latin America. Therefore, even though Canada is more than self-sufficient in its net production and consumption of petroleum, immense quantities of the commodity and its refined products move within, out of, and into the country and its regions.

On the global scale, most petroleum and its refined products are transported by oceanic tankers and overland pipelines. Local distribution systems involve smaller tankers, barges, pipelines, railroads, and trucks. There is a risk of accidental spillage from all of these means of transportation. Some of the spills have been spectacular in their volume and environmental damage. In addition, petroleum is discharged into the environment by many smaller sources, which sum to a large cumulative amount.

In this chapter we examine the causes of oil spills and the ecological damage that can be caused in aquatic and terrestrial environments.

Petroleum and Its Products

Petroleum is a naturally occurring mixture of liquid organic compounds, almost all of which are hydrocarbons (molecules made up only of hydrogen and carbon atoms). Petroleum is a fossil fuel, as are coal, oil-sand (or bitumen-sand), and natural gas. Fossil fuels are derived from ancient plant biomass that became buried in deep sedimentary formations. Over geologically long periods of time, the biomass was subjected to high pressure, high temperature, and anoxia. The resulting chemical reactions eventually produced a rich mixture of gaseous, liquid, and solid compounds. Naturally occurring hydrocarbons range in complexity from gaseous methane, with a weight of only 16 g/mole, to solid substances in coal with molecular weights exceeding 20,000 g/mole. (In chemistry, a mole is a standard quantity of a substance, equivalent to the amount contained in 6.02×10^{23} atoms or molecules.)

Hydrocarbons can be classified into the following three groups:

- Aliphatic hydrocarbons are compounds in which the carbon atoms are organized in a simple chain. Saturated aliphatics (also called paraffins or alkanes) have a single bond between adjacent carbon atoms, while unsaturated molecules have one or more double or triple bonds. This is illustrated by the two-carbon aliphatic hydrocarbons ethane ($H_3C{-}CH_3$), ethylene ($H_2C{=}CH_2$), and acetylene ($HC{\equiv}CH$). Unsaturated aliphatics are relatively unstable and do not occur naturally in petroleum. Rather, they are produced during industrial refining, and photochemically in the environment after crude oil is spilled.
- Alicyclic hydrocarbons have some or all of their carbon atoms arranged in a ring structure, which may be saturated or unsaturated. Cyclopropane (C_3H_6) is the simplest alicyclcic hydrocarbon.
- Aromatic hydrocarbons contain one or more five- or six-carbon rings in their molecular structure. Benzene (C_6H_6) is the simplest aromatic hydrocarbons.

Crude petroleums vary greatly in their specific mixtures of hydrocarbons and other chemicals. They typically consist of about 98% liquid hydrocarbons, 1-2% sulphur (or less), and < 1% nitrogen, plus vanadium and nickel up to 0.15%. When petroleum is processed in an industrial refinery, various hydrocarbon fractions are separated by distillation at different temperatures. This is done to produce such products as gasoline, kerosene, heating oil, jet fuel, lubricating oils, waxes, and residual fuel oil (also known as bunker fuel). In addition, a process known as catalytic cracking converts some of the heavier fractions into lighter, more valuable hydrocarbons such as those in gasoline.

Oil Spills

Oil pollution is caused by any spillage of petroleum or its refined products. The largest spills typically involve a discharge of petroleum or bunker fuel to the ocean from a disabled tanker or a drilling platform, to an inland waterway from a barge or ship, or to land or fresh water from a well blowout or broken pipeline. In addition, some enormous oil spills have resulted from deliberate acts of warfare.

Terrestrial Spills

Oil spills onto land are relatively common. Between 1989 and 1995, about 3,500 spills per year were reported in Canada – most all were relatively small, although by law they must be reported (Environment Canada, 1998). About 42% of the spills occurred in the vicinity of production wells, while 29% were from pipelines, and 16% from tanker trucks. During that period, up to 140-thousand t of oil was spilled per year in petroleum-producing areas, due to accidental losses and well blowouts. In another study of the period 2000 to 2011, a total of 1,047 spills were reported from oil or gas pipelines in Canada (Kheraj, 2013).

Most large terrestrial spills involve a ruptured pipeline. Canada has about 36-thousand km of pipeline for transporting petroleum and refined liquids and 255-thousand km for natural gas (CAPP, 2014; for comparison, there are about 1.0-million kilometers of roads, of which 416-thousand are paved; Transport Canada, 2014). Pipeline breaks may be caused by faulty welding, corrosion, or pump malfunctions, as well as by erosion slumps earthquakes, and even armed vandals engaged in target practice. Operator negligence may also be an issue, as was the case of the Lake Mégantic disaster in 2013 (Canadian Focus 21.1).

The extensive Canadian network of pipelines incorporates spill sensors and other advanced technologies that allow damaged sections to be rapidly shut down. When this system works well, it allows individual accidents to be kept relatively small. Some other countries use fewer of these technologies, and consequently may suffer huge petroleum spills from overland pipelines. For example, in northern Russia, some pipelines have become corroded, and insufficient countermeasures are in place to prevent or contain oil spills.

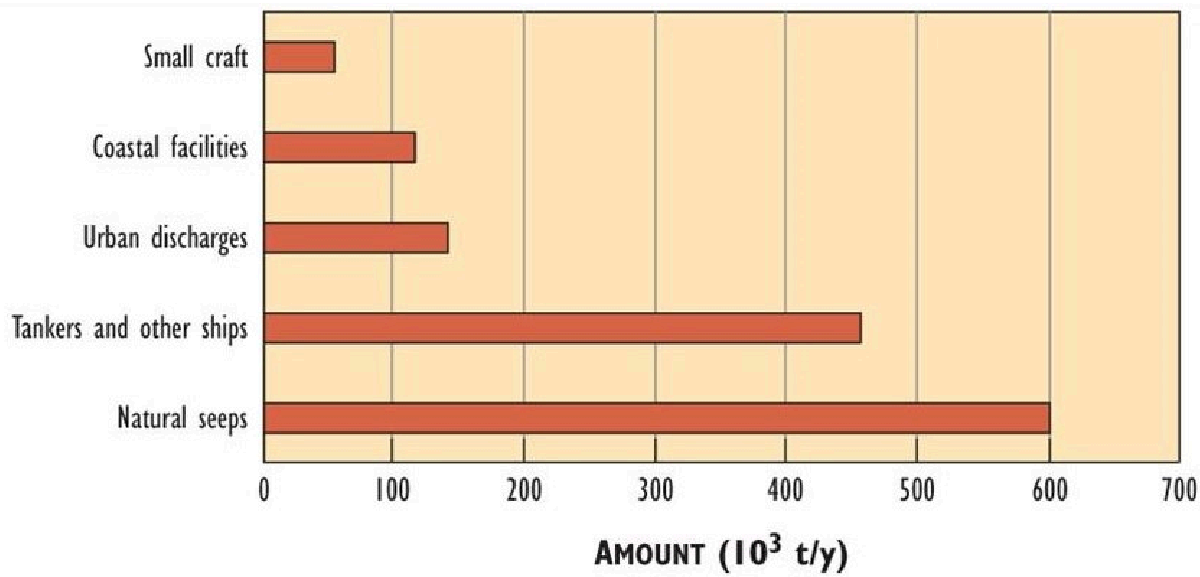
In general, oil spilled on land affects relatively localized areas of terrain because most soils absorb petroleum well. However, much larger areas of aquatic habitat are affected if spilled oil reaches a watercourse, because wind and currents cause slicks to spread and disperse widely.

> Canadian Focus 21.1. Off the Rails at Lake Mégantic. Late one night in June, 2013, a train carrying a 72-car load of petroleum to a refinery in Saint John, NB derailed in the town of Lac-Mégantic, QC (Wikipedia, 2015). The train had actually passed through the town some hours previously, but had been parked 11 km further along for the night, but its conductor (the sole operator of the train), prior to going to a local hotel to sleep, did not set enough manual brakes to keep the train in place. When the brakes failed, the unattended train rolled backward, reaching a speed as fast as 100 km/hour, and eventually derailed in the downtown core of Lac-Mégantic.
>
> Because the cargo of light petroleum was so inflammable, 63 of the 72 tank cars caught fire and exploded as immense fireballs that destroyed 30 buildings, some of them historic, and caused the deaths of 47 people, most of whom were late-night patrons of a popular nightclub. Associated environmental damage included pollution of groundwater and a nearby river with petroleum residues, as well as air pollution from the smoky plumes. The financial losses were in the hundreds of millions of dollars. Aided by funds provided by the provincial and federal governments, as well as insurance monies, the town of Lac-Mégantic is rebuilding its downtown, but the trauma of this terrible accident will linger for many decades.
>
> Although Canada has a good safety record for transporting petroleum, natural gas, and other hazardous goods, there is always a risk of an accident happening. Such events most often occur because of a failure of infrastructure or equipment, but inattention and negligence can also be a cause. There are no good excuses for either of those reasons for tragic and dangerous outcomes when it comes to transporting dangerous materials.

Marine Spills

Petroleum spills into the world's oceans currently amount to about 1.4-million tonnes/year (Figure 21.1). This is considerably less than the spillage that occurred in the 1970s and early 1980s, which was 3-6 million tonnes/year (Koons, 1984). In addition to petroleum spills, there is a large natural emission to the oceans of hydrocarbons not derived from petroleum. These chemicals are synthesized and released by phytoplankton, at an estimated 26-million tonnes/year. These huge biological releases contribute to the background concentration of hydrocarbons of about 1 ppb (1 µg/L) in seawater. The biogenic emissions are a natural contamination and do not result in known biological damage. There are also natural emissions from underwater seeps, which amount to about 0.6-million tonnes/year and may sometimes cause local ecological damage.

Figure 21.1. Petroleum Inputs to the Oceans. The data are in 10^3 tonnes per year over the period 1988 to 2007. Sources: "Best estimate" data from National Academy of Sciences (2003) and GESAMP (2007).



Massive spills associated with wrecked supertankers or well platforms attract a great deal of attention, and deservedly so. On average, they amount to about 170,000 t/y of oil spillage. It is important to recognize, however, that relatively small but frequent discharges are associated with urban runoff, oil refineries, "normal" tanker discharges, and other coastal effluents. Because these discharges are frequent, they account for a large volume of petroleum and are responsible for the local contamination and pollution by hydrocarbons that is typical of many coastal cities and harbours. Overall, based on tanker traffic and the regulatory environment governing the transport and handling of petroleum at sea and on inland waterways, it has been estimated that Canada can expect to experience more than 100 small spills per year (< 1t), more than 10 medium-sized spills (1-100 t), and more than one major spill (100-10 000 t) (Environment Canada, 1998). A catastrophic spill exceeding 10,000 t is expected about every 15 years.

Another important source of petroleum inputs to the oceans has been discharges of oily washings from the storage tanks of ships that transport petroleum and liquid fuels. After a tanker delivers a load of petroleum to a refinery, it fills some of its storage tanks with seawater, which acts as stabilizing ballast while the ship travels to get its next load. As the tanker approaches its destination, the ballast may be discharged into the ocean. If the waste water is not treated, it contains hydrocarbon residues equivalent to about 1.5% of the tanker's capacity in the case of bunker fuel, less than 1% for petroleum, and about 0.1% for light refined products such as gasoline. For large oil tankers, this could amount to as much as 800 t of hydrocarbons.

This large operational source of marine pollution has decreased greatly since the 1970s due to widespread adoption of two procedures: the load-on-top (LOT) method and the crude oil washing (COW) method. LOT separates and contains most of the oily residues before ballast water is discharged to the marine environment (the residual oil is combined with the next load). If used in calm seas, the LOT technique can recover 99% of the oily residues, although the efficiency may be 90% or less if the tanker has had a turbulent passage.

The COW method is a more recent innovation than LOT. It involves washing the petroleum storage tanks with a spray of crude oil before the new cargo is loaded. The spray dissolves the residual sludge, allowing it to combine with the next load. The advantage of the COW method is that it eliminates the need to rinse the empty tanker compartments with seawater, so there are no bilge washings to discharge to the marine environment.

Thanks to the widespread use of LOT and COW, the operational discharges from tankers has been reduced from about 1.1-million tonnes in 1973 to 19-thousand t in 2007. Although LOT and COW are now widely used, some tankers and other ships continue to illegally discharge oily wastes at sea. This pollution is still an important cause of seabird mortality off the coasts of Canada and other countries.

The most disastrous marine spills of petroleum (several of which are described later in this chapter) include the following accidents involving "supertankers" (having a capacity of 500-thousand tonnes or more):

- In 1967, the Torrey Canyon spilled 117-thousand t of petroleum off southern England
- In 1973, the Metula spilled 53-thousand t in the Strait of Magellan
- In 1978, the Amoco Cadiz spilled 230-thousand t in the English Channel
- In 1989, the Exxon Valdez spilled 36-thousand 000 t in southern Alaska
- In 1993, the Braer spilled 84-thousand t off the Shetland Islands of Scotland
- In 1996, the Sea Empress spilled 72-thousand t off Wales
- In 1999, the Erica spilled 20-thousand t into the Bay of Biscay off France and Spain
- In 2002, the Prestige spilled 63-thousand t into the Atlantic off France and Spain
- In 2003, the Tasman Spirit spilled 30-thousand t off Pakistan
- In 2009, the Montera spilled 30-thousand t off northern Australia

Some enormous accidental spills have occurred from offshore platforms used for exploratory drilling for petroleum:

- In 1979, the blowout of the IXTOC–I exploration well in the Gulf of Mexico spilled about 500-thousand t
- In 1977, a blowout from the Ekofisk platform in the North Sea off Norway spilled 30-tonnes
- In 2011, a blowout from the Deepwater Horizon off the Gulf coast of Louisiana, an exploration well that was drilling in extremely deep water (about 1,500 m), resulted in an immense spill of as much as 669-thousand t of petroleum and caused tens of billions of dollars of economic damage.

Although Canada has never suffered a marine spill of petroleum as large as the ones listed above, our country has had several notable tanker spills:

- The Arrow ran aground in Chedabucto Bay, Nova Scotia, in 1970, and spilled 11-thousand tonnes of bunker-C fuel (a common industrial fuel). About 300 km of shoreline was polluted and many seabirds were killed (about 2-thousand dead birds were collected from Chedabucto Bay and another 5-thousand from Sable Island, 320 km away).
- The Kurdistan spilled 7,500 t of bunker fuel in Cabot Strait between Newfoundland and Nova Scotia in 1979.
- The Nestucca spilled 875 t of bunker fuel in 1988 off Washington State and extensively polluted shorelines on the west side of Vancouver Island, British Columbia. About 3,600 dead birds of 31 species were collected on western beaches of Vancouver Island, but the total mortality was estimated at more than 10-thousand birds.

Image 21.1. Aquatic birds are among the most evocative and tragic victims of oil spills. This blue-winged teal

(Anas discors) was killed by a spill of heavy fuel oil on the St. Lawrence River. Source: B. Freedman.

Oil Spills through Warfare

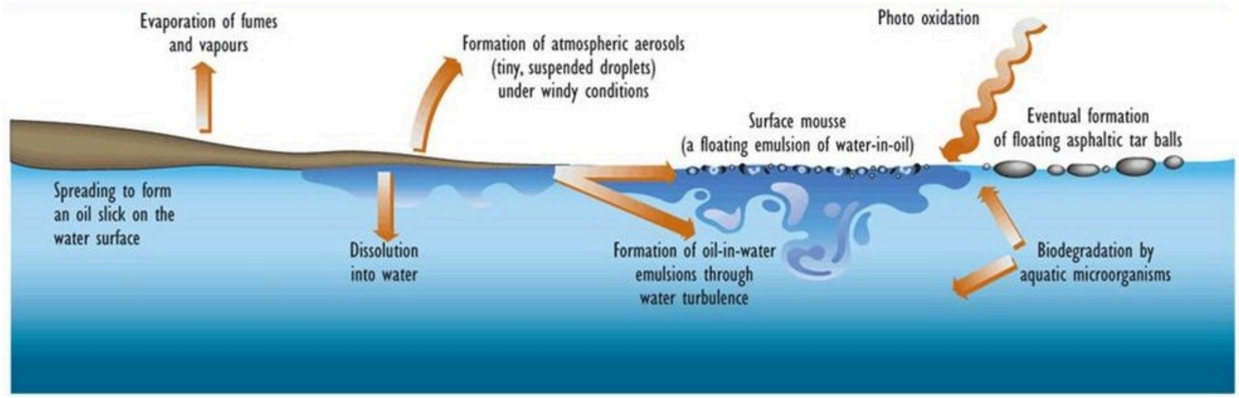
Huge amounts of petroleum and refined products have been spilled during warfare. During the Second World War, German submarines sank 42 tankers off eastern North America, resulting in the spillage of about 417-thousand tonnes of oil and fuels. During the Iran-Iraq War (1981-1987) there were 314 attacks on oil tankers, 70% of them by Iraqi forces. That war's largest spill occurred in 1983, when Iraq damaged five tankers and three production wells at the Iranian Nowruz offshore facility, spilling more than 260-thousand t of petroleum into the Gulf of Arabia. The world's largest-ever marine spill occurred during the brief Gulf War of 1991. Iraqi forces deliberately released huge quantities of petroleum (about 0.8-million tonnes) into the Gulf of Arabia from a Kuwaiti coastal loading facility. In part, this spill was a tactic of warfare – an attempt to make it difficult for Allied forces to execute an amphibious landing during the liberation of Kuwait. Mostly, however, the spill was an act of economic and ecological terrorism. The Iraqis also caused an enormous spillage on land during that war by igniting the more than 700 production wells in Kuwait. An estimated 2-6 million tonnes of petroleum per day were emitted from the burning wells. After the Gulf War was over, it took 11 months to control and cap the blowouts. By that time, an immense 42-126-million tonnes of petroleum had spilled. Most of the crude oil burned in the atmosphere or evaporated, but 5-21 million tonnes accumulated as vast crude-oil lakes in the desert around the blowouts. More recently, during the aftermath of a U.S.-led invasion of Iraq in 2003, insurgent forces routinely attacked oil-exporting pipelines as acts of resistance and economic terrorism. This caused large petroleum spills to occur, although information about the volumes of pollution or environmental damage is not available.

Fate of Spilled Oil

Various natural processes affect petroleum and refined products after they are spilled into the environment (Figure

21.2). Depending on their chemical and physical characteristics, various hydrocarbon fractions will selectively evaporate, spread over the surface, dissolve into water, accumulate as persistent residues, or be degraded by microorganisms and solar ultraviolet radiation:

Figure 21.2. Fate of Spilled Petroleum on Water. Source: Modified from Clark and MacLeod (1977).



- ***Evaporation*** of vapours is important in reducing the amount of spillage remaining in the aquatic or terrestrial environment. Evaporation typically dissipates almost 100% of gasoline spilled at sea, 30-50% of crude oil, and 10% of bunker fuel. In other words, the relatively light, volatile hydrocarbon fractions are selectively evaporated, leaving heavier residues behind. Rates of evaporation are increased by warm temperatures and vigorous winds.
- ***Spreading*** refers to the movement of an oil slick over the surface of water or land. Spreading can occur over extremely large areas on water, but it is much more restricted on land because of the high absorptive capacity of soil. The degree of spreading on water is influenced by the viscosity of the spilled material and by environmental factors such as windspeed, water turbulence and currents, and the presence of surface ice. One experimental spillage of 1 m^3 of petroleum onto calm seawater created a slick 0.1 mm thick, with a diameter of 100 m, after 100 minutes. A petroleum slick only 0.3 μm thick or less is visible as a glossy sheen on calm water. In addition, a slick on water is moved about by currents and wind and may eventually wash onto a shore.
- ***Dissolution*** causes pollution of the water beneath an oil slick. Lighter hydrocarbons are more soluble in water than heavier ones, while aromatics are much more soluble than alkanes (Table 21.2). After a spill of petroleum at sea, the hydrocarbon concentration in water a few metres beneath the slick may be 4-5 ppm (g/m^3), thousands of times greater than the 1 ppb (mg/m^3) that normally occurs in ambient seawater.

Table 21.2. Solubility of Alkane and Aromatic Hydrocarbons. Solubility is reported in g/m^3 (ppm) in fresh water. Within the aromatics, aqueous solubility decreases with increasing molecular size and with the number of

aromatic rings.

Hydrocarbon	Solubility
Alkanes	
Gases (1–4 carbons)	24–62
Liquids (5–9 carbons)	0.05–39
Kerosenes (10–17 carbons)	$1–2 \times 10^{-4}$
Lubricating oils (23–37 carbons)	$<10^{-7}$
Residual hydrocarbons (>37 carbons)	$<10^{-14}$
Aromatics	
Benzene (C_6H_6)	1780
Toluene (C_7H_6)	515
Naphthalene ($C_{10}H_8$, two rings)	31

- ***Residual materials*** remain after the lighter fractions of spilled petroleum have evaporated or dissolved. At sea, residual materials typically form a gelatinous, water-in-oil emulsion known as "mousse" because of its vague resemblance to the whipped chocolate dessert. Oil spilled offshore usually washes onto shorelines as mousse, which may then weather to form a long-lasting tarry residue on rocks. Alternatively, mousse may eventually combine with particles of sediment on the beach to form sticky, tar-like patties that subsequently become buried or may be washed back to sea during a storm. Mousse that does not wash ashore eventually weathers into semisolid, floating asphaltic residues known as "tar balls".
- ***Degradation*** refers to the slow decomposition of spilled materials by microorganisms and by photo-oxidation by solar ultraviolet radiation. Many species of bacteria, fungi, and other microorganisms can utilize hydrocarbons as an energy source. The rate of biodegradation varies greatly, however, depending on ambient temperature, the concentration of oxygen, and the availability of key nutrients such as nitrogen and phosphorus. In general, lighter hydrocarbons are relatively easily decomposed by biological and inorganic oxidations, while heavier fractions resist degradation and can be quite persistent in the environment.

Toxicity

Acute toxicity caused by petroleum, refined products, or pure hydrocarbons is typically associated with the ingestion of the materials, followed by the destruction of cellular membranes, which results in the death of tissues. The toxic effects are influenced by several factors:

- the chemical composition of the spilled material, including its component hydrocarbons
- the intensity of exposure, or the amount or concentration of specific hydrocarbons or type of petroleum
- the frequency of exposure events, such as whether the pollution is a single event, chronic (continuous), or frequent (a series of episodes)
- the timing of the exposure, especially whether it occurs during a critical time for a species or ecosystem
- the condition of the spilled material, including thickness of a slick, nature of the emulsion, degree of weathering, and persistence of residues
- environmental influences on exposure and toxicity, including weather conditions, oxygen status, and the presence of other pollutants

- toxicity associated with chemical dispersants or detergents that are used during a cleanup
- the sensitivity of particular species in an affected ecosystem to suffering toxic effects of hydrocarbons

It is important to recognize that severe damage may be caused by methods used during a cleanup, such as the use of dispersants and emulsifiers, hot-water washing, the removal of oiled substrates, burning, and the tilling of oiled soil to improve aeration and decomposition. Ecological effects are also influenced by damage caused to keystone species in the food web, which has disproportionate effects on the community.

Effects on Birds

Seabirds are extremely vulnerable to oil spills. These include cormorants, sea ducks (eiders, mergansers, scaup, scoters), alcids (auklets, murres, puffins, razorbills), and penguins. During the non-breeding season, a spill can cause enormous mortality to these birds because they may congregate in large, seasonal flocks. Moreover, since alcids and penguins have low reproductive rates, their abundance can take a long time to recover from an event of mass mortality caused by an oil spill. Murres, for example, do not begin to breed until they are five years old, lay a one-egg clutch, and raise only about 0.5 young per pair of breeding adults per year.

The most common cause of death of seabirds results from their feathers becoming oiled when they dive through or swim in oil-polluted water. This causes the birds to lose critical insulation and buoyancy, and they die from excessive heat loss leading to hypothermia or by drowning. They also ingest toxic oil while attempting to clean their feathers by preening. In addition, bird embryos can be killed by even a light oiling of the egg by the feathers of a contaminated parent.

The size of a petroleum spill is not an accurate indicator of its potential to damage bird populations. The ecological context is also critically important, because even a small spill in a sensitive habitat can wreak havoc. For example, in 1981, a relatively small discharge of oily bilge water from the tanker Stylis off Norway killed about 30-thousand seabirds. This happened because the spill affected a critical habitat where seabirds are abundant during the winter. In another case, more than 16-thousand oiled Magellanic penguins (Spheniscus magellanicus) were discovered on beaches in Argentina in 1991, even though no offshore slick could be found. The oil likely came from the bilge washings of a passing tanker. Similar damage has occurred off Newfoundland and Nova Scotia because of illegal discharges of oily bilge water by tankers. In January 1997, about 30-thousand murres and other seabirds were killed in this way near Cape St. Mary's in southern Newfoundland.

Ecological Effects

In the following sections we will examine case studies of oil spills to understand the kinds of ecological damage that are caused by oil pollution and cleanup methods. We will examine spills from wrecked supertankers and offshore drilling platforms, chronic emissions near petroleum refineries, and oiling of terrestrial vegetation.

Oil Spills from Wrecked Tankers

The Torrey Canyon wreck in 1967 was the first oil spill involving a supertanker. The ship was bound for a refinery in Wales with 117-thousand tonnes of crude oil when it ran aground, spilling its entire cargo and polluting hundreds of kilometres of coast. Seabirds were among the most tragic victims of this spill, with at least 30-thousand killed.

Although almost 8-thousand oiled birds were captured and cleaned, the rehabilitation methods of the time were not very successful and only a few of the birds survived long enough to be released (see In Detail 21.1).

Immediately after the wreck occurred, an intensive cleanup of oiled beaches began. This effort used large amounts of detergent and dispersant to create oil-in-water emulsions on polluted shorelines, which were then rinsed to shore waters using pressurized water streams from hoses. Unfortunately, the chemicals used as emulsifiers were extremely toxic and their enthusiastic use greatly increased the damage already caused by petroleum to the flora and fauna of coastal habitats.

However, emulsifiers were not used during the cleanup of rocky beaches. There, the marine algae, although damaged by oily residues, preserved some of their regenerative tissue and then regrew relatively quickly. Some species of intertidal invertebrates also proved rather tolerant to oiling. Many limpets (Patella spp.), for example, survived and were later able to graze on algae on oiled rocks.

The unanticipated damage caused by toxic emulsifiers was an important lesson from the cleanup of the Torrey Canyon disaster. Soon after, less-toxic dispersants were developed for use in oil-spill emergencies. Techniques improved too, so these chemicals could be used more judiciously, mainly to clean sites of high value for industrial or recreational purposes and to treat offshore locations where ecological damage would be less.

A post-oiling succession occurred after the Torrey Canyon spill, which eventually restored ecosystems that are typical of the region. Oiled habitat in the rocky intertidal zone was initially colonized by the opportunistic green alga Enteromorpha. As invertebrate herbivores recovered, this alga was grazed and replaced by species of perennial seaweeds, which are the typical algae of rocky intertidal habitats. Except for lingering effects on seabird populations, ecological damage caused by the Torrey Canyon spill turned out to be relatively short term because the recovery was vigorous.

In habitats that were cleaned with emulsifiers, however, the recovery was much slower. Some areas took up to 10 years to recover communities similar to those present before the spill.

> In Detail 21.1. Cleaning Oiled Birds Birds become fouled if they swim or dive in water polluted by oil. Because of the great empathy that people have for these victims of pollution, intense efforts are often made to rehabilitate oiled birds by cleaning them of residues and treating their poisoning (Clark, 1984; Holmes, 1984; Harvey-Clark, 1990).
>
> The first significant effort to do this was after the Torrey Canyon spill of 1967, when about 8-thousand oiled birds, mostly murres (Uria aalge) and razorbills (Alca torda), were captured and treated. Unfortunately, the methods available at that time for rehabilitating oiled birds were not particularly effective and only 6% of the treated animals survived for more than one month. Similarly, more than 1,600 oiled birds were cleaned after the Santa Barbara spill in 1969, mostly western grebes (Aechmophorus occidentalis) and loons (Gavia immer), but only 15% survived.
>
> These early rehabilitation efforts were not successful because biologists did not yet understand that removing oily residues from birds is not all that is needed – their physiological stress (including poisoning) must also be addressed. Biologists determined several reasons for the deaths of oiled birds:
>
> - Because oiled birds were not captured and treated soon enough, they became hypothermic (excessively cooled)
> - Birds were ingesting residues while trying to clean themselves, and that toxicity had to be mitigated
> - The methods for removing oily residues involved the use of harsh solvents and emulsifiers that were themselves toxic, caused damage to feather structure, or did not clean the feathers sufficiently
> - Most oiled birds are hypoglycemic to some degree, a condition involving low blood sugar and weight loss

and requiring rapid treatment with an intravenous glucose solution

- An important effect of hydrocarbon poisoning in birds, particularly by aromatics, is disruption of the ability to regulate concentrations of sodium and potassium in blood plasma, a condition that requires an oral administration of an electrolyte solution
- Aromatic hydrocarbons are toxic to red blood cells, resulting in a hemolytic anemia that needs several weeks of treatment by appropriate nutrition

Today, better methods are available to capture, clean, and rehabilitate oiled birds. These improved techniques have been developed through trial and error while treating accidentally oiled birds, and by research on experimental animals. Because it is now known that oiled birds must be treated as soon as possible, spill-response teams try to capture them quickly. In addition, relatively gentle cleaning agents known as polysorbates are used to de-oil birds, and electrolyte solutions and glucose are routinely administered to treat dehydration and hypoglycemia.

The methods of post-cleaning rehabilitation and release have also improved. Typically, birds are kept for 7 to 10 days after cleaning. They are released as soon as the waterproofing of their feathers has been restored, their salt-excreting metabolism has recovered, their anemia is corrected, and they have started to regain weight.

As a result of the improved methods, up to 75% of oiled birds may be released after timely cleaning and rehabilitation. However, the success rate varies greatly, depending on bird species, the type of oil, and other factors, especially how much time has passed between the oiling event and the capture and treatment.

Nevertheless, despite the relatively effective cleaning methods of today, studies have shown that the post-release survival of birds can be poor. It appears that as few as 1% of treated and released seabirds survive for even one year (Sharp, 1996). With such poor survival, it is questionable whether any substantial ecological benefit is gained from cleaning programs. It is expensive to treat oiled birds, and many volunteers are needed, including specialists such as veterinarians. It is, of course, enormously better to avoid oil spills altogether than to try to deal with the terrible damage caused to wild animals and ecosystems.

The Amoco Cadiz supertanker accident occurred in 1978, about a decade after the Torrey Canyon and in the same general area, but closer to France. The wreck of the Amoco Cadiz spilled 233-thousand t of petroleum and fouled about 360 km of shoreline, of which 140 km were heavily oiled. The cleanup of some beaches involved digging up and removing oily sand and sediment. Detergent and low-toxicity dispersants were used only to remove fouling residues in harbours and to disperse floating slicks of mousse in offshore waters. Because emulsifiers were used judiciously, many of the ecological damages caused by oil pollution and the cleanup were much less severe than after the Torrey Canyon spill. Recovery from the Amoco Cadiz spill was substantially complete within several years. However, some effects on benthic invertebrates lasted for a decade, and there was lingering damage to local colonies of alcid seabirds.

The Exxon Valdez suffered an accidental grounding in 1989 in southern Alaska, and this caused the most damaging tanker accident ever to occur in North American waters. A significant amount of the petroleum extracted in the United States is mined in northern Alaska, from where a 1,280 km pipeline carries it south to the port of Valdez. The oil is then transported to markets in the western U.S. by a fleet of supertankers. The first part of the oceanic passage runs through a narrow shipping channel in Prince William Sound.

Before the Exxon Valdez accident in March, 1989, tankers had navigated that passage about 16-thousand times. However, the Exxon Valdez, the newest tanker in the Exxon fleet, was incompetently steered onto a submerged reef, resulting in a spill of 36-thousand tonnes of its 176-thousand t load of petroleum. About 40% of the spill washed onto shoreline habitat of Prince William Sound, while 25% was carried out of the sound by currents, and 35% evaporated at sea. Less than 10% was recovered or burned at sea.

This accident could have been avoided by more sensible operation of the tanker. At the time that the ship went aground, its bridge was under the command of an unqualified mate. Unaccountably, the captain was in his cabin. Only some 10 minutes after assuming control of the ship, the mate, who was not well familiar with the shipping channel and its aids to navigation, had run the supertanker onto the unforgiving reef.

The environmental damage was compounded by a lack of preparedness by industry and government for dealing with an oil-spill emergency. Essential equipment for containment and oil recovery was not immediately available, and it took too long to mobilize trained personnel. Consequently, despite favourable sea conditions during the first critical days after the grounding, few effective oil-spill countermeasures were mounted. Not until the second day of the spill was it possible to off-load unspilled petroleum from the Exxon Valdez to another tanker, and not until the third day were floating booms deployed to contain part of the spill. Unfortunately, a gale developed on the fourth day, making it impossible to contain or recover spilled petroleum, which then became widely dispersed.

The region around Prince William Sound is famous for its spectacular scenery and large populations of wildlife. Some ecological communities and species were severely damaged by the oil spill. However, controversies have arisen about both the poor understanding of some ecological effects, and the role of science and scientists in sorting out legal and political aspects of the disaster (Holloway, 1996; Weins, 1996). For a long time, some scientists were prohibited from sharing their information because of legal needs for confidentiality. Controversies arose among scientists, environmental advocates, and other interest groups about the scale and intensity of some of the reported damages.

About 1,900 km of shoreline habitat was oiled to some degree. A survey found that 140 km was "heavily oiled," meaning there was at least a 6 m wide oiled zone. Another 93 km were "moderately oiled" (3-6 m wide zone), 323 km were "lightly oiled" (3 m wide), and the rest "very lightly oiled" (< 10% cover of oil). Overall, about 20% of the shoreline of the Sound, plus 14% of beaches on the nearby Kenai Peninsula and Kodiak Island, suffered some degree of oiling.

A heroic and extremely expensive effort was undertaken to clean up some of the pollution from oiled beaches. About 11-thousand people were involved, costing the Exxon corporation about US$2.5 billion. The U.S. government spent an additional US$154 million. Residues were removed from heavily oiled beaches by machines and people wielding shovels and bags. Other places were cleaned by pressurized streams of hot or cold water. On some beaches, people actually wiped oiled rocks with absorbent cloths, a procedure that was ironically referred to as "rock polishing".

These cleanup efforts helped greatly, and they were aided by natural processes, especially winter storms and microbial degradation of residues. Consequently, the amount of residues on beaches declined rapidly in the years following the spill. One survey of 28 polluted sites found an average of 37% surface oil cover in the first post-spill summer of 1989, but less than 2% in 1990. Another survey in 1991, after two post-spill winters and three summers, found that fewer than 2% of the beaches still had visible surface residues, compared with 20% in the first summer after the spill. However, subsurface residues still existed in many places.

Initially, severe damage was caused to the seaweed-dominated intertidal zone of affected coastlines. These effects were made worse by certain cleanup methods, particularly washing with pressurized hot water. Fortunately, much of this damage proved to be short term, and by the end of 1991 a substantial recovery of seaweeds and invertebrates had begun. However, there were lingering effects on community structure, and vestiges of oil were still present 15 years later at some sites.

Prince William Sound supports large fisheries for salmon and herring. In 1988, before the spill, the catch had a value of about US$90 million. The fishery was closed in 1989 because of the spill, and Exxon paid compensation of $302 million to displaced fishers and processors (many of whom were also employed in the cleanup, earning $105 million in wages and vessel charters).

In 1990, the harvest of pink salmon (Oncorhynchus gorbuscha) in the Sound was 44-million fish, larger than the previous record-high catch of 29-million fish. These were two-year-old fish, about one-quarter of which would have passed through the Sound during their migration from rivers to the sea in 1989, the year of the spill. The rest had been released from hatcheries. The 1991 catch of pink salmon was also large, at 37-million fish. There was also a large harvest of herring (Clupea harengus pallasi) in 1990, when 7,500 t were landed. The largest catch in a decade was made in 1991, at 10,800 t. Clearly, the fishery landings were not devastated by the oil spill.

Sea otters (Enhydra lutris) were the hardest-hit marine mammals. More than 3,500 otters were killed by oiling, out of a population of 5-10-thousand. A total of 357 oiled sea otters were captured and treated, of which 223 survived and were released or placed in zoos.

Seabirds are very abundant in the region, particularly so in the autumn when certain species aggregate there during their southern migration. At that time, about 10-million seabirds may inhabit the Sound. Fortunately, the Exxon Valdez disaster happened in late winter, but there were still about 600-thousand seabirds present. About 36-thousand dead birds were found, but many additional corpses sank or drifted out to sea, and the total mortality may have been 375-435-thousand seabirds.

About 400 people, 140 boats, and 5 aircraft were hired by Exxon to capture and rehabilitate oiled birds. They managed to treat 1,600 birds of 71 species, but half of them died of their injuries. The rest were treated and released to the wild, but the lingering effects of hydrocarbon poisoning likely prevented most of them from surviving for long.

Although severe ecological damage was caused by the Exxon Valdez spill, the recovery was rapid. Waves and winter storms quickly removed most of the spill residues. Even bird and mammal populations that suffered large mortality recovered to their natural abundance within a decade or less. From a strictly environmental perspective, the habitats affected by the disaster showed an impressive amount of resilience. However, people and local communities were also affected by this calamity, and surveys have shown that their bad memories are deeply ingrained.

> Image 21.2. The top photo shows a heavily oiled beach on Green Island, Prince William Sound, soon after the Exxon Valdez disaster in 1989. The site was cleaned with warm-water washing in 1989, and then manually in 1990. In 1990 and 1991, it was treated with fertilizer to enhance microbial breakdown of the petroleum residues. The bottom photo shows the improved condition of the same beach in 1992, as a result of the natural and managed cleanups. Although little visible damage occurs on the surface, there are hydrocarbon residues deeper in the substrate. Source: Exxon Corporation.

Global Focus 21.1. Cross-Boundary Pollution on the West Coast In late December, 1988, the oil-carrying barge Nestucca broke loose from a tug that was towing it in coastal waters off Washington State. Unfortunately, the hull of the Nestucca suffered a 2 m gash when it collided with the tug as its crew tried to re-establish a towline, spilling about 890 tonnes of heavy bunker fuel into the ocean. Initially, it was thought the spill was small, because only a sheen of hydrocarbons could be seen on the surface. As it turned out, however, most of the spilled fuel was suspended below the surface as sticky globs that could not be visually tracked. The oil weathered into a gelatinous, sticky mousse that became widely dispersed by currents running northward along the coast. The thick mousse soon fouled beaches in Washington and then, beginning two weeks after the spill, large amounts washed onto more than 150 km of coast on western Vancouver Island. About 10-thousand oiled seabirds or their carcasses washed onto beaches, mostly on Vancouver Island, but the total mortality probably exceeded 50-thousand because most dead birds would have sunk offshore. Despite an intensive effort mounted by governments and by hundreds of volunteers, almost all of the oiled birds that were captured alive soon died. Damage was also caused to eagles and other wildlife and to fishery habitat used by Aboriginal communities and commercial interests.

Because the heavy oil had been spilled in U.S. waters by a U.S. company, but most of the damage occurred in coastal waters or on beaches in Canada, a cross-boundary dimension helped to focus the attention of governments on dealing with the calamity and preventing future occurrences. Several months after the Nestucca incident, the much larger Exxon Valdez spill in Alaska greatly added to the anxiety in both countries about the risks of large oil spills from the fleet of huge tankers that was ferrying northern petroleum to markets in the western United States. Partly because of this binational attention, more stringent regulations were enacted in both Canada and the U.S. to try to prevent these kinds of catastrophes. (Both the Nestucca and Exxon Valdez spills were caused by operator negligence, and thus were preventable accidents.) In addition, more effective action plans were developed to enhance the capabilities for oil-spill countermeasures and cleanups. Eventually, Environment Canada sued the U.S. company that was responsible for the Nestucca spill and collected CAN$4.4 million in damages. This money was used to rehabilitate a seabird colony on Langara Island, a critical habitat off Vancouver Island.

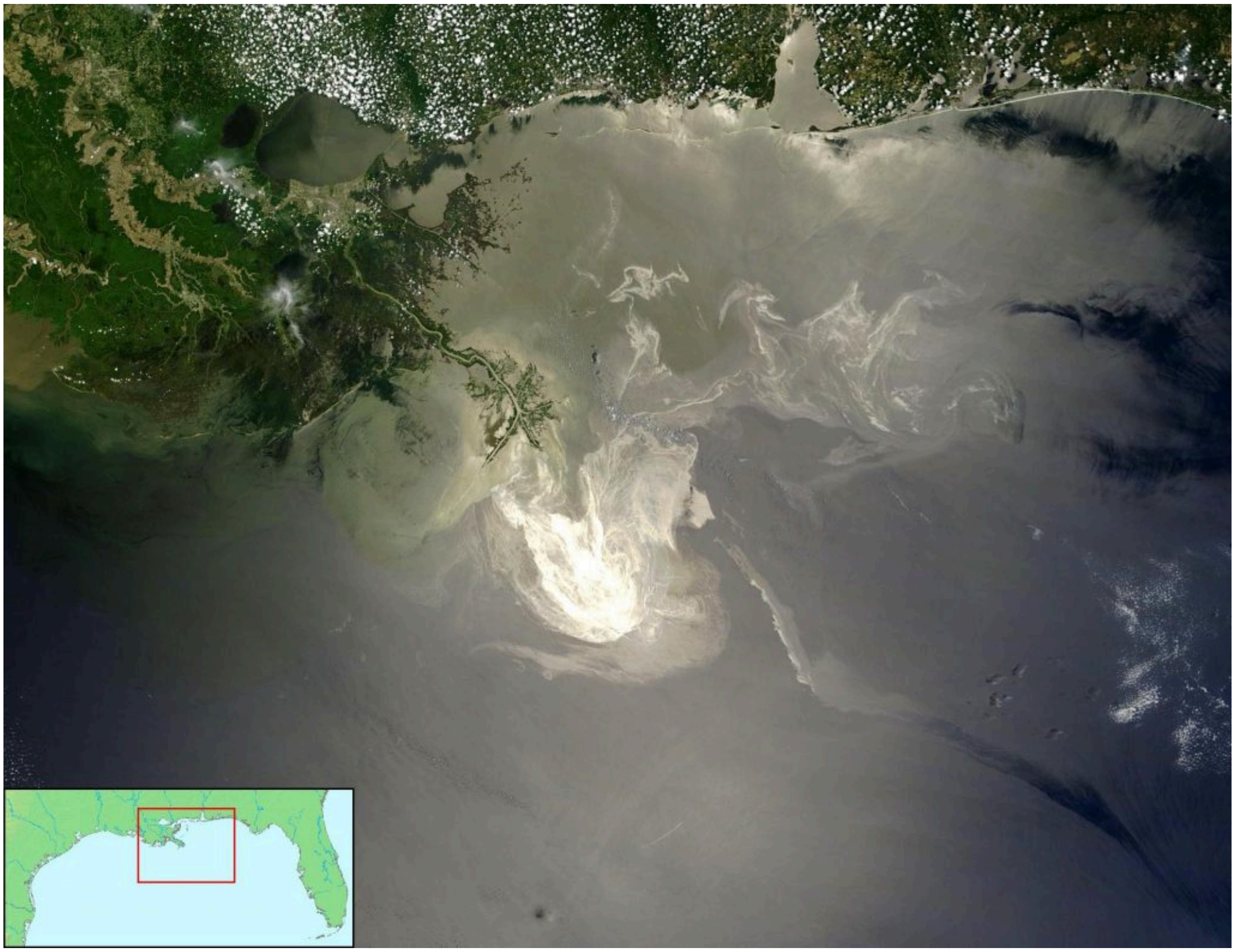
Spills from Offshore Platforms

The Deepwater Horizon spill off the Gulf coast of Louisiana in 2011 was the largest accidental blowout (an uncontrolled discharge from a wellhead) in history. The Deepwater Horizon was a drilling and exploration platform working in extremely deep water (about 1,500 m). The blowout was apparently caused by a failure of the casing of the borehole and also of the fail-safe blowout preventer. These likely occurred because of an unwise engineering decision to use an insufficient cementing regime for the borehole despite encountering extremely high geological pressure during the drilling. This resulted in a fire and explosion on the drilling platform, which sank during the fire-fighting action because of the enormous amounts of water poured into it. The blowout lasted for 87 days and the immense spill was as much as 669-thousand tonnes of crude oil, which spread over as much as 176-thousand km^2 of water, affected beached from western Florida to Texas, and caused tens of billions of dollars of economic damage.

The spill engendered a massive effort to staunch the blowout, burn the soil at sea or recover it for disposal on land, to protect coastal habitats from fouling, and to capture and rehabilitate oiled wildlife. About 7,000 m^3 of dispersant was used to help protect coastal infrastructure and habitats, and also to disperse the petroleum as it issued from the subsea blowout itself. Despite the enormous effort, considerable damage was done to natural habitats, recreational beaches, the commercial fishery, and harbours, with some effects of residues lingering even into 2014 (when this was written). There were extensive deaths of marine mammals, birds, fish, and other marine life.

Subsequent legal actions found that British Petroleum (BP), the operator of the drilling project, bore primary responsibility for the disaster. Eventually, BP paid more than US$42-billion in criminal and civil settlements,

Image 21.3. View of the Deepwater Horizon spill. The coast of Louisiana and Alabama are shown, in the greater region of the delta of the Mississippi River. The floating slick of petroleum from the Deepwater Horizon blowout shows as bright zones, due to the spilled oil calming the surface water and affecting its reflectance properties. Source: NASA image file: Deepwater Horizon oil spill – May 24, 2010.jpg http://en.wikipedia.org/wiki/File:Deepwater*Horizon_oil_spill*-_May_24,_2010.jpg



The IXTOC-I spill in 1979 was one of the world's largest accidental spills. This was a Mexican drilling platform being used for petroleum exploration in the Gulf of Mexico. The blowout remained uncontrolled for more than nine months, resulting in a spillage estimated at 476-thousand tonnes of petroleum. About 50% of the spill is thought to have evaporated into the atmosphere, while 25% sank to the bottom, 12% was degraded photochemically or by microorganisms, 6% was burned at sea or recovered near the spill site, and 7% fouled about 600 km of shoreline in Mexico and Texas.

This enormous blowout caused great economic damage. It fouled beaches important to tourism, and affected the fishing industry by oiling boats and gear, preventing fishing near slicks, and tainting valuable fish and invertebrates with foul-tasting hydrocarbons. Many birds, sea mammals, turtles, and other wildlife were oiled and died, although these and other ecological damages were not well documented.

The Santa Barbara offshore blowout occurred in 1969 off southern California. This spill involved about 10-thousand t of petroleum and fouled 230 km of coastline. Birds were the most obvious victims, with about 9-thousand killed, or half of the population occurring at the time of the spill. About 60% of the dead birds were grebes and loons, which winter in the area. Attempts were made to capture and clean oiled birds, but the efforts were not very successful. Coastal ecosystems were also severely damaged, especially in rocky intertidal habitats, but recovery was fairly rapid. Within one year, barnacles began to re-colonize intertidal habitat, even on rocks still covered with asphaltic residue. Beaches used for recreation were cleaned by the removal of oily sand, blasting with water or steam, or spraying with solvent to wash residues back to sea. As with the Torrey Canyon cleanup, these methods using highly toxic dispersants greatly worsened the ecological damage.

Spills in the Arctic Ocean

Large but still poorly known reserves of oil and gas occur in Arctic regions of Canada and Alaska. Exploratory drilling is widespread, and there are land-based production wells in the western Arctic near Norman Wells and on the north slope of Alaska. The exploration, production, and transport of hydrocarbons from the Arctic carries the risk of accidental spillage in terrestrial or marine environments. The consequences of a petroleum spill in the Arctic Ocean are potentially catastrophic. Such a spill could result from a tanker accident in ice-choked waters or from an offshore well.

Climatic conditions in the Arctic are severe – a factor that greatly increases the likelihood of spills from offshore oil wells through equipment failure or human error. Furthermore, the icy conditions of the long winter would make it difficult to quickly drill an offshore relief well, a necessary step in controlling a blowout. Containing or cleaning up a spill in Arctic seas would also be a daunting task. Because of entrapment under sea ice and the cold, nutrient-poor conditions, spilled oil would not evaporate or dissolve into seawater as effectively as under warmer conditions, and microbial biodegradation would be extremely slow. Consequently, the amount of spilled oil would not decrease much over time, and most of the initial toxicity would persist. (Note that the spill from the Exxon Valdez occurred in boreal waters of southern Alaska, which are subject to much less severe temperature and ice conditions than occur in the Arctic Ocean.)

Arctic marine wildlife, particularly migratory seabirds and mammals, are extremely vulnerable to the effects of an oil spill. When they return to their northern breeding habitat in the early summer, marine birds and mammals often aggregate in dense populations in patches of ice-free water, known as leads and polynyas. These open-water habitats are places where spilled petroleum would accumulate. Enormous mortality of migrating sea ducks, murres, seals, whales, polar bears and other species would result as they became oiled by sticky residues. Because of the persistence of residues in the cold ocean, this threat would persist for years, and long-term debilitating damage to these animals would result. Potential damage to fish, zooplankton, and other components of the marine ecosystem are little known, but might be less intensive than the effects on marine birds and mammals.

A number of exploration wells have been drilled on the continental shelf of the Arctic Ocean off northern Canada and Alaska (and also in boreal and temperate waters off Newfoundland and Nova Scotia, where production wells now operate). Fortunately, there have not been any large spills of petroleum from the offshore drilling activities in the Arctic Ocean of North America (although there have been several blowouts involving natural gas). However, in spite of the adoption of the most modern spill-prevention technologies, a severe spill may be inevitable during offshore exploration and production activity in the Arctic. Such an accident would cause enormous ecological damage, from which recovery would be very slow.

Chronic Oil Pollution

Environments around tanker terminals and coastal petroleum refineries are chronically exposed to small but frequent oil spills, discharges of contaminated wastewater, and airborne contaminants from industrial sources. Similarly, coastal ecosystems near cities and towns, both marine and freshwater, are chronically affected by oil and fuel that are dumped into sewers, which often discharge these wastes directly into the aquatic environment. Chronic exposures such as these are much less intense than the severe pollution associated with wrecked tankers, but environmental damage still results.

Chronic exposure to hydrocarbons and other pollutants has been blamed for unusually high frequencies of cancers and other diseases in fish and shellfish. Although the exact causes of many of these wildlife diseases have not been determined, many scientists believe they are somehow caused by chronic pollution. One study of a river near Detroit, Michigan, found an unusually large incidence of gonadal tumours in fish (up to 100% in older males). However, epidemics of wildlife diseases are not always observed in chronically polluted environments. Ecological damage at the community level has been observed near effluent discharges from some coastal petroleum refineries. Studies in Britain, for example, have shown a deterioration of salt-marsh vegetation near oil refineries. Exposed bare mud was found where well-vegetated, grassy salt marshes had occurred previously. However, in places where industry made serious efforts to reduce the emission of pollutants, new vegetation was able to re-colonize the mud and re-develop a salt marsh.

Terrestrial Oil Spills

Oil spills result in severe damage to terrestrial vegetation, but usually relatively local areas are affected (except in the case of extremely large spills). This is because soil, particularly if it is rich in organic matter, has a great absorptive capacity for petroleum. In addition, much of the oil spilled on land tends to accumulate in low spots and does not spread widely. This is particularly true in much of northern Canada, where deep infiltration into the soil may be prevented by impenetrable bedrock or permafrost. The relatively localized impacts of many terrestrial spills of petroleum are very different from the effects in aquatic environments, in which spilled oil spreads widely and can affect an enormous area.

Research has also shown that a wide range of natural, soil-dwelling microorganisms can utilize petroleum residues as a metabolic substrate (as a food). These oil-degrading bacteria, fungi, and other microbes are widespread in soils and waters. After soil becomes polluted by an oil spill, they rapidly proliferate in response to the presence of hydrocarbons that can be used as a source of metabolic energy.

Petroleum is a carbon-rich substrate, but it is highly deficient in key nutrients such as nitrogen and phosphorus. Consequently, the vigour of the microbial response to oiling, and the rate of decomposition of residues, can be greatly increased by adding fertilizer. Microbial decomposition of residues can also be enhanced by tilling the soil to increase the availability of oxygen. In general, fertilizer addition and tilling are relatively inexpensive but effective ways to speed up the biodegradation of petroleum residues, while avoiding the severe damage associated with a physical cleanup. This is particularly true of agricultural areas.

Of course, any spilled oil that reaches groundwater or surface waters will cause severe damage there. Spills into high-energy streams and rivers become extensively dispersed, and some residues will flow into lakes or the ocean. Oil in ponds and lakes can be quite persistent, accumulating around the margins, where vegetation and wildlife habitat are damaged. However, after spilled petroleum has weathered for a year or more, the toxicity of the residues may decrease so that aquatic plants can grow through surface slicks without suffering much damage. The phytoplankton and zooplankton communities are also somewhat resistant to weathered oil. However, any waterfowl that attempt to use oiled waterbodies become fouled with residues, and this is usually fatal to them.

Studies have been made of the effects of petroleum on tundra and boreal forest ecosystems, including experimental spills onto vegetation. These studies found that crude oil behaves as a herbicide to terrestrial vegetation, killing foliage and woody tissue. In some plants, however, the perennating (regenerating) tissues were not all killed, allowing re-growth after the oiling.

These general observations are illustrated by a study in the western Arctic (Table 21.3). The experimental oiling caused a rapid defoliation of plants, reflected by the reduced cover of foliage after the oiling, in contrast to the non-oiled (control) vegetation. Black spruce (Picea mariana) trees are dominant in the boreal forest sites. These did not die immediately after oiling, but did became more vulnerable to physiological stress associated with the hard arctic winter and so eventually died, but only after several years has passed.

Table 21.3. Effects of Experimental Spills of Crude Oil on Arctic Vegetation. The plant communities studied in the western Canadian Arctic were: (1) mature black spruce (Picea mariana) boreal forest, (2) 40-year-old spruce forest, (3) cotton-grass (Eriophorum vaginatum) wet-meadow tundra, and (4) dwarf-shrub tundra. The oiled vegetation was treated with petroleum at 9 litres/m^2, while the control vegetation was not oiled. The forest study area is near Norman Wells, and the tundra is near Tuktoyaktuk, both in the Northwest Territories.

Community	Treatment	Pre-Spill	1 y after	2 y after	5 y after
Mature forest	Reference	195	215	255	240
	Oiled	350	18	10	20
40-yr-old forest	Reference	355	360	260	235
	Oiled	420	20	20	95
Cottongrass tundra	Reference	339	284	268	-
	Oiled	358	26	34	-
Dwarf-shrub tundra	Reference	339	338	292	-
	Oiled	322	55	82	-

After the initial damage, many plants of the forest and tundra began to recover. Black spruce was an exception, as no new seedlings were observed during the five-year study. Lichens and mosses also recovered slowly.

Of course, the environmental consequences of oil development are much broader than the ecological effects of petroleum spills on land or in water. The construction of infrastructure such as roads and pipelines in remote terrain has a variety of environmental consequences. In addition, the influx of large sums of money and wage employment into rural places has huge socio-economic impacts, some of them positive, but others disruptive. As with any industrial development, potential damage to the ecological and socio-economic environments must be identified and, as far as possible, minimized. The residual damage must then be balanced against the economic and social benefits that are expected to be gained from the development of fossil-fuel resources.

Conclusions

Petroleum is a vital natural resource that is transported over long distances from places where it is extracted to those where it is consumed. Refined products, such as gasoline and kerosene, are also transported widely. There is always a risk of accidental spills and even deliberate ones (such as acts of war or terrorism). When they occur, they may cause extreme damage to the environment. There have been some spectacularly large petroleum spills, particularly as a result of shipping accidents involving large tankers, as well as incidents during war. These large spills have had devastating effects on affected ecosystems. In some cases, the natural recovery can be aided by massive cleanup efforts and wildlife rehabilitation. It is important to recognize, however, that most large spills are accidents that can be prevented. This can be done if tankers, pipelines, and other equipment are designed and maintained to a high standard of reliability, if effective spill-containment measures are in place, and if personnel work diligently to prevent these disasters. It is always best to avoid oil spills and other environmental emergencies than to engage in very expensive post-spill actions to clean them up.

Questions for Review

1. What are the causes of petroleum spills to the oceans?
2. Why were the ecological effects of the Amoco Cadiz spill fewer and shorter-lasting than those of the Torrey Canyon?
3. Explain why the addition of fertilizer can be an effective way of treating the residues of oil spills.
4. Why does oil spilled on water affect a much larger area than a comparable volume spilled on land?

Questions for Discussion

1. Considering the poor survival of aquatic birds after they have been "rehabilitated" from oiling and returned to the ocean, do you think that it is worthwhile to treat these victims of oil spills?
2. In view of the ecological risks, do you think that oil exploration and extraction should be allowed in the Canadian Arctic?
3. Why is it not possible to prevent all spills of petroleum?
4. Examine the data in Table 21.1 and use them to inform an analysis of the reasons for the international trade in petroleum. Consider both the global context and that of North America.

Exploring Issues

1. A proposal has been made to build an oil refinery on the coast (choose whichever one you live closest to). The crude oil will be brought to the refinery by tanker ships, and the refined products will be distributed by ship, train, and truck. You are working as an environmental consultant and have been asked to recommend spill-prevention and countermeasure tactics to protect the marine and terrestrial environments around the refinery. Provide a list of practices that would provide this function of spill prevention and countermeasures.

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Chapter 22 ~ Pesticides

Key Concepts

After completing this chapter, you will be able to:

1. Explain the notions of "pest" and "weed," and provide reasons why it may be necessary to decrease their abundance.
2. Differentiate pesticides by the pests to which they are targeted.
3. Classify pesticides into major chemical groups.
4. Outline the risks and benefits of pesticide use in sanitation, agriculture, forestry, and horticulture.
5. Explain why there is a global contamination of organisms with DDT and related organochlorines, and describe the associated ecological damage.
6. Outline the ecological damage caused by carbofuran, and explain why it took so long for the use of this insecticide to be banned.
7. Describe the economic benefits and ecological risks of pesticide use in forestry.
8. Outline the concept of integrated pest management, and explain whether it is applicable to all pest-management problems.

Introduction

Humans are constantly engaged in struggles against competitors and diseases. One way to gain an advantage in many of those ecological interactions is through the use of pesticides. These substances are used to protect crop plants, livestock, domestic animals, and people from damage and diseases caused by microorganisms, fungi, insects, rodents, and other "pests," and to defend crops from competition with unwanted but abundant "weeds."

It is important to understand that the use of words like "pest" and "weed" is highly contextual. In most situations, for example, white-tailed deer are valued for their wild beauty, and they provide economic and subsistence benefits through hunting. However, this animal may also be considered a pest when it feeds in a garden, agricultural field, or forestry plantation. The same is true, to some degree, of other species that are considered to be a pest or weed.

People have been using pesticides for a long time (Hayes, 1991). There are records of unspecified chemicals being used by Egyptians to drive fleas from their home as long as 3,500 years ago. Arsenic has been used as an insecticide in China for at least 2,900 years. In his epic poem the Odyssey, the Greek poet Homer (writing about 2,800 years ago) referred to the burning of sulphur (which generates toxic SO_2 gas) to purge homes of vermin such as fleas.

However, pesticide use has become much more common in modern times, and an enormously wider variety of substances is being used. At least 300 insecticides, 290 herbicides, 165 fungicides, and many other pesticidal chemicals are available in more than 3,000 different formulations. Strictly speaking, a pesticide is a product that consists of a formulation of several chemicals – the "active ingredient" attacks the pest, while various "inert ingredients" enhance its effectiveness (see In Detail 22.1). Even larger numbers of "commercial products" are available, because many involve similar formulations manufactured by different companies.

Almost all pesticides are chemicals. The active ingredients of some of them are based on natural biochemicals that are extracted from plants grown for that purpose, while others are inorganic chemicals based on toxic metals or compounds of arsenic. Most modern pesticides, however, are organic chemicals that have been synthesized by chemists. The costs of developing a new pesticide and testing it for its efficacy (effectiveness against pests), toxicological properties, and environmental effects are quite large, equivalent to tens of millions of dollars per chemical. However, if an effective pesticide against an important pest is discovered, the profits are potentially huge, and therefore industry willingly pays the high development costs.

People have acquired important benefits from many uses of pesticides:

- increased yields of crops, because of protection from diseases, competition, defoliation, and parasites
- revention of much spoilage and destruction of stored food
- avoidance of certain diseases, thereby conserving health and saving the lives of millions of people and domestic animals

This is not to say, however, that more pesticide use would achieve even better results. In fact, it has been argued that pesticide use in North America could be decreased by half without greatly affecting crop yields (Pimentel et al., 1991). The European Union (EU) has taken some forceful steps to reduce pesticide use within its jurisdiction (Pesticide News, 2003). In 2003, EU permits for 320 pesticides were revoked, and as many as another 180 were scheduled for delisting in 2010; in total, half of the pesticides used in 1993 were no longer permitted in 2010. In large part, the withdrawals involve obsolete pesticides and others of minor commercial importance, for which the owners do not want to invest the large amounts of money needed to assure EU regulators that their products are safe for people and the environment. Similar actions are also occurring in North America, but they are less advanced than in the EU. Because of the substantial benefits that can be derived from the use of pesticides, their consumption has increased enormously during the past half-century. Overall, the use of pesticides increased ten-fold in North America between 1945 and 1989 (Pimentel et al., 1992), although it has since levelled off. Pesticide use is now a firmly integrated component of technological systems that are widely used in modern agriculture, forestry, horticulture, and public health management in most parts of the world.

Unfortunately, the considerable benefits of pesticides are partially offset by damage their use causes to ecosystems and sometimes to human health. Each year, about one-million people are poisoned by pesticides, with as many as 20-thousand fatalities (Pimentel et al., 1992). Although developing countries account for only about 20% of global pesticide use, they sustain about half of the poisonings. This is because relatively toxic insecticides are used in many developing countries, by a workforce whose widespread illiteracy hinders the understanding of instructions for proper use, and whose safety is further compromised by poor enforcement of regulations and by inadequate use of protective equipment and clothing.

The most tragic case of pesticide-related poisoning occurred in 1984 at Bhopal, India. About 2,800 people were killed and 20-thousand seriously poisoned when a factory accidentally released 40 tonnes of methyl isocyanate vapour to the atmosphere. Methyl isocyanate is a precursor chemical of carbamate insecticides (Rozencranz, 1988).

In addition, many pesticide applications cause ecological damage by killing non-target organisms (organisms that are not considered to be a pest). This damage is particularly important for broad-spectrum pesticides, which are toxic to organisms in addition to the specific pest. Pesticides applied as a broadcast spray are spread over a large area, such as an agricultural field, lawn, or stand of forest.

If a broad-spectrum pesticide is broadcast-sprayed, many non-target organisms are exposed and they may be damaged or killed. For example, in a typical agricultural field or forestry plantation, only a few plant species are abundant enough to compete significantly with crops and reduce their productivity. These are the “weeds” that are the target of a broadcast herbicide application, but many other plants are also affected. The non-target plants may provide habitat or food for animals, and they help to prevent erosion and loss of nutrients. These benefits are degraded by non-target damage – by damage to organisms that are not pests. Similarly, broadcast insecticide spraying causes non-target mortality to many beneficial arthropods in addition to the species that is considered to be a pest. Many birds, mammals, and other creatures may also be poisoned. The non-target mortality may include predators and competitors of the pest, an ecological change that may release it from some of its biological controls. Clearly, the great challenge of pest control is to develop effective, pest-specific pesticides and to invent non-pesticidal methods.

Pesticide use has been expanding rapidly, and this is happening in all countries, although to varying degrees. Although much is known about the environmental damage caused by the use of pesticides, not all of the potential effects are well understood. In this chapter we examine the nature of pesticides and their important uses. We then examine cases of ecological damage caused by their routine use to deal with pest-management problems.

> In Detail 22.1. Pesticides, Formulations, and Inert Ingredients. A commercial pesticide product is a mixture of chemicals that can be used to kill or otherwise control pests. The "active ingredient" is the chemical that actually attacks the pest, while so-called "inert ingredients" are added to the formulation to enhance its effectiveness. Inert ingredients may do this by making the pesticide easier to apply (such as by making it soluble in water), by helping it to spread or stick to leaf surfaces, or by stabilizing the formulation to increase its shelf-life.
>
> Many inert ingredients are, however, biologically active, so they are not really passive substances (Environment Canada, 2001; EPA, 2005). It is more realistic to refer to them as "other ingredients." In general, the percentage of other ingredients in a pesticide is specified on the product label, but their identity and concentrations are not given because they are considered to be proprietary information of commercial value. Sometimes, however, a manufacturer will identify these ingredients, and may even specify their concentration. Some inert ingredients carry risks of causing toxicity through normal use of the pesticide. Examples of particular concern include chlorobenzene, dioctyl phthalate, formaldehyde, hexane, hydroquinone, isophorone, nonylphenol, phenol, and rhodamine.
>
> One inert ingredient that has engendered particular controversy about its potential toxicity to humans is nonylphenol (NP), which is used as an emulsifier in some pesticides. NP is a degradation product of nonylphenol ethoxylates (NPEs), which have been used for decades as detergents and emulsifiers. They are used in manufacturing processes for paint, paper, pesticides, petrochemicals, resins, steel, and textiles, and are ingredients in many cleaning products.
>
> NPEs and NP are anthropogenic chemicals that enter the environment with discharges of industrial and municipal wastewater. NPEs degrade by microbial reactions, and some of the metabolites are bioactive through toxicity and estrogenic (hormonal) effects, including NP, nonylphenol diethoxylate, nonylphenol ethoxylate, nonylphenoxyacetic acid, and nonylphenoxyethoxyacetic acid. These may have a moderate persistence in the environment, especially in anaerobic habitats and in groundwater, and they now have developed a widespread but low level of contamination and bioaccumulation. Species vary widely in their vulnerability to toxicity from NP and NPEs, but many studies have reported toxic and estrogenic effects on aquatic organisms.
>
> Some toxicologists believe that humans are also exposed to significant risks from these chemicals, through the use of consumer products, food, and other pathways. In a risk assessment, Environment Canada (2001) concluded that "nonylphenol and its ethoxylates are entering the environment in a quantity or concentration . . . [that has] or may have an immediate or long-term harmful effect on the environment or its biological diversity," so they should be regulated as "toxic" chemicals under the Canadian Environmental Protection Act. Although these chemicals are not "considered a priority for investigation of options to reduce human exposure through control of sources," it was recommended that further studies of their bioactivity and environmental risks be undertaken.
>
> Although the major releases of NP and related chemicals are via industrial and municipal effluents, they are also present as "other ingredients" in pesticides. This has led to controversy about damage that may be caused to

people and wild organisms exposed to NPEs and NP through the use of pesticides. The case of NPEs and their metabolites reinforces the fact that product formulations should be known and comprehensively evaluated when considering the risks of pesticide use to human and environmental safety.

The Nature of Pesticides

Classification by Target

Pesticides are defined by their usefulness in killing or otherwise decreasing the abundance of species that are deemed to be "pests." Pesticides are, however, an extremely diverse group of substances. To better understand their usefulness and toxicity, and the damage they cause, it is helpful to categorize them in various ways. One classification is based on the intended target of the use:

- a fungicide is used against fungi that cause diseases and other damage to crop plants and animals
- a herbicide is used to kill weeds, which are unwanted plants that interfere with some human purpose; most use in agriculture and forestry is intended to release crop plants from competition, while horticultural use is mostly for aesthetics
- an insecticide is used to kill insects that are pests in agriculture, horticulture, or forestry, or that spread diseases such as mosquito vectors (a path by which a disease is spread) of malaria, yellow fever, and encephalitis
- an acaricide is used to kill mites that are pests in agriculture, and ticks that are vectors of ailments such as Lyme disease and typhus
- a molluscicide is used to kill snails and slugs in agriculture and gardens, and aquatic snails that are vectors of diseases such as schistosomiasis
- a nematicide is used against nematodes, which can damage the roots of agricultural plants
- a rodenticide is used to control mice, rats, gophers, and other rodents that are pests in agriculture or around the home
- an avicide is used to kill birds, which are sometimes considered pests in agriculture
- a piscicide is used to kill fish, which may be pests in aquaculture
- an algicide is used to kill unwanted growths of algae, for example, in swimming pools
- bactericides, disinfectants, and antibiotics are used to control infections and diseases caused by bacteria (Note that antibiotics are not actually classified as "pesticides" under the Pest Control Products Act)

Chemical Classification

Because almost all pesticides are chemicals, they can be categorized according to similarities in chemical structure. The most important groups are described below and in Table 22.1. A few "non-chemical" pesticides are based on microbes, and are discussed later under "Biological Pesticides."

Table 22.1. Some Important Pesticides.

Class	Major Use	Examples
1. Inorganic Pesticides		
(a) Bordeaux mixture	fungicide	tetracupric + pentacupric sulphate (copper sulphates)
(b) arsenicals	herbicides & insecticides	arsenate
2. Organic Pesticides		
(a) organics extracted from plants (plus laboratory analogues)	mostly insecticides	nicotine, nicotine sulphate, neonicotinoids, pyrethrum, red squill, rotenone, strychnine
(b) organomercurials	fungicides	phenyl mercuric acetate, methyl mercury, methoxyethyl mercuric chloride
(c) phenols	fungicides	trichlorophenol, pentachlorophenol
(d) chlorinated hydrocarbons	insecticides	DDT, DDD, TDE, methoxychlor
lindane	insecticide	lindane
cyclodienes	insecticides	chlordane, heptachlor, aldrin, dieldrin
chlorophenoxy acids	herbicides	2,4-D, 2,4,5-T, MCPA, silvex
(e) organophosphates	insecticides	diazinon parathion, methyl parathion, fenitrothion, malathion, monocrotophos, phosphamidon
(f) carbamates	mostly insecticides	carbaryl, aminocarb, carbofuran, aldicarb, methiocarb
(g) triazines	herbicides	simazine, atrazine, hexazinone, cynazine, metribuzin
(h) amides	herbicides	alachlor, metolachlor
(i) thiocarbamates	herbicides	Butylate
(j) dinitroaniline	herbicide	Trifluralin
(k) organophosphorus compound	herbicide	Glyphosate
(l) acetaldehyde polymer	molluscicide	metaldehyde
(m) pyrethroids (synthetic)	insecticides	cypermethrin, deltamethrin, permethrin, tetramethrin

Inorganic pesticides are compounds that contain toxic elements such as arsenic, copper, lead, or mercury. They are highly persistent in terrestrial environments, being only slowly dispersed by leaching and erosion by wind or water. Recently, inorganic pesticides have been widely replaced by synthetic organics. Prominent examples include Bordeaux mixture, a complex of copper-based compounds that is used as a fungicide to protect fruit and vegetable crops, and arsenicals such as arsenic trioxide, sodium arsenite, and calcium arsenate, which are used as herbicides and soil sterilants. Paris green, lead arsenate, and calcium arsenate are used as insecticides.

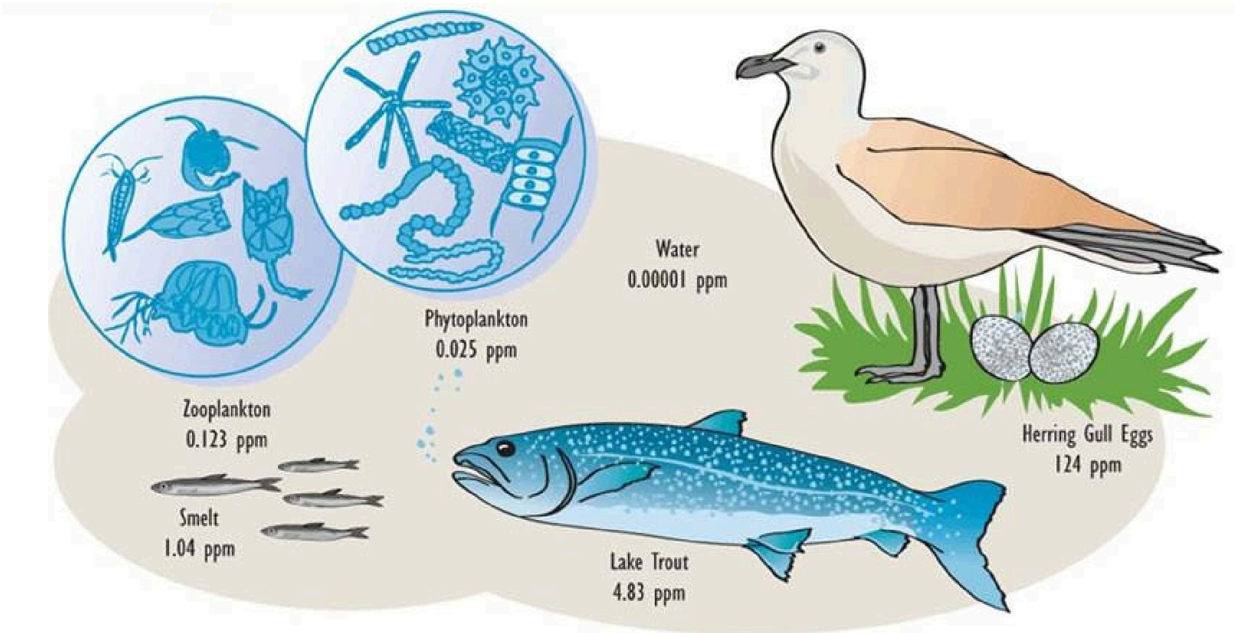
Organic pesticides are mostly synthesized chemicals, but some are natural toxins produced by certain plants that are extracted and used as pesticides. Important examples include the following:

- Natural organic pesticides are extracted from plants. For example, nicotine and related alkaloids are extracted from tobacco (Nicotiana tabacum) and used as insecticides, usually applied as nicotine sulphate. Neonicotinoids are a synthetic analogue. Pyrethrum is a complex of chemicals extracted from certain chrysanthemums (Chrysanthemum cinerariaefolium and C. coccinium) and used as an insecticide. Rotenone is extracted from several tropical shrubs (Derris elliptica and Lonchocarpus utilis) and used as an insecticide, rodenticide, or piscicide. Red squill, extracted from the sea onion (Scilla maritima), is a rodenticide, as is strychnine, extracted from the tropical shrub Strychnos nux-vomica.

- Synthetic organometallic pesticides are used as fungicides and include organomercurials such as methylmercury and phenylmercuric acetate.
- Phenols include trichlorophenols, tetrachlorophenol, and pentachlorophenol, which are fungicides used mostly to preserve wood.
- Chlorinated hydrocarbons (organochlorines) are a diverse group of synthetic pesticides (see In Detail 22.2). Most are quite persistent, having a half-life of about 10 years in soil because they are not easily degraded by microorganisms or by physical agents such as sunlight or heat. The persistence of organochlorines, coupled with their strongly lipophilic nature (they are highly soluble in fats and lipids, but virtually insoluble in water), means that they strongly bioconcentrate and biomagnify, with the highest concentrations occurring in top predators (see In Detail 18.1 and Figure 22.1). Organochlorines include the following:
- DDT and its insecticidal relatives, such as DDD and methoxychlor, were once widely used insecticides. Because of bans in North America and Europe in the early 1970s, their use is now confined to tropical countries. DDE is a persistent non-insecticidal metabolite of DDT and DDD that accumulates in organisms.
- Lindane is the active constituent of hexachlorocyclohexane, an insecticide.
- Cyclodienes are highly chlorinated cyclic hydrocarbons, such as chlordane, heptachlor, aldrin, and dieldrin, all of which are insecticides.
- Chlorophenoxy acids have growth-regulating influences on plants and are used as herbicides against broad-leafed weeds. The most important compound is 2,4-D, but others are 2,4,5-T, MCPA, and silvex.
- Other organochlorines include polychlorinated biphenyls (PCBs), dioxins, and furans. These are not pesticides but are mentioned here because their ecotoxicological properties are similar to those of the pesticide organochlorines: they are persistent in the environment and are lipophilic, so they bioconcentrate and food-web magnify.
- Organophosphorus pesticides are used mostly as insecticides, acaricides, and nematicides. They are not persistent in the environment, but are extremely toxic to arthropods and also to non-target fish, birds, and mammals. Parathion, fenitrothion, malathion, and phosphamidon are prominent examples of organophosphate insecticides. Glyphosate, a phosphonoalkyl compound, is an important herbicide (it is not toxic to animals).
- Carbamate pesticides have a moderate persistence in the environment but are highly toxic to arthropods, and in some cases, to vertebrates. Aminocarb, carbaryl, and carbofuran are important insecticides.
- Triazine pesticides are used as herbicides and sometimes as soil sterilants. Prominent examples are atrazine, simazine, and hexazinone.
- Synthetic pyrethroids are analogues of natural pyrethrum and are used mostly as insecticides and acaricides. Pyrethroids are highly toxic to invertebrates and fish, but they are of variable toxicity to mammals and of low toxicity to birds. Important examples are cypermethrin, deltamethrin, permethrin, synthetic pyrethrum and pyrethrins, and tetramethrin.
- Biological Pesticides are formulations of microbes that are pathogenic to specific pests and so have a narrow spectrum of toxicity in ecosystems. The best examples are insecticides based on the bacterium Bacillus thuringiensis (B.t.), types of which are used against moths, flies, and beetles. Insecticides based on nuclear polyhedrosis virus (NPV) and insect hormones have also been developed.
- Genetically modified organisms (GMOs; see Environmental Issues 6.1) have been biologically “engineered” by inserting portions of DNA from another species into their genome. This high-tech procedure has been used to develop new varieties of commercial crops that are more resistant to certain pesticides or pests, which can make it easier to cultivate them. For example, GMO varieties of soybean and canola have been developed to be resistant to glyphosate, meaning this herbicide can be used on those crops, providing reduced costs of energy and machinery to control weeds. In addition, there are GMO varieties of maize (corn) that contain DNA of Bacillus thuringiensis, which provides resistance to some insect pests and allows farmers to use less insecticide. These and other GMO crops are widely cultivated in North America, although they are banned in many countries, including

most of Europe and Brazil. The use of these GMO crops is controversial because there is incomplete knowledge about the biological and ecological risks of their use, including the potential escape of their GMO factors to wild plants.

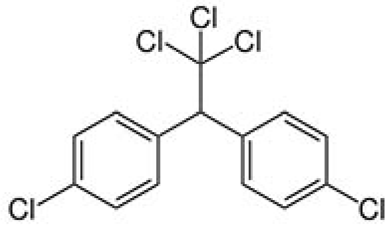
Figure 22.1. Residues of PCBs in the Food Web of Lake Ontario. Organochlorine insecticides, such as DDT, DDD, and dieldrin, show a similar pattern of bioaccumulation and biomagnification as PCBs, but their residue levels are different. Source: Data from Environmental Protection Agency (2003).

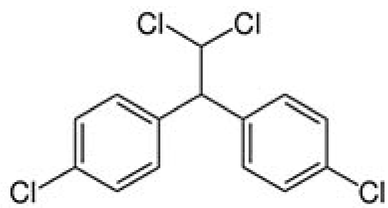


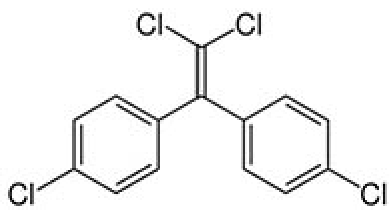
In Detail 22.2. Chemical Structure of Organochlorines Organochlorines are a diverse group of compounds that are made up of atoms of carbon, hydrogen, and chlorine. Their biochemical activity (including toxicity) and potential usefulness depend entirely on their chemical structure. Certain organochlorines are used as insecticides (such as DDT, DDD, dieldrin), herbicides (2,4-D, 2,4,5-T), or insulating fluids (PCBs). Others have no particular use at all but are nevertheless important environmental contaminants. For example, DDT and DDD are metabolized in organisms to DDE, which is a non-pesticide that can accumulate to a high concentration in fatty tissues. Another example is the extremely toxic dioxin TCDD, which is non-intentionally synthesized as a contaminant during the manufacturing of certain organochlorines (such as trichlorophenol) and through reactions occurring when organic waste is incinerated.

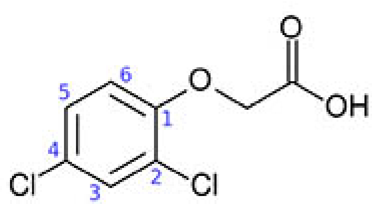
The following diagrams illustrate the specific chemical structures of a number of environmentally important organochlorines. In the diagrams, the ring-like structures are derived from benzene, which has the formula C6H6. Organochlorines are formed by the substitution of one or more of the hydrogen atoms by chlorine atoms. Note the following:

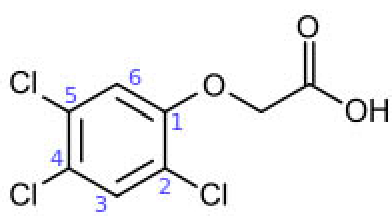
- There is great similarity among DDT, DDD, and DDE, which differ by only a single chlorine atom
- Similarly, 2,4-D and 2,4,5-T differ by only one chlorine atom
- PCBs are a complex mixture of molecules with a basic biphenyl structure, but varying in the amount of substitution of chlorine for hydrogen atoms; in the diagram, “X” can be either H or Cl
- TCDD, strictly speaking, is not an organochlorine because it contains two oxygen atoms

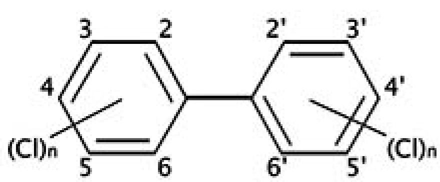

DDT or 2,2-bis-(p-chlorophenyl)-1,1,1-trichloroethane (an insecticide)

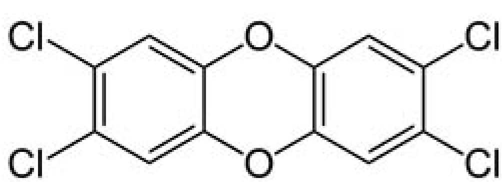

DDD or 2,2-bis-(p-chlorophenyl)-1,1-dichloroethane (an insecticide)


DDE or 2,2-bis-(p-chlorophenyl)-1,1-dichloroethylene (non-insecticidal metabolite of DDT and DDD)


2,4-D or 2,4-dichlorophenoxyacetic acid (a herbicide)


2,4,5-T or 2,4,5-trichlorophenoxyacetic acid (a herbicide)


PCBs or polychlorinated biphenyls (electrical insulating fluid)


TCDD or 2,3,7,8-tetrachlorodibenzo-p-dioxin (a trace contaminant)

Pesticide Use

The global use of pesticides was about 2.4-million tonnes in 2007, a total that includes insecticides, herbicides, fungicides, preservatives, and disinfectants (Grube et al., 2007). Global pesticide trade in 2007 had a value of about US$39 billion. About 39% (by weight) of pesticides used were herbicides; insecticides accounted for 18%, fungicides for 10%, and “other chemicals” for 33% (mostly used as soil fumigants). Data for the United States were herbicides 44%, insecticides 9%, and fungicides 6%. Data for Canada are not available but would be proportionately similar to those for the United States (Canada accounts for about one-ninth of the North American market for pesticides). Total expenditures for pesticides in the United States were about US$12 billion in 2007. The following is a top-20 list of conventional pesticides recently used in the United States (values are 10^6 kg of active ingredient per year):

1. glyphosate; herbicide; 83
2. atrazine; herbicide; 34
3. metam sodium; soil fumigant; 24
4. metolachlor-S; herbicide; 15
5. acetochlor; herbicide; 14
6. dichloropropene; fumigant; 13
7. 2,4-D; herbicide; 12
8. methyl bromide; soil fumigant; 6
9. chloropicrin; fumigant; 5
10. pendimethalin; herbicide; 4
11. ethephon; plant growth regulator; 4
12. chlorothalonil; fumigant; 4
13. metam potassium; fumigant; 4
14. chloropyrifos; insecticide; 4
15. copper hydroxoide; fumigant; 4
16. simazine; herbicide; 3
17. trifluralin; herbicide; 3
18. propanil; herbicide; 3
19. mancozeb; fungicide; 3
20. aldicarb; insecticide; 3

In addition, about $1{,}180 \times 10^6$ kg of chlorine and hypochlorite was used as disinfecting agents, 35×10^6kg of sulphur as fungicide, 47×10^6 kg of oil as insecticide, 22×10^6 kg of sulphuric acid as fumigant, and 434×10^6 kg of various substances as wood preservatives. Strictly speaking, these chemicals are not considered pesticides, even though they are used against certain pests. The most important uses of pesticides are in agriculture and forestry, around the home, and in human health and sanitation programs. We examine these uses in the following sections.

Pesticide Use for Human Health

Various insects and ticks are vectors that transmit pathogens among individuals of the same species, or from an alternate host to people, or to domestic and wild animals. Important human diseases that are vectored by invertebrates incluse the following:

- malaria, which is caused by the protozoan Plasmodium and spread to people by Anopheles mosquitoes
- yellow fever, encephalitis, and West Nile virus, caused by viruses and spread by mosquitoes
- sleeping sickness, caused by the protozoan Trypanosoma and spread by the tsetse fly Glossina

- plague or black death, caused by the bacterium Yersinia pestis and transmitted by the rat flea Xenopsylla cheops
- typhoid, caused by the bacterium Rickettsia prowazeki and transmitted by the louse Pediculus humanus
- schistosomiasis or bilharziasis, caused by the blood fluke Schistosoma, with freshwater snails as the alternate host

To varying degrees, the incidence of these maladies can be controlled by using pesticides against the invertebrate vectors or the alternate hosts. The abundance of mosquitoes, for example, can be reduced by spraying insecticide in their aquatic breeding habitat or by applying a persistent insecticide to the interior walls of buildings, where they rest. Similarly, people infested with body lice may receive a surface dusting with an insecticide – this was an early use of DDT. Plague can be controlled by using rodenticide along with sanitation programs to reduce rat populations. Over the past half-century, pesticides have decreased the abundance of vectors and alternate hosts and have spared hundreds of millions of humans from the debilitating or deadly effects of certain diseases, particularly in tropical countries. (This has been an important factor in reducing death rates and allowed rapid population growth.)

In fact, one of the first important uses of DDT was in Naples, Italy, during the Second World War, to prevent a deadly plague of typhus that could have decimated Allied troops and the civilian population. Because of the success of this use of DDT and its contribution to the victorious war effort, the British prime minister at the time, Winston Churchill, referred to the insecticide as "that miraculous DDT powder."

Malaria has long been an important disease in tropical countries. During the 1950s, about 5% of the global population was infected with malaria. The use of insecticide to reduce the abundance of mosquitoes achieved huge reductions in the incidence of malaria in some countries. For instance, during 1933-1935, India recorded about 100-million cases of malaria per year and 750-thousand deaths. However, the incidence was reduced to 150-thousand cases and 1,500 deaths in 1966 because of spraying with DDT and the draining of mosquito-breeding wetlands (McEwen and Stephenson, 1979). Similarly, 2.9-million cases of malaria occurred in Sri Lanka in 1934, and 2.8 million in 1946, but DDT use helped to reduce that incidence to only 17 cases in 1963 (Hayes, 1991). However, malaria has recently been resurging in some tropical countries, partly because mosquitoes have developed a genetically based tolerance of previously effective insecticides. Many people are again being exposed to the malarial parasite, although the disease can today be controlled by drugs that prevent Plasmodium from multiplying in the blood. (However, there are also signs that Plasmodium is becoming resistant to those drugs.)

Pesticides and Agriculture

Modern agriculture is a highly technological activity. Machines, energy, fertilizer, pesticides, and high-yield crop varieties are used in intensive management systems to grow crops (see Chapters 14 and 24). The role of pesticides is to help control the abundance of the following problems:

- weeds that compete with crop plants
- invertebrates and rodents that feed on crops or stored produce
- microbial diseases that can kill the crop or diminish its yield

Undeniably, these uses of pesticides are important factors in modern agriculture. Even with pesticide use, the damage caused by pests and diseases around the world are equivalent to about 24% of the potential crop of wheat, 46% of rice, 35% of corn (maize), 55% of sugar cane, 37% of grapes, and 28% of vegetables (McEwen and Stephenson, 1979). In North America pests destroy about 37% of the potential production of food and fibre crops (Pimentel et al., 1992).

Of course, management practices in agriculture have intensified greatly, particularly during the twentieth century and since. This change has resulted in increases in crop productivity. The gains in agricultural yield have been largely achieved by the combined influences of the following:

- fossil-fuelled mechanization
- fertilizer use
- improved crop varieties grown in monocultural systems
- the use of pesticides

The recent intensification of agrotechnology is sometimes referred to as the “green revolution”. Although agricultural yields have increased greatly, it must be recognized that the gains are highly subsidized by the following (see also Chapters 14 and 24):

- intense use (and depletion) of non-renewable fossil fuels and metals
- depletion of potentially renewable resources, such as soil fertility and tilth, and groundwater and surface water needed for irrigation
- loss of soil mass through erosion
- extensive salinization of soils in semi-arid regions (caused by inappropriate methods of irrigation)
- ecological damage associated with the conversion of natural ecosystems into agricultural ones
- ecotoxicological damage caused by the use of pesticides

In the United States, for example, the yield of corn was typically about 1.4 t/ha-yr in 1933, but it increased to 4.2 t/ha-yr in 1963 and to 5.1-7.1 t/ ha-yr during 1978-1984. In Mexico, wheat yields increased from 0.75 t/ ha-yr in 1945 to 2.6 t/ ha-yr in 1964. The yield of rice in Japan increased from a pre-war average of 1.8 t/ ha-yr to 4.0 t/ ha-yr in 1963, while in the United States, rice yields have reached 4.9–5.5 t/ ha-yr (Hayes, 1991). Similar gains in agricultural yield have been realized in Canada (see Figure 14.1).

Almost all intensively managed agricultural systems depend to some degree on pest control. High-yield crop varieties are often vulnerable to infestation by insect pests, diseases, and competition from weeds. Pesticides are routinely prescribed to manage those problems. Moreover, monocultural systems (in which only a single crop is grown in a field) result in reduced populations of natural predators and parasites, which can exacerbate existing pests and allow new ones to develop. Some environmentalists have described intensively managed agricultural systems as being a pesticide treadmill, because they rely on pesticides, often in increasing quantities, to deal with unanticipated pests that emerge as “surprises.”

The use of pesticides in Canadian agriculture has increased greatly in recent decades. Herbicide was applied to 26.7-million hectares of farmland in 2011, a three-fold increase over 1971 (Table 14.10). Insecticide and fungicide were applied to 8.7-million hectares, an 11-fold increase. Overall, pesticide use in North American agriculture increased by about ten-fold between 1945 and 1989 (Pimentel et al., 1992). Interestingly, during that same period, crop losses (to insects only) actually increased somewhat, from about 7% during 1941-1951 to 13% during 1951-1974 (Hayes, 1991). These trends, which might seem to contradict each other, may be due to such factors as the development of tolerance by some pests to pesticides, the emergence of new pests because of accidental introductions, changes in predator-prey relationships caused by pesticide use, and the introduction of new crop varieties that are vulnerable to pests.

Agricultural damage caused by arthropod pests varies greatly. Sometimes there is direct competition with humans for a food resource, as when insects defoliate crops in fields or attack stored food. Such depredations can sometimes obliterate agricultural yield, as can happen during a severe infestation of locusts. More commonly, however, insects reduce the yield only somewhat.

In some cases, however, even minor damage by pests can make the produce unsaleable. This can be the case of damage caused to apples by the codling moth (Carpocapsa pomonella). “Wormy” apples with larvae of this insect are not saleable to consumers, and up to 90% of the fruit in unsprayed orchards may be infested (McEwen and Stephenson, 1979). Even a minor discoloration of fruit, such as apple scab and russeting of oranges (neither affect the productivity or nutritional quality of the crop) are considered unacceptable by many consumers. Therefore, seemingly unimportant crop damage can be a critical economic consideration for farmers and the food industry. As with some potentially life-saving drugs, pesticides are over-prescribed for some uses.

Much pesticide use in agriculture is targeted against weeds, which interfere with crop plants by competing for limited resources of light, water, and nutrients. (Of course, "weediness" is partly a matter of context – in other situations, some weed species have positive attributes.) It is well known that weeds, if abundant, can cause large decreases in the productivity of agricultural crops, even by 50-90%. This is the reason why farmers have always taken measures to reduce the abundance of weeds, initially by hand-pulling or hoeing them and later by mechanical cultivation (ploughing) to disrupt their growth. More recently, chemical herbicides have been widely used to control agricultural weeds. In the United States, for example, herbicide is used on 85% of the planted area for most crops (Gianessi and Sankula, 2003). Crops receiving the most herbicide are canola (on 99% its cultivated area), dry beans (99%), carrot (98%), maize (98%), rice (98%), sugarbeet (98%), peanut (97%), green bean (96%), soybean (96%), tomato (96%), blueberry (95%), citrus (95%), cotton (95%), and potato (93%). Herbicide use in wheat is relatively low (55%) because mechanical cultivation during sowing is effective in reducing weeds for this crop.

According to Gianessi and Sankula (2003), if herbicide use were discontinued for the 40 crops they studied, then weed management would have to rely on increased mechanical cultivation and manual weeding. They calculated that would have an annual cost of US$14 billion, about double that of herbicide use ($6.6 billion per year). If herbicide use were discontinued and replaced by alternative practices, they estimated that 35 of the 40 crops studied would suffer a decline in productivity, by an average of 21% (range of 5-67%). The productivity loss would have a value of about $21 billion per year (including $13 billion in lost productivity and $8 billion in increased costs of management). Note, however, that the "direct costs" of herbicide use cited above ($6.6 billion/yr) do not include the value of environmental damage that might be caused, for instance, by toxicity to non-target plants, wildlife, or agricultural workers. It must be remembered that non-herbicidal methods of weed control also cause environmental damage, particularly mechanical cultivation, which increases soil erosion and compaction. No-till management systems, which greatly reduce the rate of erosion, must rely on the use of herbicide to control weeds.

Of course, the weeds must be vulnerable to the toxicity of the herbicide being used against them, while the crop plant must be tolerant. Some herbicides are toxic to broad-leaved weeds (dicotyledonous plants) but not to corn, wheat, barley, or other crops in the grass family (monocotyledonous plants). Consequently, herbicides are widely used in grain agriculture in North America. For instance, about 98% of the maize and rice acreage is treated. Some important diseases of agricultural plants can be managed with pesticide. Sometimes, insecticide is sprayed to control arthropod vectors of microbial diseases. More commonly, fungicide is used to control pathogenic fungi such as late blight (Phytophthora infestans) of potato, apple scab (Venturia inequalis), powdery mildew (Sphaerotheca pannosa) of peach, and seedrot and damping-off of many crop species (Pythium spp.). Fungicide also helps to prevent the spoilage of stored crops by fungi such as Aspergillus flavus, which can grow in stored legumes, grains, and nuts, producing deadly aflatoxins that make foods poisonous to humans and livestock.

Pesticides in Forestry

The use of pesticides in forestry raises a great deal of controversy, often more so than use of the same chemicals in agriculture. The controversy partly concerns damage that may be caused to the many native species that are exposed to forestry sprays, compared to mostly aliens in agriculture. In addition, spraying in forestry is mostly done by government agencies and large companies, while in agriculture it often involves individual farmers working a family farm. Most people have greater empathy for individuals than for big government or big business, and this can influence their opinions about pesticide use.

Pesticides are used in forestry mainly to control epidemics of defoliating insects and to manage weeds in re-forested areas and plantations. The largest insecticide spraying campaigns have been undertaken against spruce budworm

(Choristoneura fumiferana) in New Brunswick, where a cumulative area of about 49-million hectares was sprayed between 1952 and 1992 (this is examined later as a case study). Other large spray programs have included those against gypsy moth (Lymantria dispar, an introduced pest that defoliates many tree species), hemlock looper (Lambdina fiscellaria), and bark beetles (especially species of Ambrosia and Ips).

Pesticides in the Home and Horticulture

Pesticides are commonly used in and around homes. For instance, insecticide may be used to kill bedbugs and cockroaches, and rodenticide to poison rats and mice. As well, large amounts of pesticide are used in horticulture. Herbicides are especially widely applied, mostly to achieve the grass-lawn aesthetic that many homeowners seek. To this end, herbicide is used to kill broad-leaved plants such as dandelion and plantain. The “weed” in common “weed-and-feed” lawn preparations is the herbicide 2,4-D, dicamba, or mecoprop.

Some of the most intensive pesticide usage occurs in the management of golf courses, particularly on putting greens where the lawn quality must be very consistent. Fungicide is used in especially large amounts to prevent turf-grass diseases. On a per-unit area basis, the use of pesticides on putting greens can be more intensive than almost any in agriculture.

Environmental Effects

Pesticide applications are intended to manage the impacts of pests by reducing their abundance and damage to below an economically or aesthetically acceptable threshold. This objective can sometimes be achieved selectively, thereby avoiding non-target damage. For example, rodenticide can be used judiciously to kill rats and mice around the home, while minimizing toxic exposures to non-target cats, dogs, and children (although risk is never eliminated).

More typically, however, pesticide use involves a less-selective broadcast application, usually by spraying. A crop-dusting aircraft or tractor-drawn sprayer is often used, which results in many non-target species being exposed to the spray. The non-target organisms may live on the sprayed site, or they may be off-site and suffer exposure from aerial or aquatic drift of a pesticide. Non-target exposures include both direct contact with a sprayed pesticide as well as indirect exposure through the food web.

The ecotoxicological risk that is inherent in an exposure to pesticide (and to other chemicals) is influenced by a complex of variables, as we previously examined in Chapter 15. Several points should be considered when interpreting exposures of non-target organisms (including people) to pesticides and other chemicals:

- All chemicals are potentially toxic
- Not all exposures to potentially toxic chemicals result in poisoning (because organisms are to some degree tolerant to pesticides and other chemicals)
- Some pesticides and some naturally occurring chemicals are extremely toxic to many organisms, including humans
- Humans are subject to both involuntary and voluntary exposures to certain toxic chemicals (the latter includes prescription and recreational drugs)

Of course, pesticides vary enormously in their toxicity. Herbicides, for example, are extremely toxic to at least some plants, but not necessarily to animals, which differ in important physiological respects from plants. In contrast, most insecticides and rodenticides are toxic to a wide range of animals and can cause non-target poisoning of diverse species, including humans.

The acute toxicity of a chemical to animals is defined by its LD_{50}, or the dose needed to kill one-half of a test population that is exposed through food, water, or air. The oral LD_{50} for rats is an indicator of acute toxicity to mammals. Rats are widely used in toxicological research and are similar to humans in many aspects of their physiology. Table 22.2 compares the acute toxicity of a wide range of pesticides and some other chemicals, using rat oral LD_{50} (see also Table 15.3). Note that some of the most poisonous chemicals listed are natural biochemicals, such as saxitoxin, a potent neurotoxin produced by certain marine algae. Others are chemicals to which many people expose themselves in their pursuit of pleasure, such as nicotine, the addicting alkaloid in tobacco.

Table 22.2. Acute Toxicity of Various Chemicals to Rats. The oral LD50, measured in milligrams of chemical per kilogram of body weight, is the amount required to kill 50% of a trial population of rats, exposed through their food in a controlled laboratory test. Source: Modified from Freedman (1995)

Chemical	LD_{50} (mg/kg)
TCDD (dioxin isomer)	0.01
tetrodotoxin (globefish toxin)	0.01
saxitoxin (paralytic shellfish neurotoxin)	0.3
aldicarb (insecticide)	0.8
TEPP (insecticide)	6.8
carbofuran (insecticide)	10
parathion (insecticide)	13
methylparathion (insecticide)	14
phosphamidon (insecticide)	24
strychnine (rodenticide)	30
deltamethrin (insecticide)	31
aminocarb (insecticide)	39
nicotine (alkaloid in tobacco)	50
methiocarb (molluscicide)	65
lindane (insecticide)	88
diazinon (insecticide)	108
paraquat (herbicide)	150
caffeine (alkaloid in coffee & tea)	200
DDT (insecticide)	200
fenitrothion (insecticide)	250
2,4-D (herbicide)	370
2,4,5-T (herbicide)	500
carbaryl (insecticide)	500
triclopyr (herbicide)	650
mirex (insecticide)	740
DDE (DDT, DDD metabolite)	880
tetramethrin (insecticide)	1,000
hexazinone (herbicide)	1,690
acetylsalicylic acid (Aspirin)	1,700
atrazine (herbicide)	1,750
malathion (insecticide)	2,000
sodium hypochlorite (household bleach)	2,000
sodium bicarbonate (baking soda)	3,500
sodium chloride (table salt)	3,750
permethrin (insecticide)	3,800
DDD (insecticide)	4,000
glyphosate (herbicide)	5,600
picloram (herbicide)	8,200
captan (fungicide)	9,000
ethanol (drinking alcohol)	13,700

By poisoning organisms, pesticides may also cause habitat changes to occur, which can indirectly affect many species. For example, herbicide kills plants and thereby changes the habitat of animals, perhaps depriving herbivores of their preferred foods. Similarly, broad-spectrum insecticides kill large numbers of arthropods, which reduces the amount of food available for birds and other animals. These and other indirect effects of pesticide use can result in ecological damage, in addition to the directly toxic effects.

In the remainder of this chapter, we will examine several case studies of particular uses of pesticides. These are useful in illustrating the broader principles and patterns of the ecological damage caused by these chemicals.

DDT and Related Organochlorines

The first case study involves DDT and related organochlorine insecticides, such as DDD, dieldrin, and aldrin. These chemicals were once widely used in Canada and most other developed countries. Although these organochlorines were banned here in the early 1970s, they continue to be used in some less-developed nations.

DDT and its relatives are persistent in the environment. Consequently, even though these chemicals have not been used in Canada for several decades, there are still substantial residues in the ecosystems of our country. In part, this is also a result of the continued use of these organochlorines in some tropical countries, because small amounts of residue from those ongoing uses are transported to high-latitude countries by global cycling processes. In addition, organochlorines are more persistent in cooler environments than in warmer ones. As a result, these and some non-insecticidal organochlorines (such as PCBs and dioxins) are still important contaminants in Canada.

DDT was first synthesized in 1874, but its insecticidal properties were not discovered until 1939. Its first important use was during World War II in programs to control body lice, mosquitoes, and other disease vectors. DDT was quickly recognized as being an extremely effective insecticide, and it became widely used in agriculture, forestry, and against malaria. The use of DDT peaked in 1970, when 175-million kilograms were manufactured globally. Soon afterward, developed countries began to ban most uses of DDT because it was found to be causing ecological damage, including the contamination of people and their food web. Some researchers thought this contamination could be causing illnesses, such as increases in cancer and liver disease. However, DDT use has continued in some tropical countries, mostly against mosquito vectors of disease.

However, even in those countries the use of DDT and other organochlorine insecticides has been decreasing. This is partly because many pests have developed a genetically based tolerance of these chemicals (sometimes known as resistance), which decreases their effectiveness as pesticides. The development of tolerance is an evolutionary process in which exposure to a toxic substance selects for resistant individuals within a genetically variable population (see Chapters 6 and 15). Although tolerant individuals are normally rare in unsprayed populations, they may become rapidly dominant in sprayed habitat. If the insecticide does not kill them, they survive to reproduce, and pass on the genes for tolerance to their offspring. More than 500 species of insects and mites have populations tolerant to at least one insecticide, and there are more than 100 fungicide-resistant plant pathogens, 55 herbicide-tolerant weeds, and five rodents resistant to anticoagulants (NRC, 1986; Winston, 199; Landis et al., 2002).

Several physical and chemical properties of organochlorines have an important influence on their ability to cause ecological damage. First, they have an extended persistence, or a tendency to remain chemically unchanged in the environment because they are not easily degraded by microorganisms or by physical agents such as sunlight or heat. For example, DDT has a half-life in soil of 3-10 years. The primary breakdown product of DDT is the closely related organochlorine DDE, which has a similar persistence.

In addition, DDT and related organochlorines are essentially insoluble in water and so cannot be “diluted” into that abundant solvent. Instead, these chemicals are highly soluble in fats (or lipids), which occur mostly in organisms.

Therefore, DDT and related organochlorines have a strong affinity for organisms, and they accumulate in living things in strong preference to the non-living environment – this process is called bioconcentration.

Moreover, organisms are highly efficient at assimilating organochlorines that are present in their food. As a result, predators at the top of the food web develop the highest residues of organochlorines, particularly in their fatty tissues (this is known as biomagnification or food-web magnification). Both bioconcentration and food-web magnification are progressive with age, so the oldest individuals in a population are the most contaminated (see In Detail 18.1).

These properties of organochlorines are illustrated in Figure 22.1 and Table 22.3. Note that the concentrations are miniscule in air, water, and non-agricultural soil, compared with the much higher residues that occur in organisms. Note also that concentrations in plants are lower than in herbivores, and that residues are highest at the top of the food web, such as in predatory birds and humans.

Table 22.3. Typical Residues of DDT in the 1960s and 1970s. Sources: Data from Edwards (1975) and Freedman (1995).

Component	Concentration (ppm)
Non-Living Environment	
Atmosphere	1×10^{-5} to 2×10^{-10}
Atmospheric dust	0.3
Rainwater	5×10^{-4}
Fresh surface water	1×10^{-5}
Seawater	1×10^{-6}
Natural soil	0.01
Agricultural soil	2
Terrestrial Organisms	
Plants	0.05
Terrestrial insects	1
Soil-dwelling invertebrates	4
Small mammals	0.5
Predatory mammals	1
Insectivorous birds	2
Aquatic Organisms	
Aquatic plants	0.01
Zooplankton	0.05
Benthic invertebrates	0.1
Freshwater fish	2
Marine fish	0.5
Fish-eating birds	10
Humans	
Vegetable foods	0.02
Meat foods	0.2
Humans (in fat)	6

Another characteristic of organochlorines is their ubiquity – their residues occur in all organisms throughout the biosphere. This widespread contamination occurs because organochlorines enter a global cycle and become widely dispersed in the bodies of migrating organisms and in the atmosphere by evaporation and in wind-eroded dust. Residues of DDT are found even in organisms in Antarctica, far remote from areas where it was ever used. In one study in that far-southern region, the concentration of "total DDT" (almost all of which occur as the metabolic residue, DDE) in the fat of skuas (a marine bird, Catharacta maccormicki) was 5 ppm (or 5 µg/g). Smaller residues (< 0.44 ppm) occurred in birds feeding lower in the food web, such as fulmar (Fulmarus glacialoides) and macaroni penguin (Eudyptes chrysolophus) (Norheim et al., 1982).

Although organochlorine residues are ubiquitous in the biosphere, much higher concentrations occur in animals that live close to areas where these chemicals have been used, such as North America. Because marine mammals feed at or near the top of their food web and are long-lived, they can have extremely high residues of organochlorines. For example, harbour porpoises (Phocoena phocoena) in Atlantic Canada have had DDT residues as high as 520 ppm in their fat (Edwards, 1975). High residues of organochlorines also occur in top-predator birds, especially raptors (such as eagles, falcons, hawks, and owls). Prior to the banning of DDT, residues averaged 12 ppm (with a maximum of 356 ppm) in a sample of 69 bald eagles (Haliaeetus leucocephalus), up to 460 ppm among 11 western grebes (Aechmophorus occidentalis), and up to 131 ppm among 13 herring gulls (Larus argentatus) (Edwards, 1975).

Intense exposures to organochlorines caused important ecological damage, including bird poisonings. During the 1950s and 1960s, bird kills resulted when DDT was sprayed in urban areas to kill the beetle vectors of Dutch elm disease, caused by a fungal pathogen (Ceratocyctis ulmi) that was accidentally introduced to North America from Europe. The fungus is transported between trees by bark beetles, which can be controlled to some degree by the use of insecticide. Spraying for this purpose was intensive, and typically involved an application of 0.7-1.4 kg of DDT per tree. Birds feeding on invertebrates in treated areas were exposed to lethal doses. One study in New Hampshire found 117 dead birds in a 6 ha spray area, and estimated that 70% of the breeding robins (Turdus migratorius) had been killed (Wurster et al., 1965). So much avian mortality occurred in sprayed neighbourhoods that bird song was markedly reduced – hence the title of Rachel Carson's 1962 book, Silent Spring (In Detail 22.3).

In addition to acute poisoning caused by organochlorines in sprayed areas, more insidious damage was occurring over large regions. Many species experienced long-term chronic toxicity, even well away from sprayed areas. It took years of population monitoring and ecotoxicological research before organochlorines were identified as the cause of this widespread damage. In fact, we can view the chronic poisoning of birds and other wildlife as an ecological "surprise" that occurred because scientists (and society) had no experience with the long-term effects of persistent, biomagnifying organochlorines.

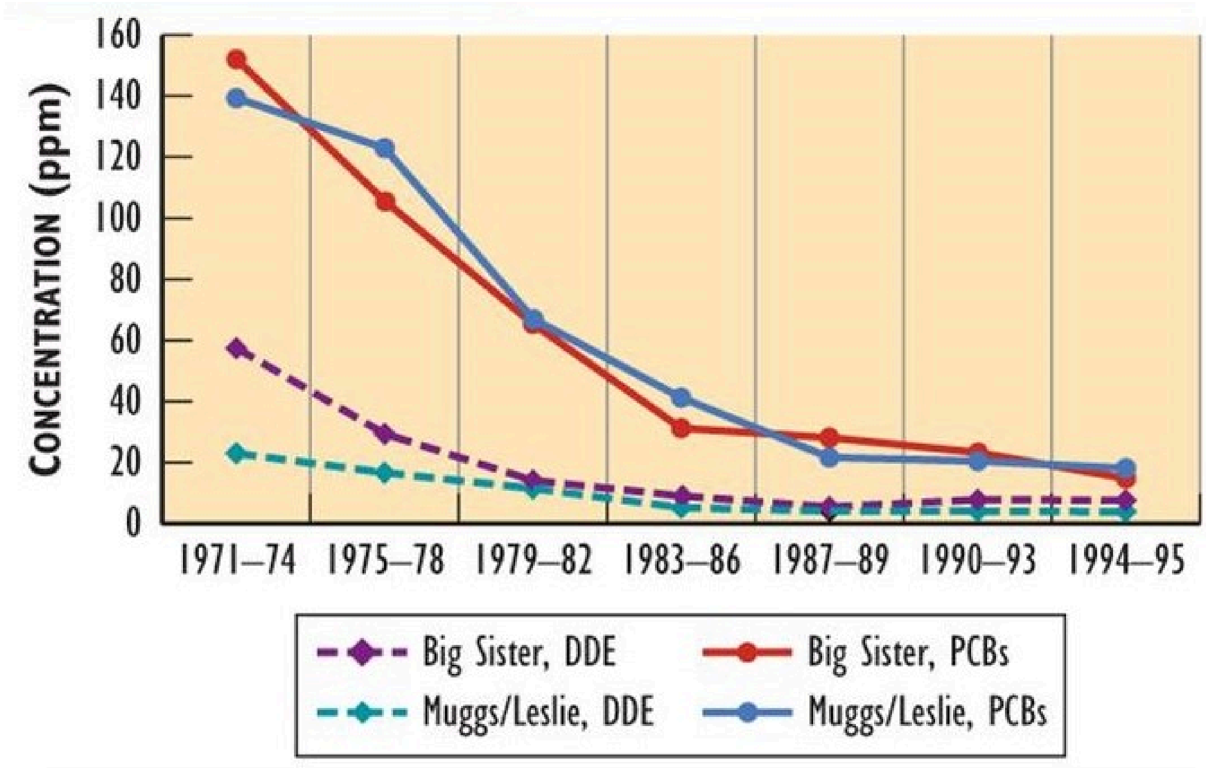
Raptorial birds were among the prominent victims of organochlorine insecticides. These birds are vulnerable because they are top predators and accumulate high residues of organochlorines. Breeding populations of various raptors suffered large declines. Severely affected species included the peregrine falcon (Falco peregrinus), osprey (Pandion haliaetus), bald eagle (Haliaeetus leucocephalus), and golden eagle (Aquila chrysaetos) (see Canadian Focus 22.1). In all cases, these species were exposed to a "cocktail" of organochlorines, including the insecticides DDT, DDD (both are metabolized to DDE), aldrin, dieldrin, and heptachlor, as well as PCBs, a group of non-insecticidal compounds with many industrial uses. Researchers have investigated the relative importance of these various organochlorines in causing the population declines of raptors. It appears that DDT may have been the more important toxin to birds in North America, while cyclodienes (particularly dieldrin) were more influential in Britain (Cooper, 1991; Moriarty, 1999).

Damage to raptors was mainly associated with chronic effects on their reproduction, rather than toxicity caused to adults. Reproductive damage included the production of thin eggshells that would break under the weight of an incubating parent, high mortality of embryos and nestlings, and abnormal adult behaviour. The numbers of fledged chicks declined, and that resulted in rapid population declines.

Since the bans of DDT and other organochlorines in North America, their residues in wildlife have been progressively decreasing. Data showing this decline have been obtained by analyzing eggs of herring gulls (Larus argentatus) breeding on the Great Lakes (Figure 22.2). Although eggs from various places differ in their residues (partly depending on local sources), they all exhibit large decreases in DDE and PCB. Decreases in residues have also occurred in double-crested cormorants (Phalacrocorax auritus).

Figure 22.2. Changes in Organochlorine Residues in Bird Eggs. Eggs of herring gull have shown decreasing residues since the use of DDT, PCBs, and other persistent organochlorines was banned in North America in the early 1970s. Muggs/Leslie are breeding sites in the Toronto waterfront, while Big Sister Island is in Green Bay in Lake Michigan. Residues are measured in ppm. Sources: Data from Bishop and Weseloh (1990), Environment

Canada (1993), and Ryckman et al. (2005).



In Detail 22.3. Silent Spring Rachel Carson, an American biologist, wrote many scientific articles and several books, the most famous of which, Silent Spring, was published in 1962. Silent Spring was aimed at a popular audience, and it was a lively and controversial indictment of pesticide use as it was practised at the time, particularly the use of DDT and other organochlorine insecticides. Silent Spring was written to warn society about the known and potential dangers that these pesticides pose to wildlife, and also to people through contamination of their food. Silent Spring achieved that objective and, in fact, was a literary bombshell that caused an eruption of public awareness about pesticide issues.

Although DDT and its organochlorine relatives were clearly useful in killing pests, Carson described how they were also causing extensive mortality to non-pest arthropods, and also to birds, mammals, and other wildlife. She also warned that people were being widely exposed to organochlorines, with significant residues being found, for example, in the milk of nursing mothers. She noted, “For the first time in the history of the world, every human being is now subjected to dangerous chemicals, from the moment of conception until death.” Although little was known about the subject at the time, Carson warned that the chronic, low-level exposure of people to organochlorines was potentially dangerous.

A best-seller, Silent Spring stirred up an enormous controversy about the effects of anthropogenic chemicals in the environment. Companies that manufactured pesticides mounted their own information and advertising programs. They attempted to discredit Carson by labelling her as an irresponsible agitator and by claiming that she did not represent the views of most scientists. In fact, some of the technical details of Carson’s analysis were later found to be incorrect, but this is not surprising considering the incomplete understanding at the time about pesticides and their environmental impacts. Nevertheless, the essential thesis of Silent Spring was that organochlorine insecticides were widely contaminating organisms and the environment, were persistent, and were causing extensive damage. In large part, these assertions were correct.

Unfortunately, Rachel Carson died an early death from cancer in 1964, just as the message of Silent Spring was becoming widely recognized. Today, Carson is known as one of the most influential environmentalists in history, a pioneer who deserves much of the credit for the birth of the environmental movement during the mid-1960s. Like all environmentalists, Rachel Carson promoted an ethic of human responsibility for taking care of the biosphere and its species.

The Case of Carbofuran

Important replacements for DDT and related organochlorines have been organophosphate and carbamate insecticides. These poison insects and other arthropods by inhibiting a specific enzyme, acetylcholinesterase (AChE), which is critical in the transmission of nerve impulses. Vertebrates such as amphibians, fish, birds, and mammals are also sensitive to poisoning of their AChE system. In all of these animals, acute poisoning by organophosphate and carbamate insecticides causes tremors, convulsions, and ultimately death.

Carbofuran is a carbamate insecticide that can be used for many purposes in agriculture. One formulation is a liquid suspension that can be diluted in water and then broadcast-sprayed against pests such as grasshoppers and leaf beetles. It is also available in a granular formulation, in which the insecticide coats particles of grit and is sown along with seeds to protect tender seedlings from insect damage. The granular formulation has been commonly used when sowing canola and maize.

Unfortunately, wildlife is exposed to toxic doses of carbofuran when either of these formulations is used. For example, if not all of the carbofuran granules are buried in the planting furrows, they remain exposed on the surface (Mineau, 1993). In one method of seeding, used for corn in Ontario, 15-31% of the granules remained exposed on the surface, or 515-1065 exposed granules per metre of furrow. Methods used to plant canola in western Canada often left about 5% of the granules on the surface. The exposed granules may be ingested by seed-eating birds, which require hard particles of that size as "grit" for macerating hard-coated seeds in their muscular gizzard. The carbofuran is extremely toxic: consumption of only 1-5 granules can kill a small bird. Raptors and mammals are secondarily poisoned if they scavenge the dead bodies.

In addition, fields treated with carbofuran may become flooded during the spring and autumn, and the surface water may then contain large residues of the insecticide. This is particularly the case if the soil and water are acidic, which greatly reduces the rate of breakdown of carbofuran into less toxic chemicals.

Of all the pesticides used recently in agriculture, carbofuran has probably caused the most non-target mortality of birds and other wild animals. Even though there is no systematic program for reporting bird kills caused by pesticide use in Canada or the United States, a large number of toxic incidents were documented for carbofuran (Mineau, 1993), a few of which were:

- More than 2,000 Lapland longspurs (Calcarius lapponicus), a seed-eating finch, were killed after eating carbofuran granules in a freshly planted canola field in Saskatchewan in May 1984
- About 1,200 birds, mostly savannah sparrows (Passerculus sandwichensis), were killed in by granular carbofuran in turnip and radish fields in British Columbia in September 1986
- More than 1,000 green-winged teal (Anas carolinensis) were killed within hours of landing in a flooded turnip field in British Columbia in the autumn of 1975
- At least 50 mallards (Anas platyrhynchos) and pintails (A. acuta) were poisoned in a flooded field in British Columbia in December 1973
- 2,450 dead widgeon (Mareca americana) found one day after spraying of an alfalfa field in California in March 1974

These examples are only a small fraction of the known bird kills caused by the routine use of carbofuran in agriculture. There are also, of course, larger numbers of unreported incidents. Because carbofuran use in agriculture carries such a well-known risk of poisoning birds and other wildlife, ecologists and environmentalists lobbied vigorously to have its registration withdrawn for those uses, or at least more tightly controlled. In 1993, the U.S. Environmental Protection Agency banned the sand-based granular formulation of carbofuran, except for some relatively minor uses and a major one (with rice crops) for which there was no suitable alternative. In 1996, Agriculture Canada, the federal agency that regulates pesticide use, prohibited most uses of carbofuran in liquid suspension, as well as all granular formulations. These were positive actions in terms of pesticide regulation, although in the view of many wildlife toxicologists it took an excessively long time for those necessary steps to be taken.

Canadian Focus 22.1. Organochlorines and the Peregrine Falcon The most famous avian victim of organochlorines was the peregrine falcon, whose population declines were first noticed in the early 1950s in North America and Western Europe (Peakall, 1990; Freedman, 1995). By 1970, peregrines in eastern North America (the subspecies Falco peregrinus anatum) had stopped reproducing and were critically endangered. At the same time, the tundrius subspecies of the Arctic was rapidly declining. Only the pealei subspecies that breeds on islands off British Columbia and Alaska had normal reproduction success and a stable population.

The pealei falcons do not migrate. Moreover, they live in a region where pesticides are not used and mainly feed on non-migratory seabirds. In contrast, anatum peregrines breed in a region where organochlorines were widely used, and they fed on contaminated prey. The tundrius falcons breed in a northern wilderness where pesticides are not used, but they winter in Central and South America where their food was contaminated by organochlorines, as was their prey of migratory waterfowl and shorebirds in the Arctic. Studies by wildlife toxicologists found that populations of peregrine falcons with high organochlorine residues were laying thin-shelled eggs and suffering other kinds of reproductive impairment. This damage was causing their populations to collapse. By 1975, the anatum birds had become extirpated in eastern North America, while the arctic tundrius birds had declined to only about 450 pairs from historical levels of more than 5-thousand pairs.

Fortunately, many countries (including Canada, the United States, and most other developed nations) banned further use of DDT and most other organochlorines in the 1970s. This resulted in a marked decrease in residues in the food of peregrines and other raptors, which allowed their populations to stabilize or recover. By 1985, arctic peregrines were increasing in abundance, and small breeding populations had re-established in more southern regions.

The recovery was greatly enhanced by a program (funded in Canada by the Canadian Wildlife Service) that bred peregrines in captivity to provide young birds for release into the former range of the anatum subspecies. Several thousand young peregrines were released in Canada and the U.S., and many of the birds survived and bred. Some of them were released in cities, where tall buildings provide cliff-like nesting habitat and there are abundant pigeons and other urban birds as prey. Thanks to declining residues of organochlorines resulting from bans on the use of these chemicals, the peregrine falcon is on its way back.

Image 22.1. The peregrine falcon is a species that suffered widespread population declines as a result of the ecotoxicological effects of DDT and other organochlorines. Source: Dennis Jarvis, Wikimedia

Commons; http://commons.wikimedia.org/wiki/File:Falco_peregrinus_-Nova_Scotia,_Canada_-eating-8.jpg

Diazinon and Monocrotophos

Other modern insecticides are also poisoning Canadian birds. Diazinon, an organophosphate insecticide, has caused numerous cases of mass mortality. For instance, in the late 1980s, there were at least five events in which entire flocks of Canada goose (Branta canadensis) were killed when they fed on grass on golf courses in southern Ontario that had been treated to reduce infestations of turf insects (Mineau, 1999). The geese died within minutes, as is typical of acute poisoning by AChE inhibitors. Similar toxic events have occurred in the United States, including one in which 700 Brant geese (Branta bernicla) were killed on a golf course in New York. Diazinon has now been banned for use on golf courses in the U.S., but it can still be used in Canada for that purpose and also for horticultural and agricultural purposes, although its use is declining.

In 1996, it was discovered that agricultural use of monocrotophos and other organophosphate insecticides against grasshoppers in Argentina was killing large numbers of Swainson's hawks (Buteo swainsoni). This raptor breeds in western Canada and the U.S. and migrates to winter on the pampas of South America. Populations of this hawk had been declining for several years. However, it was not until some birds were fitted with satellite transmitters and followed to Argentina that wildlife toxicologists discovered a probable cause of the decline – poorly regulated use of monocrotophos on the wintering grounds. Field studies in Argentina discovered that more than 20-thousand Swainson's hawks had been killed in just one agricultural area (other regions were not surveyed), out of a total breeding population of only 400-thousand (of which up to one-quarter breed in Canada).

Monocrotophos is extremely toxic to birds, although it is not persistent in the environment. Because of the risk of ecological damage, monocrotophos has been banned in the United States and was never registered for use in Canada. In Argentina, however, the insecticide could be legally used. Swainson's hawks were exposed to lethal doses of monocrotophos when they fluttered behind spray tractors to feed on grasshoppers flushed by the machinery, and also when they later fed on insecticide-contaminated prey. Argentina has since banned monocrotophos, replacing its applications with pyrethroids.

Neonicotinoids

Perhaps the most contentious pesticide-related issue of recent years (this was written in 2015) is the use of neonicotinoid insecticides agriculture (Jeschke et al., 2011; Mineau and Palmer, 2013; van der Sluijs et al, 2014). These are a class of synthetic AChE-inhibiting insecticides that are chemically similar to nicotine, the key alkaloid in tobacco. Neonicotinoids are much less toxic to vertebrate animals that carbamate and organophosphate insecticides, but they are persistent and broad-spectrum poisons to non-target arthropods. The “neonic” group includes a variety of compounds, with imidacloprid recently being one of the most widely used insecticides in the world.

Neonicotinoids are a systemic insecticide. The chemical can be applied with irrigation water, as a water-based spray, or as a coating on seed intended for planting. In all of those cases, the neonic is absorbed and then distributed throughout the plant to confer protection against herbivorous insects. These have become popular uses – since the introduction of neonics in the early 1990s, they have grown to account for several billions of dollars of annual sales. Neonicotinoids are used on a wide range of crops. In the United States, they are used on 95% of the canola and maize acreage, and at least half of cotton, sorghum, soybean, and sugar beet. They are used on many fruit crops, including almonds, apples, berries, cherries, grapes, oranges, and peaches, as well as vegetables such as leafy greens, potatoes, and tomatoes, and even cereal grains. They are also used as a wood preservative.

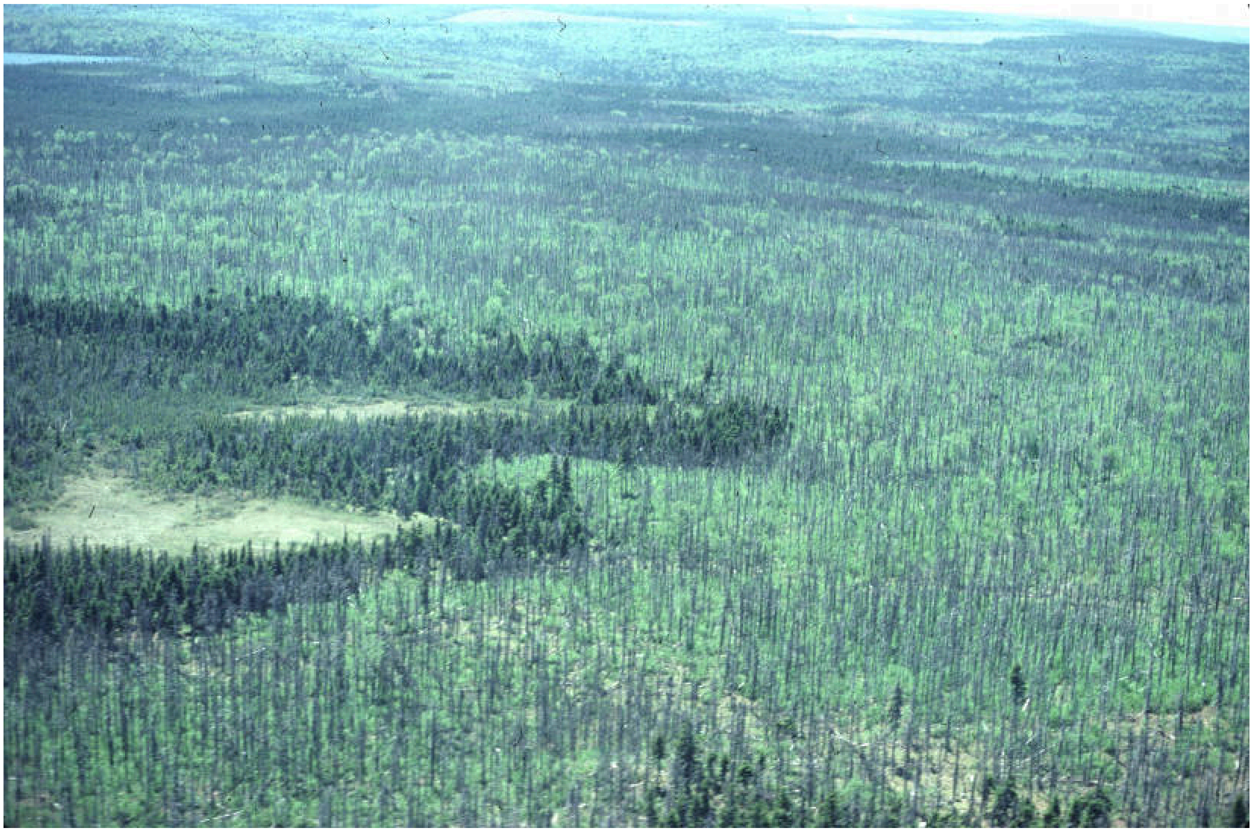
Recently, the use of neonicotinoids has been linked to some important environmental problems. One is the general decline in pollinating insects, which are vital both to agricultural production and to natural ecosystems. The agricultural linkage involves that fact that most commercial fruits, ranging from apples to zucchinis, rely on insects to pollinate their flowers so that fruit development can occur. Honeybees are especially important in this regard, yet these vitally important pollinators have been badly declining because of a syndrome referred to as colony collapse disorder. The cause of that damage is not exactly known, but neonics are suspected as having a contributing influence. Another indirect effect of the widespread use of neonics could be declines of some bird species due to a reduction of their arthropod food base (Hallmann et al., 2014).

As a result of the growing concerns about the environmental effects of neonicotinoid insecticides, many countries have been restricting or banning their use. In 2013, a study by the European Food Safety Authority reported an unacceptably high risk to honeybees from many uses of neonics, and in 2014 a critical integrated study was published (van der Sluijs et al, 2014). In 2014, in response to this and other research, 15 of the 27 European Union member states voted to restrict the use of three neonicotinoids (clothianidin, imidacloprid, and thiamethoxam) for two years while additional studies were undertaken. The U.S. Environmental Protection Agency is reviewing their registration, and Canadian authorities are monitoring those international developments.

Pest Problems in Forestry

Pesticides are used much more extensively in agriculture than in forestry (about 80% of pesticide sales in Canada are for use in agriculture, 12% for domestic and industrial use, and 2% for forestry purposes; Environment Canada, 1996). However, forestry case studies better illustrate many of the ecological effects of pesticide use because the treated habitats support mainly native species and natural or semi-natural ecosystems. In contrast, agricultural habitats are dominated by non-native species and are intensively managed, making them less amenable to the examination of some of the ecological effects of pesticides.

Image 22.2. This is an area of intensive forest damage caused by spruce budworm on the highlands of Cape Breton Island. The living trees fringing the bog are black spruce, which is resistant to the budworm. The extensive area of dead trees was dominated by balsam fir, a vulnerable species. This photograph was taken several years after the collapse of the outbreak. Source: B. Freedman.



Spruce Budworm

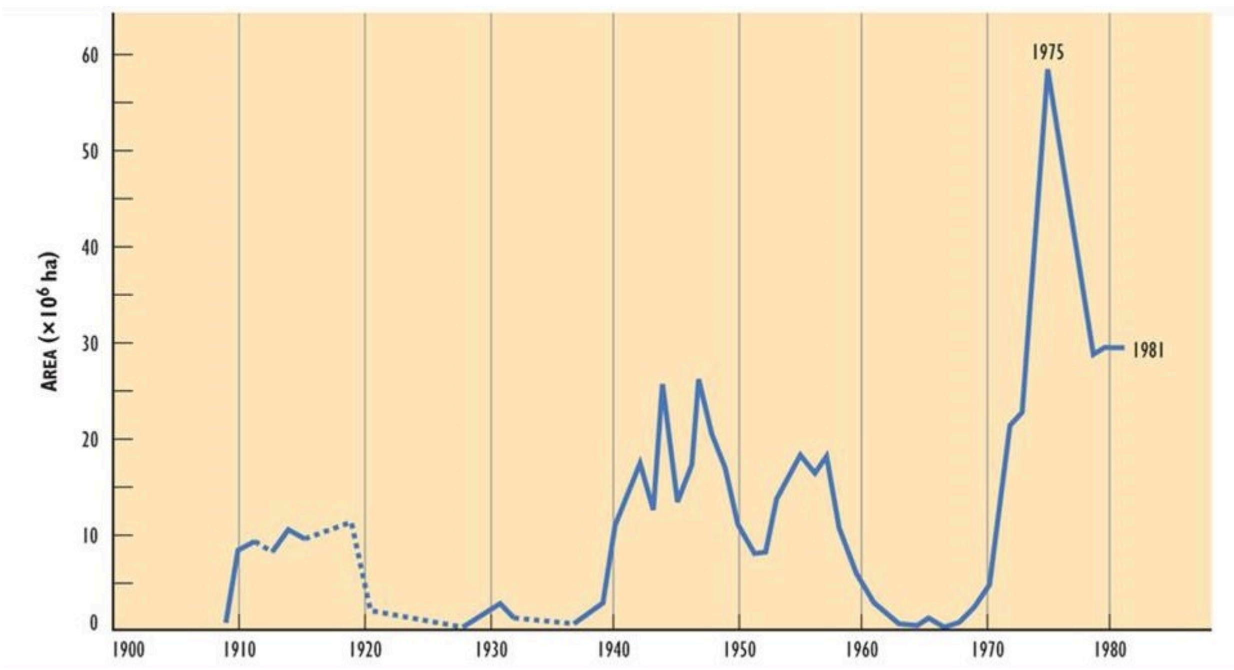
The largest insecticide spray programs in forestry have been mounted against spruce budworm (Choristoneura fumiferana), particularly in New Brunswick. Because the spraying occurs over extensive natural forests, whose biodiversity consists of native species, it represents an excellent case study to examine the ecological effects of insecticide use. Spruce budworm is a native moth whose larvae are pests of fir- and spruce-dominated forest. An infestation can affect tens of millions of hectares, and trees are killed after several years of defoliation. Mature stands dominated by balsam fir (Abies balsamea) are particularly vulnerable. White spruce (Picea glauca) is also a preferred food, but red spruce (P. rubens) and black spruce (P. mariana) are less apt to suffer lethal damage. Spruce budworm is always present in small populations in its fir-spruce habitat, but it occasionally irrupts to an enormous abundance and becomes a pest. Under normal conditions, only about five larvae may occur on each conifer tree, but this increases to 2-thousand at the beginning of an irruption, and to more than 20-thousand during the peak. A local outbreak is typically sustained for 6-10 years, and then collapses. Studies in Quebec have shown that outbreaks have occurred at an average interval of about 35 years (Blais, 1985). An outbreak is typically synchronous (occurring at the same time) over an extensive area of vulnerable forest, although there are large variations in the abundance of budworm among stands. The exact reasons for the irruptions are not known, but they may involve several years of warm, dry weather in the springtime, which favours the survival of larvae.

Forest Damage

It appears that the extent of damage caused by spruce budworm may have increased during the three outbreaks of the twentieth century. The outbreak that began in 1910 affected about 10-million hectares, one starting in 1940 involved 25-million ha, and another in 1970 affected more than 55-million ha (Figure 22.3). The enlarging areas of infestation may be related to an increase in the extent of vulnerable fir-spruce forest, possibly due to the following influences:

- regeneration of conifer stands on abandoned farmland, particularly since the 1920s
- protection of forests from wildfire
- forestry practices such as clear-cutting
- spraying of infested stands with insecticide, which may help maintain the habitat in a condition suitable for budworm

Figure 22.3. Forest Area Defoliated by Spruce Budworm in the Twentieth Century. The area corresponds to stands suffering severe or moderate defoliation. Source: Modified from Kettela (1983).



Enormous damage has been caused by budworm to economically important forest resources. During the most recent outbreak (1971-1984), tree mortality was equivalent to more than 38-million cubic metres of saleable timber. During the peak of the infestation, substantial tree mortality occurred over about 26.5-million hectares in eastern Canada (Ostaff, 1985). The rapid development of an infestation can be illustrated by the case of Cape Breton Island (Ostaff and MacLean, 1989). No defoliation by budworm was observed in 1973, but in 1974 there was moderate-to-severe defoliation over 165-thousand hectares. This increased to 486-thousand ha in 1975, and to 1.22-million hectares in 1976, when essentially all of the vulnerable fir-spruce forest was infested.

An irruption of budworm can last for 10 or more years, with the damage increasing over time. During the first two years of severe defoliation on Cape Breton, 4% of the balsam fir trees died. The cumulative mortality increased to 9% after four years of heavy defoliation, 37% after six years, 48% after eight years, 75% after 10 years, and 95% after 12 years (Ostaff and MacLean, 1989). Across eastern Canada, tree mortality averaged 85% in mature fir-dominated stands, 42% in immature fir stands, and 36% in mature spruce stands (MacLean, 1990).

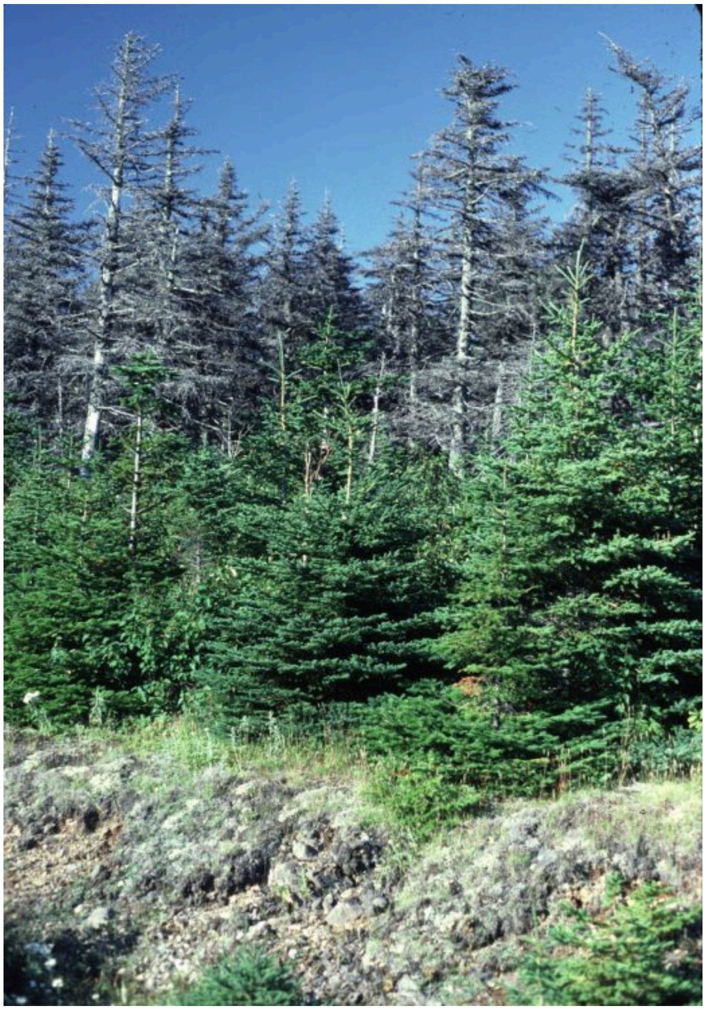
Mature trees are much more vulnerable to budworm than are smaller immature ones, which commonly survive an outbreak. Consequently, the understorey of a damaged stand typically contains a dense population of small fir and spruce. Known as advanced regeneration, this is important in re-establishing the next fir-spruce forest after an infestation collapses. On Cape Breton, severely damaged stands typically had an advanced regeneration of 45-thousand small fir plus 3-thousand spruce per hectare, most of which survived the infestation (MacLean, 1988).

After the mature trees die and the canopy opens up, the small conifers grow rapidly and establish another fir-spruce forest, which becomes vulnerable decades later to another irruption of budworm. These observations suggest that, over the long term, the interaction between the forest and budworm can be viewed as an ecologically stable, cyclic succession. The natural cycle of disturbance and recovery has probably been occurring for thousands of years, although human influences may have increased its scale since the nineteenth century.

Of course, spruce budworm causes great economic instability in the forest-products industry, which is in competition with this moth for the fir-spruce resource. The periodic irruptions of budworm severely damage the forest, making it difficult for humans to plan their own orderly harvesting and management of the trees. Spraying is one way of dealing with this problem, because it can limit the defoliation and prevent some tree mortality. The objective of spraying is not to eradicate the budworm, but to decrease the damage it causes, and thereby maintain the forest resource and its dependent economy.

> Image 22.3. This is a ground-level view of a stand damaged by spruce budworm on Cape Breton Island. Although the mature balsam fir trees have been killed, dense regeneration is occurring in the understorey. After 40-50 years, another mature forest will have developed, ready to be harvested by budworm or by humans.

Source: B. Freedman.



Insecticide Spraying

After the Second World War, an early use of DDT was against spruce budworm. In 1953 alone, 804-thousand hectares of forest were sprayed in Quebec and New Brunswick. By 1968, when further use of DDT for this purpose was banned, a total of 15-million ha had been sprayed at least once (Ennis and Caldwell, 1991). In New Brunswick alone, 5.75-million kilograms of DDT were sprayed onto budworm-infested forest (Armstrong, 1985).

After the further use of DDT was banned in 1968, the insecticides used were fenitrothion and phosphamidon, both organophosphates, and aminocarb, a carbamate. Of these, fenitrothion was used most widely. By 1985, phosphamidon had been sprayed on 8.1-million hectares, aminocarb on 19-million ha, and fenitrothion on 64-million ha (these are sums of annual sprayed areas, with most treated stands receiving two sprays per year; Ennis and Caldwell, 1991). New Brunswick had the biggest spray program to "protect" the forest resource against budworm – up to 1985, a cumulative total of 69-million ha was treated, compared to 37-million ha in Quebec, 10-million ha in Maine, and 1.7-million ha in Newfoundland. The most extensive spraying in New Brunswick was in 1976, when 4.2-million hectares were treated. Afterward, spraying decreased to less than 1-million ha after 1985, to less than 0.5-million ha after 1990, and to zero after 1993 due to collapse of the budworm outbreak.

During the late 1980s, a biological insecticide based on the bacterium Bacillus thuringiensis var. kurstaki (abbreviated B.t.) began to displace the synthetic pesticides in budworm spraying. B.t. is toxic to most lepidopterans (moths and butterflies) and to some other insects, including blackflies and mosquitoes. Otherwise, this insecticide causes little non-target damage. Initially, budworm control using B.t. was variable in effectiveness, and the cost was high compared with fenitrothion. Since then, however, the effectiveness and cost of spraying B.t. have improved. This, along with concern about ecological damage caused by fenitrothion, has resulted in B.t. becoming the insecticide of choice in spray programs against budworm.

Non-Target Damage

The synthetic insecticides used against budworm caused a great deal of non-target mortality. Typical spray rates and toxicities for the insecticides are summarized in Table 22.4. DDT is the least toxic to budworm, but the most toxic to salmonid fish. Perhaps the most important reason for the 1968 ban on using DDT against budworm was the mortality caused to sportfish, particularly Atlantic salmon (Salmo salar) and brook trout (Salvelinus fontinalis).

Table 22.4. Acute Toxicity of Insecticides Used against Spruce Budworm. Typical application rates for forestry purposes are in kilograms per hectare. Acute toxicity to budworm larvae and selected vertebrate species was determined under laboratory conditions. The units of toxicity to budworm are in micrograms per square centimetre of body surface; for trout, data are ppm in water; and for pheasant and rat, data are ppm in food. Note: the 96-hr LC50 is the concentration in water that killed 50% of a population of trout after a 96-hour exposure. Source: Freedman (1995).

Insecticide	Spray Rate	Budworm	Rainbow Trout	Pheasant	Rat
	kg/ha	LD_{50}; µg/cm^2	96-h LC_{50}, ppm	LD_{50}, ppm	LD_{50}, ppm
DDT	0.3-2.2	1.3	0.009	1,334	87-500
Phosphamidon	0.3	0.39	7.8	4.2	15-33
Fenitrothion	0.21	0.31	2.4	56	250-600
Aminocarb	0.07	0.04	13.5	42	30
Mexacarbate	0.07	0.04	12	4.6	15-63

The insecticides that initially replaced DDT are more toxic to budworm and so could be sprayed at lower rates while achieving a similar degree of pest control. Although these insecticides are less toxic to fish than DDT was, they can be very poisonous to other animals. Fenitrothion and aminocarb, for example, are highly toxic to all arthropods, so their use results in an enormous kill of non-target insects and spiders, including many predators of budworm. One study estimated that a typical fenitrothion spray killed as many as 7.5-million individuals of hundreds of species of arthropods per hectare, although more than 90% of the dead biomass was budworm (Varty, 1975). Overall, a typical spray with fenitrothion caused a short-term decrease in arthropod biomass of 35%, and a decrease in total individuals of 50% (Agriculture Canada, 1993). However, studies found that the non-target damage to arthropods was temporary and long-term decreases in abundance were not detectable (Varty, 1975; Millikin, 1990). The post-spray recovery was due to recolonization from non-sprayed forest, along with increases by arthropods that survived the spraying.

Bird populations are unusually abundant in infested forest because budworm is a plentiful and nutritious food for insect-eating animals. In fact, some birds are uncommon except in budworm-infested forest. In one study, the breeding population of bay-breasted warbler increased from only 0.25 pairs/ha in non-infested forest to 30 pairs/ha during a budworm outbreak, while Tennessee warbler increased from 0 to 12.5 pairs/ha (Morris et al., 1958).

During an outbreak of budworm, most birds rely heavily on the larvae as food for raising nestlings. One study estimated that birds eat 89-thousand budworm larvae and pupae per hectare of infested forest, compared with 6-thousand/ha in stands without an irruption (Crawford et al., 1983). However, despite the enthusiastic effort, bird predation has no substantial effect on the abundance of budworm during an outbreak – birds consume only about 2% of the larvae. In essence, insectivorous birds are satiated by the extremely abundant food resource and are incapable of controlling the huge population of larvae. Predation by birds may, however, be important in reducing less-abundant budworm populations, and may help to lengthen the interval between outbreaks.

Because birds are abundant in a budworm-infested forest, they are exposed to any insecticide that might be sprayed. Even though some of the insecticides used against budworm are extremely toxic to birds, it has proved difficult to document actual damage to avian populations by spraying. First, it is extremely difficult to find dead or dying birds in forest habitat because they occur in a small density and are quickly scavenged by other animals. Even with all the insecticide spraying in New Brunswick between 1965 and 1987, the Canadian Wildlife Service has records of only 125 dead birds (Busby et al., 1989), which is a gross underestimate of the actual mortality.

In addition, it is difficult to detect population changes resulting from mortality of birds in forest. A census of forest birds is taken by mapping the locations from which male birds sing; this information is then used to determine the boundaries of their territories. The song censuses are conducted in the spring over a period of four to six weeks. During that time, bird populations are dynamic because migratory species are returning from their wintering grounds, and they arrive at different times. Moreover, if a territory-holding bird is killed by an insecticide spray, it may be quickly replaced from a "surplus" of non-breeding individuals that wander extensively, searching for suitable habitat that is not occupied by another of their species. Because of the temporal variations in bird abundance and the rapid replacement of killed individuals, it is difficult to document population changes caused by insecticide spraying.

Phosphamidon is very poisonous to birds (Table 22.4), and its use likely caused severe mortality of some species. One study suggested that as many as 376-thousand ruby-crowned kinglets were killed in New Brunswick during the 1975 spray season, mostly by phosphamidon (Pearce and Peakall, 1977). Because they forage high in the canopy, kinglets are particularly vulnerable to insecticide exposure during an aerial spray. The presumed damage to birds was the key reason why phosphamidon was banned for use against budworm after 1975.

Fenitrothion is less poisonous to birds, but it nevertheless has a small margin of toxicological safety during operational sprays. While a normal application appears to cause little avian mortality, exposure to a double spray, as commonly occurs with overlapping spray swaths, can be lethal. Studies of white-throated sparrows found much greater mortality and behavioural impairment after a double application of fenitrothion, compared with the normal spray rate (Busby et al., 1989).

Table 22.5 shows the effects of a fenitrothion spray on birds. When interpreting these census data, the trends in the sprayed habitat should be compared with those of non-sprayed forest. The comparison is necessary because the "pre-spray" census was conducted in mid-May, when many migratory birds had not yet returned to their breeding habitat. Consequently, the total avian abundance in the pre-spray census was much smaller than occurs later on. If the data are considered in this relative sense, they suggest that the fenitrothion spraying had no obvious effects on the abundance or species composition of the avian community. It is likely, however, that some birds were poisoned by fenitrothion during the spray and that the damage was not reflected in the census for the reasons we noted earlier.

Table 22.5. Effects of Fenitrothion on Bird Populations. The data show the effects of forest spraying with fenitrothion on breeding birds in the Gaspé region of Quebec. The operational spraying procedure is to treat stands twice, about one week apart. In this study, birds were censused for five days before spraying, then for seven days after the initial spray on May 21, 1976, and again for five days after the second spray on May 30. The sprayed stand ("Spr") was treated with fenitrothion at 0.56 kg/ha, while the unsprayed reference stand ("Ref") monitors changes that are unrelated to spraying. Bird density is expressed as numbers per 10 hectares. Only

prominent species are listed. Source: Data from Kingsbury and McLeod (1981).

	Pre-Spray		1st Spray		2nd Spray	
Species	**Spray**	**Ref**	**Spray**	**Ref**	**Spray**	**Ref**
Total Abundance	46.1	39.1	52.1	57.7	68.8	75.8
Number of Species	23	23	41	35	41	39
Boreal chickadee (*Parus hudsonicus*)	2.5	4.3	1.5	1.5	1.4	1.1
Winter wren (*Troglodytes troglodytes*)	1	3.9	2.3	4.6	1.7	3
American robin (*Turdus migratorius*)	3.5	3.6	4.8	3.3	5.3	1.8
Ruby-crowned kinglet (*Regulus calendula*)	8.6	4.5	5.9	3.8	4.4	6.4
Tennessee warbler (*Vermivora peregrina*)	0	0	0.3	1.5	2.3	5.8
Magnolia warbler (*Dendroica magnolia*)	0	0	0.1	1.5	0.8	3.1
Cape May warbler (*Dendroica tigrina*)	0	0	2	3.1	4.3	4
Yellow-rumped warbler (*Dendroica coronata*)	0.5	0.3	7.7	6.3	10.8	8.2
Bay-breasted warbler (*Dendroica castanea*)	0	0	0.3	0.3	2.5	4.5
Dark-eyed junco (*Junco hyemalis*)	9.6	4.1	4.2	1.8	4.5	0.5
White-throated sparrow (*Zonotrichia albicollis*)	8.9	9.6	9.7	10.5	10.4	8.4
Fox sparrow (*Paserella iliaca*)	2.1	3.8	3.3	4.2	2.5	3.1

It should also be recognized that a budworm outbreak causes severe damage to the forest, and this affects the habitat of wildlife. Table 22.6 illustrates the effects of this habitat change on birds. Defoliation by budworm caused relatively little damage to Stand A, so the decreased population of some birds (such as solitary vireo and many warblers) was caused by a decrease in the availability of food because the outbreak had collapsed and budworm is a critical resource. In contrast, Stand B was intensely damaged by budworm, with large habitat changes that included many dead trees and a lush growth of understorey plants. In this stand, the decreased abundance of some birds (such as solitary vireo, Tennessee warbler, black-throated green warbler, blackburnian warbler, and bay-breasted warbler) resulted from changes in vegetation as well as a reduced availability of larvae as food. Note, in addition, that some birds (such as least flycatcher, magnolia warbler, and white-throated sparrow) do well in recently disturbed stands: they benefit from the habitat associated with budworm damage.

Table 22.6. Abundance of Birds During and After a Spruce Budworm Outbreak. The data are from a study in New Brunswick. Stand A was monitored for eight years during an infestation (1952-1959), and then for six post-outbreak years (to 1965). However, Stand A suffered little damage to its trees – the average age of balsam fir trees was 120 years in both sampling periods. Stand B was censused for five infestation years (1955-1959) and for five post-outbreak years (to 1964). Stand B suffered intense damage to its trees – the fir averaged older than 80 years when the infestation began, but < 10 years old afterward because so many mature trees had died. The bird data are in numbers per 40 hectares. Only prominent species are listed. Source: Data from Gage and Miller

(1978).

	Stand A		Stand B	
Species	**During Outbreak**	**Post-Outbreak**	**During Outbreak**	**Post-Outbreak**
Total Abundance	192	95	201	84
Yellow-bellied flycatcher (*Empidonax flavifrons*)	4.6	<0.1	5.1	0
Least flycatcher (*Empidonax minimus*)	3.9	2.8	2.1	15.9
Winter wren (*Troglodytes troglodytes*)	5.9	8.2	2.2	3.3
Swainson's thrush (*Catharus ustulatus*)	15.1	11.9	14	8.7
Golden-crowned kinglet (*Regulus satrapa*)	8.9	3	2.3	0
Ruby-crowned kinglet (*Regulus calendula*)	<0.1	10.1	1.1	2.7
Solitary vireo (*Vireo solitarius*)	8.3	<0.1	7.7	0
Tennessee warbler (*Vermivora peregrina*)	9.9	0	25.7	0
Magnolia warbler (*Dendroica magnolia*)	22	7.9	1.3	14.9
Yellow-rumped warbler (*Dendroica coronata*)	7.1	1.6	5.1	2.1
Black-throated green warbler (*Dendroica virens*)	11.9	4.2	11.8	4.2
Blackburnian warbler (*Dendroica fusca*)	17.1	5.3	19.5	1.5
Bay-breasted warbler (*Dendroica castanea*)	55.8	16.4	78.2	2
Dark-eyed junco (*Junco hyemalis*)	5.9	3.5	8.4	4.1
White-throated sparrow (*Zonotrichia albicollis*)	9.3	5	11.4	19.5

Overall, it appears that the demonstrated ecological effects of post-DDT spray programs against spruce budworm were relatively short in duration and moderate in intensity (with the exception of the effects of phosphamidon on birds). Residues of such chemicals as fenitrothion and aminocarb are not long lived, and no magnification occurs in the food web. Although substantial mortality was caused to many non-target species, long-term decreases in their populations have not been documented (bearing in mind that such effects are hard to demonstrate, particularly at larger spatial scales). For example, although many individual birds have undoubtedly been poisoned by insecticide toxicity, measurable damage to their populations has not been demonstrated.

Spray Policies

Spraying insecticide on forest infested by spruce budworm has economic benefits that are associated with the protection of conifer trees, an important natural resource. As a result, decision makers and regulators in some provinces have considered spray programs to be necessary. Many environmentalists, however, come to different conclusions about the benefits and costs of spraying, because they valuate ecological damage more highly than do resource managers and regulators. Ecologists and environmental activists are not, however, the people who make the decisions about undertaking insecticide spray programs to manage populations of budworm or other pests.

After 1986, fenitrothion was the only synthetic insecticide used against budworm. In 1993, a risk assessment of this use (Pauli et al., 1993) concluded that many of its ecotoxicological damages are significant: "*The weight of evidence accumulated with respect to the identified and potential negative impacts caused by the forestry use of fenitrothion on non-target fauna and their potential ecological implications, supports the conclusion that the large-scale spraying of fenitrothion for forest pest control, as currently practised operationally, is environmentally unacceptable*."

Partly because of the strong conclusions of that risk assessment, the registration of fenitrothion for use in budworm spray programs in Canada was withdrawn in 1995. This action left B.t., a bacterial insecticide that causes little non-target damage, as the major insecticide available for spraying against this forest pest.

Alternatives to Insecticide

In addition to ecotoxicity caused by any insecticide, spray programs against budworm have other drawbacks from a forest-management perspective. Within limits, treating infested stands with insecticide maintains fir-spruce forest "alive and green" and therefore available as a resource for the economically important forest industry. However, spraying also maintains good habitat for budworm, and so may prolong its outbreaks. Agencies that spray insecticide can become "locked" into this pest-management tactic and must continue to spray if the forest resource is to be maintained in an economically viable condition. In the absence of an alternative control practice, spraying may be perceived to be the best available short-term tactic. Clearly, however, spray programs over extensive areas are not desirable.

An alternative to spraying insecticides may be the use of silvicultural practices that are aimed at reducing the vulnerability of stands to budworm infestation. For example, relatively tolerant species such as black spruce might be planted extensively. Alternatively, the landscape could be structured so that the total area of mature but vulnerable forest is kept small. If the landscape mosaic was dominated by less vulnerable stands that could be harvested by industry at about the rate at which the trees mature, a smaller area would be vulnerable to budworm infestation. It must be recognized, however, that such actions would represent a huge intensification of forest management and would cause enormous changes in the ecological character of the landscape. Little is known about the long-term economic viability or ecological consequences of such changes in forest-management strategy.

Further research into alternative methods of budworm control may yield novel methods that are effective. Some promise has been demonstrated by the release of large numbers of tiny Trichogramma wasps that are parasites of budworm, by the use of synthetic hormones that disrupt moulting or mating of the budworm, and by several other innovative biotechnologies. So far, however, none of these methods have proven sufficiently effective to be used in operational programs to reduce an irruption of budworm.

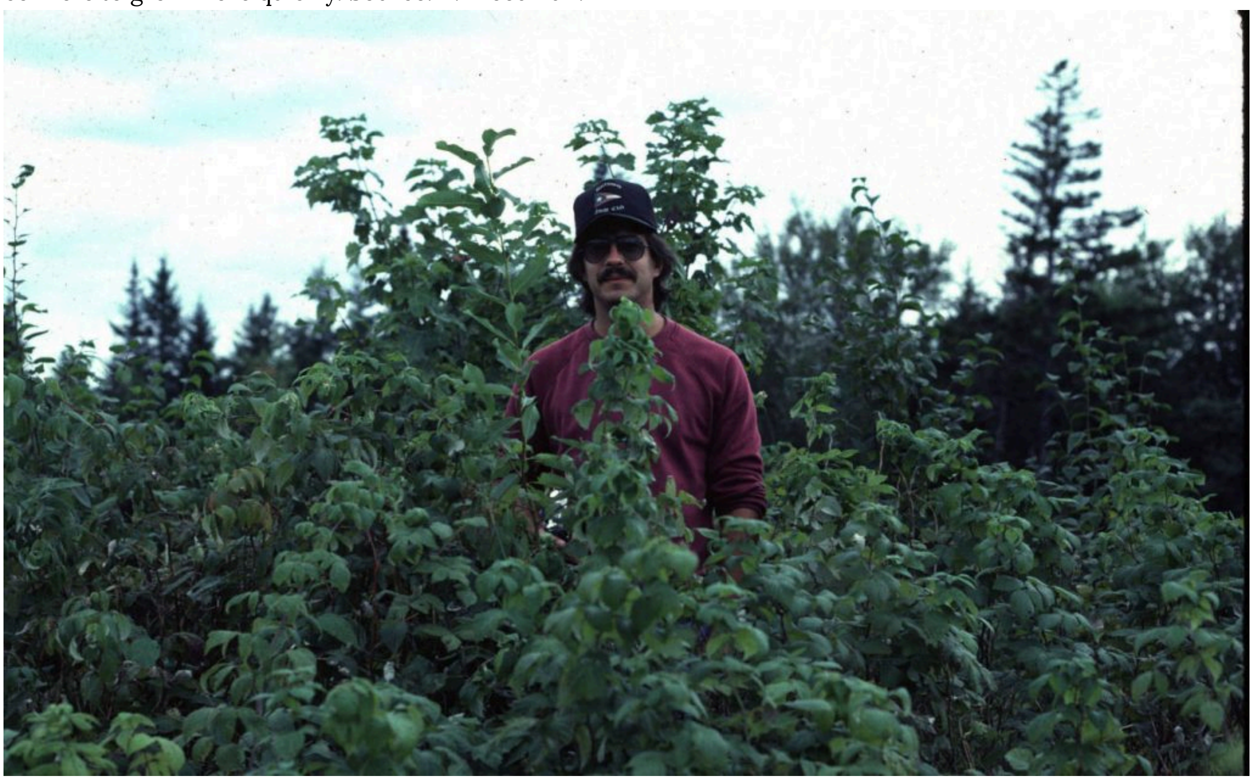
If regulators decide that the resource damage caused by spruce budworm must be controlled, it is desirable to utilize the least damaging, but still effective, options. At present, effective control appears to require insecticide, with the only available one being B.t. The use of synthetic organic insecticides in budworm spray programs, with their attendant ecotoxicological damage, appears to be history.

Herbicides in Forestry

The most common use of herbicide in forestry is to keep weeds from competing with young conifers, allowing them to grow more rapidly so that harvests can be more frequent (Newton and Knight, 1981; Freedman, 1995). The forestry use of herbicide accounts for less than 2% of the total use of these chemicals in Canada. However, forestry use affects the habitat of many native species, whereas this is not the case in agriculture and horticulture. In 2013, about 119-thousand ha of forestland were treated with herbicide in Canada (Thompson and Pitt, 2012).

As in agriculture and horticulture, there are alternatives to the use of herbicide in forestry. These options include the crushing of competing vegetation with large machines, manual cutting of weeds with brush saws, prescribed burning, and even using sheep to selectively browse weedy plants. These alternatives can provide a degree of weed control, but foresters generally regard them as more expensive and less effective than herbicide use.

Image 22.4. This is a four-year-old clear-cut of a coniferous forest in Nova Scotia. Almost all of the vegetation is considered (by foresters) to be "weeds" that compete with desired conifer seedlings for space, water, and nutrients. The objective of a herbicide treatment is to reduce the abundance of weeds, so as to allow the conifers to grow more quickly. Source: B. Freedman.

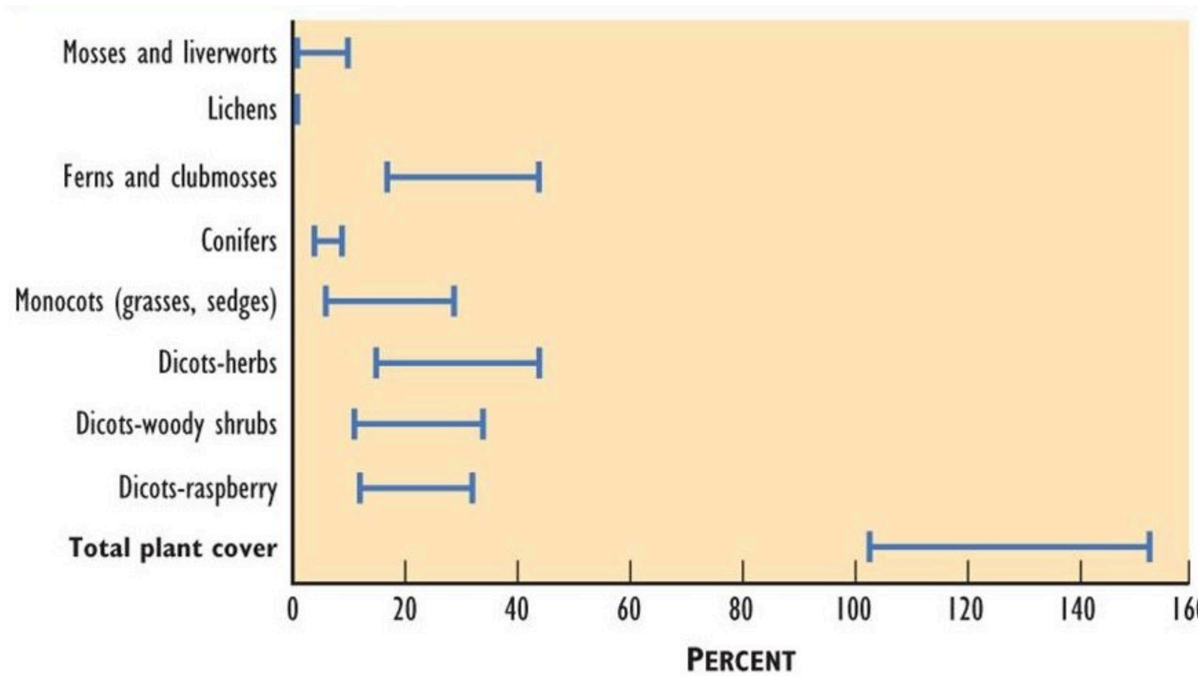


As with any pesticide, the successful use of herbicide for a management purpose requires the selection of an appropriate chemical and its proper application. If the right choices are not made, the weeds will not be adequately controlled, and the conifer crop may be injured. In addition, the suppression of "weeds" affects the useful ecological services that they provide, such as helping to control erosion and reducing losses of nutrients by leaching. Using herbicide also reduces employment opportunities available in manual weed-control programs. For these and other reasons, including the fears that many people have about the potential toxicological risks of pesticides in the environment, the use of herbicide (and insecticide) in forestry has been very controversial.

Weeds in Forestry

Any disturbance of a forest is followed by vigorous regeneration involving many species of plants that compete for space, nutrients, and moisture. This is true whether the disturbance is caused by a natural fire, insect attack, or clear-cutting. During the first 10 to 15 years of succession, the plant community is dominated by many plants other than the conifers that are desired by the forest industry. This can be illustrated by examining vegetation data for young clear-cuts in Nova Scotia, where conifers contributed only 4-9% of the plant cover (Figure 22.4). Other species that are not economically desirable (from the forestry perspective) are much more abundant – these “weeds” include ferns, monocotyledonous plants such as sedges and grasses, dicotyledonous herbs such as asters and goldenrods, low shrubs such as raspberries and blackberries, and taller shrubs such as birches, maples, and cherries. The dominance of the site by “undesirable” plants inhibits the growth of commercially desired conifers, and provides an economic justification for a weed-management treatment.

Figure 22.4. Dominant Plants in Disturbed Forest. The vegetation was surveyed in four clear-cuts of conifer forest in Nova Scotia that were 4-6 years old. The data represent the range of average plant cover among the four sites, expressed as the percentage of ground that is obscured by foliage. Because of overlap, cover values can exceed 100%. Source: Data from Freedman (1995).

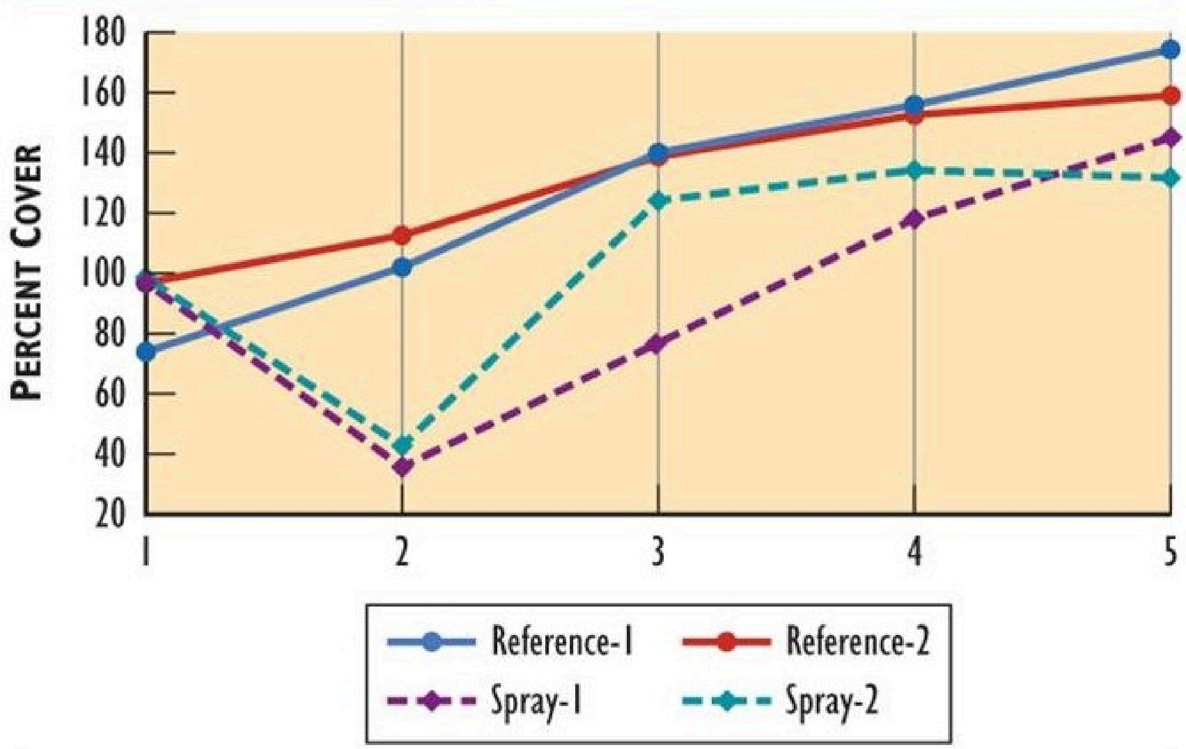


The effects of competing plants on conifer productivity are illustrated by a study of a site in New Brunswick that had been treated with herbicides 28 years previously (MacLean and Morgan, 1983). Prior to the herbicide treatment, the vigorously growing vegetation had been dominated by angiosperm shrubs that formed a dense, 2-m-tall canopy that overtopped the shorter conifers. The herbicide spray had released the conifers from some of the stresses of competition. The study consequently found, 28 years after the herbicide treatment, that the biomass of balsam fir on the sprayed plots was about three-times larger than on an adjacent unsprayed plot. From the forestry perspective, this means that the herbicide treatment allowed a conifer-dominated stand to develop more quickly, shortening the time to the next harvest.

Toxicological and Ecological Effects

The silvicultural objective of herbicide spraying is to manage vegetation by changing its character. A herbicide treatment in forestry reduces the abundance of competing vegetation, but it rapidly recovers. In essence, a herbicide treatment returns the post-harvest regeneration (usually post-clear-cutting) to an earlier successional stage, while for several years releasing small conifer plants from some effects of competition. The changes in vegetation are illustrated by a study in Nova Scotia, in which a substantial recovery occurred within only one growing season after a herbicide treatment (Figure 22.5). The recovery involved species whose seeds colonize sprayed sites, as well as plants that were not killed by the herbicide. This study found that no species were eliminated from sprayed clear-cuts, although large differences occurred in their relative abundance between sprayed and reference (unsprayed) plots. This is because species vary in susceptibility to herbicides and in their ability to recover from a disturbance.

Figure 22.5. Recovery of Vegetation after a Herbicide Treatment. Regenerating clear-cuts were treated with the herbicide glyphosate at two sites in Nova Scotia. The reference plots were not sprayed and illustrate the normal recovery of vegetation after clear-cutting. The sprayed plots were sampled for one year prior to the herbicide treatment, and the post-spray recovery was then monitored for several years. The data are percentage plant cover at the end of the summer. Source: Data from Freedman et al. (1993).



Compared with many insecticides, herbicides used in forestry (such as 2,4,5-T, 2,4-D, and glyphosate) are not very toxic to animals (see Table 22.2). At exposures encountered by animals during typical forestry uses, the direct toxicological risks are probably unimportant. This is particularly true of glyphosate, the most commonly used herbicide.

Glyphosate is extremely toxic to most plants, acting by blocking the synthesis of several essential amino acids. All plants and some microorganisms use this metabolic pathway, but animals obtain these amino acids in their food. Consequently, glyphosate is non-toxic to animals (see Tables 15.2 and 22.2).

Nevertheless, glyphosate causes large changes to occur in habitat because it affects the productivity and biomass of plants. Birds and other animals can be affected by a decreased availability of berries and other plant foods. In addition, the reduced foliage biomass on sprayed areas sustains a lower abundance of insects and spiders, which are important foods for most birds. These are indirect ecotoxicological effects of herbicide spraying, and they affect birds and other wildlife even if they are not directly poisoned.

Image 22.5. A helicopter releases a silvicultural application of the herbicide glyphosate to a clear-cut in Nova

Scotia. Source: B. Freedman.

A study in Nova Scotia found only small changes in the abundance of birds that were breeding on clear-cuts treated with glyphosate (Table 22.7). Although the avian population decreased between the pre-spray and first post-spray years, this also occurred on the reference plot, suggesting it was caused by a factor unrelated to the herbicide treatment, such as bad weather. In the second year after spraying, the abundance of birds on the sprayed plots was similar to the first post-spray year, while on the unsprayed plot it increased to about the pre-spray value.

Table 22.7. Populations of Breeding Birds on Herbicide-Treated Clear-Cuts. Average data are presented for four sprayed plots and one unsprayed reference plot from a study in Nova Scotia. The sprayed plots were treated with glyphosate. The data are pairs of breeding birds per square kilometre, surveyed for one year before the herbicide treatment (year 0), and then for four post-spray years. Only abundant species are listed here. Source:

Data from MacKinnon and Freedman (1993).

	Sprayed Plots				Reference Plot			
Species Year:	**0**	**1**	**2**	**4**	**0**	**1**	**2**	**4**
Alder flycatcher	36	7	17	63	20	40	41	102
American robin	14	21	30	31	10	10	20	10
Red-eyed vireo	0	0	0	4	0	10	31	41
Magnolia warbler	5	5	5	102	0	20	20	143
Palm warbler	0	4	18	53	0	10	51	31
Mourning warbler	50	13	12	19	71	41	20	31
Common yellowthroat	151	140	90	136	122	112	122	163
Lincoln's sparrow	23	20	41	44	20	<1	<1	0
White-throated sparrow	203	118	89	155	143	71	93	163
Dark-eyed junco	42	62	61	69	31	41	61	102
Song sparrow	43	28	60	86	41	20	10	10
American goldfinch	52	24	15	13	61	41	20	20
Total abundance	623	447	444	805	539	396	528	836

The most common species were white-throated sparrow and common yellowthroat, which had a decreased abundance on both the sprayed and reference plots up to the second year after spraying, and then recovered by the fourth post-spray year. On the reference plot, song sparrow and Lincoln's sparrow declined during the course of the study, whereas on the sprayed plots they were most abundant in the second and fourth years after spraying. The reference plot became colonized by some new species, including black-and-white warbler, red-eyed vireo, ruby-throated hummingbird, and palm warbler. These species did not invade the sprayed plots because the herbicide treatment caused the habitat to revert to a younger stage that was less favourable to these birds.

Most studies of the effects of herbicides on deer and moose have examined the availability of their food. Broad-leaved shrubs are a preferred food (known as browse) for species of deer, but they are also important weeds in forestry and are a target of herbicide treatments. The quantity of browse, although initially reduced by herbicide spraying, is often increased in the medium-term through the regeneration of shrubs. For example, studies in Maine found that several years after spraying, the availability of browse was greater on treated clear-cuts, partly because the height of the shrub canopy was lower, which gave white-tailed deer easier access to this food (Newton et al., 1989). This is not always the case, however, and some studies have shown that herbicide spraying may decrease the habitat quality for deer.

Overall, field research suggests that herbicide use in forestry has relatively small effects on birds and other wildlife that utilize clear-cuts as habitat. Other disturbances associated with forestry cause much larger effects on wildlife, particularly clear-cutting and the conversion of the natural forest into a plantation (see Chapter 23).

The hazards to people from herbicide use in forestry have also been scrutinized. The concerns include occupational risks for people who are engaged in spraying or are working in recently sprayed areas, as well as risks for the general population. These issues are highly controversial. Much of the concern has focused on the phenoxy herbicides 2,4,5-T and 2,4-D, partly because 2,4,5-T may contain a trace contamination of TCDD, a toxic dioxin. However, the use of other herbicides, such as glyphosate, is also controversial.

It is somewhat reassuring to know that many scientists believe that herbicides can be used safely in forestry (and in agriculture and horticulture), provided the instructions for their use are followed carefully. Many scientists also believe that herbicides do not cause undue risks to sprayers or people living near the treated areas. These are among the reasons why governments have registered these pesticides for uses that are economically beneficial by allowing greater productivity of both agricultural and forest crops. It must be remembered, however, that scientists have not achieved a full consensus on these issues. Partly for this reason, the use of pesticides in forestry and for other purposes continues to be highly controversial.

Integrated Pest Management

Pesticides are commonly used in agriculture, horticulture, and forestry. It is clear from this fact that most politicians, bureaucrats, and resource managers – and many scientists – have decided that the environmental "costs" associated with the use of pesticides are "acceptable" in view of economic benefits that are achieved. It is debatable, however, whether reliance on pesticide use is desirable over the long term. This is particularly true for those pesticides that are toxic to a broad spectrum of organisms. Most people would prefer that less reliance be placed on such non-specific methods of pest control.

A much preferable approach is known as integrated pest management (IPM), which employs an array of complementary tactics toward achieving pest control, with the aim of there being fewer environmental and health risks. Elements of an IPM system can include the following:

- use of natural predators, parasites, and other biological agents that can help to control a pest, while causing few non-target damages
- use of crop varieties that are resistant to pests
- management of habitat to make it less suitable for pests
- careful monitoring of pest abundance, so control measures are undertaken only when necessary
- use of pesticides, but only if required as a component of an IPM strategy

A successful IPM program can greatly reduce, but not necessarily eliminate, reliance on pesticides. For example, for many years the cultivation of cotton in the southern United States relied on the intensive application of insecticides against pests such as the boll weevil. Widespread use of an IPM system to control this insect in Texas cottonfields reduced insecticide use from 8.8 million kilogram in 1964 to 1.05 million kilogram in 1976 (Bottrell and Smith, 1982). Nevertheless, insecticide use against this pest remained necessary.

Wherever possible, IPM systems utilize control methods that are as specific as possible to the pest so that non-target damage can be avoided or greatly reduced. Some of the best examples of such specific methods involve biological control (the use of a biological agent). The usefulness of biological control can be illustrated with the following successful controls of introduced agricultural pests (Freedman, 1995):

- The cottony-cushion scale (Icyera purchasi) is a sap-sucking insect that was accidentally introduced to the United States, where it became a threat to citrus agriculture. Research in its native Australia discovered that the pest was naturally controlled by certain insect predators and parasites. In 1888, two of its predators, a lady beetle and a parasitic fly, were introduced to California. This allowed almost total control over this potentially disastrous pest. Unfortunately, this biological control was disrupted when DDT and other broad-spectrum insecticides were used to deal with other orchard pests beginning in the late 1940s.
- St. John's wort (Hypericum perforatum), a common weed, is toxic to cattle. It became a serious pest in pastures after it was introduced from Europe. In 1943, two leaf beetles that feed on this plant were released to North America, and this pest is no longer an important problem.
- The prickly pear cactus (Opuntia stricta) was imported to Australia from North America and grown as an ornamental plant and a "living fence." It escaped and became a serious weed in rangelands. This pest was controlled by the introduction of one of its herbivores, a moth whose larvae feed on the cactus.

- Ragwort (Senecio jacobea) is a Eurasian plant that has been introduced to the Americas and Australia. It became an important weed in rangeland because it crowds out native plants and is toxic to cattle. Several of its Eurasian herbivores are now being used to control its abundance, including the cinnabar moth, ragwort flea beetle, and ragwort seed fly.
- The screw-worm fly (Callitroga hominivorax) causes damage to cattle when its larvae feed on open wounds. This pest has been controlled in some areas through the release of large numbers of male flies that were reared in laboratories and sterilized by irradiation. Because the female flies mate only once, copulation with a sterile male results in unsuccessful reproduction. If this happens to enough females, the abundance of the pest decreases to an acceptable level.

Unfortunately, biological control may not be suitable for all pest problems, and in fact it has not succeeded in most cases in which it has been attempted. The list of failures includes forest pests such as spruce budworm and gypsy moth. Researchers have investigated the potential for controlling budworm using pest-specific bacteria, viruses, and other agents of diseases, wasps that parasitize and kill larvae, and sex and developmental hormones to disrupt mating and growth. Some of the biological control methods have shown promise, but they do not yet achieve a consistent kill of budworm and are relatively expensive. For these reasons, they are not considered ready for routine use against this important pest.

The only viable alternative to the broadcast spraying of synthetic insecticides to control budworm is an insecticide based on the bacterium B.t. (examined earlier). Research into other biological controls continues, and some may yet prove successful and would allow managers to develop an effective IPM system that does not rely on broadcast spraying of insecticides, even relatively specific ones such as B.t.

At the present time, however, it appears that society will continue to rely heavily on pesticide use in intensively managed systems in agriculture and forestry. This will happen even though the intensive systems cause ecological damage (partly because this damage is not fully accounted for as an economic "cost").

It is important that additional research is undertaken to develop viable methods of biological control and other elements of IPM systems. This is necessary if the present reliance on the pesticide treadmill is to be replaced with less-damaging methods of pest management. Such a change would deliver substantial benefits to society, because the agricultural and forestry systems that we require for sustenance could be managed on a more ecologically sustainable basis. In part, this will require that more attention be directed to the ecological damage caused by the intensive use of pesticides.

Because of this damage, it is highly desirable that non-pesticidal alternatives to pest control are discovered as quickly as possible. Until this happens, pesticide use should be reduced to the lowest levels that continue to effectively control the pests. Some environmentalists have argued that pesticide use in North America is much greater than necessary and that it could be decreased without causing a significant adverse effect on crop yields. In fact, the European Union has already passed legislation requiring that agricultural pesticide use be reduced by half, and many pesticides have been banned. Serious consideration should also be given to such actions in Canada.

> Canadian Focus 22.2 Municipal Bans on Pesticide Use Most Canadian municipalities have banned the routine use of pesticides to manage lawns and gardens. This was done in response to concerns about the exposure of humans and pets to pesticide residues in the urban environment. Because most pesticide use in horticulture is essentially for cosmetic purposes, and alternative pest-management practices are available, it is believed that no substantial economic detriment would be suffered from the pesticide bans.
>
> In 1991, the town of Hudson, Quebec, passed the first bylaw to regulate horticultural pesticide use. Opponents of that law included lawn-care companies and pesticide manufacturers, and they were successful in having it struck down by the Quebec Court of Appeal. In 2000, however, the Supreme Court of Canada reversed that

decision and made it legal for municipalities to regulate pesticide use on lands within their jurisdiction. Since then, many additional municipalities have banned the use of pesticides for cosmetic horticultural purposes.

In 2000, the Halifax Regional Municipality enacted a bylaw that prohibits the use of horticultural pesticides within 50 m of any park or playground, daycare centre, senior-citizen residence, public school, university, church, or hospital. In the remaining places where pesticides could still be used, homeowners wanting to use them must apply for a permit, and if it is granted, they must post a prominent sign for one day before and four days after the application. In a typical year, several hundred permit applications are received, most of which are for use against chinch bugs (Blissus leucopterus) in lawns. Almost all of the applications are made by lawn-care companies on behalf of their clients, and about half are approved. The Halifax bylaw is controversial, and it has been resisted by lawn-care companies, some gardeners, and other interests. Paradoxically, a weakness in the Halifax bylaw is that it does not ban the sale of pesticides – only most of their uses. Because pesticides can be so easily obtained, compliance with the bylaw is substantially voluntary, and no one has ever been charged with violating it. In spite of this weakness, the bylaw has been widely applauded as a step forward in the broader environmental sense.

In 2003, the council of Toronto, the largest city in Canada, passed a pesticide bylaw and in so doing greatly bolstered country-wide efforts across our country. In 2009, Ontario enacted a province-wide ban on the sale and use of pesticides for cosmetic purposes. These and ongoing actions to restrict the unnecessary use of pesticides have resulted from concerted actions of citizens and appropriate governmental responses, and they are an environmental "success story".

Conclusions

Pesticides are a wide range of substances that are used to gain an advantage over species that cause diseases or are pests in agriculture, forestry, or horticulture. However, the use of many pesticides carries risks of causing damage to human health or the environment. Pesticides have become an integrated component of most of the intensive systems by which foods and other crops are grown, and there are not yet good replacements for all of their uses. For this reason, the use of pesticides will continue into the foreseeable future. Nevertheless, it is important that more research be done to find effective ways of reducing the dependence on pesticides, especially on integrated pest-management systems and on means of biological control. In the meantime, it is important that pesticide use be reduced to the lowest amounts possible and that the most damaging chemicals are withdrawn from legal use.

Questions for Review

1. Classify pesticides according to their intended targets and also by their major chemical groups.
2. What is a "pest"? Why do people consider it necessary to manage their abundance in agriculture, horticulture, forestry, and public health?
3. What characteristics of organochlorines have caused them to become global contaminants? Why do they pose special toxicological risks to top predators?
4. In view of the fact that spruce budworm is a native insect, why is the damage it causes to conifer forest considered to be a problem?

Questions for Discussion

1. Identify and compare the benefits and environmental risks associated with pesticide use in one of agriculture, horticulture, or forestry.
2. Are there effective alternatives to the continued use of pesticides? Consider the roles of integrated pest management, biological controls, and other options.
3. For many common uses of pesticides, there are alternative ways of managing the targeted pest. For example, weeds in a lawn can be controlled by digging them out, rather than by using a herbicide. Pest rodents could be trapped instead of being killed with a rodenticide. What do you think should be the key considerations when deciding whether to use pesticides or alternative means of control?
4. Some people believe that the use of pesticides should be allowed only in extreme cases, for example, to save human lives or to prevent a food catastrophe. Most pesticide use, however, is more routine than this. What do you think about this issue? Should it be made more difficult for people to use pesticides? Or should farmers and other potential users have freedom to make their own choices about pesticide use?

Exploring Issues

1. A large corporation is seeking permission from the government to market a new insecticide in Canada. You are a wildlife biologist and have been asked to recommend studies to identify whether unacceptable damages would be caused to animals, plants, or ecosystems by the new insecticide. How would you design such a study? What specific questions would you want to answer?
2. You are an environmental scientist and have been asked to provide expert advice about a proposed new municipal bylaw regulating the cosmetic use of pesticides in horticulture. The bylaw itself could be similar to the one used in Halifax, as described in Canadian Focus 22.2. From the environmental perspective, what would you consider to be the benefits and problems with the proposed bylaw?

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Chapter 23 ~ Environmental Effects of Forestry

Key Concepts

After completing this chapter, you will be able to:

1. Explain how forest harvesting removes nutrient capital from the site.
2. Outline how forestry can damage aquatic ecosystems, and how many of those effects can be avoided.
3. Describe how clear-cutting affects biodiversity.
4. Explain the special qualities of old-growth forest, and how they are affected by timber harvesting.
5. Discuss ecological consequences of the conversion of natural forest into plantations.
6. Explain the concept of integrated forest management.

Introduction

Forestry includes both the harvesting of trees and the management of post-harvest succession to foster the regeneration of another forest. Forest science guides these activities by providing an understanding of the environmental factors that affect the productivity of trees. The primary goal of commercial forestry is to provide sustainable harvests of tree biomass that can be used to manufacture lumber, paper, and other industrial products, or as a source of bio-energy. Secondary goals are related to the management of hunted animals (such as deer and fish) on forest landscapes, and sometimes the designation of certain areas as protected (where no timber harvesting occurs).

Forestry is an important economic sector in many countries. This is the case in Canada, where a large industrial enterprise depends on a continuous supply of tree biomass for the production of products that have a great economic value ($34 billion in 2013; see Chapter 14 for forestry-related economics).

Of course, to achieve these economic benefits, trees must be harvested from extensive areas of mature forest. In Canada, clear-cutting is the most commonly used method of forest harvesting – this method removes all of the economically useful trees on a site at the same time. Clear-cutting accounts for about 90% of the annual timber harvest.

However, clear-cutting is not the same as deforestation. Deforestation involves the permanent conversion of a forest into some other kind of ecosystem, such as an agricultural or urbanized land-use. In Canada and most other developed countries, industrial clear-cutting is generally followed by the regeneration of another forest. In fact, it is common practice to manage the post-harvest succession to speed up the rate of regeneration of trees. This allows the next harvest to be made after a relatively short time, so more profit can be made. (This period of time is known as a harvest rotation.) In this sense, forestry as it is usually practised does not result in a net deforestation, and if appropriately managed the forest resource is not depleted. Even though hundreds of thousands of hectares are harvested each year in Canada (638-thousand ha in 2013), the net deforestation is essentially zero (Table 14.11).

Timber harvesting can be viewed as a disturbance of the forest ecosystem, followed by regeneration. Additional disturbances are associated with silvicultural activities, such as preparing the site for planting, thinning dense stands, and applying herbicide or insecticide to deal with pest problems. Silviculture, the branch of forestry that involves tending and growing forests, is practised over an extensive area in Canada. For instance, about 67% of the area harvested (in 2012) is planted to tree seedlings (the other 33% regenerates naturally.) Some planted areas are managed intensively to develop a plantation, which is an anthropogenic forest, but one that lacks many of the ecological and aesthetic values of natural forest.

In this chapter we examine some of the ecological effects of timber harvesting and silviculture, with a focus on site quality, hunted animals, and biodiversity. Additional effects of forestry are examined in other chapters: pesticide spraying in Chapter 22, implications for carbon storage in Chapter 17, and tropical deforestation and global biodiversity in Chapter 26.

Forest Harvesting and Site Capability

In Chapter 14, we defined site capability (or site quality) as the potential of land to sustain the productivity of agricultural crops. This is also relevant to forestry, in terms of the ability of land to sustain the productivity of trees. Site capability is a complex attribute that involves the amounts of nutrients and organic matter in soil, the availability of moisture, and other factors affecting plant growth. These factors are influenced by soil type, climate, drainage, rate of nutrient cycling, and the kinds of plant and microbial communities that are present.

The ability of soil to supply plants with nutrients is a critical aspect of site capability. In large part, this ecological function depends on the nutrient capital of a site, which is the amount of nutrients present in the soil, living vegetation, and dead organic matter. When trees are harvested, the nutrients in their biomass are also removed, which can deplete the nutrient capital of the site.

A stand of forest may be harvested using a variety of methods, which vary in the amount of biomass and nutrients that are removed from the site. A selection harvest is a relatively "soft" method because it involves the harvesting of only some of the trees from a stand, leaving others behind and the structure of the forest substantially intact. The most intensive harvest is a clear-cut, in which all economically useful trees are removed. The smallest clear-cuts, typically involving a hectare or less, are known as a group-selection harvest. More typically, clear-cuts entail the harvesting of trees from larger areas, on the order of 20-100 ha. The largest clear-cuts may extend over hundreds, and even thousands, of hectares. However, such extensive operations are unusual, and are usually associated with the salvaging of trees that have been damaged by a wildfire, windstorm, or insect infestation.

There are also some less intensive methods of clear-cutting. A shelterwood harvest is a staged clear-cut, in which some larger trees of economically desirable species are left standing during the initial cut. These provide a seed source and a partially shaded environment that encourages natural regeneration. Once the regeneration is well underway, the large "leave" trees are harvested. A strip-cut is another kind of staged harvest, in which long and narrow clear-cuts are made at intervals, with uncut forest left in between to provide a source of seed to regenerate trees in the cut strips. Once the regeneration is established, another strip-cut is made, again leaving intact forest on one of the sides. This system of progressive strip-cutting continues until all the forest in the management block (the specific area being managed this way) has been harvested. Typically, an area is harvested in three to four strips. To regenerate trees on the final strips, foresters may rely on advanced regeneration – that is, on small individuals of tree species that existed in the stand prior to harvesting and that survived the disturbance of clear-cutting. Alternatively, they may plant the last strip with seedlings.

Image 23.1. This photo shows a three-year-old shelterwood cut of hardwood forest in Nova Scotia. About 60% of the trees were removed during the harvest, but many of the "best" trees were left to grow into high-quality sawlogs and to shed seeds to promote regeneration. This treatment produces a complex habitat that supports a mixture of birds and other wildlife typical of both clear-cuts and mature forest. Source: B. Freedman.

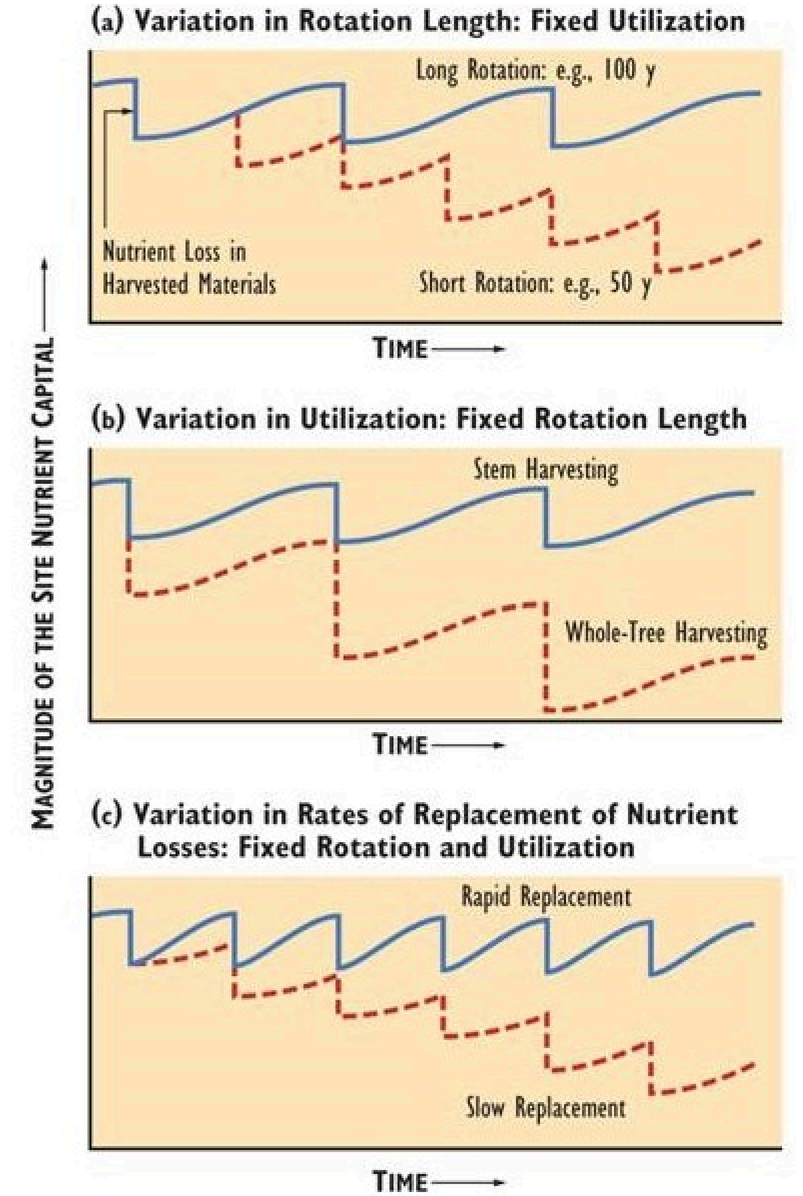
Clear-cutting systems also vary in how intensively the biomass of individual trees is harvested. The usual stem-only harvest involves the removal of tree trunks, leaving the roots, stumps, and logging "slash" (cut branches and foliage) on the site. The harvested logs can then be processed into lumber or pulp for manufacturing paper. A whole-tree harvest is more intensive because it removes all of the above-ground biomass of the trees, including the branches and foliage. This intensive kind of harvest will recover considerably more biomass than a stem-only cut, which is an advantage if the wood is to be used as a source of bio-energy.

Nutrient Losses during Harvesting

Although intensive harvests such as a whole-tree clear-cut increases the yield of biomass, there is also considerably more removal of nutrients. Some forest scientists have suggested that the nutrient removals from whole-tree harvests could degrade the capability of sites to sustain tree productivity. The problem would be especially severe if the harvests are conducted over a short rotation. This might not allow enough time for the nutrient capital to recover by natural inputs, such as by precipitation, nitrogen fixation, and weathering of minerals (Figure 23.1).

Figure 23.1. Effects of Harvest Intensity and Length of Rotation on Nutrient Capital. Diagram (a) suggests that a relatively long rotation can allow harvested nutrients to be replenished by natural inputs through rainfall, weathering of minerals, nitrogen fixation, and other means. An adequate post-harvest recovery means that harvesting is sustainable with respect to the nutrient capital of the site. Under the shorter rotation (dashed line), the harvested nutrients are not totally replenished between successive clear-cuts, resulting in a degradation of nutrient capital. Site capability can also be degraded by an increase in the intensity of the harvest. This is illustrated in diagram (b), in which a whole-tree clear-cut removes twice as much nutrient as a stem-only harvest. Diagram (c) indicates that fertile sites (solid line) are less likely to be degraded by intensive

harvests over short rotations, compared with less fertile sites (dashed line). Source: Modified from Kimmins (2003).



Site impoverishment caused by intensive cropping is a well-known problem in farming, in which severely degraded land may have to be abandoned for some or all agricultural purposes. However, usually this problem can be managed, to a degree, by applying fertilizer or composted organic matter to the land. Sometimes, however, the degradation of site capability, especially of tilth, is too severe, and this simple mitigation is not successful. Of course, the harvest rotation in agriculture is usually annual, whereas in forestry it ranges from about 20 to 100 years. However, each timber harvest involves the removal of a huge quantity of biomass, and thus of nutrients.

Compare, for example, the amounts of biomass and nutrients removed by clear-cuts of a conifer forest in Nova Scotia (Table 23.1). In this case, a whole-tree clear-cut yielded 30% more biomass than a stem-only harvest. The increased yield may be an advantage, particularly if the harvest is to be used for energy production. The increased harvest of biomass is, however, due to the removal of nutrient-rich tissues such as foliage and small branches. Consequently, the whole-tree harvest removed up to twice as many nutrients as did the stem-only clear-cut. In effect, a 30% increase in biomass yield by the whole-tree method was "purchased" at the ecological "expense" of 54-99% increases in the removal of nutrients.

Table 23.1. Removal of Biomass and Nutrients by Clear-Cuts of a Conifer Forest in Nova Scotia. This study involved weighing the biomass harvested by (a) a stem-only clear-cut and (b) a whole-tree clear-cut (each 0.5 ha). Nutrient concentrations were determined in subsamples of the biomass and were used to calculate the amounts of nutrients removed. "Percentage increase" refers to the whole-tree removals, compared with stem-only removals. Source: Data from Freedman et al. (1981).

Component	Biomass (t/ha)	N (kg/ha)	P (kg/ha)	K (kg/ha)	Ca (kg/ha)	Mg (kg/ha)
(a) Stem-only clear-cut						
Tree stems	105.2	98	16	92	181	17
(b) Whole-tree clear-cut						
Tree stems	117.7	120	18	76	219	20
Branches & foliage	34.8	119	17	57	118	17
Total harvest	152.5	239	35	133	337	37
Percentage increase	30%	99%	93%	74%	54%	81%
Nutrients in forest floor		900	62	110	290	32
Nutrients in mineral soil (top 30 cm)		3,860	1,220	13,300	5,460	1,740

Unfortunately, there are few studies that allow foresters to compare the productivity of subsequent harvest rotations on the same site. Such studies would take more than 50-100 years, requiring several generations of foresters! Therefore, it is difficult to evaluate the implications of nutrient removal by clear-cutting. Overall, however, it appears that a degradation of site nutrient capital is a less severe problem in forest harvesting than in agriculture. Consequently, nutrient removals by timber harvesting should be viewed as a potential long-term problem. Because forestry is an economically important activity, and the maintenance of site capability is critical to the sustainability of the enterprise, scientists should continue to study the effects of harvesting on nutrient capital. In the short term, however, forestry causes more immediate kinds of damage to site capability and biodiversity that deserve our attention.

Leaching of Nutrients

The disturbance of forested land can increase the rate at which dissolved nutrients are transported downward into the soil with percolating rainwater (a process known as leaching). If the nutrients leach deeper into the soil than tree roots can penetrate, they are effectively lost from the "working" nutrient capital of the site. Eventually, leached nutrients can find their way into groundwater and surface waters.

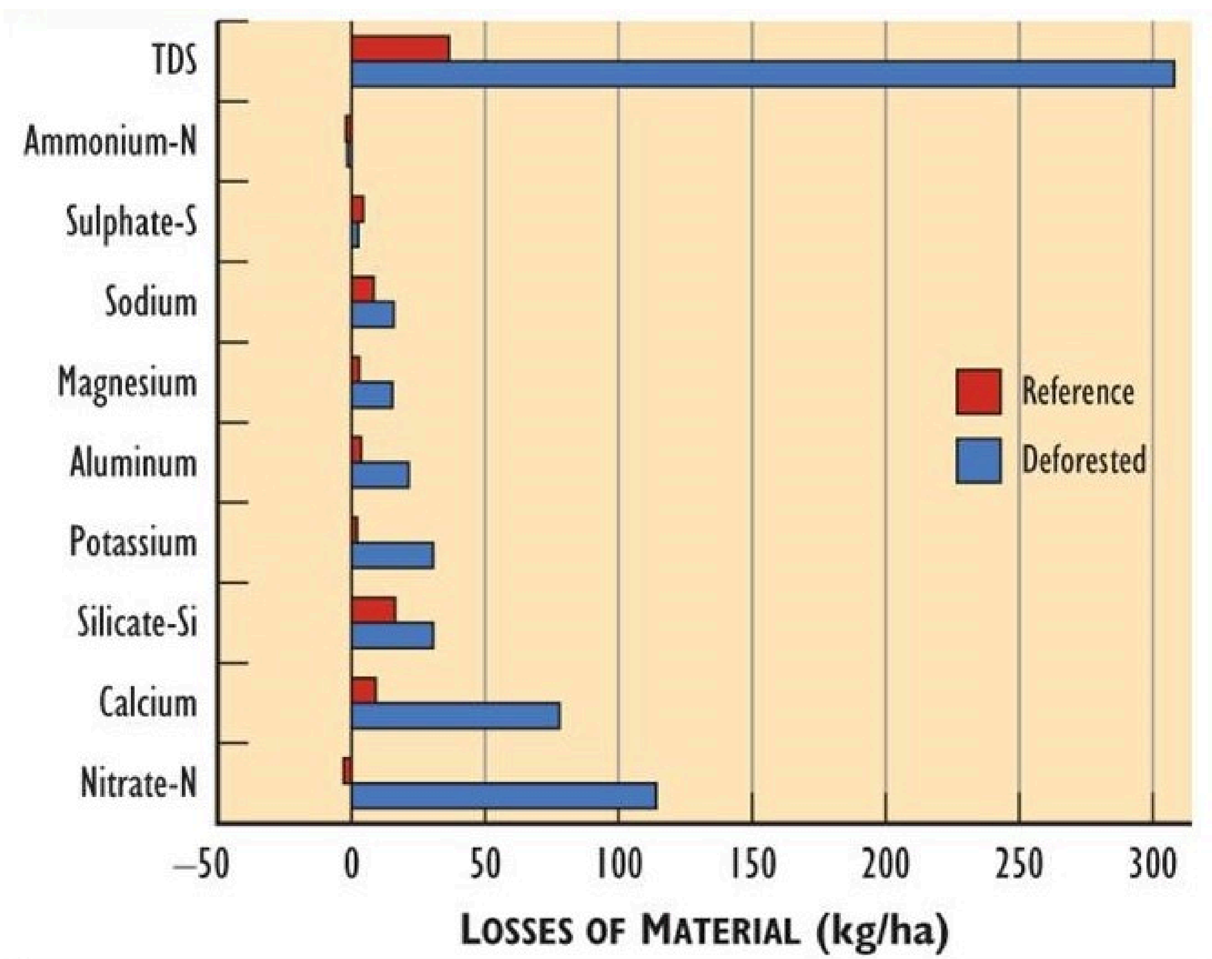
The nutrients with the greatest tendency to leach are nitrate and potassium, both of which are highly soluble in water. However, calcium, magnesium, and sulphate may also leach in significant amounts. Of course, following a clear-cut, any nutrient losses by leaching are in addition to that removed with tree biomass.

A well-known study of nutrient leaching caused by forest disturbance was done at Hubbard Brook, New Hampshire. This large-scale experiment involved felling all of the trees on a 16-ha watershed, but without removing any biomass – the cut trees were left on the ground. The watershed was then treated with herbicide for three years to suppress regeneration. This experiment was designed to examine the effects of intense disturbance, by de-vegetation, on biological control of watershed functions such as nutrient cycling and hydrology. The research was not intended to examine the effects of a typical forestry practice.

Overall, during a 10-year period following the cutting, the de-vegetated watershed lost 50 kg/ha-year of NO_3-N (i.e., nitrogen in the form of nitrate), 45 kg/ha-y of Ca, and 17 kg/ha-y of K in streamflow (Bormann and Likens, 1994; Figure 23.2 shows data for the first three years, which were the most dramatic). The losses were much larger than from an undisturbed reference watershed: 4.3 kg/ha-y of NO_3-N, 13 kg/ha-y of Ca, and 2.2 kg/ha-y of K.

In part, the increased losses of nutrients were due to a 31% increase in the yield of water from the de-vegetated watershed (during the first three years after cutting). The increased streamflow was caused by the disruption of transpiration from plant foliage. However, increases in nutrient concentration in the streamwater were more important: during the first three years, NO_3 increased by an average factor of 40; K, by 11; Ca, by 5.2; and Mg, by 3.9. The losses of N, Ca, and Mg in the streamwater were similar to their amounts in the above-ground biomass of the forest.

Figure 23.2. Nutrient Losses in Streamflow after Deforestation. The experimental watersheds are located at Hubbard Brook, New Hampshire. The data represent "net flux", or the difference between inputs from precipitation and outputs due to leaching and streamflow. The data are for the first three years following deforestation of a 16-ha watershed, compared with an uncut reference watershed of similar size. Losses are stated in kilograms per hectare per three-year period. TDS = total dissolved solids. Source: Modified from Bormann and Likens (1979).



Because this experiment in de-vegetation did not involve a typical forestry practice, the measured effects are unrealistically large. However, watershed-level studies of clear-cutting have also found an increase in nutrient leaching, although to a lesser degree than that caused by the de-vegetation at Hubbard Brook. For example, in the first three years after clear-cutting a 391 ha watershed in New Brunswick, there was an increased loss of nitrate in streamwater of 7 kg NO_3-N/ha-yr (Krause, 1982). A study of nine clear-cut watersheds in New Hampshire found an average nitrate loss of 18 kg NO_3-N/ha-y during the first four years, compared with 3.5 kg/ha-y for five uncut watersheds (Martin et al., 1986). In addition, calcium losses from the clear-cuts averaged 28 kg/ha-y, compared with 13 kg/ha-y for reference watersheds, while potassium losses were 6 kg/ha-y compared with 2 kg/ha-y. However, other studies have found smaller effects of clear-cutting on nutrient losses with streamflow, especially if only a portion of the watershed was cut.

Nitrate and other highly soluble ions are leached from watersheds after clear-cutting (and after other disturbances, such as wildfire) for several reasons. First, disturbance stimulates the activity of microbes involved in the decomposition of organic matter. This occurs because removal of the tree canopy results in warming of the forest floor and surface soil, and decreased uptake by plants leads to an increase of soil nutrients and moisture. Second, disturbance often stimulates the microbial processes of ammonification and nitrification (see Chapter 5), resulting in increased rates of production of nitrate, which is extremely soluble and readily lost from soil.

Forestry and Erosion

Forestry activities can cause severe losses of soil, or erosion, particularly in terrain with steep slopes. In most cases, erosion is triggered by improperly constructing logging roads, using streams as trails to haul logs, running log-removal trails down slopes instead of along them, and harvesting trees from steep slopes that are extremely vulnerable to soil loss. In general, however, road building is the most important cause of erosion on forestry lands, especially where culverts (channelled stream crossings) are not sufficiently large or numerous, or are poorly installed.

Severe erosion causes many environmental damages. In extreme cases, the loss of soil may expose bedrock, making forest regeneration impossible. Soil loss also represents a depletion of site nutrient capital. Erosion also causes secondary damage to aquatic habitats, including the deposition of silt (or siltation), which covers gravel substrates that are important to spawning fish. Also, the shallower water increases the risk of flooding.

However, in many cases erosion is a largely avoidable environmental effect of forestry. The irresponsible practices that can cause erosion are restricted by provincial regulations and occur much less frequently now than in the past. Practices that help to reduce erosion include the following:

- planning the route of forest roads to avoid stream crossings as much as possible
- installing a sufficient number of properly sized culverts
- avoiding the disturbance of stream channels by heavy equipment
- leaving buffer strips of uncut forest beside watercourses
- using log-removal practices that avoid disturbance of the forest floor (such as cable yarding, in which a tall spar anchors cables radiating into the clear-cut, which allows logs to be dragged to a central place without the use of a wheeled skidder)
- allowing vegetation to regenerate quickly, which speeds the re-establishment of biological moderation of erosion
- deciding to selectively harvest, or to not harvest, steep sites that are highly vulnerable to erosion

It has become a common practice to leave strips of uncut forest beside streams, rivers, and lakes. These buffer zones greatly reduce the erosion of streambanks, eliminate temperature increases in the water, maintain riparian (lake- and stream-side) habitat for wildlife, and mitigate some of the aesthetic damage from forest harvesting.

While it is widely accepted that riparian buffers provide important benefits, there is no consensus about how wide the uncut strips should be. This is an economically important consideration, because large areas of valuable timber are withdrawn from the potential harvest when buffer strips are left. The requirements in New Brunswick, for example, are for a 30-m buffer on each side of a watercourse, with wider buffers recommended in some circumstances (such as 60 m if the slope exceeds 24°, and up to 100 m beside waters that are used for recreation or as a source of drinking water).

In some cases, selective harvesting of trees may be allowed within riparian buffers, as long as this does not compromise the ecological services provided by these special management zones.

Forestry and Hydrology

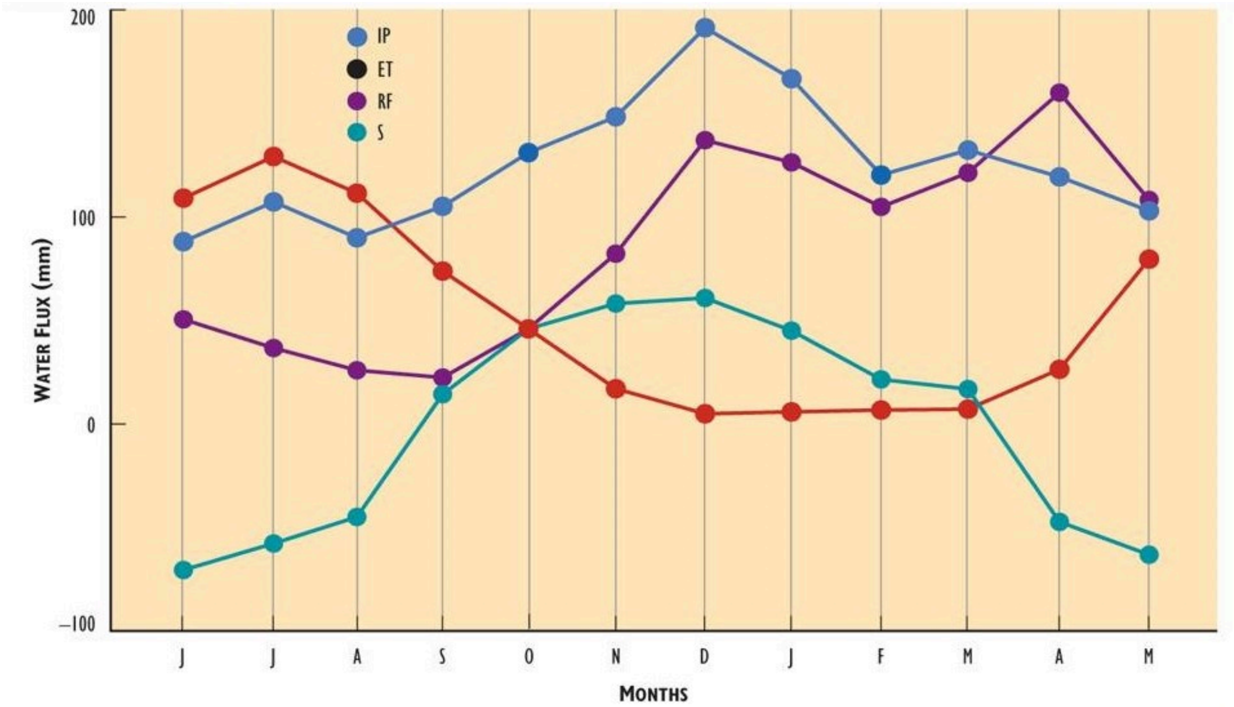
The cover of forest on a watershed has a strong influence on its hydrology. Large amounts of water are evaporated into the atmosphere by vegetation, especially by trees because they have so much foliage (this is transpiration; evapotranspiration includes evaporation from non-living surfaces). In the absence of transpiration, an equivalent quantity of water would leave the watershed as streamflow or as seepage to deeper groundwater.

For example, studies of four well-forested watersheds in Nova Scotia found that evapotranspiration was equivalent to 15-29% of the annual input of water by precipitation (rain plus snow), with runoff in streams accounting for the other 71-85% (these watersheds have no substantial drainage to deep groundwater; Freedman et al., 1985).

The hydrologic budget of watersheds is extremely seasonal, particularly in the temperate and boreal climates that are typical of forested regions of Canada. This can be illustrated by the watershed of the Mersey River in Nova Scotia (Figure 23.3). The annual input of water from precipitation was 146 cm/y, with 82% arriving as rain and 18% as snow. About 62% of the annual input was dispersed by riverflow and 38% by evapotranspiration. Evapotranspiration is highest during the growing season, which results in relatively sparse riverflow. Runoff is greater during late autumn and early winter, when there is little transpiration because deciduous trees have dropped their foliage, and even conifers are in a quiescent state. However, much of the precipitation during that period recharges groundwater storage, which had been depleted by the uptake of water by vegetation during the summer. Runoff is greatest during the spring, when the accumulated snowpack melts, and that results in a spate of riverflow.

Figure 23.3. Seasonal Hydrology of the Mersey River in Nova Scotia. Water inputs from incident precipitation (IP) into the 723 km^2 watershed, and riverflow (RF) from the watershed, are displayed as monthly averages for the period 1968-1982. Evapotranspiration (ET) was estimated using a climatic model, and groundwater storage

(S) was calculated as IP – RF – ET. Source: Modified from Freedman et al. (1985)



Disturbances such as wildfire and timber harvesting alter the hydrology of watersheds. The seasonality and amounts of flow can change, and erosion and flooding may occur downstream. Some poorly drained sites may become wetter, because reduced transpiration can raise the water table. In general, the increase in streamflow is related to the proportion of the watershed that was disturbed. If an entire watershed is clear-cut, the increase in streamflow can be as much as 40% in the first year. The increase is proportionately less after partial cuts.

Clear-cuts usually regenerate quickly, and in some cases the vigorous regrowth of shrubs and herbs can restore most of the original foliage area in as few as four to six years. Consequently, the biggest increases in streamflow occur in the first year after cutting, followed by rapid recovery to the pre-harvest condition. In the temperate and boreal climates prevalent in much of Canada, the largest increases in streamflow occur during the late spring, summer, and early autumn, these being the seasons when transpiration is most important.

Hydrology can also be affected by a change in the type of forest that is dominant on a watershed. For example, if an area of hardwood forest is converted into conifer plantations, the annual streamflow may decrease. This happens because the conifers maintain their foliage throughout the year, and so extend the transpiration season into times when angiosperm trees lack foliage.

Weeds and Reorganization

Clear-cuts usually regenerate rather quickly. Initially, however, most of the regenerating biomass involves plants other than the tree species that foresters consider desirable. As a result, the vigorous regrowth is often regarded as being detrimental to silvicultural objectives. Such non-crop plants may be viewed as “weeds,” and their abundance may be controlled by a herbicide application (see Chapter 22).

However, a rapid re-vegetation of clear-cuts and other disturbed lands does provide important ecological benefits. The regenerating plants influence the ecological “reorganization” of disturbed lands. They re-establish a measure of biological control over nutrient cycling, erosion, and hydrology, while also restoring habitat for animals.

For example, during the first few years after clear-cutting, fast-growing vegetation restores a high rate of nutrient uptake from the soil. Through this uptake, the regenerating vegetation acts as a “sponge” that absorbs some of the soluble nutrients that might otherwise leach from the site. Eventually, the early successional plants die, and their nutrients are recycled by decomposition and made available to trees. In addition, the re-vegetation restores habitat for birds, mammals, and other wildlife. Clearly, the early reorganization phase of succession is enhanced by the rapid regeneration of many plant species, including those considered to be weeds by foresters.

Forestry and Biodiversity

Clear-cutting and other forestry practices inflict intense disturbances on forests. They cause dramatic changes in the habitat available to support plants, animals, and microbes, as well as their various communities. Some species benefit from habitat changes that occur because of forestry, but others suffer damage.

In the following sections, we examine the effects of forestry on aspects of Canadian biodiversity – the richness of biological variation in our country. The effects of clear-cutting on plants, mammals, birds, and fish will be examined because these groups are relatively well studied and are considered to be important by our society.

Vegetation

Any severe disturbance results in changes in the dominant species of plants that are living on a site. Because they have such a great influence on local environmental conditions, trees are the dominant organisms in forests. After clear-cutting, many smaller plants take advantage of the relatively uncompetitive conditions that occur, and they dominate the initial stages of the post-harvest succession. They are then reduced in abundance, or even eliminated from the community, once several decades of regeneration have gone by and tree-sized plants re-establish their dominance.

Many plants of early post-cutting succession can only be successful in open habitats –they are intolerant of the shade and other stressful conditions beneath a forest canopy. These relatively short-lived ruderal plants can typically disperse widely, a propagation strategy made necessary because of their ephemeral habitat (see Chapter 9). Ruderal plants that can proliferate in recently disturbed forests include asters, goldenrods, grasses, and sedges. A specific example is the fireweed (Chamerion angustifolium), a purple-flowered herb that is often abundant after wildfire (hence its name) and also after clear-cutting. Some woody plants are also ruderals, because they are most abundant during the recovery after disturbance. Examples are the red raspberry (Rubus strigosus), pin cherry (Prunus pensylvanica), and elderberry (Sambucus racemosa). Because of their need for open, recently disrupted habitat, ruderal plants benefit from clear-cutting and other disturbances that are associated with forestry.

Unlike ruderal plants, some other species are tolerant of the environmental stress that occurs beneath a closed forest canopy. Examples are the white trillium (Trillium grandiflorum), shield fern (Dryopteris marginalis), feather mosses (such as Pleurozium schreberi and Hylocomium splendens), and certain lichens, such as lungwort (Lobaria pulmonaria). These species are not tolerant of open conditions, and they decline after clear-cutting. Once suitable conditions re-develop, these plants may again increase in abundance.

In general, once a clear-cut has had two to four years to regenerate, the plant community is actually richer in species than the mature forest that was harvested (this is particularly true of vascular plants). The increase in species diversity occurs because recently disturbed habitats are relatively flush in such resources as light, nutrients, and water. This allows many species of low-growing plants to be supported, including a diversity of ruderal ones. In comparison, stressful habitats, such as the understorey beneath a mature forest canopy, support fewer species of plants.

A study of a hardwood forest in Nova Scotia illustrates the species-rich nature of vegetation after a clear-cut (Crowell and Freedman, 1994). That study examined stands of mature forest, plus clear-cuts of various age. The number of plant species in the ground vegetation (shorter than 2 m) averaged $11/m^2$ on two one-year-old clear-cuts, and increased to

14/m^2 on six-year-old clear-cuts. Mature forest and clear-cuts older than 30 years had fewer species – only 3-6/m^2 in stands with a closed canopy dominated by maple trees, but 9-11/m^2 in birch-dominated stands, which have a more open canopy. This comparison suggests that many plants, especially ruderals, can utilize open habitats associated with clear-cutting. However, species that need mature forest as habitat are threatened by this kind of disturbance.

Deer, Moose, Elk, and Caribou

White-tailed deer (Odocoileus virginianus) and mule deer (O. hemionus) are the most common wild ungulates in southern Canada. They feed on woody stems (known as browse) and low-growing herbaceous plants, and they need brushy habitat for at least part of their yearly range. The abundance of these deer has increased in many regions since the European colonization of Canada, prior to which landscapes were more extensively covered with mature and old-growth forest. In Nova Scotia, for example, white-tailed deer were initially uncommon and were soon extirpated by over-hunting. However, these deer were re-established in the nineteenth century by deliberate introductions and natural immigration from New Brunswick. Today, this species is likely more abundant in the region than at any time since deglaciation.

The modern abundance of Odocoileus deer is largely due to an increased availability of early successional, shrubby habitat, along with decreased populations of their natural predators. The shrubby habitat was created by the abandonment of poorer-quality agricultural land, timber harvesting, and wildfire. These all result in habitat dominated for several decades by shrub-sized plants, with a rich understorey of forbs (herbaceous dicot plants) and graminoids (grasses, sedges, and rushes).

The shrubby habitat tends to be distributed on the landscape as a mosaic of stands in various stages of succession within a matrix of mature forest. This spatial arrangement enhances the suitability of the landscape for Odocoileus if the following conditions are present: (1) extensive production of nutritious and palatable browse in younger stands; (2) abundance of ecotonal (or edge) habitat; (3) availability of good yarding habitat of mature conifer forest, which provides shelter in regions where the winter is severe and the snowpack is deep. If these habitat qualities occur within a mosaic of stands of various ages, the landscape is more favourable to these deer than either extensive clear-cuts or unbroken expanses of mature forest.

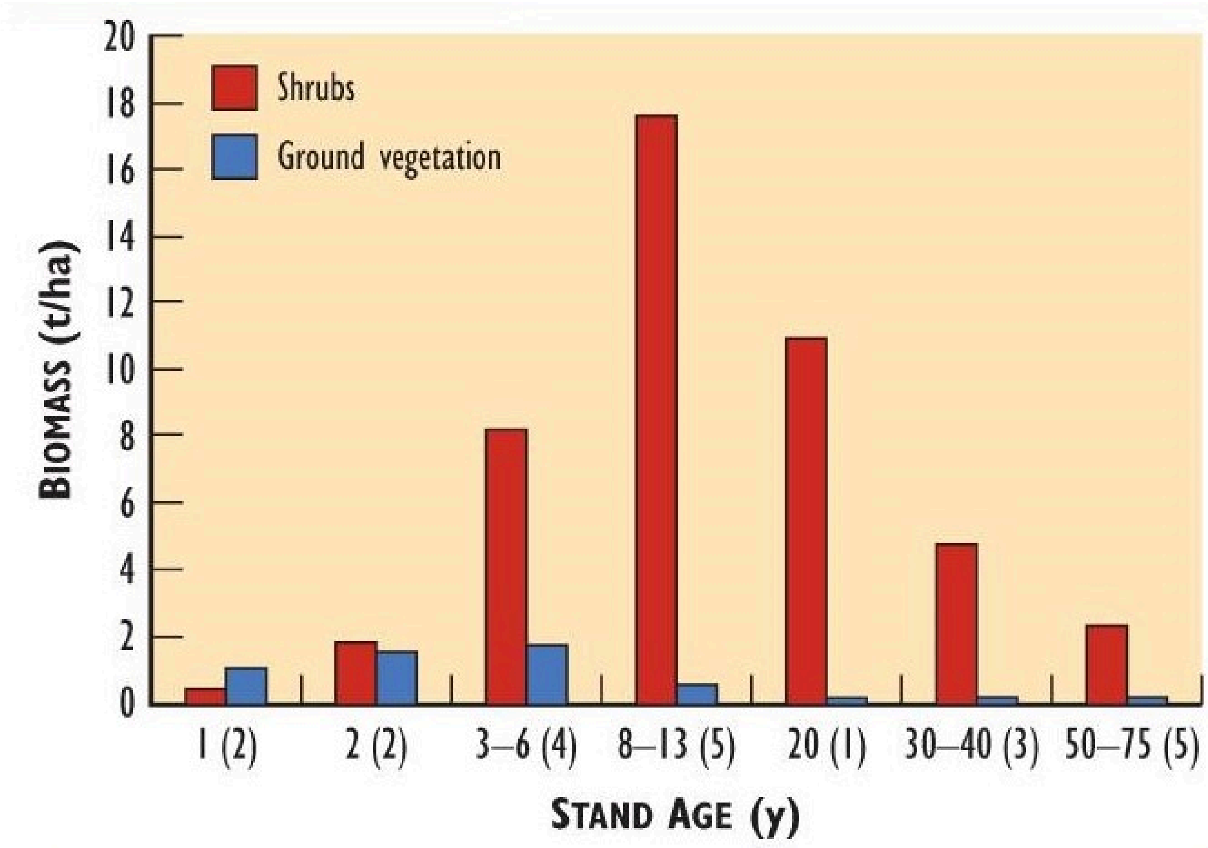
The central parts of a large clear-cut are not well used by deer, as they like to be close to protective forest cover. A study in eastern Canada found that white-tailed deer fed about seven times more intensively in the centre of clear-cuts less than 80 ha in area than in the middle of larger clear-cuts up to 410 hectares in size (Drolet, 1978). In fact, optimal clear-cuts for white-tailed deer are rather small in area, although this varies regionally. For example, clear-cuts smaller than 4 hectares in New Brunswick and smaller than 2 hectares in southern Ontario have been recommended to improve habitat for white-tailed deer.

To some degree, the amount of useful habitat on larger clear-cuts is greater if they have an irregular shape. Erratic shapes have a higher ratio of edge to area than do circular, square, or rectangular shapes. Consequently, an irregular shaped clear-cut provides more edge habitat, while also making the central part of the harvested area more accessible to deer.

Clear-cuts may also have physical obstructions to deer movements, such as tangles of logging slash. They may also have deep snow during the winter because snowfall is not intercepted by an overhead canopy of conifer trees. In general, deer movements are severely restricted by snow deeper than 50-70 cm.

Deer eat a variety of woody plants, forbs, and graminoids, and these foods are often much more abundant on cutover and burned sites than in mature forest. After clear-cutting, the biomass of browse and herbaceous plants typically increases to a peak after 8-15 years, followed by a decline as the tree canopy matures and shades the understorey. This successional pattern is illustrated in Figure 23.4 for stands of various ages following clear-cutting. The quantity of browse peaked at 8-13 years and then declined. The pattern for herbaceous plants was similar, but the biomass peaked at two to six years.

Figure 23.4. Shrub and Herb Biomass in Stands of Different Ages. The data are from a region of maple-birch forest in Nova Scotia. Stands aged 20 years and younger were created by clear-cutting. Biomass is reported in tonnes of dry weight per hectare. The data are the average for the indicated age range, with the number of replicate stands given in brackets. Source: Data from Crowell and Freedman (1994).



Browse is not only more abundant, but also of better nutritional quality in clear-cuts and burns than in mature forest. Recently sprouted, rapidly growing twigs have higher concentrations of protein, nitrogen, and phosphorus, and are more succulent and more easily digested than the older browse that is found in mature forest.

Ongoing disturbances in forest management areas can also affect habitat use by deer. These include frequent traffic along logging roads, noise from harvesting operations, and the excessive hunting pressure that can result from easy access along forestry roads.

Moose (Alces alces) and elk (Cervus elaphus) may also benefit from some forest-harvesting practices. Moose feed primarily on browse, although they also eat aquatic and terrestrial forbs during the summer. Elk graze on graminoids and forbs during the growing season, but eat browse during the winter. Because the abundance of browse and herbs usually increases after timber harvesting, the habitat of moose and elk can be somewhat improved. In general, however, these species are less favoured by forestry than are white-tailed and mule deer.

The woodland caribou (Rangifer tarandus; known as reindeer in Eurasia) is another abundant species of deer, particularly in the north. They require an extensive habitat of mature conifer forest, particularly during the winter when “reindeer mosses” (actually species of Cladina lichens) make up much of their diet. These lichens grow on the forest floor and are most abundant in open conifer stands that are 40 to 100 years old. However, if the tree density is high enough to allow the canopy to close, these lichens decline and are replaced by feather mosses, which are not palatable to caribou. The disturbance of forests by wildfire and logging can regenerate the supply of reindeer lichens in areas with extensive closed-canopied stands. In general, however, caribou are not favoured by extensive logging of their habitat.

All of the species of wild ungulates in Canada are important in hunting, an activity that generates economic value while also providing subsistence for many rural people (see Chapter 14). Increasingly, foresters and wildlife biologists are working together to develop integrated management plans that can accommodate the need to harvest both timber and ungulates from landscapes. These plans can allow relatively large populations of white-tailed deer, mule deer, moose, and elk to occur, even while clear-cutting and other forestry practices take place. In general, however, caribou do not do well in regions where a great deal of timber harvesting occurs, and they are also intolerant of other industrial activities, such as those related to oil and gas. We will examine integrated forest management in more detail at the end of this chapter.

Smaller Mammals

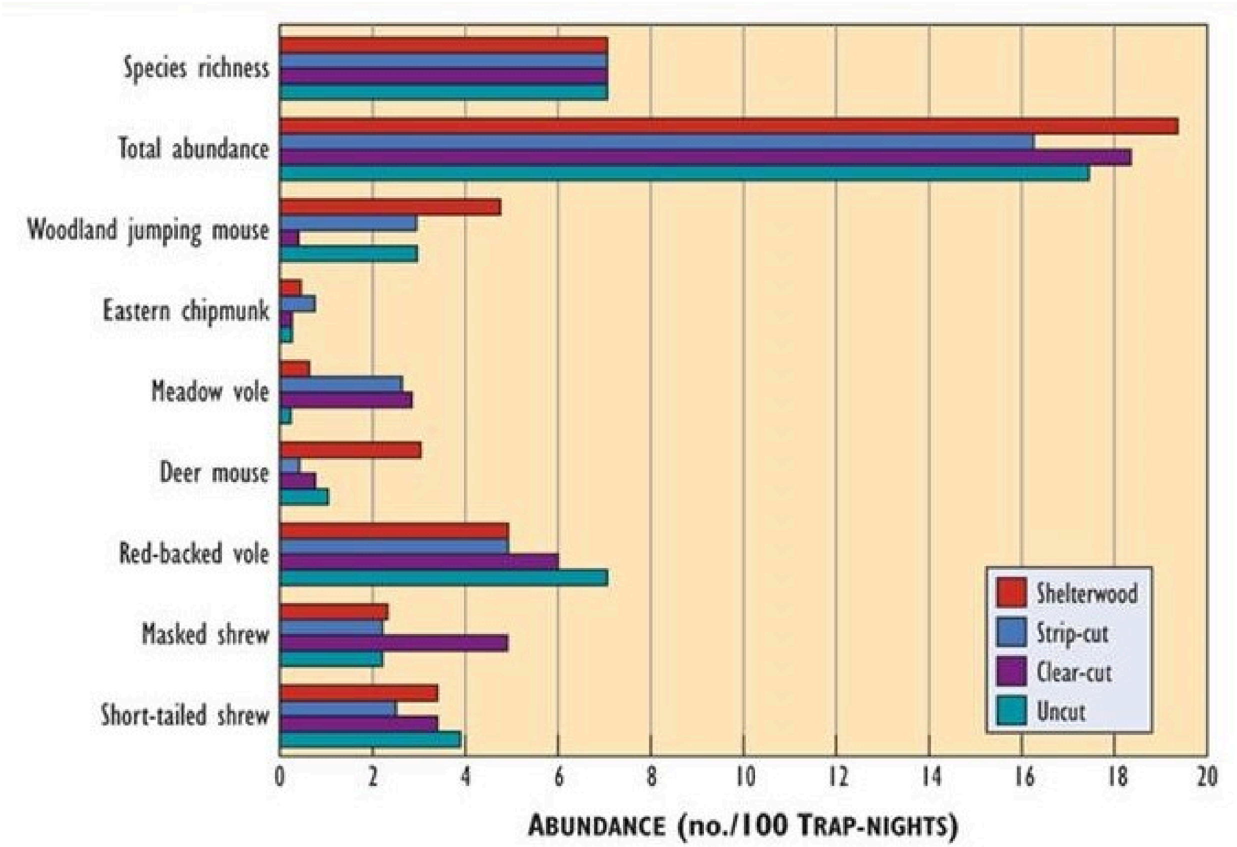
Hares and rabbits are abundant in most regions of Canada and are economically important as small game, as pests, and in recreational wildlife viewing. They feed by browsing and grazing and can benefit from an increase of low shrubs and herbs after timber harvesting, the abandonment of agricultural land, and wildfire. In fact, hares and rabbits can be abundant enough to impede tree regeneration through girdling (gnawing the bark around a sapling, which kills the young tree) and clipping (chewing the foliage and growing points of a young tree).

Other small mammals, such as mice, voles, shrews, and moles, are important as components of food webs. They also sometimes impede forest regeneration by consuming tree seeds and by girdling saplings. In some cases, they are considered beneficial because they eat potentially damaging insects.

Most studies report that forest harvesting has relatively minor effects on small mammals. For example, no substantial differences were found in their overall abundance, species richness, or diversity among stands of mature forest, three- to five-year-old clear-cuts, strip-cuts, and shelterwood cuts (Figure 23.5).

Figure 23.5. Comparison of Small-Mammal Communities among Habitat Types. Data are from various habitats in a maple-birch forest in Nova Scotia. Abundance is indexed by the numbers of animals caught per 100 days of

trapping effort. Species richness is the number of species observed. Source: Data from Swan et al. (1984).



Pine marten (Martes americana) and fisher (M. pennanti) are medium-sized carnivores with extensive ranges in North America. Unfortunately, these furbearers have suffered large population declines in many regions, mostly because they have been trapped too intensively. In addition, marten and fisher appear to depend partly on the complex habitat structure of older coniferous forest. Consequently, they are considered to be at risk from timber harvesting.

Birds

Many birds require mature forest as habitat for breeding, wintering, or during migration. However, many other species need the types of habitat that occur during early stages of forest succession, including those created through such forestry activities as clear-cutting.

Ruffed grouse (Bonasa umbellus) are commonly hunted, as are spruce grouse (Canachites canadensis) and blue grouse (Dendragapus obscurus). Populations of these "upland game birds" are generally favoured by a landscape mosaic that includes both mature forest and younger, brushy stands. Ruffed grouse prefer areas dominated by hardwood forest with some conifers mixed in, especially stands dominated by poplars and birches. These birds feed mainly on the foliage, young twigs, catkins, and buds of woody plants, and also eat fleshy fruits when available. In Nova Scotia, they utilize clear-cuts of maple-birch forest that are five or more years old. Clear-cuts of aspen forest in Minnesota become suitable after 4 to 12 years of regeneration, and are then used for 10 to 15 years, while older aspen stands are wintering habitat (Gullion, 1988). Wildlife biologists recommend that, to provide habitat for ruffed grouse in aspen forest, forestry should be conducted to create a mosaic of different-aged stands, each of 10 hectares or less, with adjacent ones differing in age by 10 to 15 years.

Wildlife managers sometimes refer to the many birds that are not hunted as "non-game" species. These birds can, however, be economically important as predators of insects that damage trees or other crops, and as the object of bird-watching (or birding), a popular outdoor sport. Forestry affects these birds and their communities by changing the physical structure and plant-species composition of the available habitat.

An important aspect of habitat structure is the distribution of distinct patches, either within a stand or on a landscape. The shape of a patch affects its ratio of edge to area, and thus the amount of ecotonal habitat. Patch size is also important because small, isolated habitats cannot sustain birds that maintain a large territory. In addition, the species composition of the vegetation affects the types of food and other habitat elements that occur in a stand. The presence of cavity trees, standing dead trees (or snags), and logs on the forest floor is also critical to many birds and other animals (this is discussed in the next section). Finally, the abundance of many birds often increases in stands in which there is an outbreak of insects, such as spruce budworm (see Chapter 22).

Many birders have a general knowledge of the relationships between bird species and habitats, and they use this understanding to predict what they might see under certain conditions. Ecologists know enough about the specific requirements of some birds to manage their habitat. The best forestry-related example of this practice is the use of prescribed fire to create even-aged stands of jack pine (Pinus banksiana) in Michigan. This ensures an appropriate habitat for the endangered Kirtland's warbler (Dendroica kirtlandii).

Of course, each bird species has particular habitat needs. If the physical and botanical character of a habitat is changed by a disturbance such as wildfire or clear-cutting, many species can no longer breed in the affected stand. The same disturbance, however, will create opportunities for early successional birds.

These changes are illustrated in Table 23.2, which compares the birds in mature stands and in clear-cuts of hardwood forest. The mature forest supported an average population of 663 pairs/km^2, dominated by ovenbird, least flycatcher, red-eyed vireo, black-throated green warbler, and hermit thrush. The three- to five-year-old clear-cuts supported a slightly less abundant population of 588 pairs/km^2, dominated by chestnut-sided warbler, common yellowthroat, white-throated sparrow, and dark-eyed junco. Note that although the forest and clear-cuts had similar densities of birds, the species were almost entirely different. This occurred because the habitats were very different in terms of physical structure and the species composition and biomass of vegetation. Although clear-cutting deprived mature-forest birds of habitat, it created opportunities for early successional species.

Table 23.2. Breeding Birds in Mature Forest and Adjacent Clear-Cuts in Nova Scotia. The three stands of mature forest had a closed canopy dominated by maple and birch, while the clear-cuts (3-5 years old) had a vigorous regeneration of shrubs and herbaceous plants. Less-abundant birds are not included. Data are in pairs per square kilometre. Source: Data from Freedman et al. (1981).

Species	Mature Forest			Clear-Cuts		
	A	**B**	**C**	**A**	**B**	**C**
Ruby-throated hummingbird (*Archilochus colubris*)	0	0	0	25	30	15
Least flycatcher (*Empidonax minimus*)	290	120	0	0	**0**	0
Hermit thrush (*Catharus guttatus*)	60	40	30	0	0	0
Red-eyed vireo (*Vireo olivaceous*)	80	50	30	0	0	0
Black-and-white warbler (*Mniotilta varia*)	15	50	40	0	0	0
Black-throated green warbler (*Dendroica virens*)	50	30	30	0	0	0
Chestnut-sided warbler (*Dendroica pensylvanica*)	0	0	0	100	40	190
Ovenbird (*Seiurus aurocapillus*)	150	120	200	0	0	0
Common yellowthroat (*Geothlypis trichas*)	0	0	0	25	300	130
American redstart (*Setophaga ruticilla*)	15	80	100	0	0	0
Dark-eyed junco (*Junco hyemalis*)	15	20	15	50	70	30
White-throated sparrow (*Zonotrichia albicollis*)	0	20	0	90	190	100
Song sparrow (*Melospiza melodia*)	0	0	0	90	70	0
Total density (pairs/km^2)	815	660	515	435	745	585
Number of species	12	16	9	10	8	7

Welsh and Fillman (1980) examined the effects on birds of clear-cutting spruce forest in northern Ontario. The largest populations of birds (1020-1970 pairs/km^2) occurred in moderate-aged (11 to 24 years) clear-cuts. This was a higher abundance than occurred in uncut forest (561 pairs/km^2). The lowest densities of birds occurred in a three-year-old clear-cut (200 pairs/km^2). By five years after the cutting, this had increased to 690 pairs/km^2. In general, the clear-cuts and mature forest supported different birds, although there was some overlap.

Image 23.2. This is a two-year-old clear-cut of hardwood forest in Nova Scotia. Birds breeding in this habitat included dark-eyed junco (Junco hyemalis), white-throated sparrow (Zonotrichia albicollis), song sparrow

(Melospiza melodia), and common snipe (Capella gallinago). Source: B. Freedman.

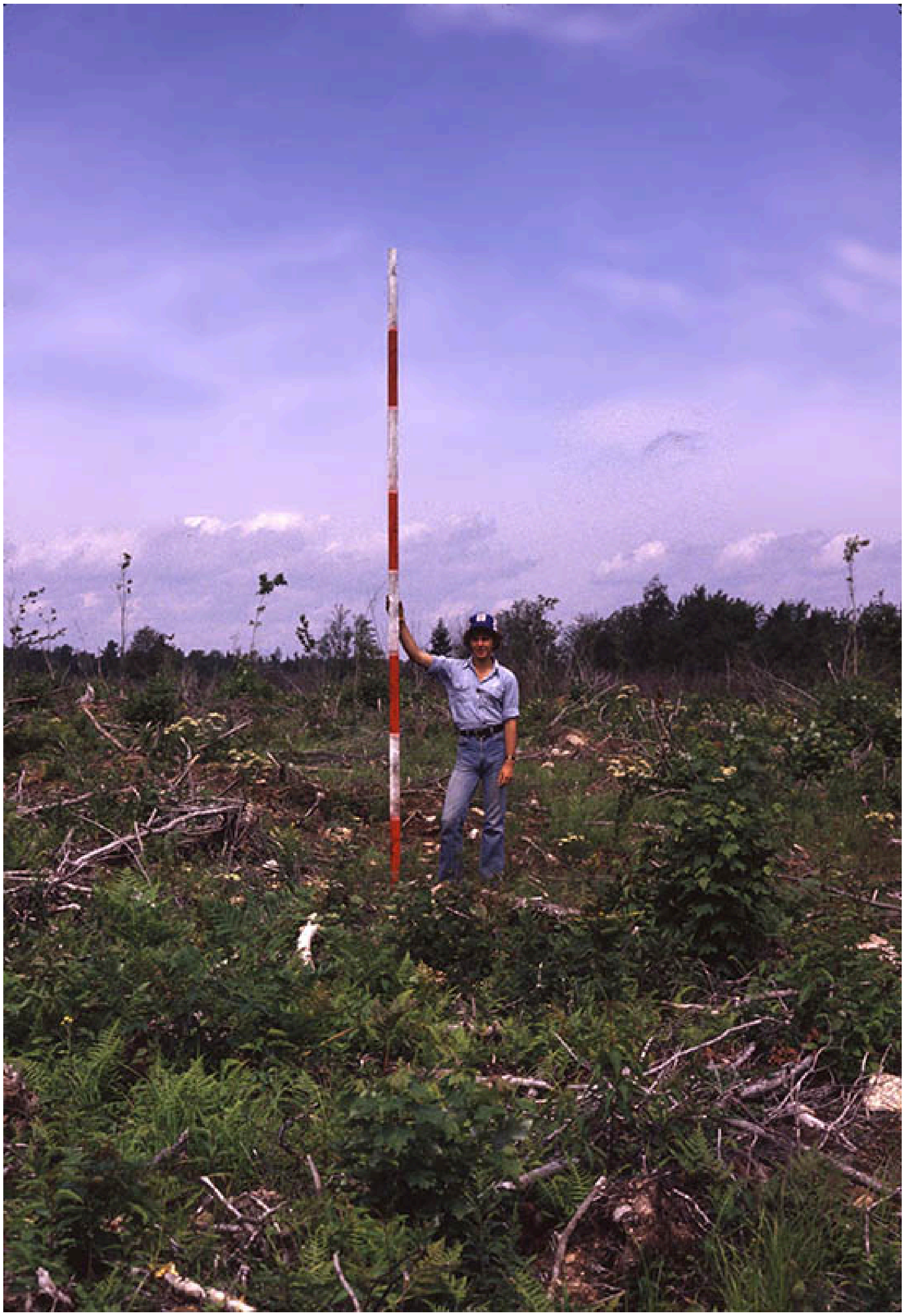


Image 23.3. This is an eight-year-old clear-cut of hardwood forest. Birds breeding in this habitat include chestnut-sided warbler (Dendroica pensylvanica), common yellowthroat (Geothlypis trichas), and alder

flycatcher (Empidonax alnorum). Source: B. Freedman.

Cavity Trees and Deadwood

Living trees with heart-rot cavities, standing dead trees (snags), and logs lying on the forest floor (coarse or large woody debris) are critical habitat elements for many animals. This is particularly true of many birds, which use these habitat features for nesting, as substrates for foraging, and as perches for hunting, resting, or singing. In fact, about one-third of the birds that breed in temperate and boreal forest depend on these features, particularly on cavities.

For example, all 12 species of woodpeckers that breed in Canada excavate cavities in snags or in living, heart-rotted trees. The cavities are used as nesting sites and for roosting at night. In addition, most woodpeckers forage for their food of invertebrates by drilling and excavating into the bark and wood of dead and living trees. Many other birds nest in the abandoned cavities made by woodpeckers, or they use natural cavities formed in rotten parts of trees. Some other birds nest in or beneath woody debris, or they build platform nests on tall snags or living trees with a damaged top.

Because so many birds depend on cavities, maintaining this habitat feature has become an important consideration in forest management. The issue is especially prominent in the older-growth forests of the West Coast, where as many as six species of woodpeckers may co-occur in relatively large populations, along with many other cavity-dependent birds. If we wish these species to remain in regions where forestry is being practised, a substantial part of any management area must be maintained as mature or old-growth forest. If plantations are established, they should be designed to provide habitat for birds that require snags and dead logs. For example, cavity trees can be left standing during the harvest. Cavity- and snag-dependent species are also better accommodated by less intensive harvesting methods, such as selection cuts.

Image 23.4. Snags, or standing dead trees, are a critical habitat element for many animals. This photo shows four young kestrels (Falco sparverius) that recently fledged from a nest in a natural cavity in a pine snag left in a clear-cut in Nova Scotia. Source: I.A. McLaren.

Freshwater Biota

Forestry practices can degrade freshwater habitats in four major ways:

- by siltation (the settling of soil eroded from the land and streambanks)
- by increases in water temperature caused by the removal of shading vegetation from stream edges
- by blocking stream channels with logging debris
- by changes in hydrology

Damage may also be caused by accidental spills of fuel and as a result of pesticide spraying (see Chapter 22). Any of these assaults on freshwater habitat can affect populations of fish, amphibians, and aquatic invertebrates. These problems are especially severe in hilly or mountainous terrain because of the many small streams and rivers that occur there, and because steep slopes are highly vulnerable to erosion.

In most cases, it is possible to avoid or mitigate many of the damages caused to aquatic ecosystems. As we previously noted, erosion can be greatly reduced if roads and culverts are constructed carefully, logs are hauled correctly, and riparian buffers of uncut forest are left beside water-courses. Leaving buffer strips also avoids an accumulation of logging debris in streams, as does not felling trees into aquatic habitats. Riparian buffers are also effective at preventing increases in water temperature, because they shade streams even if the nearby forest has been harvested.

Image 23.5. This photo of a riparian buffer of uncut forest beside a stream in New Brunswick was taken in winter. The shading vegetation prevents increases in water temperature that would be caused by clear-cutting to the stream edge. It also helps to prevent erosion and maintains a corridor of mature vegetation for use by wildlife. Source: M. Sullivan.

Old-Growth Forest

Old-growth forest is a late-successional (or climax) ecosystem that is characterized by at least some old trees, a multi-aged population (all age classes are represented, from young to old), and a complex physical structure. The structure of the habitat includes multiple layers within the canopy, some massive trees, large snags, and big logs lying on the forest floor. In some ecological contexts, the term "old-growth" is also used to refer to senescent populations of shorter-lived trees, such as older stands of poplar, birch, or cherry. This is not, however, the meaning of "old-growth forest" that is considered here.

Old-growth forest is a natural ecosystem with special values that are not replicated in plantations or even in natural regenerated secondary forests. For this reason, old-growth forest has great intrinsic value and is an important component of natural heritage. It also supports certain plants and animals that do not occur in other Canadian habitats. (However, this is a relatively minor attribute of temperate and boreal old-growth forest –tropical old-growth sustains enormously larger numbers of dependent species; see Chapters 7 and 26.) In addition, old-growth forest delivers important ecological services, such as storing carbon and providing clean water and air, and it has economic value for outdoor recreation and ecotourism.

Old-growth forest was once much more extensive in Canada (and elsewhere in the world) than it is today. In eastern Canada, for example, early "development" of the land by European settlers involved the extensive clearing of old-growth forest into agricultural land-uses, as well as its conversion into younger second-growth forest by timber harvesting. As a result, there is little of this ecosystem type left in the eastern provinces, where only a few percent of the total forest is now in an old-growth condition.

Old-growth forest is more abundant in parts of western Canada, particularly on the Pacific coast, where the wet climate favours the development of this natural ecosystem (because wildfires are uncommon). Even in British Columbia, however, extensive tracts of old-growth have been logged or converted to urbanized land-uses, especially near Vancouver and Victoria. And because old-growth timber is such a valuable resource, much of the remaining older forest is threatened by harvesting. It is likely that virtually all of the remaining old-growth forest will be logged during the next several decades and converted into second-growth forest, except where tracts are protected in ecological reserves and parks.

Many of the characteristics of old-growth forest, including elements of biodiversity, can be accommodated by so-called "new forestry" harvesting systems that are relatively "soft" in the intensity of disturbance that they cause. The best example of a new forestry system is selection cutting with retention of snags and cavity-trees. Because only some of the valuable timber is removed during a selection harvest, the physical and ecological integrity of the forest are left substantially intact, which conserves many of the old-growth values.

However, there are limits to what can be achieved through the new-forestry practices. If a goal of society is to preserve old-growth forest as a special kind of natural ecosystem, this is best done by establishing large, landscape-scale protected areas. The size of the protected areas is a critical factor because they must be big enough to sustain the long-term ecological dynamics that permit old-growth forest to develop, especially the natural disturbance regime. This landscape perspective is important because particular stands of old-growth forest cannot be preserved forever – they will inevitably become degraded by natural disturbance and/or environmental change. Consequently, old-growth forest can be sustained only if large protected areas are designated to preserve the necessary ecological dynamics.

Old-growth forest is an extremely valuable natural resource, more so than any other kind of forest. This is because it contains large individuals of economically desirable tree species. This timber can be used to manufacture valuable products, such as fine-grained, large-dimension lumber and plywood. However, stands of old-growth forest are rarely managed by foresters to maintain their defining characteristics. Rather, they are "mined" by harvesting, followed by silvicultural management to convert the site into a younger, second-growth forest. The second-growth forest will only be allowed to develop into a middle-aged forest before it is again harvested.

There is an economic rationale for this kind of management strategy. In the old-growth condition, a forest does not sustain a positive net production of biomass. This happens because, at the stand level, the productivity by living trees is more-or-less balanced by the deaths of other individuals through disease, accident, or old age. If the objective of management is to optimize the productivity of tree biomass, it is better to harvest a middle-aged forest soon after its net productivity begins to decrease, which is well before its attains an old-growth condition. Of course, this kind of economic thinking does not take account of the special ecological and aesthetic values of old-growth forest, which are degraded by logging.

Because old-growth forest has particular characteristics, some species of wildlife will only occur in this habitat. This is especially true of tropical old-growth forest. In Canada, animals that depend substantially on old-growth forest include the marbled murrelet (Brachyramphus marmoratus), the northern spotted owl (Strix occidentalis caurina), and the American marten (Martes americana). In addition, some plants are more abundant in old-growth than in younger, mature forest. Examples include the Pacific yew (Taxus brevifolia) and lungwort lichen (Lobaria pulmonaria). Ongoing studies will discover additional examples, especially of insects, lichens, mosses, and other less conspicuous elements of forest biodiversity. These indigenous biodiversity values are endangered by the continued logging of old-growth forest in Canada.

> Canadian Focus 23.1. Controversy in Clayoquot Sound Clayoquot Sound is a Pacific embayment that reaches inland in central Vancouver Island to encompass a watershed of about 2,630 km^2. The mountainous terrain supports a great variety of habitats, including extensive forest on the interior mountains and the flatter coastal plain. The climate is mild temperate, with abundant rainfall. The wet climate encourages the natural

development of old-growth rainforest. This is a relatively uncommon ecosystem because few places have the conditions necessary for its development. Before commercial timber harvesting began, most of the Clayoquot forest was old-growth, with many trees being large and ancient – some >3 m in diameter and more than 1,000 years old. These old-growth trees have fine-grained wood because of their slow growth rate, which makes them extremely valuable as lumber.

Because of the extensive logging of old-growth forest in Clayoquot Sound (and elsewhere), this ecosystem is much less extensive today than it used to be. This is particularly true of the coastal plain and lower elevations in the mountains, where the most accessible forest occurred. Today, about 80% of the remaining forest occurs at higher elevations and on steeper slopes.

Almost all of the old-growth stands that are logged on Vancouver Island and elsewhere in coastal British Columbia regenerate to another forest. Moreover, the second-growth forest is dominated by the same species of trees as occurred in the original old-growth stands. However, the second-growth forest is harvested soon after its trees are large enough to be used to manufacture lumber or pulp, and this happens at a much younger age than is required to re-develop an old-growth condition. Much controversy has arisen over the rapid and extensive conversion of old-growth into second-growth forest. Many people believe that old-growth forest has great intrinsic value because it is a distinct natural ecosystem, and it is also valued for cultural, aesthetic, and ecological reasons.

Environmentalists have targeted the remaining old-growth forest of the Clayoquot area for protection, and over the years have focused much activism to that end. In part, this has occurred because the area is accessible and traversed by many people travelling to Pacific Rim National Park and the tourism area of Tofino. In fact, there are more extensive tracts of old-growth forest elsewhere on Vancouver Island and on the mainland of British Columbia. However, because those other forests are remote, protests there would have been less effective in attracting media and public attention than actions in the Clayoquot region.

The most intense protests began in March 1993, soon after the government of B.C. purchased stock in a company that had a licence to harvest timber in the Clayoquot region. A few weeks later, the government issued permits to log 74% of the area. This sparked an explosion of public demonstrations, including a large gathering at Clayoquot Sound. Some of the attendees had travelled across Canada by train, as part of a media event that symbolically began in Newfoundland and ended in coastal British Columbia. In addition to the protests and publicity stunts, there were blockades of logging roads and other kinds of civil disobedience, leading to the arrest of more than 850 people.

Image 23.6. This landscape in the Clayoquot Sound region was once covered mainly by old-growth rainforest. Because the valley floor supported the largest trees and was accessible, it was harvested first, in this case about 15 years prior to this photo being taken. The clear-cuts regenerate well through planted seedlings and natural seeding-in, and another mixed-species forest will again develop. However, this secondary forest will be harvested before it re-attains an old-growth condition. The stands at mid-slope were clear-cut three years before the photo, while the upper slopes have not yet been harvested. Source: B. Freedman.

In October 1993, the premier of B.C. announced the establishment of a Scientific Panel for Sustainable Ecosystem Management in Clayoquot Sound. The panel was made up of 23 members, including experts in ecology, biodiversity, forestry, ecotourism, and other relevant interests. The mandate of this highly regarded group was to "make forest practice in Clayoquot not only the best in the province, but the best in the world."

In June 1995, after a series of public meetings and other deliberations, the panel released a report containing 120 recommendations. These were accepted by the government and passed into law. The panel recommended that sustainable ecosystem management should be the over-riding objective for the Clayoquot region, and that all activities, including those of forestry, should be conducted with that objective in mind.

Many of the recommendations advocated silvicultural systems that would retain the key characteristics of old-growth rainforest, such as an uneven age structure, snags and cavity trees, woody debris, and healthy aquatic ecosystems. The panel felt that those objectives could be largely met by restricting the proportion of any large watershed that could be converted into younger age classes, accomplished by limiting the cut rate to no more than 1% of a catchment per year. That practice would ensure that sufficient areas of old-growth forest, or of managed forest having most of its habitat values, would always be present to satisfy the needs of dependent species. The panel also recommended that large areas be fully protected from forestry, particularly areas and sites of great value because of their ecological features, aesthetics, cultural significance, or utility for recreation.

The recommendations of the panel, and their acceptance by government, satisfied most people regarding the ecological sustainability of the forest-management plan for the Clayoquot Sound region. The panel's work should not, however, be regarded as a perfect model of sustainability or as a permanent solution to the controversy over forestry in regions of old-growth forest.

Despite these positive developments, the controversy over logging the old-growth rainforest has not disappeared. Although logging companies and the British Columbia government committed to implementing the recommendations of the panel, the development of an ecosystem-based management plan did not happen in a timely fashion. Public protests again erupted over the continuation of relatively intensive logging within Clayoquot Sound, such as harvesting on steep slopes, the use of clear-cutting rather than selection-harvesting systems, harvesting at rates (within watersheds) greater than recommended by the panel, and failure to monitor effects of logging at the ecosystem level (Friends of Clayoquot Sound, 2014). New public protests were sparked by the resumption of road building and extensive logging on Catface Mountain. Some important lessons can be learned from this ongoing controversy:

1. Scientists can recommend actions to make forestry more environmentally sustainable (this is true of all economic activities).
2. The various interested parties may commit to undertake recommended changes, thereby alleviating the economic and political disruptions associated with public controversy.
3. However, economic and political priorities may again shift, and thereby delay or prevent the implementation of changes.
4. Therefore, citizens and environmentalists should always be skeptical about promises made by government and industry to protect environmental quality. Moreover, there is never a guarantee that a future government will not change agreed-upon rules (including legislated ones) in ways that provide less protection for the environment. It is even possible that the priorities of future generations of Canadians may support such an action.

The best hope of preventing future damage is to ensure that the social contract of forestry always includes an obligation to: (1) conduct industrial activities in a manner that does not degrade the timber resource, (2) maintain non-timber economic values such as hunted species and tourism, and (3) sustain the carbon-storage, hydrologic, and biodiversity values of old-growth forest and other elements of natural heritage. All of these forest values are important and must be maintained, and it is crucial that Canadians understand this. Unless this happens, the controversy will surely continue.

Plantations

The clear-cutting of natural forest is often followed by the planting of a new crop of trees, usually of a conifer species. These may then be intensively managed to increase the productivity of the stand. This system results in the development of a plantation (or tree-farm), which is an anthropogenic forest of a relatively simple character in comparison with the natural, mature or old-growth, mixed-species forest that previously occupied the site. Because many native species of the natural forest are unable to utilize the habitat available in a plantation, the ecological conversion has critical implications for biodiversity.

The most important habitat changes are related to differences in the tree species and physical structure of a plantation compared to natural forest. A typical plantation is dominated by trees of a particular species and of similar age and size (in population ecology this is known as a cohort, while in agriculture it is referred to as a monoculture). This is a greatly simplified ecosystem compared with natural forest, which typically has trees of various species, ages, and sizes. Such changes are greatest when the original forest is hardwood dominated, mixed hardwood-conifer, or old-growth. The changes are fewer if natural, even-aged conifer forest is replaced with a conifer plantation.

Image 23.7. Forestry plantations are deficient in tree cavities, which are needed by many birds for nesting and roosting. In this study, artificial cavities were placed in conifer plantations and in natural forest, to see whether this feature was limiting the use of the habitat by species of cavity-dependent birds. It turned out that they only nested in the artificial cavities that were erected in plantations, which indicates that this habitat feature was limiting their abundance. Source: B. Freedman.

Of course, any changes in vegetation and habitat have secondary effects on the animals that can be sustained. Studies of conifer plantations in New Brunswick have found that they can support an abundant population of birds (Table 23.3). In fact, a 15-year-old plantation supported a larger bird population than did nearby natural forest, while species richness was similar. In this study, many birds of the natural, conifer-dominated forest began to invade the plantations once the trees were older than about 10 years.

Table 23.3. Breeding Birds in Natural Forest and Plantations. Natural, mixed-species forest and spruce and pine plantations were surveyed in New Brunswick. The plantations were surveyed at 3, 6, 7, and 15 years of age, and the natural stands were 60 years old. Only abundant species are listed here. Data are given as pairs per 10 hectares; stand age is in years. Source: Data from Johnson and Freedman (2002).

	Plantations				Forest	
Species	**3 y**	**6 y**	**7 y**	**15 y**	**60 y**	**60 y**
Yellow-bellied flycatcher (*Empidonax flaviventris*)	0	0	0	6.9	4.1	1.3
Alder flycatcher (*Empidonax alnorum*)	0	5.3	4.3	13.4	0	0
Hermit thrush (*Hylocichla guttata*)	0	0	0	2	2.2	2.6
Magnolia warbler (*Dendroica magnolia*)	0	1.9	0	13.4	9.3	2.6
Yellow-rumped warbler (*Dendroica coronata*)	0	0	0	5.5	2.2	1.3
Black-throated green warbler (*Dendroica virens*)	0	0	0	0	2.2	5.5
Blackburnian warbler (*Dendroica fusca*)	0	0	0	0	4.5	6
Common yellowthroat (*Geothlypis trichas*)	0.9	15.5	9.2	15.3	0	0
Song sparrow (*Melospiza melodia*)	4.8	4.4	7.9	0	0	0
Lincoln's sparrow (*Melospiza lincolnii*)	4.4	1.2	17.2	6	0	0
White-throated sparrow (*Zonotrichia albicollis*)	0	12.6	5.3	8.4	1.5	0.4
Northern junco (*Junco hyemalis*)	3.5	1	0.8	2.5	2.2	0.4
Total bird density	15.7	53.9	47.2	102	57.8	50.6
Number of species	16	20	22	38	42	32

Plantations are especially deficient in cavity trees, snags, and woody debris. Consequently, they support few of the many species that require these habitat features. For example, in New Brunswick, conifer plantations are established by clear-cutting natural forest, then preparing the site for planting using large machines that crush the logging debris and topple any unharvested trees and snags. This intensive management results in the presence of almost no cavity trees or snags and little woody debris (Table

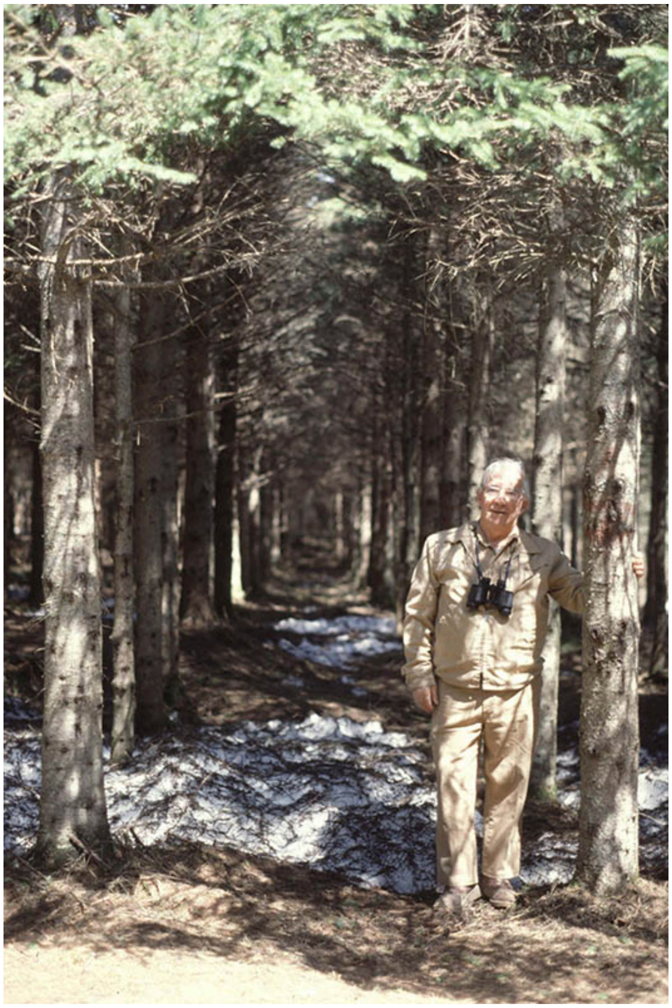
Table 23.4. Snags and Large Woody Debris in Natural Forest and Plantations. Natural mature forest and conifer plantations were surveyed in New Brunswick. Data are for snags (standing dead trees) and woody debris with a diameter greater than 5 cm. Basal area is the cross-sectional area of snags or trees and is a measure related to biomass. Volume is also related to biomass. Source: Data from Freedman et al. (1996).

	Snags		Woody Debris	
	Density (number/ha)	Basal Area (m^2/ha)	Density (10^3/ha)	Volume (m^3/ha)
Mature, Natural Forest				
Hardwood-dominated	138	3.5	0.28	18.7
Mixedwood	188	3.6	0.3	19.9
Mixedwood	200	5.4	0.36	13
Mixedwood	270	4.1	0.27	32.7
Conifer-dominated	698	11.4	0.48	41.6
Conifer-dominated	1115	19.5	0.86	45.4
Conifer-dominated	467	12.7	1.03	56.5
Plantations				
21-year-old spruce	13	0.03	0.13	0.6
15-year-old spruce	0	0	0.17	8.9
13-year-old spruce	13	0.2	0.56	14.1
8-year-old spruce	50	0.2	2.73	28
7-year-old spruce	0	0	2.2	23.9
6-year-old larch	0	0	2.04	32.1
5-year-old spruce	0	0	2.18	23.7
4-year-old spruce	0	0	3.25	52.2

If conifer plantations provide adequate winter cover and browse, snowshoe hares (Lepus americanus) may be abundant. In fact, these animals may cause damage by feeding on the bark and shoots of young trees. As soon as the trees mature and start to produce sizable cone crops, red squirrels (Tamiasciurus hudsonicus) also find conifer plantations to be acceptable habitat.

Sometimes, plantations are established on previously agricultural or industrial lands (this is known as afforestation). Depending on the particular habitat that results, these plantations are likely to enhance the populations of some native birds by providing forest habitat. This can be a benefit in regions where agriculture is the dominant land-use, for example, in southern Ontario. However, greater biodiversity benefits would be attained if an attempt were made to restore a more natural forest, rather than a plantation.

Image 23.8. This 30-year-old plantation of white spruce (Picea glauca) in New Brunswick is a conifer forest, but it is simple in physical and biological structure. Although this habitat supports some native plants and animals, many others are eliminated by the scarcity of critical habitat elements, such as cavity trees and woody debris. Source: B. Freedman.



Landscape Considerations

Biodiversity at the level of landscape is related to the distribution and richness of ecological communities, including their dynamics over time (see Chapter 7). If a landscape is covered with only one or a few types of communities, it has little biodiversity at this level. In contrast, an area with a complex and dynamic mosaic of communities has much greater landscape-level biodiversity. Landscape ecology involves the study of the patterns and dynamics of communities on landscapes (and seascapes).

Landscape-level biodiversity is influenced by disturbances that result in some stands (or patches) of older communities being replaced with younger ones. Natural causes of these stand-replacing disturbances include wildfire, windstorms, volcanic eruptions, and insect irruptions. Anthropogenic causes include those associated with forestry.

Sometimes, timber harvesting is designed to mimic the natural patch-disturbance regime. For example, many pine forests are naturally disturbed by periodic wildfires, during which most of the mature trees may be killed. Soon afterward, a new cohort of tree seedlings establishes, and with time they grow into another mature forest. To some degree, foresters can emulate this natural disturbance regime when they develop plans to harvest and manage pine forest.

Forestry, by its nature, imposes an anthropogenic patch dynamic onto the landscape. This may occur if an un-natural mosaic of clear-cuts and plantations of various ages is created, interspersed in checkerboard fashion within a matrix of any remaining natural forest and non-forest habitats (such as wetlands). A landscape mosaic of this sort may even be recommended by game managers, because it can favour certain hunted species, such as deer and grouse. However, the patch dynamics created by forestry have important implications for many other elements of biodiversity. For example, if the remaining patches of natural forest are too small or isolated from each other, they will not sustain all of their native species and communities over the long term. These losses would have negative implications for the ecological sustainability of the forestry system (see Chapter 12).

Forestry creates fragmented landscapes that contain successionally dynamic patches of silvicultural and natural-forest habitats. Many species of native wildlife find the silvicultural habitats to be adequate for their purposes. However, such habitats and their dynamics are incapable of supporting other native elements of biodiversity, whose survival may therefore be at risk. If these native values are to be conserved, large patches of natural forest must be set aside as protected areas.

To achieve a balance between the needs of forestry and the responsibility to conserve indigenous biodiversity, consideration must be given to the size, shape, and spatial arrangement of the patches on managed landscapes, including the protected areas. For example, if the protected areas are too few, small, isolated, or young to accommodate all of their biodiversity objectives, then it will be necessary to design a landscape that is more ecologically appropriate. Design options that have been recommended to meet the biodiversity objectives of protected areas are examined in Chapter 26.

Some of the national parks of Canada are among the largest protected areas in the world. Yet many of these are too small to maintain viable populations of certain species, or to maintain the ecological dynamics required to allow old-growth forest to persist. Species that are most at risk need extensive areas of habitat to sustain their populations. They include the grizzly bear (Ursus arctos), wolf (Canis lupus), spotted owl, and marbled murrelet. Even the largest national parks may not be big enough to sustain these species over the centuries.

In such cases, the protected areas and their surrounding landscape must be managed as "greater protected areas" – as an integrated ecosystem. If forestry continues to be an important economic activity in the landscape around protected areas, it must be conducted with a view to sustaining those species and natural communities that might be at risk. In many cases, this will require changes in the forestry-management system. Such changes might include maintaining a network of protected areas that are connected by corridors and incorporate critical habitat elements, such as cavity trees and woody debris, into managed stands.

> Global Focus 23.1. Is Canada "the Brazil of the North"? Sometimes, to gain an edge in the public sphere, individuals or organizations may use relatively extreme rhetoric when making arguments for or against an environmental position. For example, some opponents of intensive forestry practices have claimed that Canada should be viewed as "the Brazil of the North" because of the kinds of forestry being practised here. The point has been especially made in reference to the clear-cutting of old-growth coastal rainforest in British Columbia. But is it reasonable to assign a "Brazil of the North" label to Canada?
>
> Obviously, Canada and Brazil are very different places in terms of people, culture, economy, and natural ecosystems. Nevertheless, there are key similarities with respect to forests and forestry between the two countries, as well as major differences. For example, although both countries are still heavily forested, each has lost a major part of the original forest to agricultural development and urbanization. In Brazil, the worst losses are of Atlantic tropical and subtropical forest, as well as forest in Amazonia. In Canada, it is mostly temperate forest in southern regions of the eastern provinces. Both countries have a large forest industry, although Canada's is more export-oriented. Both countries have designated many protected areas (such as national parks), but neither has created enough such areas and their stewardship is deficient (for example, by not

preventing damage caused by illegal logging or poaching of wildlife, controlling the damage caused by transportation corridors and tourism facilities, or protecting indigenous cultures).

A key ecological difference is in the biodiversity that is supported by the two countries. Canada has many indigenous species, but only a few are endemic (having a local distribution and occurring nowhere else). This is because Canada is a young country, in the ecological sense, having only been released from continental glaciation about ten-thousand years ago. In marked contrast, the natural ecosystems of Brazil are much older, and most have developed under subtropical and tropical climatic regimes. The humid forests of such regions support much higher levels of biodiversity, including many endemic species, compared with the natural ecosystems of Canada, which range from polar to temperate. In this vital respect, deforestation in Brazil causes enormously more grievous damage to biodiversity than it does in Canada because many more species and ecosystem types are affected, and the risks of causing extinctions are much greater. This context does not trivialize the importance of avoiding actions that cause native species or natural ecosystems of Canada to become at risk, but it is a valid comparison.

There are many additional comparisons that could be made when trying to understand whether we are the "Brazil of the North" or they are the "Canada of the South" (see selected data in table). Ultimately, however, subjective and extreme rhetoric is not particularly helpful when trying to help people develop informed opinions about important environmental issues. Table 23.5.

	Canada	**Brazil**
Population, 2013	34×10^6	201×10^6
Total land area (ha)	997×10^6	855×10^6
Forest area, 2000 (ha)	310×10^6	478×10^6
Deforestation, 1990–2010	0.00%	–9.6%
Original forest, % of land area	66%	64%
Forest, as % of original forest	91%	64%
Protected areas, 2013, as % of area	11%	29%
Forest harvest, 2012 (m^3/y)	153×10^6	292×10^6
Trade in forest products, 2012		
Imports	US$5.0 billion	US$1.7 billion
Exports	US$21.8 billion	US$7.5 billion
Biodiversity		
Vascular plant species	3,270	56,215
Fish species	128	471
Amphibian species	44	695
Reptile species	39	651
Bird species	472	1,712
Mammal species	211	578

Sources: Data from World Resources Institute (2008), Chapter 14

Integrated Forest Management

Increasingly, foresters in many parts of Canada are working with other interested parties to develop integrated forest management plans that accommodate the need to harvest timber from forested landscapes while also sustaining other values. Usually, these plans focus on finding ways to conduct forestry while also supporting hunted species such as deer, elk, trout, and salmon. Efforts may also be made to accommodate other uses and values, such as non-consumptive recreation, for example, birding and hiking.

By co-operating in the design of integrated management plans, the forest industry is attempting to come to grips with some of the controversies that arise from their woodland operations. Society expects that the vast forests of Canada will continue to deliver a wide range of goods and services. These include the economic benefits from timber harvesting, while also satisfying the needs of sport hunters, fishers, hikers, and other outdoor recreationists. Even while they are used in these ways, forest landscapes are also expected to provide such ecologically important services as carbon storage, clean air and water, and to sustain native biodiversity.

The forest industry is making progress in the directions that society expects, but much more has to be done. This is particularly true of the need to set aside additional areas that are protected from forestry. If they are large enough, the protected areas can allow ecological processes to continue in a manner that is unfettered by major human stressors, so that natural ecosystems can develop and native species can sustain their populations. In addition, forestry will have to change to accommodate more of the habitat needs of biodiversity on managed sites.

If the Canadian forest industry is to legitimately claim that it is conducting its operations in an ecologically sustainable manner, it must achieve several broad objectives. First, it is critical that the rate of timber harvesting does not exceed that of forest productivity. At the same time, other economic values must be sustained, such as viable populations of hunted animals and opportunities for outdoor recreation. Finally, it is critical that no indigenous elements of biodiversity are made endangered by forestry. Although the forest industry has been making headway toward improving its environmental practices in Canada, not all of the requirements of ecologically sustainable forestry are being satisfied. Therefore, considerably more progress is required in this direction.

Conclusions

Forestry is a key economic sector in Canada, each year affecting millions of hectares of landscape. Timber harvesting and management of the subsequent regeneration cause many environmental changes, including decreases of carbon storage, alterations of hydrology, erosion, and effects on the habitat of wildlife. Because timber harvesting and silvicultural practices are severe disturbances of forested sites, some environmental damage is inevitable. To a large degree, however, many of the damages could be mitigated by adopting different forestry practices than are currently used. These include less use of the predominant clear-cutting system, and replacing it with softer practices such as selection harvesting. Greater attention to the protection of aquatic habitat is also necessary, such as retaining buffer strips of uncut forest along all watercourses. Some damage to the habitat of wildlife on cutovers can also be mitigated, for instance, by retaining cavity trees and by greater reliance on natural regeneration rather than on plantations. It is also necessary to protect large areas of natural forest from intensive resource harvesting. This requires the implementation of a connected network of protected areas that is sufficient to conserve those species and ecological communities that are incompatible with use of the landscape for forestry purposes.

Questions for Review

1. How do forestry practices threaten the nutrient capital and site quality of harvested stands?
2. How does timber harvesting affect the hydrology of streams and rivers?
3. What elements should an integrated management plan include for a typical forested watershed in your region? Consider the needs to ensure a constant supply of timber, deer, sportfish, clean water, and habitat for non-game species.
4. What are the characteristics of a typical old-growth forest in the region where you live? Do you think that the special values of the old-growth forest can be accommodated by forestry, or can old-growth forest be preserved only by creating large protected areas where trees are not harvested? What are the economic implications of setting aside such large tracts of potentially valuable timber? What are the ecological implications?

Questions for Discussion

1. Consider a typical forest in the region where you live. What are the dominant species of trees, other plants, and animals that live in that forest? What are some important interactions among those species? Consider, for example, the habitat needs of certain animals, including their foods.
2. Are forest products important in your life and in the functioning of your community? Compile a list that shows how trees are used for bio-energy, lumber, paper, and other products. Also consider non-timber uses of forests, such as hunted animals, recreation, carbon storage, and the provision of clean air and water.
3. How might forest resources make a larger contribution to the Canadian economy, or to that of your region? Would it be possible, for example, to harvest more wood without degrading the timber resource? Could more people be employed in woodland operations if harvesting and management activities were less mechanized? Consider also the prospects for reducing the export of raw materials, such as logs, through increased local processing into manufactured products.
4. Why is it essential that a large and connected system of protected areas be a key part of any landscape-scale plan for ecologically sustainable forestry?

Exploring Issues

1. A proposal is being made to build a lumber mill in an area that is now wilderness. About 40% of the forest in the area is in an old-growth condition. You are an ecologist, working as part of a team of scientists to assess the potential environmental impacts of the forest management plan to supply timber to the proposed sawmill. Your responsibility is to consider the sustainability of the supply of timber and other forest resources, as well as effects on rare species and natural ecosystems. What would you examine to ensure that the forest management is ecologically sustainable?

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Chapter 24 ~ Agriculture and the Environment

Key Concepts

After completing this chapter, you will be able to:

1. Explain how agricultural production is essential to the survival of large numbers of people and domestic animals.
2. Define the term "domestication," and relate it to humans, their agricultural crops, and livestock.
3. List the most important plants and animals in agriculture, and describe the management systems used in their cultivation.
4. Identify the most important environmental effects of agriculture, and describe the damage that they cause.
5. Explain how organic agriculture uses a more ecological approach to the cultivation of crops, resulting in less environmental damage.

Introduction

Agriculture can be defined as the science, and art, of cultivating the soil, producing crops, and raising livestock. Even relatively simple agricultural practices can greatly increase the production of food, compared with the hunting and gathering of wild animals and plants. Prior to the development of agriculture, which first appeared around 10,500 years ago, perhaps 5-10 million people were able to subsist through a hunting and gathering lifestyle. Today, the world supports an enormous population (more than 7.3 billion in 2015), and almost all depend on the agricultural production of food (fishing and hunting also provide some food). Clearly, the development of agricultural practices and technologies, and their improvements over time, are among the most crucial of the "revolutions" that have marked the socio-cultural evolution of Homo sapiens.

Agriculture was probably first practised in the Fertile Crescent, a region of southwestern Asia that includes parts of what are now Iran, Iraq, Israel, Jordan, Lebanon, Syria, and Turkey. Similar developments likely occurred at about the same time in China, although the archaeological evidence is less clear. Other cultures discovered the benefits of agriculture somewhat later, in part through the domestication of local species of plants and animals (for instance, in parts of Central America, western South America, and New Guinea). In other regions, however, domesticated species were mostly imported from elsewhere, as occurred in Australia, Europe, and North America.

In any event, beginning with the cultivation and then domestication of a few useful plants and animals, agricultural technology has advanced to the point where it is now able to support enormous populations of humans and our mutualist species (see Chapter 10).

Modern agriculture involves a number of distinct management practices. In the case of crop plants, they include: selective breeding, tillage, the use of fertilizer and pesticides, irrigation, and reaping. Each practice helps to increase the yield of biomass that can be harvested for food or other uses. The practices are typically used in various combinations, which are undertaken as an integrated system of ecosystem and species management to achieve a large production of crops. However, the management practices also cause important environmental damages.

We previously examined agricultural production and economics in Chapter 14. In this chapter we investigate environmental damages that are associated with agriculture, with particular attention to effects that occur in Canada. We will examine the intensive cultivation of crop plants and livestock, as well as softer management practices that are used in organic agriculture.

Crop Plants

Almost all of the important agricultural crops have been domesticated. Domestication refers to the progressive modification of crops through the selective breeding of cultivated races (or cultivars), which are now genetically, anatomically, and physiologically different from their wild ancestors. Crop plants have been selectively bred to increase their yield and response to management practices and to enhance their palatability. In some cases, thousands of years of domestication have resulted in crop plants that bear so little resemblance to their wild ancestors that they are now incapable of maintaining themselves in the absence of management by people. For example, several millennia of selective breeding of maize (corn; Zea mays) have resulted in its cob becoming tightly wrapped within leafy bracts. As a consequence, its seeds are no longer able to scatter from the cob, so they cannot germinate and develop new plants unless assisted to do so by humans.

A few crop plants have not yet been domesticated. One example is the lowbush blueberry (Vaccinium angustifolium), which has been cultivated for only a few decades. In this case, the habitat of wild plants (in the genetic sense) is being managed to increase their abundance and fruit production as a perennial crop. Because not much selective breeding has been conducted, the blueberry is not yet a domesticated plant. Most crop plants are grown as food, while others are sources of fibre, fuel, or medicine. Important domesticated food plants include the following:

- Small grains: barley (Hordeum vulgare), maize (corn, Zea mays), millet (Panicum miliaceum), oats (Avena sativa), rice (Oryza sativa), sorghum (Sorghum vulgare), wheat (Triticum aestivum and T. durum)
- Legumes (pulses): broad bean (Vicia faba), garden bean (Phaseolus vulgaris), garden pea (Pisum sativum), lentil (Lens culinaris), peanut (Arachis hypogaea), soybean (Glycine max)
- Sweet fruits: apple (Malus domestica), banana (Musa sapientum), grape (Vitis vinifera), grapefruit (Citrus maxima), mango (Mangifera indica), orange (Citrus sinensis), peach (Prunus persica), pear (Pyrus communis), plum (Prunus domestica), raspberry (Rubus idaeus), strawberry (Fragaria virginiana and F. chiloensis), sweet cherry (Prunus avium), watermelon (Citrullus lanatus)
- Vegetable fruits: cucumber (Cucumis sativus), pumpkin (squash, Cucurbita pepo), red pepper (Capsicum annuum), tomato (Lycopersicon esculentum)
- Roots and tubers: beet (Beta vulgaris), carrot (Daucus carota), garlic (Allium sativum), onion (Allium cepa), parsnip (Pastinaca sativa), potato (Solanum tuberosum), radish (Raphanus sativus), sweet potato (Ipomoea batatas), turnip (Brassica rapa)
- Vegetables: asparagus (Asparagus officinalis); broccoli, cabbage, cauliflower (all varieties of Brassica oleracea); celery (Apium graveolens); lettuce (Lactuca sativa); spinach (Spinacia oleracea)
- Edible oils: canola (or rape, Brassica napus), oil palm (Elaeis guineensis), olive (Olea europaea), peanut, soybean
- Sugar crops: sugar beet (Beta vulgaris), sugar cane (Saccharum officinarum)
- Herbs and spices: chili pepper (Capsicum annuum), mint (Mentha spp.), pepper (Piper nigrum)
- Beverages: cocoa (Theobroma cacao), coffee (Coffea arabica), cola (Cola acuminata), hops (Humulus lupulus), tea (Camellia sinensis)
- Recreational drugs: cannabis (marijuana, Cannabis sativa), coca (Erythroxylum coca), opium poppy (Papaver somniferum), tobacco (Nicotiana tabacum)

Other domesticated plants are cultivated as sources of fibre, which is used to manufacture thread, woven textiles, cordage (such as rope), and paper. Important fibre plants include cotton (Gossypium hirsutum), flax (Linum usitatissimum), and hemp (Cannabis sativa). Some species of trees, such as pines (Pinus species), poplars (Populus spp.), Douglas-fir (Pseudotsuga menziesii), and spruces (Picea spp.), are grown in plantations (called agroforestry) as sources of fibre. However, these species have not been selectivel bred to the degree that they would be considered domesticated.

A few plants are grown for the production of bio-energy, such as maize, sugar cane, and other carbohydrate-rich crops that are fermented to manufacture industrial ethanol used to power motor vehicles (as a mixture with gasoline known as gasohol).

Other crops are grown as sources of rubber (especially para rubber, Hevea brasiliensis), for medicinal purposes (such as digitalis, Digitalis purpurea), as chewing gum (chicle, Achras zapota), as dyes (indigo, Indigofera tinctoria), or for other relatively minor uses.

Image 24.1. Agricultural plants are usually intensively managed to develop a monoculture, which is an ecosystem comprised almost entirely of a single crop. This field of canola is in Prince Edward Island. Source: B. Freedman.

The parts of plants that are used for food include seeds (beans, wheat, and other grains and pulses), flowers (broccoli), fruits (melons, grapes, tomato), leaves (lettuce, cabbage), stems (asparagus, celery), and roots, tubers, and other underground tissues (onion, potato, radish). In many cases, the edible parts are tissues that evolved to store energy for the plant, such as swollen leaves and stems, and tubers. In other cases, the edible parts are energy-rich tissues that are involved in sexual reproduction, such as fruits and seeds. An important aspect of the domestication process is the selective breeding of crops to exaggerate their desirable traits, which usually results in cultivars that are very different from their wild ancestors.

Production of Crops

The above lists suggest a rich diversity of crop species. We must remember, however, that the inventory of cultivated plants is only a tiny fraction of the number of species that are potentially useful as foods or for other purposes, but have not yet been investigated for their usefulness (there are about 250-thousand species of vascular plants, but only tiny faction of them most have been investigated for their usefulness; Table 7.1).

Overall, people eat several thousand species of plants, of which about 200 have been domesticated. Of these, only 12 species account for about 80% of global food production (Diamond, 1999). They are:

- five cereals: wheat, maize, rice, barley, and sorghum
- one pulse: soybean
- three root or tuber crops: potato, manioc, and sweet potato
- two sweeteners: sugar cane and sugar beet
- the soft fruit banana Of these top-12 crops, the cereals account for about half of the calories that are consumed.

As we examined in Chapter 14, the cultivation of agricultural crops is an extremely important economic activity. The Canadian production of cereal crops was 66.4-million tonnes in 2013 (a 31% decrease from a decade earlier), while that of root and tuber crops was 4.6-million tonnes (14% decrease), and meat 4.5-million tonnes (7% increase) (FAO, 2015). The most important plant crops grown in Canada are listed in Table 24.1. Note the general increase in crop productivity (yield) during the 20-year period, due to an intensification of management practices. Note also the large increases in the production of certain crops, in particular canola, lentils, peas, and soybean. The production of wheat, barley, and maize also increased, partly in response to improved opportunities to export these commodities.

Table 24.1. The Production of Leading Plant Crops in Canada over a 20-year period (in 2014 and 1995). Crops are listed in order of decreasing area harvested. Source: Data from Statistics Canada (2014a,b).

Crop	Area (10^6 ha)		Production (10^6 t)		Yield (t/ha)	
	2014	1995	2014	1995	2014	1995
Wheat	9.46	11.12	29.28	24.99	3.1	2.2
Canola	8.07	5.27	15.56	6.43	1.9	1.2
Soybean	2.24	0.82	6.05	2.3	2.7	2.8
Barley	2.13	4.36	7.12	13.03	3.3	3
Peas	1.47	0.79	3.44	1.45	2.3	1.8
Maize	1.23	1	11.49	7.28	9.4	7.3
Lentils	1.18	0.33	1.84	0.43	1.6	1.3
Oats	0.91	1.21	2.91	2.87	3.2	2.4
Flaxseed	0.61	0.86	0.85	11.1	1.4	1.3
Rye	0.08	0.16	0.19	0.31	2.4	1.9
Potatoes	0.14	0.14	2.01	1.66	23.8	1.89
Sugar Beet	0.02	0.01	0.57	1.03	71.7	41.6

Management Systems

Various management practices and systems, which vary greatly in their intensity, can be applied to the cultivation of any crop plant (or to livestock). The most intensive systems may involve cultivating a monoculture (only one crop species) using a series of such practices as tilling the soil, planting, applying fertilizer and pesticide, and a harvest when the crop is ripe. Intensive agricultural systems are typically used on relatively large farms and they rely on specialized, fossil-fuelled machinery (known as mechanization). Intensive systems may also be used on smaller farms in order to achieve higher production on a limited area of land.

The use of intensive agricultural systems is common in relatively developed countries, such as Canada. It also occurs in plantation-style agriculture in less-developed countries, where commodities are grown mostly for an export market. In contrast, subsistence farming, as is commonly practised by poor people in less-developed countries, involves little or no use of fertilizer or pesticide and no mechanization. So-called organic agricultural systems used in developed countries also eschew the use of synthetic fertilizer and pesticides (this approach to farming is examined in detail later in this chapter).

Key practices for growing crop plants in intensively managed systems include the following:

- selective breeding of crop varieties for higher yield, greater response to management practices, adaptation to local climatic or soil conditions, and resistance to disease or herbicide
- tilling the soil so that seeds can establish and to reduce competition from weeds
- planting the crop at an optimal spacing, usually as a monoculture, to increase productivity and the ease of harvesting
- applying inorganic fertilizer or organic matter (including animal dung) to enhance the nutrient supply
- irrigating to enhance the availability of water
- controlling weeds by mechanical means (such as tillage) or by the use of herbicide
- controlling invertebrate pests using pesticide (most commonly insecticide or nematicide), by introducing diseases or predators of the pests, or by managing the habitat to make it less suitable for them
- controlling fungal pathogens by using fungicide or by managing habitat to make it less suitable
- harvesting the crop biomass as efficiently as possible
- developing crop-rotation systems that maintain site quality and help prevent the build-up of pests and pathogens
- using mechanized systems to till the soil, plant seed, apply fertilizer and pesticide, and harvest the crop
- cultivating some crops, such as tomato and cucumber, in greenhouses
- developing so-called organic systems that maintain high crop yields while reducing or eliminating the use of synthetic fertilizer and pesticide

As we noted previously, intensive management systems vary greatly among crop species and among regions, and it is far beyond the scope of this chapter to describe such systems in detail. Nevertheless, we can get an idea of what an intensive system can involve by examining case studies dealing with selected crops (see Canadian Focus 24.1, 24.2, and 24.3). Practices used in organic agriculture are examined later in this chapter.

> Canadian Focus 24.1. Growing Wheat on the Prairies Wheat is the most important crop grown in Canada, ranking first in both area under cultivation (average of 9.5-million hectares sown during 2010-2014) and harvest (28.5-million tonnes annually during the same period). Most wheat is grown on large, mechanized farms in the Prairie Provinces. The management system used depends on the climatic zone and soil type. The practices described here are recommended for spring-planted wheat in the dark-brown soil zone of Saskatchewan (Saskatchewan Agriculture and Food, 2014).

- Tillage: No ploughing is recommended, and instead the wheat is directly seeded into the soil using specialized tractor-drawn machinery.
- Choosing the Variety: Different varieties are used in the various climatic regions of the Prairie Provinces (about eight varieties are commonly grown). Each is bred to be adapted to local growing conditions, responsive to management practices, and resistant to diseases and pests.
- Planting: Wheat seeds are directly planted through the stubble of the previous crop (the over-wintering crop residues help to prevent erosion, conserve soil moisture, and add organic matter to the soil). The recommended planting rate is 0.11 m^3 of seed per hectare.
- Fertilizer: Inorganic fertilizer is added at a rate of 50 kg nitrogen per hectare and 25 kg phosphorus/ha.
- Weed Control: One or more herbicide applications are required, including a pre-planting treatment with glyphosate.
- Pathogens: Various fungal pathogens may affect wheat, including stem rust (Puccinia graminis tritici), loose smut (Ustilago tritici), and powdery mildew (Erysiphe graminis). These may be controlled by planting resistant varieties, by the use of cultivation practices that make the habitat less suitable for the pathogen, and by using fungicide. Wheat is also susceptible to bacterial pathogens such as leaf blight (Pseudomonas syringae), which are managed by using disease-free seed and by growing wheat in rotation with other crops.
- Insect Control: Pest insects include irruptions of grasshoppers (Melanoplus spp.) and the orange wheat-blossom midge (Sitodiplosis mosellana). One or more insecticide treatments may be required. Some pests can be controlled by cultivation practices, including residue management and growing wheat in rotation with other crops.
- Harvesting: Wheat is harvested using specialized combine harvesters.
- Other Considerations: This management system should be a component of a crop rotation, such as: grow canola in year 1, spring wheat in year 2, lentils in year 3, durum wheat in year 4, and summer fallow in year 5,. There is no tillage except at the beginning of year 1 (canola); all other crops are direct-seeded. The practice of direct-seeding helps to reduce erosion.

Image 24.2. Farming in Canada mostly involves intensively managed, mechanized operations. This photo shows a combine harvesting wheat in Alberta. Source: M. Willison.

Canadian Focus 24.2. Growing Potatoes in the Maritimes One of the most intensive management systems used in Canada involves the cultivation of potatoes in the Maritimes, particularly in Prince Edward Island and New Brunswick. The practices described below are typically used on relatively large, mechanized farms (Atlantic Potato Committee, 1993).

- Tillage: The first tilling is done before planting to break up the soil and facilitate drainage and aeration. This may be done in late autumn or early spring. Tilling in the spring avoids some of the erosion occurs if sloped fields are ploughed in the autumn and left without a cover of crop residue or winter rye. However, spring tilling requires that the fields be dry enough to support heavy machinery, so it often results in a later seeding and less growing time for the crop. A lighter, secondary tillage prepares the seedbed and is followed by periodic between-row tillage to reduce the abundance of weeds as the crop grows.
- Choosing the Variety: Specific varieties are grown, with the choice depending on site conditions and whether the crop is to be used as table potatoes, to process into frozen fries or potato chips, or to be used as "seed" (see below). About 20-25 varieties are cultivated in the Maritimes (of which six-eight comprise about 80% of the crop). However, this is only a fraction of the diversity of the potato – hundreds of local cultivars are grown in the Andean highlands, where this crop was first domesticated.
- Preparing the "Seed": Potatoes are grown from slices of a tuber that contains several "eyes" (a bud from which a shoot can sprout). The "seed" is surface-sterilized and dusted with fungicide to prevent soft rot and other diseases. This is a vegetative (or clonal) means of propagation that results in plants being genetically identical.

- Planting: Once the soil temperature exceeds 7°C, seed potatoes are planted 15-40 cm apart and 8-13 cm deep, in rows 90 cm apart, and overall equivalent to a density of 28-74/m^2. A wider spacing is used for food crops and a closer one for seed potatoes. A tractor-drawn planter is used in the planting.
- Fertilizer: Potatoes are a "soil-depleting" crop, so fields must be treated with fertilizer, typically at 800-1000 kg/ha-year with a 15-15-15 NPK fertilizer (this means that the fertilizer contains 15% each of nitrogen, phosphorus, and potassium). Fertilizer is applied when the seed is planted and often during the growing season as well
- Liming: The optimum soil pH is 5.5-6.0, largely to prevent fungal disease. This pH range is maintained by adding agricultural lime or crushed limestone.
- Weed Control: Weeds are controlled by between-row tillage, which is done several times during the growing season. Herbicide may also be used, typically one spray per year.
- Fungal Pathogens: Late blight (Phytopthora infestans) can destroy potato crops, and it is controlled by growing resistant varieties, destroying waste tubers, and spraying fungicide. Other fungal diseases are early blight (Alternaria solani), verticillium wilt (Verticillium spp.), and pathogens that cause stored tubers to rot. These are controlled with fungicide and by using cultivation practices that develop conditions that are less favourable to the pathogens. A range of 5-15 fungicide treatments are required per year, depending on the severity of the problem.
- Other Pathogens: Bacterial and viral diseases are controlled by growing disease-free seedstock and by using cultivation practices that are less favourable to the pathogens.
- Pest Control: The Colorado potato beetle (Leptinotarsa decemlineata) is the most important pest, but other beetles, aphids, and additional insects may also cause damage. Typically 2-5 sprays of an insecticide are needed per year. The root-lesion nematode (Pratylenchus neglectus) and other nematodes are controlled by crop rotation or by fumigation with a nematicide.
- Top-Killing: This aid to harvesting involves one or two late-season sprays with a non-systemic herbicide to kill the potato vines and to induce the tubers to form a firmer skin, which gives them a degree of protection during harvesting and storage. Although the vines will die back naturally, top-killing with herbicide allows for a controlled timing of the harvest.
- Harvesting: Specialized tractor-drawn machinery is used to harvest potatoes, typically four rows at a time.
- Other Considerations: Continuous cultivation of potatoes results in a depletion of tilth and organic matter, compaction by machinery, erosion from slopes, and a buildup of pathogens and pests. Consequently, potatoes are best grown in a three-year rotation with a cereal and forage crop. Measures to enhance soil organic matter are recommended, such as adding manure, leaving crop residues, and using a green-manure crop in the rotation. Although potatoes can be grown without pesticide, this is considered impractical in industrial agriculture.

Image 24.3. A field of potatoes in flower in Prince Edward Island. Source: B. Freedman.

Livestock

Livestock are raised primarily as sources of food. The most important domesticated livestock in Canada are the cow (Bos taurus), horse (Equus caballus), pig (Sus scrofa), sheep (Ovis aries), and goat (Capra hircus). The most prominent birds are chicken (Gallus gallus), duck (Anas platyrhynchos), and turkey (Meleagris gallopavo). The most important fish are Atlantic salmon (Salmo salar) and rainbow trout (Oncorhyncus mykiss) – the cultivation of fish is known as aquaculture. Ranching of non-domesticated livestock, such as bison (Bison bison) and elk (Cervus elaphus), is also increasing.

Livestock in developed countries are mostly grown under intensive management systems. In large part this involves rearing animals on "factory farms," although beef cattle may spend much of their lives foraging on rangeland, as do sheep. Key practices for growing livestock under intensive management include the following:

- selective breeding of varieties for higher yield and greater response to management practices
- developing "tame" or converted (seeded) pastures to supply fresh fodder, and hayfields for hay feeding, silage production, or bedding
- feeding livestock with concentrated foods that are manufactured from fish, slaughterhouse offal (meat "wastes"), pulses, and other products, together with mineral supplements
- using antibiotics and other medicines to prevent or treat diseases
- using growth hormones to increase production in certain animals (particularly cows)

- killing natural predators of free-ranging livestock, such as bear, cougar, coyote, and wolf
- confining livestock in dense feedlots or factory farms, with feeding to satiation and other intensive husbandry practices
- developing organic systems that maintain high yields of livestock, while reducing or eliminating such intensive practices as close confinement and the routine use of medicines and growth hormones

Again, it is beyond the scope of this chapter to describe intensive management systems for livestock in detail. We can, however, examine a case study to get an idea of what the systems may involve (Canadian Focus 24.3).

Canadian Focus 24.3. Raising Livestock on Factory Farms Enormous numbers of animals are raised in Canada to provide meat, milk, eggs, and other products. In 2013, about 167-million chickens were slaughtered, as were 5.7-million turkeys. The most important livestock are cows (16 million including 2-million milk cows) and pigs (26 million) (Chapter 14).

To increase productivity, most poultry, cows, and pigs are reared on "factory farms" in extremely crowded quarters, with feeding to satiation, plus other intensive practices. (However, many cows spend much of their life on rangeland or pasture, being kept under close confinement only during a "finishing" phase of rapid growth in a feedlot before slaughter.)

Because of the obvious potential for treating animals cruelly under such conditions, livestock rearing on factory farms is a controversial practice. Animal-rights groups protest against the conditions imposed on livestock during rearing, transportation, and slaughter. In addition, many people choose to not purchase foods from factory farms, or they have adopted a vegetarian lifestyle in order to not participate in what they consider an inhumane economic activity. Partly because of these protests, factory farms have become well-guarded facilities with tightly controlled access.

Agriculture Canada, the Canadian Federation of Humane Societies, and food-industry associations have developed guidelines for the acceptable treatment of livestock in our country. The following is a list of recommended practices for rearing livestock; all are routinely used on industrial farms and are considered "acceptable" by regulators (Agriculture Canada, 1989, 2009, 2013).

Poultry

- The distal third of the beak and tips of the toes may be amputated to prevent injuries from fighting under close confinement.
- Non-saleable chicks may be euthanized by maceration (grinding), lethal exposure to CO_2 or CO, electrocution, or decapitation.
- Day-old chicks may be transported from a hatchery to a rearing facility in boxes containing no more than 100 chicks and providing each with a floor space of at least 21 cm^2 (about four times the area of a $1 coin). The transportation should not exceed 48 hours.
- For the production of eggs by chickens living in an open pen, mature birds (up to 1.8 kg) should be provided with the equivalent of at least 0.2 m^2 of space (this is three times the area of a letter-sized piece of paper). For the production of meat in an open pen, mature birds (> 3.6 kg) require 0.186 m^2 each. This is considered sufficient to allow the chickens to stand, turn around, and stretch their wings. Smaller chickens may be provided with less space.
- For chickens reared in cages, mature birds (up to 2.2 kg) should have at least 0.045 m^2 each (0.75 times a letter-sized paper). No more than seven adult birds should be in one cage.
- The concentration of ammonia in the air during rearing should be less than 25 ppm. (At this level, a person would experience considerable discomfort.)

Cows

- A mature dairy cow should have a space of at least 11 m^2, and a pregnant cow 15 m^2. These dimensions are considered sufficient to allow the cow to groom, get up and lie down, and stretch its limbs.
- Mature beef cattle that are confined in a feedlot, with paved ground and a shed for cover, should have a space of at least 4.5 m^2 per animal.
- If there is no shed, the space should be at least 8 m^2. A somewhat larger area is needed if the ground is not paved.
- The concentration of ammonia in the air during rearing should be less than 25 ppm.

Pigs

- Mature pigs (> 110 kg) confined in a slat-floored stall (this allows drainage of feces and urine) should be provided with a space of at least 1.8-2.2 m^2 per animal. If non-slatted, there should be at least 2.0-2.4 m^2 per animal. These dimensions are considered sufficient to allow the pig to get up and lie down comfortably. Smaller animals may be provided with less space.
- Breeding sows > 340 kg kept in an individual stall should have a space at least 80 cm wide and 210 cm long (1.5 m^2). Smaller animals may be provided with less width.

There are also recommended practices for transporting livestock from rearing facilities to slaughterhouses, which is usually by truck or train. For example, cows and other ruminant animals can be transported for as long as 52 hours without receiving any water, food, or rest. For pigs, horses, and poultry this period is 36 hours.

Guidelines for the humane killing of animals also exist. This is usually done by electrocution, shooting, or bleeding, and sometimes by lethal injection. All of these practices are controversial because many people regard them as inhumane. Moreover, facilities for rearing, transporting, and slaughtering animals are inspected irregularly, and sometimes infrequently. This means that, in many respects, compliance with the guidelines is voluntary.

Environmental Impacts of Agriculture

Declining Site Capability

Agricultural site capability (or site quality) refers to the ability of an ecosystem to sustain the productivity of crops (Chapter 14). Soil fertility is an important aspect of this – it is related to the amount of nutrients present and to factors affecting their availability, such as drainage, tilth, and organic matter in the soil. Site quality can be degraded by agricultural practices, which may result in the erosion of topsoil, loss of organic matter and nutrients, and a buildup of weed populations. These result in decreased crop yields, which may then require intensive management practices (such as fertilizer and herbicide application) to try to compensate for the damage. Allowing site quality to degrade is a non-sustainable use of agricultural land.

Nutrient Loss

As plants grow, they take up nutrients from the soil (Table 24.2). When a crop is harvested, the nutrients contained in their biomass are removed from the site. The ability of the soil to supply nutrients may then diminish if the removals exceed the rate at which nutrients are regenerated by atmospheric deposition, nitrogen fixation, and the weathering of soil minerals.

In fact, nutrient depletion is a common problem with agricultural systems, and it is most often treated by applying inorganic fertilizer to the land. However, careful attention to the conservation of organic matter and nutrient content of soil can greatly alleviate nutrient depletion and may even eliminate the need to add inorganic fertilizer (we examine this later in the context of organic agriculture).

In any event, the use of fertilizer in agriculture has increased greatly in Canada. In 1971, fertilizer was added to about 6.9-million hectares, but this increased to 25-million hectares in 2011 (Chapter 14). Canadian fertilizer application rates are considerably lower than in some other countries: in 2012, an average of 66 kg of fertilizer was applied per hectare of agricultural land in Canada, compared with 443 kg/ha in China, 234 kg/ha in Japan, 124 kg/ha in France, and 116 kg/ha in the United States. In countries with the highest rates of fertilizer application, agricultural land is relatively valuable and property taxes are high, which creates an economic incentive to use intensive management practices to increase the productivity.

Table 24.2. Annual Uptake of Key Nutrients by Selected Crop Species. Data are in kg/ha. Sources: Data from Hausenbuiller (1985) and Atlantic Potato Committee (1993).

Crop	Nitrogen	Phosphorus	Potassium
Alfalfa	500	40	450
Soybean	375	30	134
Orchard grass	335	50	350
Bluegrass	225	25	165
Potato	211	40	321
Wheat	210	25	150
Maize (corn)	200	40	200
Barley	170	25	140
Oats	170	25	140
Hardwood forest	95	9	30

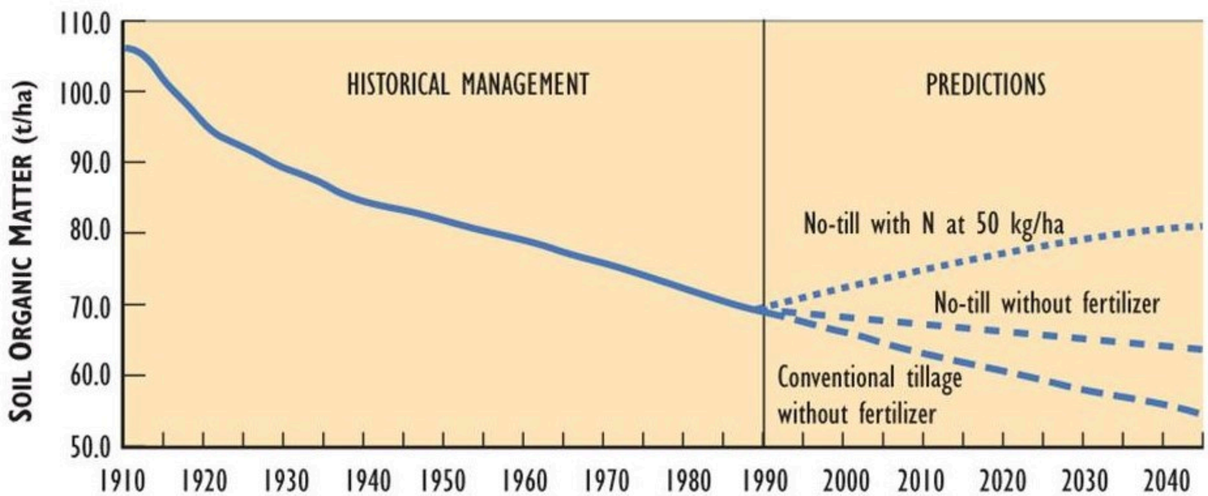
Often, the rate of fertilizer application is intended to satiate the needs of the crop so that its productivity is not limited by the availability of nutrients. This may result in an excess of nutrients in the soil, which may cause several environmental problems:

- pollution of the groundwater with nitrate
- eutrophication of surface waters
- acidification caused by the nitrification of ammonium to nitrate (which is followed by the leaching of nitrate)
- emission of nitrous oxide to the atmosphere
- a need to use herbicide to control the weeds that flourish under fertile conditions Fertilizers are manufactured from non-renewable resources, and large amounts of energy are used in the process. The principal sources of fertilizer are:
- urea and ammonium nitrate, which are manufactured by combining nitrogen gas with hydrogen obtained from methane (or natural gas)
- phosphate fertilizer made from mined rock phosphate
- potassium from mined potash

Organic Matter

Soil organic matter is a crucial factor that affects fertility and site capability. Organic matter has a strong influence on the capacity of soil to hold water and nutrients, and on its aeration, drainage, and tilth (see Chapter 14). Typical agricultural soil has an organic concentration of 1-10% (it can exceed 90% in the peaty substrate of drained wetlands, but this soil is uncommon in agriculture). This is considerably less than what occurs in the soil of natural prairie or forest. Those natural ecosystems have a surface layer of litter and humus, and within the mineral soil itself the concentration of organic matter is at least 15-30% higher than occurs in agricultural soil (Acton and Gregorich, 1995). Therefore, when an area of prairie or forest is converted to an agriculture use, there is a large decrease in the amount of organic matter on the surface and within the mineral soil (Figure 24.1). A depletion of organic matter is widely regarded as an important problem that affects the sustainability of agricultural production.

Figure 24.1. Changes in Organic Matter in a Prairie Soil. The data are for the surface 30 cm of soil and reflect historical management practices of annual tillage and fertilizer application. The data since 1990 show the potential effects on soil organic matter of conventional tillage without fertilizer, no-tillage without fertilizer, and no-tillage with nitrogen fertilizer at 50 kg/ha-y. Source: Modified from Acton and Gregorich (1995).



Several practices are recommended for increasing the amount of organic matter in soil. They include adding crop residues, livestock manure, or other organic-rich materials, such as composted municipal waste or sewage sludge. The use of no-tillage or low-tillage systems is also helpful, because ploughing encourages the decomposition of organic matter (no-tillage involves sowing seeds by drilling them directly into the ground without prior cultivation). The use of no-tillage in combination with fertilizer application is also effective at increasing organic matter in prairie soil (Figure 24.1). The regular addition of manure is also useful. A 50-year study in Ontario found that yearly additions of manure increased the organic matter in soil from an initial 85 t/ha to 100 t/ha, compared with 56 t/ha where no manure was applied (this is within the plough depth of the soil, about 30 cm; Environment Canada, 1996).

Soil Erosion

Soil is eroded by wind and by the runoff of rain and melted snow. Although erosion is a natural process, its rate can be greatly increased by agricultural practices, and this may be a serious environmental problem. Erosion represents a loss of soil capital, which can impoverish site capability and can cause deep gullying of fields, a damage that is almost impossible to rehabilitate. Erosion also damages aquatic ecosystems by increasing sedimentation and turbidity, which are destructive of fish habitat. Wind-eroded soil can also be a local nuisance (for example, as a source of dirt inside homes and by soiling laundry hung out to dry), and in severe cases it can literally bury machinery and buildings (as occurred on the prairies during the “dust-bowl” years of the 1930s).

Agricultural practices that increase the rate of soil erosion include the following:

- cultivating land on moderate to steep slopes
- ploughing furrows up and down slopes rather than contouring along them
- leaving fields without a cover (such as stubble or a cover-crop) during the winter

Averaged across Canada, about 20% of the cultivated land is at severe or high risk of erosion caused by flowing water. However, this varies greatly among the provinces, with British Columbia having 75% of its cultivated land in this risk category, New Brunswick 80%, and Prince Edward Island 81% (Table 24.3). Although land in the southern Prairie Provinces is at relatively low risk from water erosion, it is prone to wind-caused erosion (because there are few trees, and fields are often left bare in winter). On average, 36% of the cultivated land in the prairie region is at severe or high risk of wind erosion, and 29% is at moderate risk.

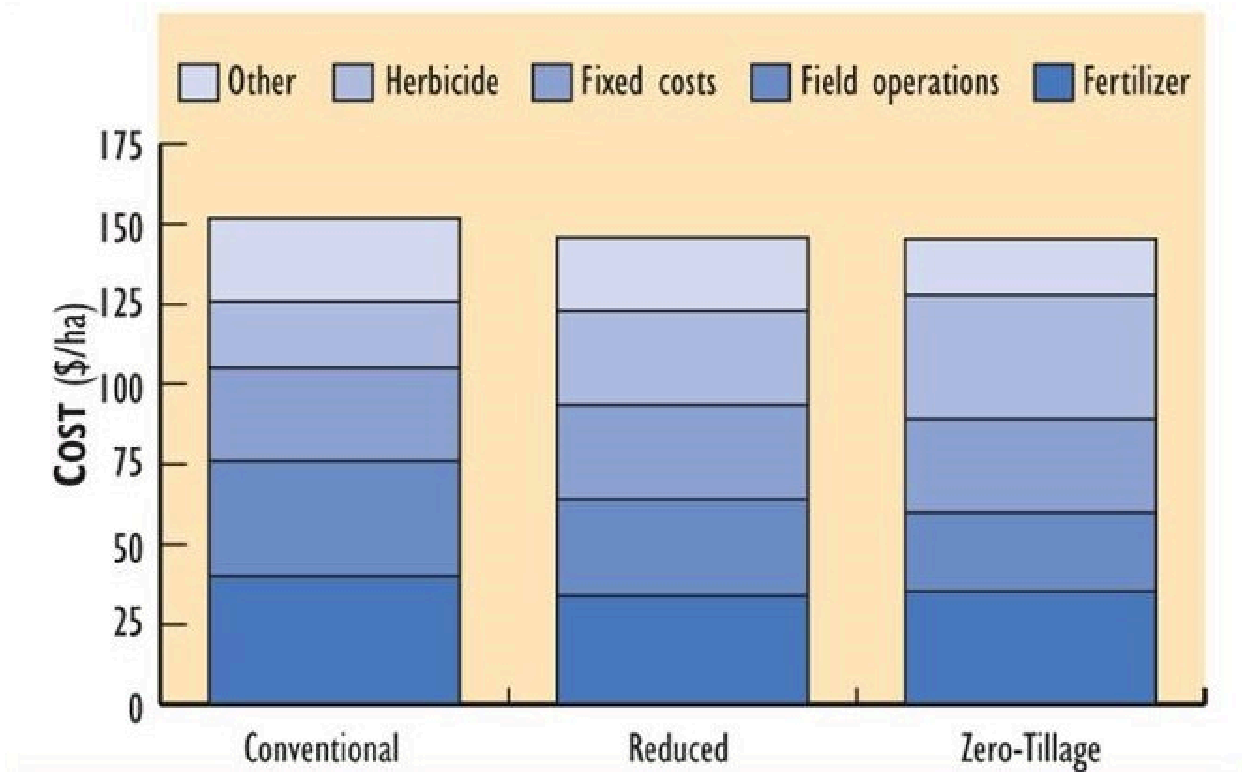
Table 24.3. Risk of Erosion by Water on Cultivated Land. Data are percent of cultivated land. Source: Data from Acton and Gregorich (1995).

Province	Negligible-Low	Moderate	High	Severe
Canada	63	17	7	13
BC	13	13	3	72
AB	55	17	10	18
SK	76	19	3	1
MB	76	6	4	14
ON	23	24	25	27
QC	39	14	4	43
NB	4	16	13	67
NS	9	4	3	84
PE	8	11	37	44

Fortunately, there is an increasing use of soil-conservation practices (such as those listed below), and this is reducing the risks of erosion by wind or water:

- leaving crop residues and/or stubble in the field
- using longer crop rotations
- incorporating a forage crop into the rotation
- growing winter cover-crops (such as winter wheat)
- planting perennial shelter-belts (such as trees)
- strip-cropping
- not cultivating beside streams (leaving a riparian buffer)
- ploughing along contours rather than across them
- using no-till or low-till planting (Figure 24.2)
- maintaining perennial pastures (instead of using erosion-prone land for crops)

Figure 24.2. Costs of Tillage Systems. The data are for prairie wheat, obtained by a survey of 250 fields in Alberta during 1988–1992. Conventional tillage results in crop residues being incorporated into the soil. Reduced tillage leaves crop residues on the surface, helping to reduce erosion. Zero-tillage involves no cultivation; the crop seed is drilled into the ground. Note that the three systems have similar overall costs: $152, $146, and $145, respectively. The no-tillage system incurs higher herbicide cost because tillage helps to reduce the abundance of weeds. The greater use of herbicide is, however, offset by lower operating and fertilizer costs. There is also, of course, an environmental benefit because less erosion is caused. Source: Modified from Acton and Gregorich (1995).



Compaction

The frequent passage of heavy machinery, or the yarding of a dense livestock population, can compress the air spaces in soil, a condition known as compaction. Soil compaction is a serious problem that results in waterlogging, oxygen-poor conditions, impaired nutrient cycling, poor root growth, and decreased crop productivity. Compaction can be largely avoided by avoiding any unnecessary passages of heavy machinery over fields, using large tires to spread the load, and reducing the density of livestock kept in outdoor stockades.

Salinization

The buildup of soluble minerals in the surface soil, or salinization, is a major problem in drier regions. The most important salts are usually sulphates and chlorides of sodium, calcium, and magnesium, which in severe cases are visible as a whitish crust on the surface. Salinization occurs when there are high concentrations of salts in the soil, and the rate of evaporation exceeds the water input from precipitation. These conditions bring salts to the surface, where they are deposited as the water evaporates. Irrigation practices can also be a cause of salinization if insufficient water is added to allow dissolved salts to drain to below the rooting depth of the crop. Saline soil is toxic to most crops, largely because of interference with the uptake of water, along with ion imbalance and toxicity.

In Canada, this problem is mostly restricted to low-rainfall regions of the Prairie Provinces and to a small area in southeastern British Columbia. About 2% of the cultivated land in the Prairies has more than 15% of its area affected by salinization, while 36% has 1-15% of the area affected, and the remaining 62% has < 1% affected (Acton and Gregorich, 1995).

The control of salinization requires practices that keep the height of the water table low or prevent dissolved salts from rising. These practices include the diversion of surface flows, installation of a subsurface drainage system, using longer crop rotations (including deep-rooted forage species), practising conservation tillage, and increasing organic matter in the soil. Salt-tolerant crops may be grown on moderately salinized soil, such as barley (Hordeum vulgare) or forage plants such as alfalfa (Medicago sativa) and slender wheatgrass (Agropyron trachycaulum).

Desertification

The increasing aridity of drylands, or desertification, can make agriculture difficult or impossible. Desertification may be affecting as much as 30% of the land surface of the planet, directly affecting 250 million people and putting another billion at risk in more than 100 countries (FAO, 2007). Desertification is a complex problem, caused by both climate change and other anthropogenic influences. The latter include unsustainable land-use practices in drylands, such as over-grazing, intensive cultivation, deforestation (often to obtain fuelwood), and improper irrigation. These practices can cause the loss of topsoil and vegetation cover and a degradation of agricultural capability. These effects are greatly intensified by drought.

Desertification is largely a problem of regions that are already marginal in terms of the amounts of precipitation and soil moisture that are available to support agriculture. The best-known cases occur in less developed countries, such as dryland regions in Africa, south and central Asia, and Latin America. However, it is also an important problem in the interior regions of North America and Australia. In Canada, about 300-thousand km^2 in southern Alberta and Saskatchewan are at risk of desertification. This region experienced widespread loss of topsoil by wind erosion during the drought of the 1930s, and it is still vulnerable to this degradation. The best agricultural land-use in this semi-arid region is livestock grazing on unbroken perennial range. The development of “tame” pastures and the cultivation of annual crops are more likely to cause desertification.

Pollution Caused by Agriculture

Groundwater and surface waters can become polluted by runoff containing fertilizer, pesticides, and livestock sewage. Inputs of nutrients and organic matter from fertilizer and sewage can cause severe ecological damage to surface waters through eutrophication and oxygen depletion. These changes, coupled with the presence of pathogenic and parasitic organisms, can result in waters becoming unsuitable for drinking by people, perhaps even by livestock, or for use in irrigation (see Environmental Issues 14.1).

The worst problems involve the disposal of the enormous quantities of manure that are produced by livestock kept in feedlots and factory farms. These animals produce about 181-million tonnes of manure per year, considerably more than the amount of human feces produced in Canada (2.2 million tonnes per year) (Statistics Canada, 2009). Moreover, human fecal waste is mostly treated in sewage-treatment plants (Chapters 20 and 25) rather than dumped onto agricultural land or into surface waters, as is commonly done with livestock manure.

The most important agricultural pollutant of groundwater is nitrate, which originates with manure applications to farmland and the use of fertilizer. This problem occurs because the nitrate ion (NO3–) leaches readily with water that percolates through the soil to groundwater (nitrate is highly soluble in water and is not retained by ion-exchange reactions in the soil). Nitrate pollution is a hazard for people who use groundwater as a source of drinking water. Although nitrate itself is not very toxic, it is converted by microbes in the human gut to nitrite, which when absorbed into the blood strongly binds with hemoglobin (forming a compound known as methemoglobin), thereby reducing the capacity to carry oxygen. Children are especially vulnerable to this effect; the so-called “blue-baby syndrome” refers to oxygen-starved infants who have been poisoned by nitrate in their drinking water or food.

Nitrate pollution of groundwater is a widespread problem. A study of 900 rural wells in southern Ontario found that 15% had concentrations exceeding the safe limit (the Health Canada guideline is 10 ppm of NO3-N). A study in the Okanagan Valley of British Columbia found that 33% of wells have nitrate contamination (Acton and Gregorich, 1995).

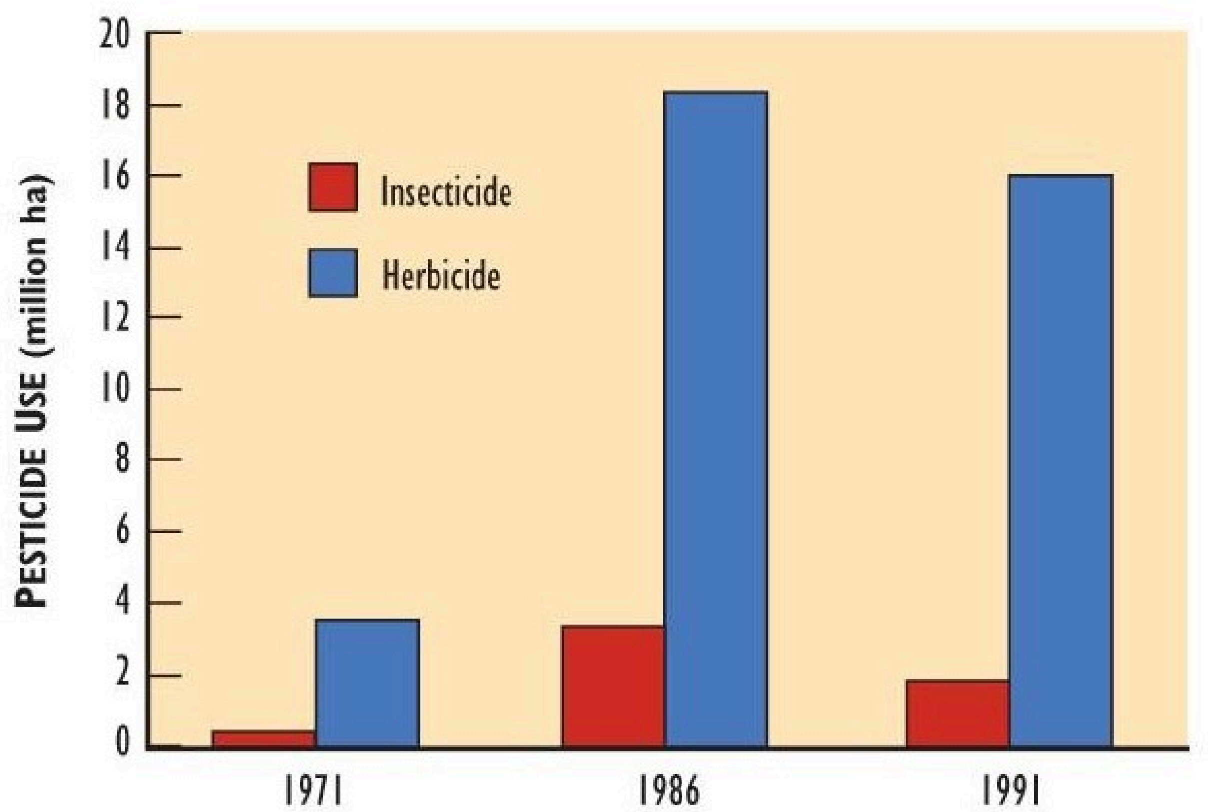
In fact, nitrate exceeding hundreds of ppm (as NO3-N) has been found in groundwater in agricultural regions as a result of the application of manure and/or fertilizer. This important and extensive problem can only be resolved through more prudent fertilizer application and by prohibiting the disposal of untreated manure onto agricultural land. Manure should undergo sewage treatment, just like most human sewage does (Chapters 20 and 25).

The dumping of raw manure can also pollute groundwater and surface waters with fecal coliforms and other intestinal pathogens and parasites. These are health hazards to anyone using a polluted waterbody or aquifer as a source of drinking water or even for swimming. Health Canada has set a safe limit of 50 coliforms/L for drinking water, but this is commonly exceeded in well waters in areas where untreated manure is spread onto agricultural land. A study in Ontario found that 32% of 900 rural wells had coliform counts that exceeded the safe limit, and another in Ile d'Orléans in Quebec found that 83% of 35 sampled wells exceeded the limit (Acton and Gregorich, 1995).

Groundwater and surface waters can also be contaminated by agricultural pesticides, whose use has increased enormously (Figure 24.3). Moreover, some commonly used pesticides are highly leachable in soil, with important examples being atrazine, dinoseb, metolachlor, metribuzin, and simazine. Once a pesticide reaches groundwater, it may persist for a long time. Atrazine, for example, persists for at least five years.

A study of 900 wells in Ontario found that 12% had detectable concentrations of pesticides (mainly atrazine), although only 0.2% had residues exceeding the limit considered safe (5 μg/L of atrazine). Another study in the Annapolis Valley of Nova Scotia found pesticides in 41% of domestic wells (again, most frequently atrazine), but none exceeded the safe limit (Acton and Gregorich, 1995). Moreover, important damage has been caused to wildlife (including birds and mammals) by seasonal residues of carbofuran, diazinon, and some other insecticides (see Chapter 22).

Figure 24.3. Changes in Pesticide Use in Agriculture in the Prairie Ecozone. Source: Modified from Acton and Gregorich (1995).



Extremely large areas of natural habitat have been converted into agroecosystems that are used for the production of food. This change has resulted in huge losses of natural ecosystems, and in some regions, grievous damage has been caused to indigenous biodiversity (see Chapter 26).

Agricultural conversion is the leading cause of deforestation in the world today, particularly in subtropical and tropical countries. In southern Canada (especially in southern Quebec and Ontario), almost all of the initially forested land with good capability for agriculture has been converted into crop production (or into urbanized land-use). The deforestation has imperilled the Carolinian ecosystem and its many endangered species in southwestern Ontario (see Chapters 8 and 26). Similarly, the tall-grass prairie of southeastern Manitoba and southwestern Ontario (the Windsor area) has become endangered through agricultural conversion, as have the semi-desert and desert of extreme southern Saskatchewan, Alberta, and British Columbia. Although not yet critically endangered, the mixed-grass and short-grass prairies of western Canada are also threatened by agricultural conversion. In fact, most of the rare and endangered plants and animals of the original ecosystems of southern Canada are at risk because of the loss of their natural habitat to agriculture.

The damage to biodiversity occurs because agricultural ecosystems typically provide poor habitat for native species. This is because agroecosystems are simple in their physical structure (especially compared with natural forest) and are strongly dominated by alien plants and animals. For example, natural hardwood forest in Quebec and Ontario may sustain a diverse assemblage of hundreds of native vascular plants, bryophytes, and lichens, as well as more than 80 species of birds and other vertebrate animals and perhaps thousands of invertebrates. When that natural forest is converted to, for example, cultivated pasture for livestock, it becomes dominated by only a few forage plants that are not native to Canada. Those aliens include barnyard grass (Dactylis glomerata), meadow grass (Alopecurus pratensis), ryegrass (Lolium perenne and L. multiflorum), timothy (Phleum pratense), alfalfa (Medicago sativa), red clover (Trifolium pratense), and white clover (Trifolium repens). The pasture would also support other plants, including species considered to be “weeds,” but almost all would also be aliens.

Although highly productive in an agricultural context, such pastures are extremely degraded from the ecological perspective. The same is true, more or less, of other agroecosystems in Canada – they provide poor habitat for native species (the only notable exception is unbroken pasture in the Prairie Provinces, or grazing land that has never been ploughed and sown with alien forage plants).

The conversion of natural ecosystems into agroecosystems is an ongoing process in all countries. Private organizations such as the Nature Conservancy of Canada and other land trusts are attempting to purchase the best surviving tracts of natural habitat in order to protect them from being destroyed. To some degree, governmental conservation agencies are also working to do this. However, limited funds are available for this purpose, and the losses of natural habitat are proceeding rapidly (see Chapter 26).

> Image 24.4. Orchards of apples, peaches, and pears are forest-like in structure, but they contain only one species of tree (the crop) and are intensively managed to increase production and to control pests and diseases. Few native species are able to use these kinds of habitats. This orchard is on the Niagara Peninsula of southern Ontario. Source: B. Freedman.

Emissions of Greenhouse Gases

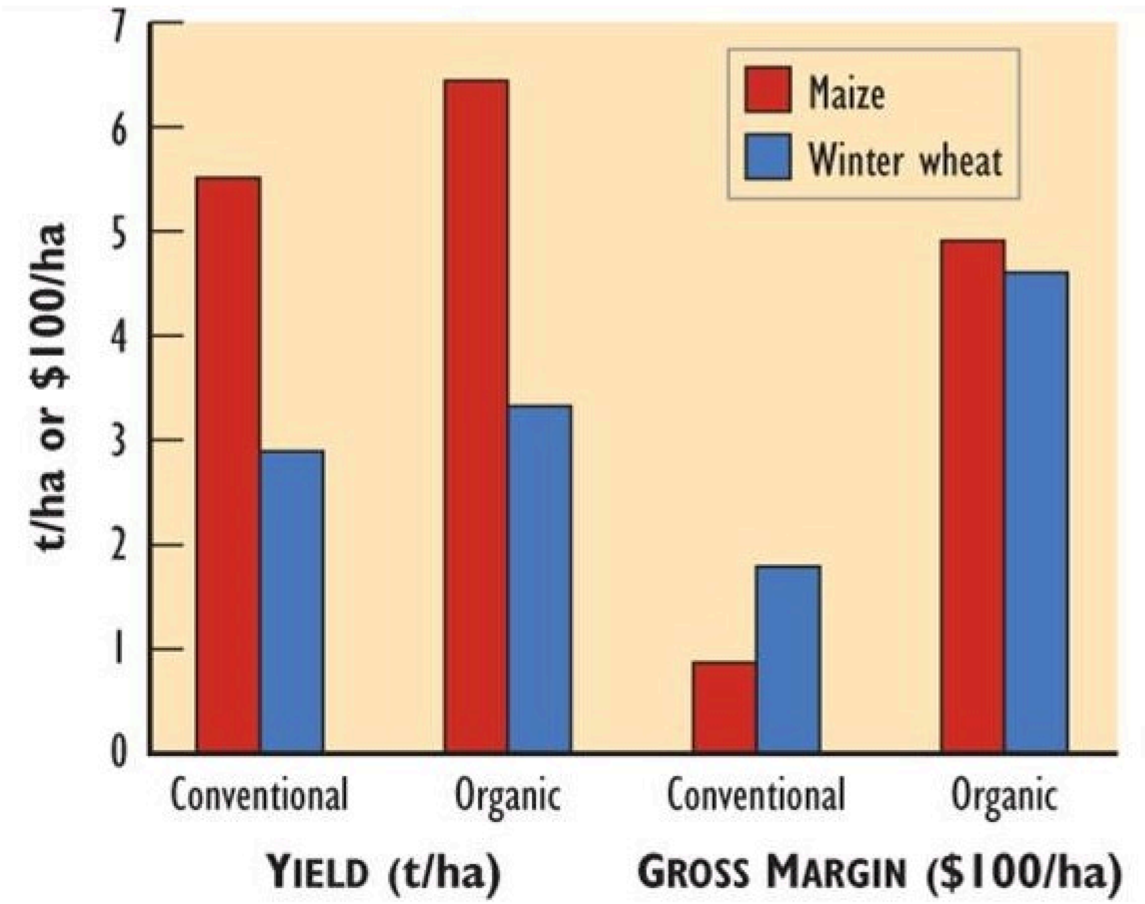
Deforestation and other conversions of natural habitat to agricultural use result in enormous emissions of carbon dioxide into the atmosphere (see Chapter 17). Natural ecosystems store a large amount of carbon in their plant biomass and soil. Because agroecosystems store much less organic carbon, a consequence of agricultural conversion is a large emission of CO_2 to the atmosphere. Since 1850, such conversions have resulted in almost as much CO_2 emission as has occurred through the combustion of fossil fuels. Prior to 1750, the atmospheric concentration of CO_2 was about 280 ppm, but by 2014 it had reached 399 ppm, a 43% increase. This change in atmospheric chemistry is an important problem because the increasing CO_2 may be helping to intensify Earth's greenhouse effect. In fact, increased CO_2 is responsible for about 60% of anthropogenic climate warming.

In addition, the use of nitrogen fertilizer results in high concentrations of nitrate occurring in the soil. This encourages the process of denitrification, which results in the emission of nitrous oxide (N_2O) to the atmosphere (Chapter 5). N_2O is also a greenhouse gas, having 310 times the warming potential of CO_2. The atmospheric concentration of N_2O has increased from about 0.27 ppm in 1750 to 0.33 ppm in 2014; this gas is responsible for about 5% of anthropogenic climate warming.

Organic Agriculture

In organic agriculture, crops are grown using relatively "natural" methods of maintaining soil fertility, and pest-control methods do not involve synthetic pesticides. Compared with conventional agricultural systems, less environmental damage is associated with organic agriculture, and it tends to result in more stable crop yields, which may even be higher in some cases (Figure 24.4). Moreover, operating costs may be lower in organic agriculture because expensive fertilizer and pesticides are not used. Overall, compared with more intensive agricultural systems, organic practices better sustain soil quality, energy and material resources, and ecological integrity.

Figure 24.4. Comparison of Conventional and Organic Agriculture in Southern Ontario. Gross margin is the revenue from the sale of the crop minus the direct costs of its production. The data are five-year averages during 1986–1990, involving the study of 234 ha of land managed by conventional practices and 228 ha of organic agriculture. Source: Data from Henning (1994).



Organic Agriculture and Soil Fertility

A major focus of organic agriculture is the maintenance of soil fertility by enhancing natural pathways of nutrient cycling as well as soil tilth. In natural ecosystems, microorganisms continuously recycle inorganic nutrients (such as nitrate, ammonium, and phosphate) from dead organic matter, most of which is plant litter. The microbes metabolize the complex organic forms of nutrients, converting them to simple inorganic molecules. The fixation of atmospheric N_2 by microorganisms is also an important source of nitrogen input in organic agriculture (this involves legume-bacterial mutualisms as well as free-living bacteria; see Chapter 5). Overall, the release of inorganic nutrients is typically slow enough that they can be effectively taken up by crop plants, so relatively little is lost to groundwater or surface water.

In conventional agriculture, most inorganic nutrients are added directly as synthetic fertilizer. In contrast, organic methods of maintaining fertility rely on the management and enhancement of soil organic matter, from which decomposition makes inorganic nutrients available to crops.

Organic matter is also critical to maintaining tilth, a vital soil property that helps to:

- bind nutrients and release them slowly for efficient uptake
- hold water so that it can be used more effectively by plants
- and give the soil an aggregated structure with good aeration and easy penetration by roots

In contrast, tilth becomes degraded in conventional agriculture because frequent ploughing increases the decomposition of soil organic matter, even while there are relatively small inputs of new organic matter from crop debris, and heavy machines compact the soil.

Organic farmers enhance the organic content and fertility of cultivated soil in three major ways.

1. They add livestock manure and urine (often these are first composted) to the soil because these materials contain useful organic matter and nutrients. However, as mentioned earlier, this practice must be controlled because excess applications can pollute groundwater and surface water with nutrients and pathogens and cause local air pollution with ammonia and odours.
2. They add green manure, which is living plant biomass that is incorporated into the soil by ploughing. The most fertile green manure is legume biomass, such as that of alfalfa and clover, because these fix atmospheric nitrogen gas, making them a good organic source of nitrogenous fertilizer. Organic farmers often grow legumes in a crop rotation to maintain soil nitrogen.
3. They add compost, or partially decomposed and humified organic material, to the soil. Composting is a partly aerobic process by which microbes and soil animals fragment and decompose organic material, eventually forming complex, high-molecular-weight humic substances. These are resistant to further decay and are extremely useful as a soil conditioner and organic fertilizer.

It is important to understand that growing plants take up the same inorganic forms of nutrients (such as nitrate, ammonium, and phosphate) from soil, regardless of whether they are supplied by organic practices or with manufactured fertilizer. The important difference is in the role of ecological processes versus manufacturing – organic methods rely on renewable sources of energy and materials, rather than non-renewable ones. Overall, the longer-term effects on soil fertility and tilth using organic practices are much less damaging than those associated with conventional agriculture.

Pest Management

All agroecosystems have problems with pests. In conventional agriculture, they are usually managed using pesticides (but often within the context of integrated pest management; see Chapter 22). Although pesticides can reduce the effects of pests on the yield of a crop, their use may cause environmental damage. Instead of synthetic pesticides, organic farmers rely on other methods of pest management, such as the following:

- using crop varieties that are resistant to pests and diseases
- using biological pest management by introducing or enhancing populations of natural predators, parasites, or diseases
- changing habitat conditions to make them less suitable for pests, for example, by growing crops in mixed culture rather than monoculture, by rotating crops or using a fallow period to avoid a buildup of pest populations, and by using mechanical methods of weed control such as hand-pulling and shallow inter-row ploughing
- undertaking careful monitoring of pest abundance, so control tactics are used only when necessary

- using pesticides that are based on natural products, such as an insecticide based on the bacterium Bacillus thuringiensis (B.t.) that may be considered acceptable in organic agriculture, or one based on pyrethrum extracted from a daisy-like plant, but not their synthetic analogues, such as genetically engineered B.t. or synthesized pyrethroids

Organic farmers, as well as the consumers of their produce, must be relatively tolerant of some of the damage and lower yields that pests may cause. For example, most consumers of organic produce are satisfied with apples that have some blemishes caused by the scab fungus (Venturia inaequalis), and aesthetic that does not affect the nutritional quality or safety of the apples. In conventional agriculture, this cosmetic damage is managed using fungicide, to provide consumers with apples having a blemish-free appearance that they have been conditioned to expect in their food.

Antibiotics, Growth-Regulating Compounds, and Transgenic Crops

Intensive livestock rearing may involve keeping animals together under crowded conditions in poorly ventilated environments, often continuously exposed to their own manure and urine. Animals kept in such unsanitary conditions are vulnerable to infection, which may retard their growth or kill them. In conventional agriculture, this problem is managed partly through the use of antibiotics, which may be given to sick animals or as a prophylactic treatment by adding them continuously to the feed of an entire herd.

Ultimately, humans are exposed to small residues of antibiotics when they eat the products of these animals. Although this low-level exposure has not been conclusively demonstrated to pose an unacceptable health risk to people, the issue is nevertheless controversial. One potential problem lies in the development of antibiotic-resistant pathogens, which can result in antibiotics becoming less effective for medical purposes.

Organic farmers might use antibiotics to treat an infection in a particular sick animal, but they do not continuously add them to livestock feed. In addition, many raise their animals under more open and sanitary conditions than those used in conventional agriculture. Animals that are relatively free of the stresses of crowding and constant exposure to manure are more resistant to diseases and have less need for antibiotic treatment.

In addition, some industrial systems for raising livestock use synthetic hormones, such as bovine growth hormone, to increase the growth rate of animals or the production of milk. Inevitably, these hormones persist as trace contaminants in animal products that are consumed by humans. Although no risk to humans has been conclusively demonstrated from these exposures, there is controversy about the potential effects. Organic farmers do not use synthetic growth hormones to enhance the productivity of their livestock.

Another recent innovation in agriculture is the use of so-called transgenic crops, which have been genetically modified by the introduction of genetic material (DNA or RNA) from another species (see Environmental Issues 6.1). The intent of this bioengineering is to confer some advantage to the crop that cannot be developed through selective breeding, which relies only on the intrinsic genetic information (the genome) that is naturally present in the species.

Varieties of several important crops are transgenic and have been patented by the private companies that developed and market them. For example, a transgenic variety of canola is resistant to glyphosate, which allows that herbicide to be used as part of the management system. Transgenic varieties of potato and maize produce the insecticide that is naturally synthesized by B.t. and so are resistant to some insect pests. Transgenic crops are increasingly being grown in conventional agriculture in Canada and elsewhere, but they are not generally used in organic agriculture.

Organic versus Conventional

Many people believe that organically grown food is safer or more nutritious than food grown by conventional agriculture. This belief is mainly influenced by the knowledge that non-organic foods may have trace contamination with antibiotics, growth hormones, and pesticides, and the idea that this poses a health risk. This topic is highly controversial, but it is important to understand that scientific research has not conclusively demonstrated that organically grown foods are generally safer or more nutritious than those from conventional agriculture.

From the environmental perspective, the most important benefits of organic agriculture are the reduced use of non-renewable sources of energy and materials, better health of the agroecosystem, and enhanced sustainability of food production.

However, it appears that organic agricultural systems will not become more widely adopted until a number of socio-economic conditions change. First, more consumers must be willing to pay the often slightly higher costs of organically grown food and to accept a lower aesthetic quality in certain products. Second, vested agricultural interests in business, government, and universities must become more sympathetic to the goals and softer environmental impact of organic agriculture. These institutions must support more research to advance organic agriculture and promote its use. Finally, the practitioners of conventional agricultural systems must deal more directly with the environmental damage that is associated with their activities, especially the use of manufactured pesticides and fertilizers. If this were done, it would probably eliminate or even reverse the existing price differential between food produced by organic and by conventional agricultural systems.

Conclusions

Agriculture is a huge and necessary enterprise because it provides food for billions of people. A variety of crops are grown in various parts of the world, many of them domesticated, but only a few key ones account for most of the food production. These are barley, maize, manioc, potato, rice, sorghum, soybean, sweet potato, and wheat. Much environmental damage is associated with agriculture, including pollution, degraded land capability, and the destruction of natural habitats. In addition, livestock are not treated well in the industrial agro-food system, often being subjected to unnecessarily inhumane conditions while being reared, transported, or slaughtered. Much of the damage associated with agriculture can be avoided by using more organic means of production and processing. This is the major environmental advantage of organic foods, along with a perception of health benefits by many consumers. Although organic foods are usually somewhat more expensive to purchase, the price differential is more than offset by the environmental benefits from improved stewardship of land, the conservation of resources, and decreased pollution.

Questions for Review

1. What are the processes by which plants and animals become domesticated? How do these processes work?
2. Make a list of the most important food crops, both plant and animal, that are grown in Canada. For comparison, make a list for any selected country not in North America.
3. Make a list of the most important environmental effects of agriculture. Which of them do you think could be avoided relatively easily, and which not?
4. How is the production of agricultural crops important to you? How does agriculture contribute to the size and functioning of the Canadian economy?

Questions for Discussion

1. Could humans be viewed as a domesticated species? Explain your answer.
2. Agricultural activities cause serious and widespread environmental damage in terms of pollution and losses of natural habitat. Why do these damages seem to attract less attention than those associated with forestry, oil and gas extraction, and other industrial activities? Are agriculture-related damages being treated seriously enough?
3. Consider the practices that are used in raising livestock on factory farms and in transporting and processing them in slaughterhouses. Do you think that these animals are being treated in an ethically acceptable manner?
4. Canadian agriculture is highly mechanized and depends on the use of large amounts of fossil fuels and non-renewable materials such as steel and plastics. Do these circumstances pose risks for the longer-term sustainability of agriculture in Canada?

Exploring Issues

1. Select a crop plant or animal that is cultivated in the province where you live. Use the website of your provincial agricultural department to find out the practices that are recommended for growing the crop and what its production costs and economic value are.
2. Make a list of key agricultural practices (such as tillage, planting, fertilizer application, and pest control), and compare how they are done in conventional and organic agriculture. Based on your comparison, to what degree do you think organic agriculture causes fewer environmental damages than conventional practices?
3. A committee of the House of Commons is examining organic agriculture in Canada. The committee has asked you to compare the environmental effects of conventional and organic agricultural practices. What information about crop production and ecological impact would you assemble for the committee?

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Chapter 25 ~ Urban Ecology

Key Concepts

After completing this chapter, you will be able to:

1. Explain the factors that allow cities to exist and support their human population.
2. Describe recent trends of rapid urbanization.
3. Describe the structural and functional characteristics of the urban ecosystem.
4. Define the concept of an ecological footprint.
5. Explain the essential elements of urban planning and how it has affected land-use in Canadian cities.
6. List the major kinds of urban pollution and describe their causes and recent trends in Canadian cities.
7. Describe the methods of waste management.
8. Compare the management of solid waste and sewage among Canadian cities.
9. Explain the major elements of urban biodiversity and how it can be better managed through the naturalization of habitats.

Introduction

The Development of Urban Areas

Urban areas are cities, towns, and other places where people live in a compact population. Most urban people are engaged in economic activities that function efficiently in dense populations, such as commerce, education, manufacturing, and services. In contrast, resource-based economic activities, such as cultivating food and harvesting minerals, fossil fuels, timber, or wildlife, occur primarily in rural areas.

Urban areas import energy, food, and materials from the local countryside, as well as from more distant regions of their country, in addition to other nations around the world in an increasingly global commerce. The resource-related connections between cities and rural areas exist at all spatial scales (local, regional, and global) and are an integral but often insufficiently appreciated aspect of urban ecology.

The development of dense habitations (initially small villages) during human cultural evolution began about 10-thousand years ago, when early agricultural practices allowed the production of local surpluses of food (harvests that exceeded the subsistence needs of the farmers themselves). The excess food encouraged the development of specialized occupations that were most efficiently performed in a central place such as a village or town. New societal activities included organized religion and political systems, artisanal manufacturing, and the means of administering these over wide areas through hierarchical economic, political, religious, and military structures.

The first villages were probably supported by both settled agriculture and local hunting-and-gathering activities. By about 9,000 years ago, small farming villages were relatively widespread in some regions, particularly in the Fertile Crescent of the Middle East (see Chapter 24). By 8,500 years ago, that region boasted sizeable walled towns. Similar developments also occurred in China and probably elsewhere in southern Asia.

From these humble beginnings, urbanization of the human population has proceeded apace, and especially rapidly during the past century. Only about 2.5% of the human population lived in towns and cities in 1800, and 5-10% in 1900. Today, about half of the human population lives in urban places, and this is predicted to rise to two-thirds by 2025 (or about 5 billion people). About 90% of this increase in urban populations will occur in less-developed countries (see Chapter 10). Globally, the urban population is now growing about four times as quickly as that of rural areas, largely because of the migration of huge numbers of people from the countryside to built-up areas.

In Canada, about 20% of the population lived in towns and cities in 1871, increasing to 38% in 1900, 63% in 1950, and 81% in 2011 (of which 45% live in cities larger than 750-thousand people; Chapter 11).

In 1750, few cities supported more than 50-thousand people – London was the only one in England, and there were none in North America. In 1830, New York and Philadelphia were the only American cities with a population greater than 100-thousand. By 1910, however, 52 cities in North America supported more than 100-thousand people (New York was the largest, with more than 1 million). In 1950, New York and Tokyo were the only two megacities in the world (that is, having a population greater than 10 million). In 2014, there were 537 cities supporting more than 1 million people, including 35 megacities, of which 29 were in the developing world (Brinkhoff, 2015). The largest megacities are listed in Table 10.5.

No effective discussion of urban population policies has occurred in any country. Consequently, no population policies exist for urban areas in Canada or elsewhere. The key issues are how large should cities be in order to provide people with safe and clean places to live, while also supplying the goods and services that urban areas can deliver most effectively? If the largest cities are considered overpopulated, how can continued population growth be discouraged? Can people be encouraged to move to smaller centres? These and other questions related to urban population policies are extremely controversial, but all will have to be addressed.

Image 25.1. Urban environments are highly artificial. This shopping atrium in Toronto has semi-natural light, an atmosphere that is temperature-controlled for comfort, some potted plants (all tropical species), a flock of fibreglass Canada geese, and an overall ambience that is contrived to stimulate consumerism. Source: B.

Freedman.

Urban Ecosystems

Any urbanized area can be viewed as being an ecosystem, because it has the following ecological attributes:

1. a need for enormous inputs of energy and materials to sustain its human population and its diverse economic activities, and to maintain its structure and grow
2. a complex metabolism, including well-developed webs of transfer, processing, and storage of materials, energy, and information among interacting organisms and economic sectors
3. and immense outputs of heat and other waste materials, which are disposed of in surrounding ecosystems, causing pollution and other environmental problems

Of course, the habitats of cities and towns are very strongly influenced by human activities. Collectively they comprise an urban–industrial techno-ecosystem (Chapter 8). The structure of this anthropogenic ecosystem is dominated by the businesses, dwellings, factories, roads, and other infrastructure of the human economy, while also supporting manicured green space as well as remnants of natural habitats in parks and other less-developed spaces. Although humans are the dominant species in the urban ecosystem, many other species are also supported, most of which are not native to the region. Important ecological functions also occur within the urban ecosystem, such as biological productivity and water and nutrient cycling, but these processes are greatly influenced by humans.

All urban areas are intrinsically dependent on surrounding ecosystems to provide them with necessary resources and to assimilate wastes that are generated. The ecological footprint (or eco-footprint) of an urban population is the area of ecoscape (landscape and seascape) that is needed to supply the necessary food, energy, materials, waste disposal, and other crucial goods and services. As a global average, the average human has an eco-footprint of about 2.7 hectares, but there are only 1.8 ha of bio-productive land and water on Earth (Ewing et al., 2010). This means that the human enterprise has already overshot global bio-capacity by 30%, and is now operating on an unsustainable basis by depleting the remaining stocks of "natural capital". Note that, in the context of ecological footprints, these data are measures in "global hectares" (gha), which represent the average productivity of all bio-productive habitats on Earth or in a country, including agricultural land, forests, and fishing grounds, but not including desert, glaciers, or the open ocean.

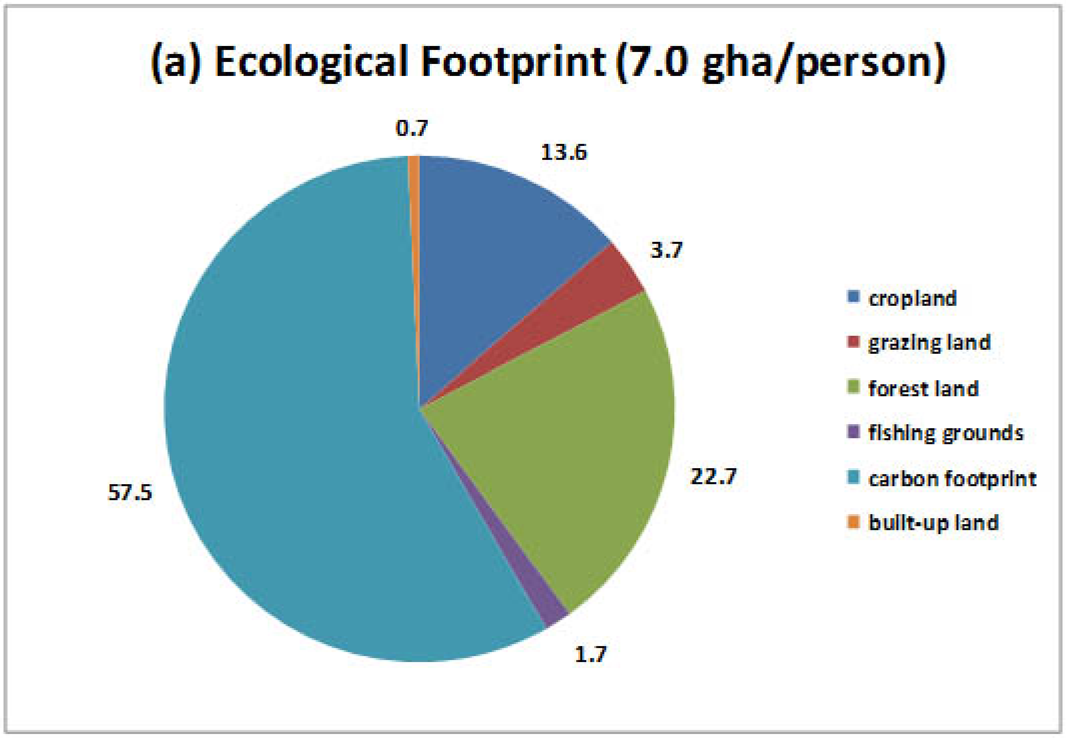
An average Canadian has an ecological footprint of about 7.3 global hectares (2007 data; Ewing et al., 2010). This is the seventh-most intensive national per-capita footprint in the world, after the United Arab Emirates (10.7 gha), Qatar (10.5 gha), Denmark (8.3 gha), Belgium (8.0 gha), the United States (8.0 gha), and Estonia (7.9 gha).

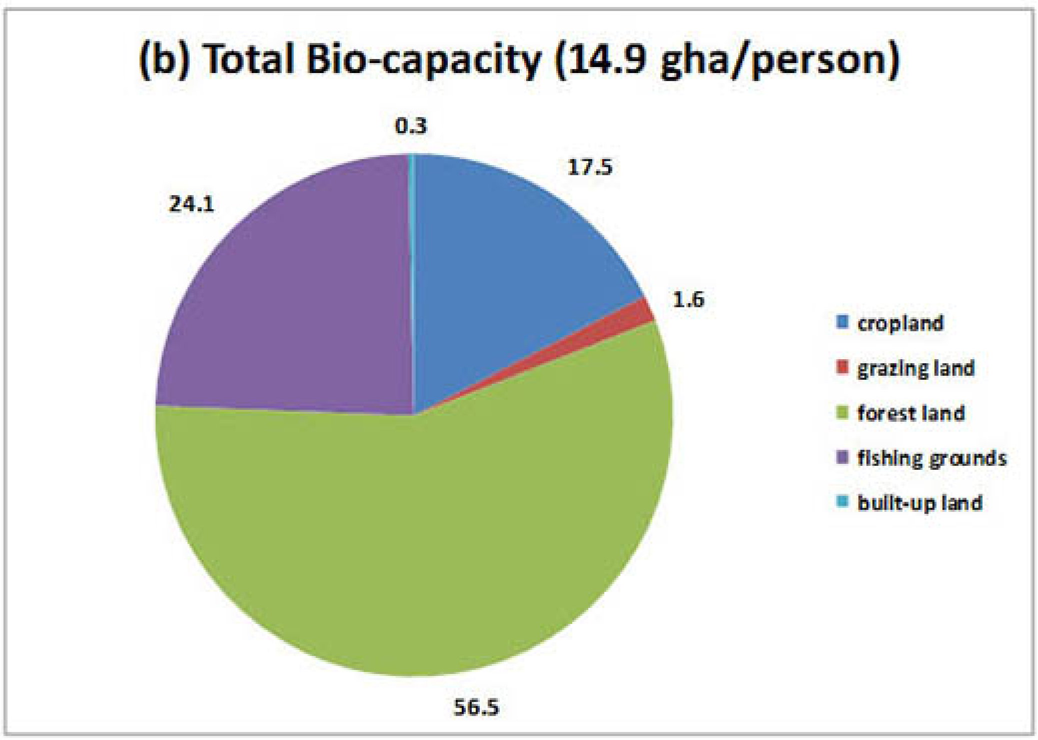
Here are some additional comparisons among wealthier countries: Australia (6.8 gha), Kuwait (6.3 gha), Ireland (6.3 gha), Norway (5.6 gha), France (5.0 gha), Germany (5.0 gha), United Kingdom (4.9 gha), and Japan(4.7 gha). The rapidly-growing economies include Russia (4.4 gha), Brazil (2.2 gha), China (2.2 gha), and India (0.9 gha).

Of course, people living in poorer countries have much smaller ecological footprints: Afghanistan (0.6 gha), Bangladesh (0.6 gha), Haiti (0.7 gha), Burundi (0.9 gha), Ethiopia (1.1 gha), Vietnam (1.4 gha), and Peru, (1.5 gha).

The major influences on the differences in these ecological footprints are related to the intensity of energy and material use and waste production within the national economies. The per-capita ecological footprint of Canada is about 7.0 global hectares per person, while the bio-capacity is 14.9 gha (Figure 25.1). The major elements of the footprint are related to emissions of carbon dioxide (a greenhouse gas; this is known as the "carbon footprint") and activities associated with harvesting or otherwise damaging forests and engaging in agricultural and fishing activities. The major contributions to bio-capacity are ecosystem services related to Canada's extensive areas of forest, agricultural land, and fishing grounds. Overall, the bio-capacity of Canada is about double the ecological footprint.

Figure 25.1. The Ecological Footprint of an Average Canadian. The data are in percentages, based on the relative contribution of each category to the (a) per-capita ecological footprint or (b) the bio-capacity of Canada. The data are related to the area of bio-productive habitat that is needed to provide resources and to assimilate waste products. Note that the data for the carbon footprint are the hectares needed to provide fossil-fuel CO_2 offsets, such as the area of forest whose productivity compensates for the energy content of an amount of fossil fuel used, or that fixes atmospheric CO_2at a comparable rate. Source: Data from Ewing et al. (2010).





Based on the Canadian national footprint of 7.0 gha, the ecological footprints of Canada's five largest cities (population data from Table 11.4) are the following (data are in millions of hectares):

1. Toronto 39.1
2. Montreal 26.8
3. Vancouver 16.2
4. Ottawa-Hull 8.7

5. Calgary 8.5

These footprints are about 71 times larger than the actual areas of these cities. Without such enormous regions to draw upon for resources, these and all other urban areas would be unable to survive.

The Organization of Cities

Urban Planning

Urban ecosystems have extremely complex structures and functions (although not more so than natural ecosystems). To some degree, their development has occurred in an orderly fashion, with certain areas being designated for particular kinds of structures and activities. Urban planning is the active process of designing and organizing the structure and function of cities. As such, urban planning contributes to the information needed by legislators and other decision makers as they develop sensible and efficient siting of the following:

- buildings, including homes, commercial properties, institutions (such as hospitals and schools), and industrial facilities
- infrastructure for transportation, utilities, and waste management, such as roads, railways, public-transit routes, electrical transmission and pipeline corridors, sewers and sewage-treatment facilities, and solid-waste disposal areas
- greenspaces, including playing fields and horticultural and natural-area parks

Well-planned urban areas have relatively pleasant neighbourhoods where people live and work. In contrast, poorly planned cities are chaotic, dirty, and unpleasant. In general, urban planning is most effective in wealthy developed countries such as Canada, but much less so in poorer developing countries where the population is growing and urbanization is proceeding most rapidly.

The dominant planning paradigm of the past 60 years has involved the segregation of major land-uses and economic activities into different areas. This kind of strategy has greatly influenced the design of modern cities, including all those in Canada. It has resulted in many urban people living in discrete inner-city neighbourhoods or more distant suburbs, while shopping in large malls, working in factory or office complexes and industrial parks, and commuting long distances among these land-use types. However, this type of planning has contributed to some important urban problems, including the following:

- the rapid growth of huge, multi-city, urbanized regions (sometimes known as conurbations)
- the inefficient segregation of residences from places of work and commerce
- long commuting times for workers
- congested transportation systems
- a decay of neighbourhood life
- environmental problems such as air and water pollution, wasteful use of energy and materials, paving of valuable farmland (many urban areas are located on excellent agricultural land), and losses of natural habitat

Some of these issues are examined in more detail later in this chapter.

The paradigm of widely segregated land-use is now being challenged by the concept of a more integrated "neighbourhood" design. This involves the development of relatively compact, self-sufficient communities that contain a mixture of residential and commercial land-uses. In some respects, this harkens back to more traditional elements of community design, in which housing, employment, local commerce, small-scale manufacturing, and recreation were all within easy walking distance. The re-emergence of this concept in urban planning has been substantially influenced by the ideas of Jane Jacobs, a geographer who taught at the University of Toronto.

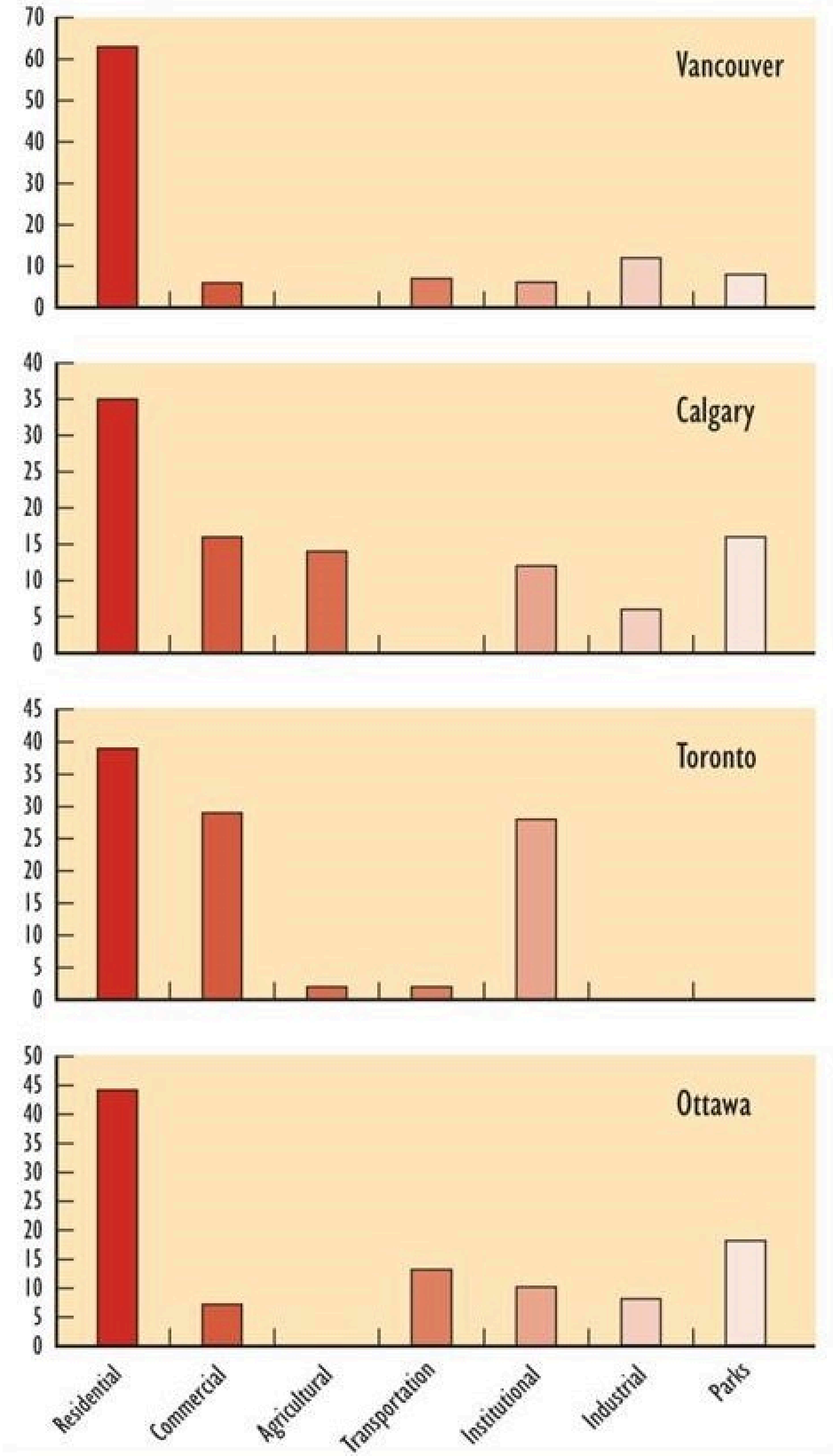
Urban Land-Use

Urbanized areas cover about 20 000 km^2 of Canada, only 0.2% of the total land. Canada is, nevertheless, a highly urbanized country because 81% of its population (about 22 million people) lives in cities and towns.

Although patterns of land-use vary among cities in Canada, the dominant uses are for residential, commercial, industrial, and transportation purposes (Figure 25.2). As such, urban areas are mostly occupied by: single-family homes, duplexes, and apartment buildings; commercial, industrial, and institutional buildings; parking lots and paved roads; and other built structures. Non-paved areas are mostly grassy lawns. All of these urban "habitats" are highly anthropogenic in character – they are, after all, places where large numbers of people live, work, and play. Some urban greenspaces also contain habitat for elements of native biodiversity, as we examine later.

Figure 25.2. Land-Use in Some Canadian Cities. The data show the percentage distribution of land-use in 1995. Note that the cities do not all report comparable units: Vancouver and Ottawa do not report agricultural land,

and Toronto includes parks in institutional use. Source: Data from National Round Table on the Environment



and Economy (1998).

Environmental Issues 25.1. Urban Sprawl Canadian cities are growing rapidly for two reasons: (1) most immigrants prefer to live in urban areas, and (2) there is immigration from rural districts. Both of these groups are seeking economic opportunities, as well as the cultural and lifestyle benefits of living in large centres. In any event, because of the rapid population growth, urbanized areas are spreading into adjacent rural habitats, a phenomenon known as "urban sprawl".

All cities and towns in Canada are located on land that was formerly occupied by natural ecosystems. However, much of the sprawl that is occurring today involves the conversion of agroecosystems into urbanized areas. When the agricultural land is lost, there is a depletion of the ability of the landscape to provide food. This is an important problem in parts of southern Canada, where much of the highest-capability land in the country is being converted into residential and commercial uses of cities.

Urban sprawl is also a threat to natural habitats, particularly in areas that sustain rare ecosystems. For example, the area around Victoria is the only place in Canada where dry forest dominated by Garry oak (Quercus garryana) occurs. This is habitat to many rare species and is one of our most endangered natural ecosystems. The expansion of residential areas is the greatest risk to this coastal oak forest. Conservation agencies in government and the private sector, including the Nature Conservancy of Canada, are trying to protect the surviving patches of this rare forest.

Urban sprawl can also be a threat to the ability of landscapes to provide key environmental "services," such as clean water. One such case involves an area known as the Oak Ridges Moraine, which has become a rallying point for habitat protection against further urbanization in the Greater Toronto Area. The moraine is a 160-km-long, 1950-km^2 ridge located north of the city, and it is composed of hilly terrain underlain by glacial sand and gravel. Because of its rough topography and poor fertility, much of its area has remained forested or is used for pasture or other low-intensity agricultural purposes. Groundwater originating in the moraine is a source of well-water recharge for about 250-thousand people and is a source of 65 rivers and streams and many wetlands. However, with the rapid growth of the greater Toronto region, the moraine has been subjected to increasing pressure from residential and commercial development. Extensive clearing of its forested and pasture areas would degrade the ability of the moraine to provide clean groundwater for use by people and to support streams and wetlands. Loss of the remaining forest would also destroy habitat for native species that are rare in the region.

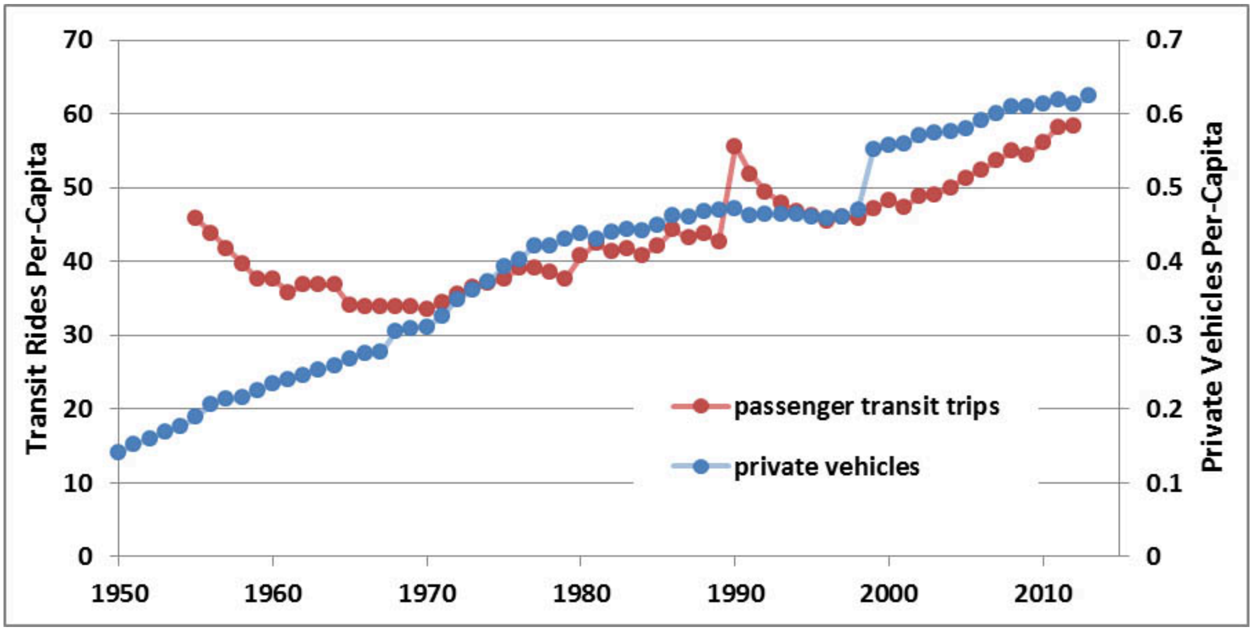
In response to intense lobbying from groups seeking to limit new developments on the moraine, the Government of Ontario formed an advisory panel to provide advice about the regulation of land-use. The panel provided many recommendations, including the need to protect 92% of the moraine from intensive development, and these were key in the preparation of The Oak Ridges Moraine Conservation Act, 2001. The Act was used to prepare a land-use plan, including provisions for core natural areas and linkages among them, comprising about 62% of the moraine. In 2002, the premier of Ontario announced the formation of a non-profit Oak Ridges Moraine Foundation and provided it with $15 million to fund public education, monitor the moraine, develop trails, and secure natural habitats. The federal government also announced that land it owns on the moraine, about 30 km^2, would be kept as greenspace. In addition, the Nature Conservancy of Canada has been acquiring properties of high conservation value and is setting them aside as protected areas.

These are positive actions, although there is still pressure from some landowners to allow more residential and commercial development in the area. Fortunately, however, these pressures have mostly been resisted and there is continuing progress in the conservation of greenspace in the Oak Ridges Moraine.

Urban Transportation

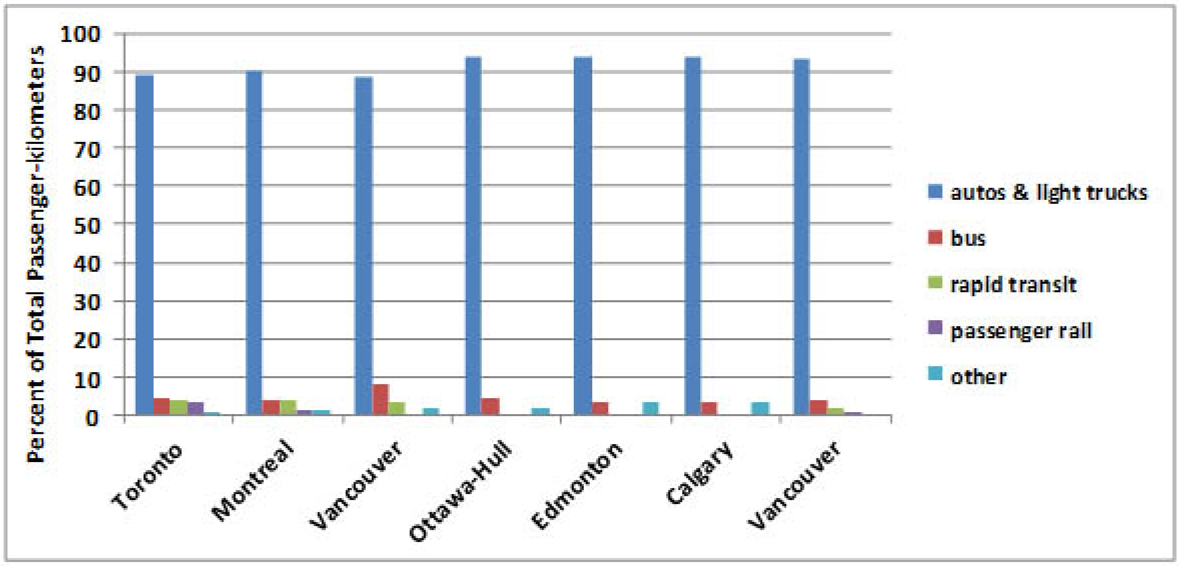
All urban areas have complex systems for moving people and goods. The physical infrastructure for transportation includes roads, parking lots, railroads, subways, airports, and water routes, plus the many kinds of vehicles that operate on these corridors. From the turn of the twentieth century to the 1950s, public transit systems were the most commonly used means of longer-distance personal transportation in Canadian cities. Public transit is still an important means of transportation in cities, although its growth is moderate and not nearly as impressive as that of automobile use (Figure 25.3).

Figure 25.3. Changes in Urban Transportation in Canada. The data show the trends in the use of urban transit systems and in automobile ownership. The jumps in the data series in certain years reflect changes in the ways that the data were reported. Source: Data are from Statistics Canada (2006, 2014) and APTA (2014).



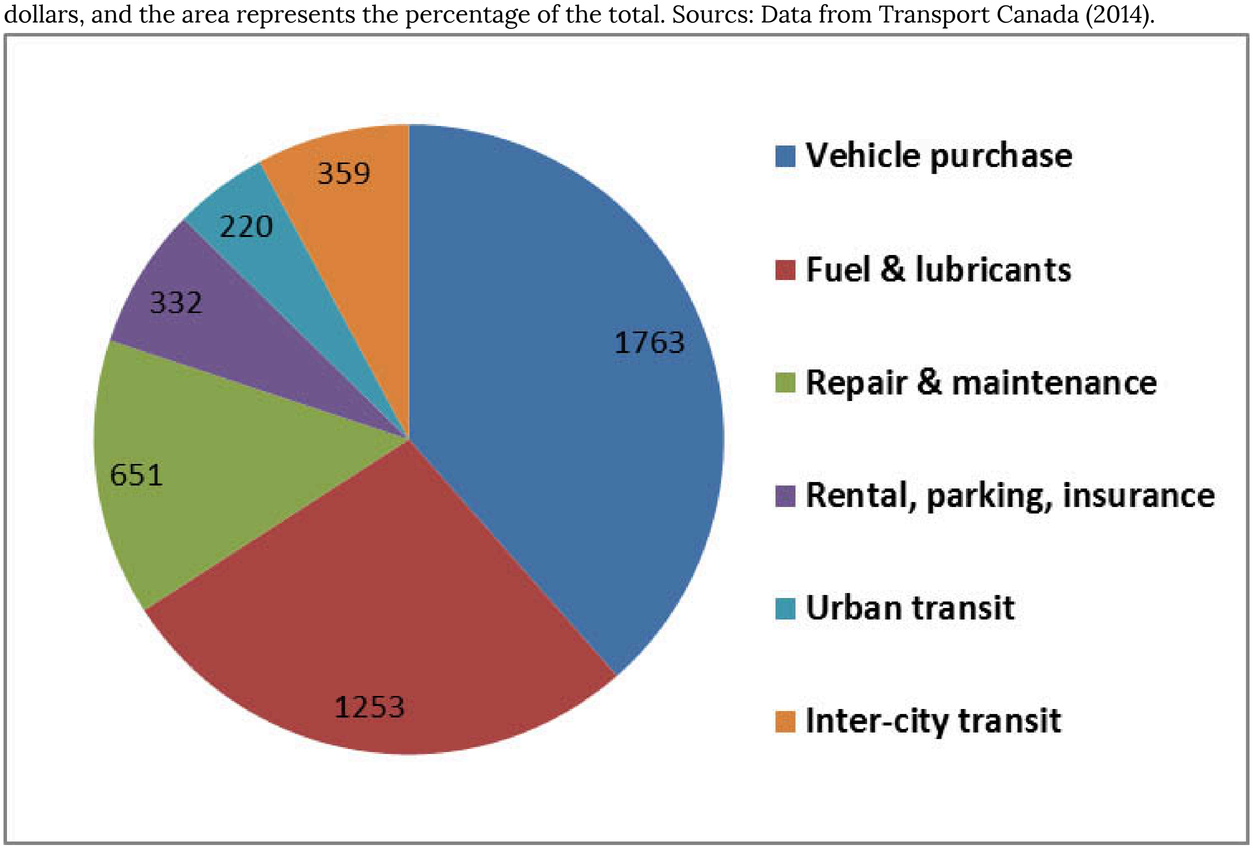
Most urban transportation involves the use of motorized vehicles (Figure 25.4). On average, about 93% of passenger-kilometres are travelled by private vehicle (car or light truck), and only 4%, by bus; 3%, by rapid transit and rail; and less than 1% by other means (such as bicycles). About 75% of trips are made by car or truck; 14%, by public transit; 10%, by walking; and 1%, by bicycle. In general, larger cities have a better developed infrastructure for public transit. For example, in Metropolitan Toronto, 65% of total trips are by automobile or small truck, 30%, by public transit, 4%, on foot, and 1%, by bicycle (NRTEE, 1998).

Figure 25.4. Means of Transportation in Some Canadian Cities. Data are for 1995 and are the percentages of the total passenger-kilometres travelled within the various cities. Source: Data from National Round Table on the Environment and Economy (1998).



These general patterns are also shown by the costs of transportation (Figure 25.5). Average household expenditures on transportation were about $9,208 in 2004, or 17% of total spending. About 83% of transportation spending was associated with owning and operating cars or light trucks. Only 0.6% was spent on bicycles, even though these are the most energy-efficient means of transportation in urban areas (see In Detail 25.1).

Figure 25.5. Costs of Transportation in Canada. Data are for 2013 and are the average annual per-capita expenditures on transportation. The value in the pie wedges indicates the annual expenditure in current dollars, and the area represents the percentage of the total. Sourcs: Data from Transport Canada (2014).



Although owning a car or truck is widely viewed as a desirable aspect of our lifestyle, the reliance on personal motor vehicles seriously affects environmental quality in cities and towns. Compared with other means of urban transportation, personal motor vehicles emit more air pollution, require more physical infrastructure (such as roads and parking space), use more material and energy resources, and are more costly to own and operate. Significant safety hazards are also associated with the use of personal motor vehicles – 2,077 Canadians died in transport accidents in 2012, equivalent to 0.9% of all deaths (Transport Canada, 2012). There were also 165-thousand injuries serious enough to require medical attention.

Image 25.2. A large amount of space is allocated to cars and other vehicles in cities, particularly roads and parking areas. If intelligent life forms on a voyage of discovery were to hover in their spacecraft over a Canadian city, they might initially conclude that the dominant form of life is the automobile. Source: B. Freedman.

In Detail 25.1. The Bicycle: A Green Machine Invented in the late nineteenth century, the bicycle rapidly became recognized as an efficient, safe, and fun way to get around. Even today, with all of the advances in technologies for powered transportation, the bicycle is still the most efficient means of transporting people on land. This fact is illustrated by comparing the energy typically used to transport a passenger using various technologies (Holcomb, 1987):

- Automobile (1 occupant) 1163 cal/km
- Automobile (2 occupants) 581
- Transit bus 575
- Transit rail 553
- Walking 63
- Bicycling 22

Unlike motorized transportation, riding a bicycle does not emit air pollutants such as NO_x, SO_2, hydrocarbons, or particulates. Moreover, bicycle manufacturing requires far less material and energy resources, and less infrastructure is needed to support these vehicles in terms of space for roads and parking. Therefore, bicycles represent an environmentally soft (or "green") alternative to motorized vehicles for personal transportation. There are more than 1-billion million bicycles in the world, about half of them in China. Canadians own about 13 million bicycles, or 0.42 per person. In spite of this number, only 1% of all trips are made using a bicycle, which suggests that many bicycles are not well used. Great environmental benefits would result if more Canadians used bicycles instead of motor vehicles as a means of personal transportation. These benefits include less air pollution, smaller costs of transportation infrastructure, and less use of energy and material resources. Personal benefits include the convenience of bicycle travel and improved health from frequent exercise.

However, bicycle riding can be dangerous, mostly because of the risk of collisions with motor vehicles. About 2% of vehicle-related deaths in North America involve bicyclists (motor-vehicle accidents are the other 98%, but the per-trip and per-kilometre risk of death associated with bicycle use is more than twice as great; Insurance Institute for Highway Safety, 2014). In the United States in 2012, there were 772 bicycle-related fatalities, and Canadian data are about 10% of that. However, bicycle fatalities have decreased by 24% since 1975 because most cyclists now wear a helmet (98% of fatalities involve people without a helmet). Safer bicycle use requires separate lanes along busy roadways, improved awareness by automobile and truck drivers of the need to share the road with bicycle riders (and vice versa), and increased use of safety equipment by bicyclists, especially helmets and lights and reflective devices at night. The use of bicycles in cities can be encouraged in the following ways:

- by developing a network of cycleways (separate paths for bicycles), bike lanes, and paved shoulders on major roads
- by providing secure parking facilities at workplaces and public-transit stations (the latter is known as "bike and ride")
- by having a fleet of bicycles for free use or inexpensive rental from a network of pick-up centres (this system, first used in several European cities, is being tried on a smaller scale in North America, including Montreal)
- by educating people about the advantages of bicycle transport and safety issues.

Other ways to increase bicycle use would be much more difficult to implement. For example, urban-planning options could encourage people to live closer to their workplaces, giving them shorter commutes. In addition, legislation could ensure that people using motorized transport pay the full costs of their choice of transportation by withdrawing subsidies for the construction of roads, bridges, parking lots, and other infrastructure and by applying realistic taxes (such as user fees) to offset the costs of associated air pollution and resource depletion.

Urban Pollution

Urban pollution includes elevated concentrations of chemicals and particulates, increased noise and heat, and impaired aesthetics. We briefly examine each of these topics in the following sections.

Chemical Pollution

Urban environments commonly have higher concentrations of various chemicals than typically occur in rural places. As well, a wider range of chemicals is present, including many synthetic ones. Often, chemical pollution of the urban environment is intense enough to damage the health of people, animals, and vegetation.

Soil in urban areas may become polluted by a wide range of substances, including petroleum products, halogenated hydrocarbons (such as PCBs), and metals. This is illustrated by the following examples.

- **Hydrocarbon spills**: Liquid hydrocarbons, such as gasoline, fuel oil, paints, and solvents (such as those used in dry-cleaning) are stored in many places. This includes underground tanks at gasoline stations and fuel-oil tanks in homes and at commercial, industrial, and institutional buildings. Smaller amounts of fuels are contained in all cars, trucks, and other vehicles. Spills of some kinds of liquid fuels, such as gasoline, can be extremely hazardous because of the risk of fire or explosion. In addition, if liquid hydrocarbons are spilled onto soil, they quickly penetrate and cause local pollution of the groundwater, which may then spread widely as a plume of tainted water. This can ruin the usefulness of an aquifer as drinking water: as little as 1 ppm of hydrocarbons can result in discernible tainting and even smaller concentrations of some chemicals are considered a health risk. It is difficult or impossible to contain a hydrocarbon spill once it reaches groundwater or to fully rehabilitate a polluted aquifer. It is much easier to avoid hydrocarbon spills than to deal with the environmental damage they cause.
- **Metals**: Urban soil can become polluted by metals in many ways. For example, people who live near metal-recycling factories may be exposed to pollution through dustfall from the atmosphere. In one case, severe pollution was found in a downtown Toronto residential neighbourhood near a car-battery recycling factory. Lead in surface soil near the factory exceeded several thousand ppm (one sample had >5% lead), and some residents had elevated lead in their blood and hair. This astonishing land-use conflict occurred because of earlier, inappropriate land-use zoning, when less attention was placed on environmental concerns. However, the battery-recycling factory still remains in the residential neighbourhood, although it operates much more cleanly than in the past. Lead pollution of urban soil has also been caused by residues of old paint, which often had very high concentrations of lead-containing pigments (commonly reaching 38% in the dried residue), especially in white and red colours. (Lead is now mostly replaced in household paints by titanium and other less-toxic metals). Soil close to busy highways is also affected by leaded gasoline (this problem has dissipated since the 1990 ban on leaded gasoline; see Figure 25.6 and Chapter 18).

Eutrophication is another kind of urban pollution. Lakes and rivers in urban areas often have an enriched nutrient supply, which results in increased productivity and eutrophication. The nutrient inputs originate from fertilizer use in horticulture, leaching from septic fields, and sometimes the dumping of sewage. Urban waterbodies are also commonly polluted with coliform bacteria and other intestinal pathogens and parasites that originate with sewage and surface runoff contaminated by pet and bird feces. Lakes and rivers may also be affected by spilled fuel, metals, garbage dumping, and sedimentation by soil eroded during construction activities. Any of these influences on urban lakes may render them less suitable or even unfit as a source of drinking water or for recreational purposes. Eutrophication and sedimentation also cause significant ecological damage in many urban waterbodies.

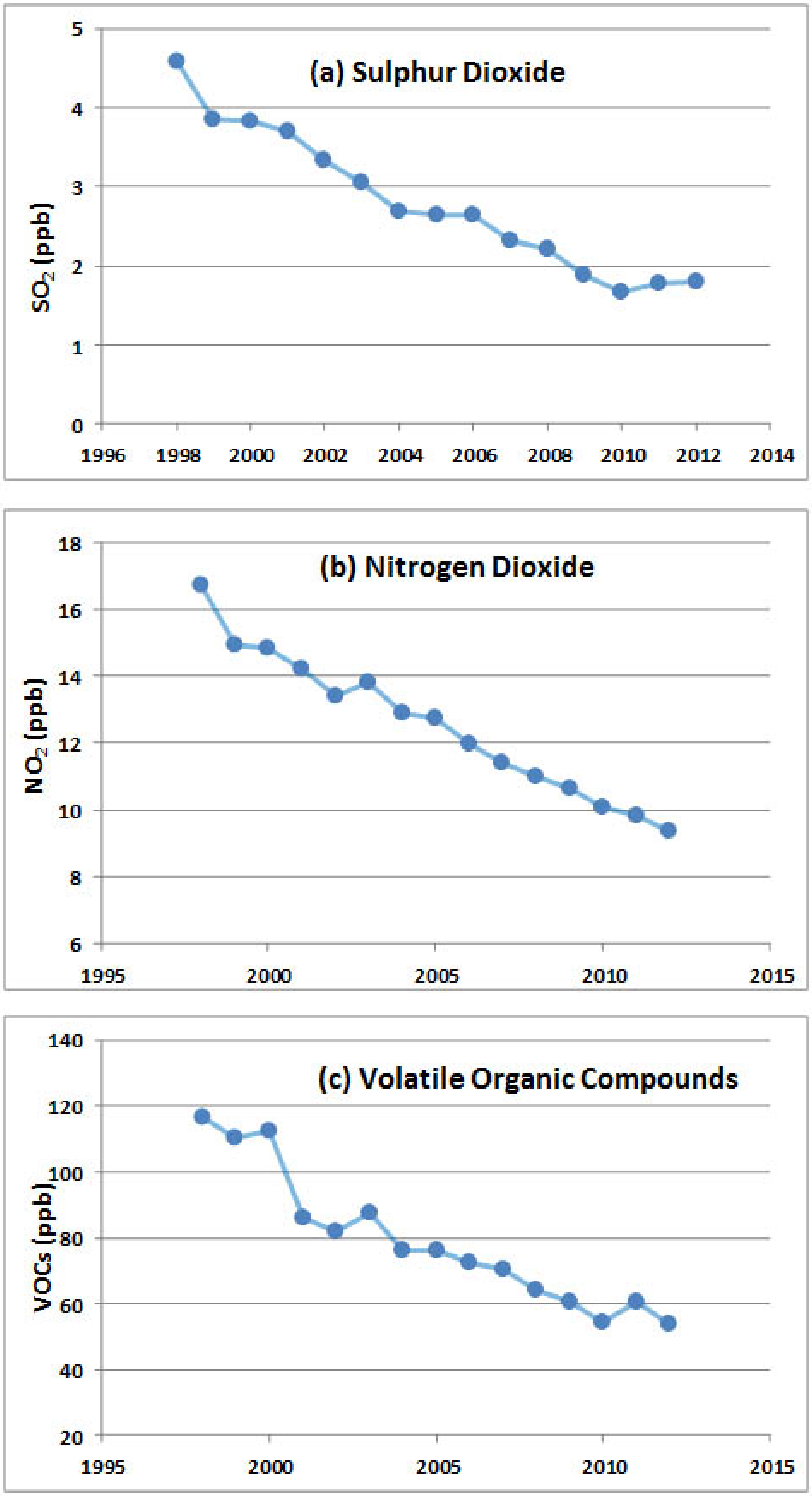
Urban air pollution can also be severe, causing life-threatening health problems for many people, particularly the old or very young and those with respiratory diseases. Severe pollution by sulphur dioxide and particulates was once common in North American and European cities, when coal was burned as an industrial and residential fuel. This problem has, however, been greatly alleviated since the early 1960s because of clean-air regulations (Chapter 16). However, this kind of reducing smog is still severe and even worsening in many rapidly developing countries, where a lower priority is given to enforcing clean-air laws.

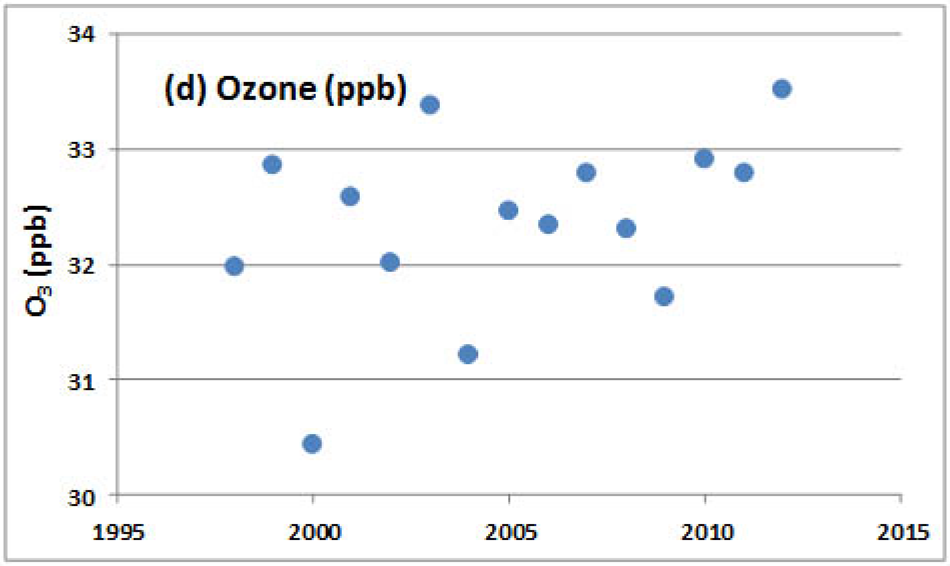
In spite of great improvements since the 1960s, cities in Canada and other developed countries continue to be affected by significant levels of air pollution (Chapter 16; Figure 25.6). The following are particularly important.

- **SO_2 and NOx gases**: Although so-called reducing smog is much less of a problem than before, urban atmospheres still have higher concentrations of SO_2 and NOx than rural areas. The dry deposition of these gases damages marble, limestone, sandstone, and other acid-sensitive building materials and statues, and it contributes to the acidification of aquatic habitats (Chapter 19). In addition, these gases may be directly toxic to sensitive urban plants and lichens.

- **Suspended particulates**: Largely originating from emissions from vehicles, furnaces, and other combustion sources, suspended particulates are mostly fine aerosols of ammonium sulphate, ammonium nitrate, and sooty organics. At high concentrations they form a haze that interferes with visibility and is a hazard to people with respiratory problems. In general, air pollution by particulates has decreased markedly during the past several decades, mainly because of better emission controls on power plants, other industrial sources, and vehicles, and because of widespread switching to natural gas as a fuel.
- **Oxidants**: Cities with a sunny climate and a large number of motor vehicles often develop a photochemical smog during the day, characterized by high concentrations of ozone, peroxy acetyl nitrate (PAN), NOx, and volatile organic compounds (Chapter 16). The ozone component is responsible for most of the oxidant damage because it is toxic to many plants, irritates people's eyes and respiratory tracts, and degrades many materials and pigments. The worst photochemical smog occurs in southern Ontario and Quebec, extending from Windsor to Quebec City, and to a lesser degree in the greater Vancouver area and around Saint John. The air-quality objective for ozone (63 ppb) is exceeded on many summer days in the Quebec-Windsor corridor, where maximum hourly concentrations can exceed 160 ppb. Niagara Falls, Sarnia, Windsor, and Guelph are among the smoggiest cities in Canada, exceeding ozone guidelines for more than 50 days per year. The photochemical smog in this region occurs because of local emissions of NOx and volatile organics (these are precursors in the photochemical production of ozone; see Chapter 16), as well as those blowing in from urban areas in the nearby United States. In contrast, local emissions are the major cause of ozone smog in the Vancouver area.

Figure 25.6. Air Quality Trends in Canada. These data are from sampling stations located throughout Canada, but mostly in urban areas. Source: Data from Environment Canada (2014).


(a) Sulphur Dioxide
SO2 (ppb)
0
1
2
3
4
5
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
(b) Nitrogen Dioxide
NO2 (ppb)
6
8
10
12
14
16
18
1995
2000
2005
2010
2015
(c) Volatile Organic Compounds
VOCs (ppb)
20
40
60
80
100
120
140
1995
2000
2005
2010
2015



Urban Climate

The climate of urban regions is different from that of nearby rural areas. Compared with rural areas, cities typically exhibit the following characteristics:

- they are warmer by 3-6°C
- have 5-10% more cloud cover
- receive about 20% less solar radiation
- have 20-30% lower wind speeds (although wind-tunnelling may increase windspeeds near large buildings)
- have 5-15% lower relative humidity
- receive 5-15% more precipitation The best known of the climatic differences, called the "heat-island" effect, refers to the warmer temperature of cities, which occurs because of the following influences on the urban energy budget:
- an emission of large amounts of heat (thermal energy) from buildings and machines (including motor vehicles)
- interference by buildings with the dispersal of warmed air by wind
- the absorption of solar radiation by dark surfaces (especially asphaltic roads and parking lots), followed by the re-radiation of long-wave infrared
- a relative lack of plant foliage in urban areas (the atmosphere is cooled by the evaporation of water from foliage, also known as transpiration)

Thermal Pollution

Thermal pollution occurs when an increase in environmental temperature is sufficient to result in ecological damage. This may be due to the direct discharge of heat into the environment, often from a point source into an aquatic ecosystem. As the water becomes warmer, the respiration of poikilothermic (cold-blooded) organisms increases, about doubling in rate for every 10°C increase in temperature. At the same time, the amount of dissolved oxygen in the water decreases (because the solubility of gases is less in warm water). The increased metabolism and decreased oxygen cause physiological stress to aquatic organisms. Associated ecological problems include changes in the communities of fish, invertebrates, aquatic plants, and algae. Extreme thermal pollution can result in anoxic water, accelerated eutrophication, and fish kills. Thermal pollution can reduce the potential for recreational, industrial, and drinking-water uses of a waterbody.

Thermal pollution is associated with discharges of warmed water from fossil-fuelled or nuclear-power plants or other large industrial facilities. These places often use a local waterbody as a source of cooling water. The warmed water is then returned to the environment to dissipate its increased heat content. Because power plants are typically 30-40% efficient in converting the energy content of their fuel into electricity, the other 60-70% of that energy must be dissipated. A power plant employs heat exchangers to warm the cooling water, which is then released into the environment.

However, some receiving waterbodies may be too small to absorb all of the heat received without becoming excessively warmed (for example, by more than about 5°C) and suffering ecological damage. In such cases, some of the heat may be dissipated into the atmosphere using special facilities, such as a constructed, shallow cooling pond, in which surface evaporation cools the water before its release into the natural environment. Alternatives include a "wet" cooling tower, in which the water is cooled by spraying it into the air, or a "dry" cooling tower, which uses a system of heat exchangers to transfer heat to the atmosphere (these options are uncommon because of their high costs of construction and operation). Better yet, some of the "waste" heat may be used to warm nearby buildings, or in commercial greenhouses to grow vegetable crops in winter (as occurs near the Bruce Nuclear Generating Station in Ontario), or in an aquaculture facility to grow fish (this is more commonly done in Europe).

Noise Pollution

Urban areas are typically much noisier than rural ones. Most of the noise comes from the operation of various kinds of machines that are abundant in urban places, such as air conditioners, lawnmowers, automobiles, heavy trucks, and air compressors. Loud music may also be important. Noise pollution begins when the level of ambient sound becomes distracting to the normal activities of people, for example, by making it difficult to understand a conversation or to have a restful sleep.

Noise intensity (also called sound pressure or loudness) is measured in units of decibels (dB). An increase of 10 dB is approximately equivalent to a doubling of the loudness. When the distance from a point source is doubled, the noise level decreases by about 6 dB. However, when the distance from a linear source of noise (such as a busy highway) is doubled, the sound level decreases by only about 3 dB.

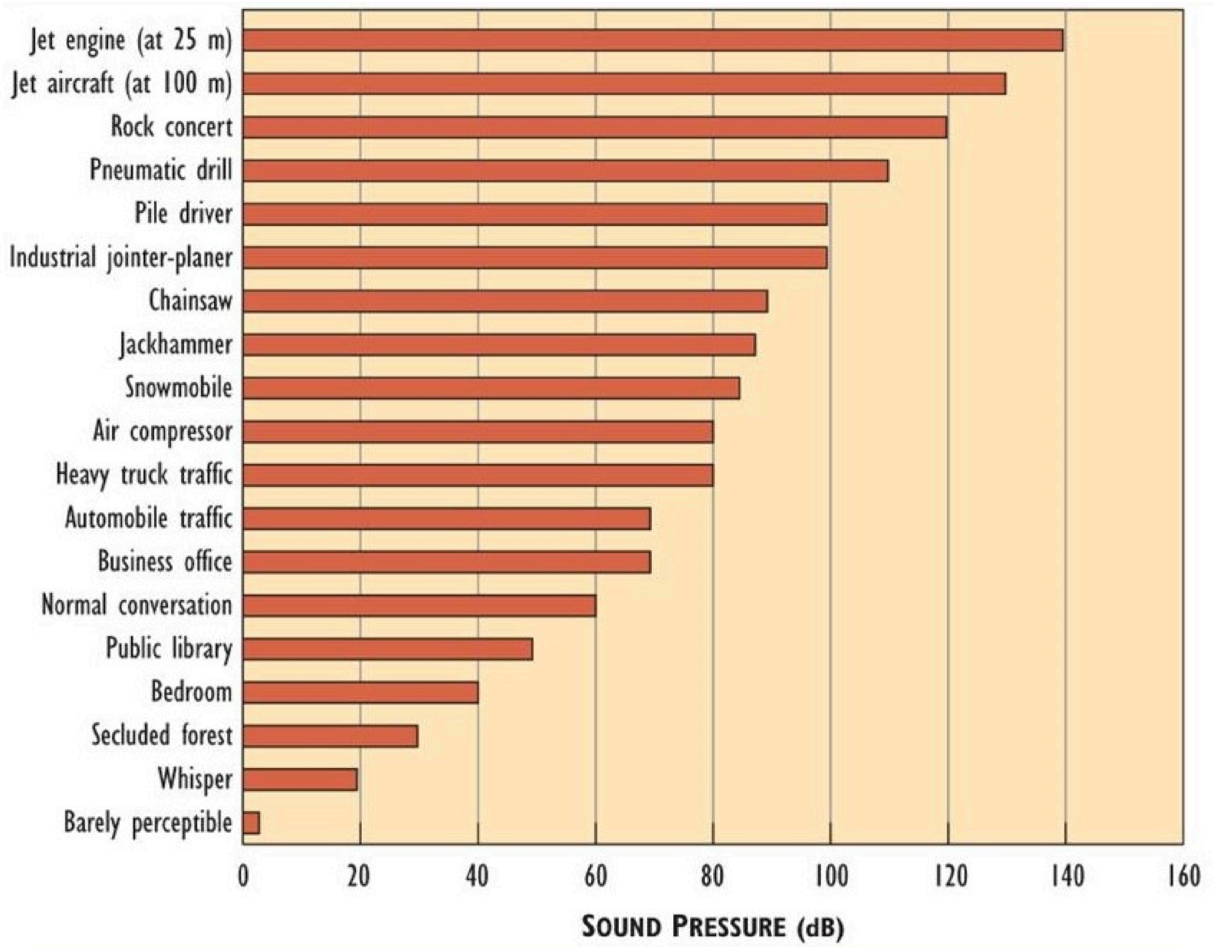
At a high intensity, noise pollution can cause a progressive and enduring hearing impairment, which begins with a decreased ability to perceive higher-pitched sound. Under prolonged exposure, the hearing loss may progress through much of the auditory range. Hearing loss is caused by both the duration and intensity of exposure. For example, an occupational exposure to 115 dB may be permitted for no longer than 15 minutes, while exposure to 100 dB may be allowed for two hours and 90 dB for up to eight hours. Noise becomes painful at about 140 dB, although prolonged exposure to levels above 80-90 dB can result in long-term hearing loss. The noise levels typically associated with various sources are shown in Figure 25.7.

People may be exposed to excessive noise in various ways. Non-voluntary exposures occur in the ambient environment, such as near a road with heavy traffic. Occupational exposures occur in noisy factories or in hangars where jet engines are serviced. Voluntary exposures to excessive noise are also common, such as when people attend thunderous rock concerts or use headphones to listen to loud music. It is well known that permanent hearing loss is common among rock musicians as well as people who regularly listen to loud music at concerts, clubs, or using headphones. Frequent target-shooting with firearms can also result in long-term hearing loss unless effective ear protection is used.

Various levels of government in Canada have set criteria for permissible exposures to noise. For example, Health

Canada sets standards and guidelines for occupational exposures, while provincial and municipal governments deal with particular sources (such as the amount of noise a vehicle can make) as well as noise levels in the ambient environment. Various actions can reduce the noise intensity in occupational and urban environments. Vehicles and other machines are required to have noise-absorbing devices (mufflers) that must perform according to regulated standards. Machines in the work environment may also be muffled, and workers may be advised or required to wear hearing protection.

Figure 25.7. Sound Pressure Levels Associated with Various Sources of Noise. Source: Data from Timerson (1999).



Aesthetic Pollution

Aesthetic pollution is substantially a matter of cultural values. It commonly involves visual images that are displeasing to many (but not necessarily all) people. As such, the criteria for aesthetic pollution cannot be precisely defined. For example, many people might find the following to be objectionable:

- a neighbourhood of dirty run-down buildings
- an area cluttered with garbage
- a street with a viewscape blocked with gaudy billboards, neon advertising, and other promotions
- overhead utility wires
- spaghetti-like networks of roads, overpasses, and underpasses crowded with grid-locked vehicles
- paved open spaces without trees, shrubs, or flowers.

However, there is, however, no broad consensus about what constitutes aesthetic pollution – some people might find that these scenes have aesthetic merit and may even seek them out. Aesthetic pollution is not generally considered to be as important a problem as chemical, noise, or thermal pollution. Nevertheless, urban planners, neighbourhood activists, and other concerned people do try to reduce the aesthetic pollution of cities and towns. For example, many urban areas have bylaws that require property owners to keep their property clean and in good repair. Some places require that utility cables be buried, or they ban certain kinds of advertising. (For example, in order to conserve pastoral viewscapes, unrestricted highway billboards are not allowed on Prince Edward Island.) Reducing aesthetic pollution in urban areas makes them nicer places in which to live and work.

Waste Management

Any discarded materials can be viewed as waste, but there are a number of categoris:

- Solid wastes are extremely variable in composition and include discarded food, leaves and lawn clippings, newspapers and other papers, glass and plastic bottles, cans, disposable diapers, construction debris, industrial chemicals, old cars, and disused furniture
- Liquid wastes include sewage and discarded industrial and household fluids
- Gaseous wastes include products of combustion or industrial reactions
- Hazardous wastes are flammable, corrosive, explosive, toxic (also called toxic waste), or otherwise dangerous, and they should either be treated before disposal or discarded into a specially designed, secure landfill to environmental damage

People have always produced wastes of many kinds. However, the amount and complexity of discarded materials have increased enormously as a result of industrial and technological development, coupled with the growth of population and consumerism. Activities in urban areas produce huge amounts of waste. Waste management is the handling of discarded materials, using various methods:

- Dumping is the long-term disposal of disused material. The disposal of solid wastes by dumping usually occurs into a sanitary landfill (see below). Liquid wastes are most commonly discarded into a nearby lake or river, with or without treatment to reduce the amounts of organic matter, toxins such as metals and hydrocarbons, and pathogens. Gaseous wastes are usually dumped into the atmosphere, although the amounts of damaging gases (such as SO_2) and particulates may be reduced by pollution-control technologies.
- Incineration is the combustion of solid wastes to reduce the amount of organic material. Small-scale incineration may involve open burning. However, incineration in urban areas and industrial plants is conducted in specially engineered facilities designed to burn efficiently, while controlling the emissions of pollutants to the atmosphere. The residual material, consisting of ash, metals, glass, and other non-combustibles, is usually disposed of in a secure landfill. Overall, incinerators reduce the volume of waste by 70-90%, depending on the initial organic content. If the heat produced is used to generate electricity or industrial steam, the incinerator is known as a waste-to-energy facility.
- Recycling involves the processing of discarded materials into useful products. For example, aluminum pop cans can be collected and re-manufactured into new containers or other products. Recycling is an extremely attractive waste-management option for three major reasons: (1) it reduces the total amount of waste, (2) it recovers valuable commodities from discarded materials, and (3) it helps to conserve non-renewable resources (such as metals and fossil fuels) and some renewable ones (such as trees used to manufacture paper). Easily recyclable materials include glass, all metals, most plastics, and almost all kinds of paper. In fact, these discarded materials should be regarded as “resources” rather than “wastes.”
- Composting is a type of recycling in which discarded organic materials are allowed to partially decay under warm, moist, oxygen-rich conditions. Backyard composting is done in simple bins or piles. To enhance the availability of

oxygen, advanced commercial systems turn the material occasionally or force air through matter contained in a vessel. All food wastes, lawn clippings, leaves, paper, sawdust, sewage sludge, and other organic discards can be composted. The material produced, known as compost, is rich in humified organic matter and is extremely useful in enhancing the tilth and fertility of garden and agricultural soil (see Chapters 14 and 24).

- Re-use involves finding another use for discarded materials, usually with relatively little modification. Re-use is an attractive waste-management option for the same reasons noted for recycling, but it is even more effective at conserving resources because little effort is put into re-manufacturing (other than repairs, if necessary). Re-use is a common practice with discarded furniture, appliances, books, tools, clothes, and other consumer products. Increasingly, institutions and industries are finding ways to re-use paper, cardboard boxes, other containers, wooden pallets, and other disused materials. Often, re-using networks are organized among industries, universities, hospitals, and other institutions, because "waste" materials produced by one partner may be a "resource" for another.
- Waste reduction and prevention are not, strictly speaking, waste-management methods. Rather, they are intended to reduce the amounts of waste that must be handled by the above methods. Waste reduction and prevention include choices by consumers to buy products that are not excessively packaged or that are sold in reusable, returnable containers. People can also choose to buy less –to have fewer shoes and items of clothing, to own fewer (or no) automobiles, and to adopt other elements of a less consumerist lifestyle. Industries also have many options to reduce or prevent their production of wastes. For example, wood-processing industries once routinely incinerated or land-filled waste tree bark and sawdust, but today they routinely use them to manufacture pulp or as a source of energy. In fact, some pulp mills now satisfy most of their needs for raw fibre by using sawdust and trimmings from nearby sawmills.

The various ways of managing waste materials differ greatly in their environmental impacts. In general, environmental problems associated with the generation and disposal of wastes are lessened by adopting any of the following "R's" into our individual and corporate lifestyles: refuse (waste prevention), reduce, reuse, and recycle.

Image 25.3. Solid-waste management is an important function carried out by municipal governments. This image shows a pile of discarded material placed at the curbside for collection. Much of this material could have been recycled, but instead it will be land-filled. Source: B. Freedman.

Municipal Solid Waste

Municipal solid waste (MSW) is generated by households, businesses, and institutions such as schools and hospitals. The components of MSW are extremely diverse, but they do not include sewage sludge (discussed in the following section) or waste generated by heavy industry. Until fairly recently, all MSW was disposed in "open dumps," a practice that may still occur in smaller communities in Canada and in poorer parts of the world. Usually, an open dump is located in a relatively out-of-the-way natural basin, such as a lake, wetland, or other low area, which is gradually in-filled with waste. Many environmental damages are associated with open dumps, including the pollution of groundwater and surface water by toxic leachate, foul smells, smoke from open burns used to decrease the volume of garbage, populations of pest animals, and terrible aesthetics.

In the 1920s, engineers began to design sanitary landfills, where MSW is dumped, compacted by heavy machines (such as bulldozers), and covered with about 10 cm of clean dirt at the end of each day. This reduces odours and populations of rodents, gulls, insects, and other pests. Sanitary landfills became common in developed countries during the 1940s, and advanced variations are now used by Canadian municipalities (although not by all smaller towns and villages). Modern sanitary landfills include the following elements in their construction:

- one or several impervious linings of clay, plastic, or concrete that prevent the downward leaching of water with high concentrations of ammonium, metals, and other toxic chemicals
- a cutoff wall of concrete or another impervious material around the edge of the landfill to prevent the sideways migration of polluted water
- a system of pipes and gravel drains to collect leachate for treatment before the water is released into the environment
- a system of piping to collect methane, a greenhouse gas produced by anaerobic decomposition of organic matter

in the landfill, which can be burned to produce electricity or heat In spite of these advanced design elements, residual problems of groundwater and surface water contamination and methane emissions to the atmosphere may still occur.

Another way of disposing of MSW is to incinerate it. During the nineteenth century, some cities burned much of their organic garbage using crude facilities known as cremators or cone-shaped teepee-burners. However, these caused intense local pollution and were replaced by the land-filling of MSW. Beginning in the 1930s, some cities built more-efficient burning facilities called incinerators, but these were also dirty and most were shut down by the late 1960s. However, beginning in the 1970s, much cleaner incinerators were built, known as waste-to-energy or resource recovery facilities. These incinerators burn organic MSW efficiently and have technology installed to reduce the emissions of particulates and other air pollutants. However, the ash produced is a toxic waste that must be disposed of in a secure landfill.

All municipalities need facilities for handling their solid wastes. However, public attitudes play a crucial role in any waste-management decisions. Any new proposal to develop a sanitary landfill, incinerator, recycling plant, or other MSW-related facility is sure to be opposed by people living near the proposed site. This phenomenon is referred to as NIMBY, an acronym for not in my backyard. If local opposition becomes highly vocal and widespread, municipal bureaucrats and politicians often will not approve a proposal, which creates an important problem for those who are attempting to deal with waste-management issues. It also strongly motivates engineers to design landfills and incinerators to operate as cleanly as possible, while increasing the pressure for society to act to reduce and recycle discarded materials more efficiently than in the past.

In 2006, Canadians produced over 35-million tonnes of MSW, or 1.04 t/person, of which 76% was dumped and the other 24% diverted by recycling and composting (FCM, 2009; Statistics Canada, 2012). Of the total, 22-million tonnes came from non-residential sources and 13 million tonnes came from residential ones. Supported by provincial legislation that establishes targets, the highest diversion rates occur in Nova Scotia (41%) and Prince Edward Island (38%), followed by New Brunswick (36%), British Columbia (32%) and Québec (27%). The lowest diversion rates are in Newfoundland & Labrador (7 %) and Saskatchewan (11%).

Still, much of the dumped MSW could yet be diverted: 45% of it consists of recyclables (metals, glass, plastics) and 28% is organic waste. Note, however, that these figures vary widely across Canada, depending on the size and density of the urban population (diversion programs are more economic in larger centres) and on the priority placed by municipal and provincial/territorial governments on advanced (but expensive) options for the management of solid wastes. Increasingly, governments are requiring or encouraging options that decrease the amount of solid waste that must be handled by land-filling or incineration.

Table 25.1. Municipal Waste Management in Canada. Data are for 2006. Disposed includes land-filled plus incinerated waste. Diverted includes recycled and reused waste. Source: Data from Statistics Canada (2007).

	Solid Waste (10^6 t/y)		
Jurisdiction	Disposed	Diverted	% Diverted
Canada	25.29	7.86	24
BC	2.69	1.25	31
AB	3.08	0.76	20
SK	0.8	0.13	24
MB	0.93	0.23	20
ON	10.25	2.91	23
QC	6.16	2.13	14
NB	0.44	0.14	25
PE	0.02	0.06	35
NS	0.4	0.22	36
NL	0.4	0.04	8
NT, NU, YK	0.08	0.01	12

Almost all Canadian municipalities are taking steps to reduce the amount of discarded material that must be land-filled or incinerated. The typical content of residential waste in Canada is:

- 40% organics, such as compostable food wastes
- 40% recyclable materials, such as metal and plastic containers
- 10% bulky goods, such as disused furniture, which can often be re-used or re-purposed
- 10% other goods, much of which is also potentially recyclable or otherwise diverted from the disposal stream

Most towns and cities are developing systems to divert material away from the waste stream and they are achieving increasing success in doing that. For example, the following cities have achieved significant diversions of residential MSW from landfills, mostly by instituting various kinds of recycling programs (FCM, 2009; plus direct reports from municipal governments):

- Vancouver, BC, 58%
- Nanaimo, BC, 64%
- Edmonton, AB, 60%
- Saskatoon, SK, 40%
- Hamilton, ON, 44%
- Owen Sound, ON, 51%
- Toronto, ON, 53%
- Victoriaville, QC, 64%
- Sherbrooke, QC, 54%
- Halifax, NS, 59%
- Charlottetown, PE, 60%

Toronto diversion rate of 53% factors in by both single-family homes and multi-unit residential buildings (>9 units). In 2013, residents of single-family homes had a diversion rate of 68%, but those in multi-unit buildings only 26%. Clearly, in this and all cases of MSW diversion in Canada, there is a lot that can yet be accomplished.

Municipal Wastewater Treatment

Issues associated with municipal wastewater include its amount and composition, ways of treating the material, and ecological effects of its disposal. First, we should distinguish among major kinds of wastewater.

- Sewage is wastewater that contains the fecal matter of humans and other animals, plus food waste from kitchens and commercial food processing. In urban areas, sewage is collected using a complex system of underground pipes called sanitary sewers, and transported to a central place for treatment and/or disposal.
- Industrial wastewater may contain many kinds of liquids, including toxic and hazardous wastes. As was previously noted, toxic waste is poisonous, while hazardous waste may be explosive, flammable, or dangerous for other reasons. Many urban areas have separate systems to collect and treat toxic and hazardous industrial wastewater.
- Stormwater is the runoff of rainfall and snowmelt. In municipal areas, it is typically collected using surface drains that feed into a combined sewage-stormflow system, or using a more advanced drainage system that keeps these wastewaters separate. Stormwater is not as grossly polluted as sewage or industrial wastewater, but it does contain significant amounts of fecal material (from pets and wild animals), metals, waste motor oil, road salt, and other substances.

Sewage Treatment

In most places, the principal objective of sewage treatment is to reduce the amounts of pathogenic microbes and oxygen-consuming organic matter that are disposed of into receiving waterbodies. In places where surface waters are vulnerable to eutrophication, sewage may also be treated to reduce the amounts of nutrients, especially phosphorus and nitrogen (see Chapter 20).

All towns and cities have networks of underground pipes to collect the sewage effluent from homes, businesses, institutions, and factories. (However, low-density residential areas may have septic systems installed at individual homes.) Some municipalities have separate collection systems for sewage and stormwater. Eventually, all of the wastewater is discharged to the environment, usually into a nearby lake, river, or ocean. To avoid environmental damage, the wastewater should be treated to reduce its pollutant load before it is discharged. However, some towns and cities still dump raw sewage. Most of these municipalities are located beside an ocean and rely on the local, well-flushed marine ecosystem to dilute and biodegrade organic pollutants and pathogens in the sewage. Because inland waters such as lakes and rivers have a much smaller capacity for diluting and biodegrading sewage wastes, municipalities located beside these waters treat their sewage. (See Chapter 20 for a description of various sewage-treatment systems.)

About 78% of Canadians were serviced by municipal wastewater treatment systems in 2006 (the rest used septic tanks, other private systems, or lived in municipalities that dump non-treated sewage; Environment Canada, 2007). Of the municipal populations, 40% were serviced by tertiary treatment, 38% by secondary, and 19% by primary (these terms are explained in Chapter 20). The remaining 3% had their sewage dumped untreated into the environment. Relatively advanced tertiary systems are used mostly in Ontario and the Prairies. This is because these regions discharge their treated wastewater into rivers and lakes, so a higher level of water treatment is needed to prevent environmental damage. The lowest standard of wastewater treatment is in parts of Atlantic Canada, Quebec, and British Columbia, where some cities are still dumping untreated or only partially treated sewage into coastal waters or large rivers.

Because of concerns about environmental quality in local receiving waters, particularly regarding fecal pathogens and ecological degradation, some cities (such as Calgary, Edmonton, and Toronto) have invested in higher-level systems of water treatment. As a result, the quality of local waterbodies has greatly improved. In contrast, coastal cities, such as St. John's and Victoria, continue to discharge poorly treated sewage into the coastal ocean, relying on "free environmental services" to dilute and biodegrade their effluents. Environmental damages associated with the discharge of untreated or poorly treated sewage include the following:

- the pollution of receiving waters with human fecal pathogens, such as coliform bacteria and viruses, which renders the area unfit for swimming and for use as drinking water
- ecological damage caused by the deoxygenation of water and sediment by the decomposition of organic wastes, resulting in the deaths of many organisms and the development of foul odours
- stimulation of algal blooms through excessive nutrients from sewage effluent
- contamination of the environment with persistent, potentially toxic chemicals, such as metals and organochlorines
- aesthetic damage associated with the presence of sewage waste

These environmental damages, which can be severe, are largely avoided if municipalities invest in facilities to treat their sewage. Because of this widely recognized fact, all Canadian cities and towns, including coastal ones, will further upgrade their facilities to treat their wastewater during the next several decades.

Image 25.4. This sewage-treatment complex serves a population of more than 1 million in the city of Calgary. Because the discharge goes into the Bow River, a relatively small waterbody, the treatment must be of a high standard to prevent ecological damage. In fact, this is perhaps the most advanced system being used in Canada, with tertiary treatment, ultraviolet disinfection, and production of composted sewage sludge for use as a soil conditioner. Source: Courtesy of the City of Calgary/Bonnybrook Wastewater Treatment Plant.

Urban Biodiversity

Urban areas are highly impoverished in terms of the amount and quality of habitat available to support plants, animals, and microorganisms. Nevertheless, many wild organisms do occur – even parking lots, sidewalks, and industrial areas, which from an ecological perspective are extremely degraded habitats, do manage to support some biodiversity.

Still, some urban places are relatively natural in character and are maintained in this condition as parks. Some prominent examples of "natural-area parks" include Stanley Park in Vancouver; a series of parks along the Bow River in Calgary and on the North Saskatchewan River in Edmonton; Assiniboine Park in Winnipeg; High Park and Hanlan's Point in Toronto; Bois de Liesse in Montreal; Point Pleasant Park in Halifax; and Signal Hill in St. John's. These greenspaces are remnants of natural habitat that have survived the urbanization process, and they contain ecological communities that are mostly dominated by native species.

Image 25.5. Stanley Park in Vancouver is a greenspace with a mixture of natural and cultural values. During the autumn and winter, geese and other migrating waterfowl use the local ponds and other habitats for feeding and other purposes. Source: B. Freedman.

More typically, however, urban habitats are dominated by alien species, which were introduced in various ways. Most non-native plants were introduced in these ways:

- as seeds contained in soil carried by ships as ballast, which was dumped in a port when the cargo was discharged (this was particularly important before the twentieth century)
- as seeds that contaminated the seedstock of crop plants (this is now less of a problem because weed seeds are "cleaned" from commercial seedstock)
- or as plants used in agriculture, forestry, or horticulture. Some alien plants have found good habitat in urban areas, where they thrive and out-compete native species. These invasive aliens are an important ecological problem and can be regarded as a kind of "biological pollution" (see Chapters 1 and 26).

Non-native animals are also common in urban areas. Some, such as the house mouse (Mus musculus) and Norway rat (Rattus norvegicus), were introduced accidentally when they escaped from infested ships and cargoes. Others were deliberately introduced. For example, the rock dove (pigeon; Columba livea), starling (Sturnus vulgaris), and house sparrow (Passer domesticus) were introduced by a nineteenth-century society of gentlemen who were dedicated to bringing all of the birds mentioned in the plays of William Shakespeare to North America. Of the various species that these misguided naturalists attempted to introduce, only these three have established widespread populations.

Many alien species now have wild, self-maintaining populations in urban areas. Examples of these invasive plants and animals and the ecological problems that are associated with them include the following:

- The dandelion (Taraxacum officinale) is a perennial, herbaceous plant that was originally native to alpine habitat in Europe, but now occurs in temperate regions throughout the world, probably having been introduced in marine ballast. The dandelion is considered an important weed of lawns and pastures.
- Japanese knotweed (Polygonum cuspidatum) is a perennial, herbaceous plant that grows up to 2-m tall and is native to Japan. It has attractive foliage and was widely introduced for horticultural use. It can be invasive in disturbed areas.
- The sticky touch-me-not (Impatiens glandulifera) is an annual wildflower native to the Himalayas. It was introduced through horticulture and can be invasive in gardens and wetlands.
- Goutweed (Aegopodium variegatum) is a perennial, herbaceous plant native to Eurasia that was widely introduced through horticulture and is invasive in gardens and other disturbed habitats.
- Purple loosestrife (Lythrum salicaria) is a perennial, herbaceous plant of Eurasia that was introduced through ships' ballast and horticulture and is a serious invader of wetlands.
- St. John's wort (Hypericum perforatum) is a perennial, herbaceous plant of Europe that was introduced probably through marine ballast and is now a serious weed of pastures that causes a photosensitivity disease in cattle.
- Norway maple (Acer platanoides) is a native tree of Europe that was introduced for horticultural use. It invades natural hardwood forest.
- The oriental cockroach (Blatta orientalis) is an insect native to eastern Asia. It was probably introduced accidentally with ship cargo and is a serious pest in homes and other places where food is stored.
- The garden snail (Cepaea hortensis) is a terrestrial mollusk native to Europe. It was probably accidentally introduced with marine ballast and is a garden pest in some regions.
- The house mouse and Norway rat are rodents native to Eurasia that were accidentally introduced from ships and are now serious pests in homes and other places where food is stored.
- The starling, rock dove, and house sparrow are songbirds native to Eurasia that were introduced by European settlers in the Americas who were anxious to have familiar species from their homeland. They displace native birds from nesting sites and are invasive pests.

These and other free-living, alien species are the most abundant plants and animals in Canadian urban areas. Of course, the domestic dog (Canis familiaris), domestic cat (Felis catus), and other pets are also common non-natives in our cities and towns. (Even though Aboriginal peoples have lived in the Americas for at least 12-thousand years, the human species might also be considered non-indigenous to these continents.)

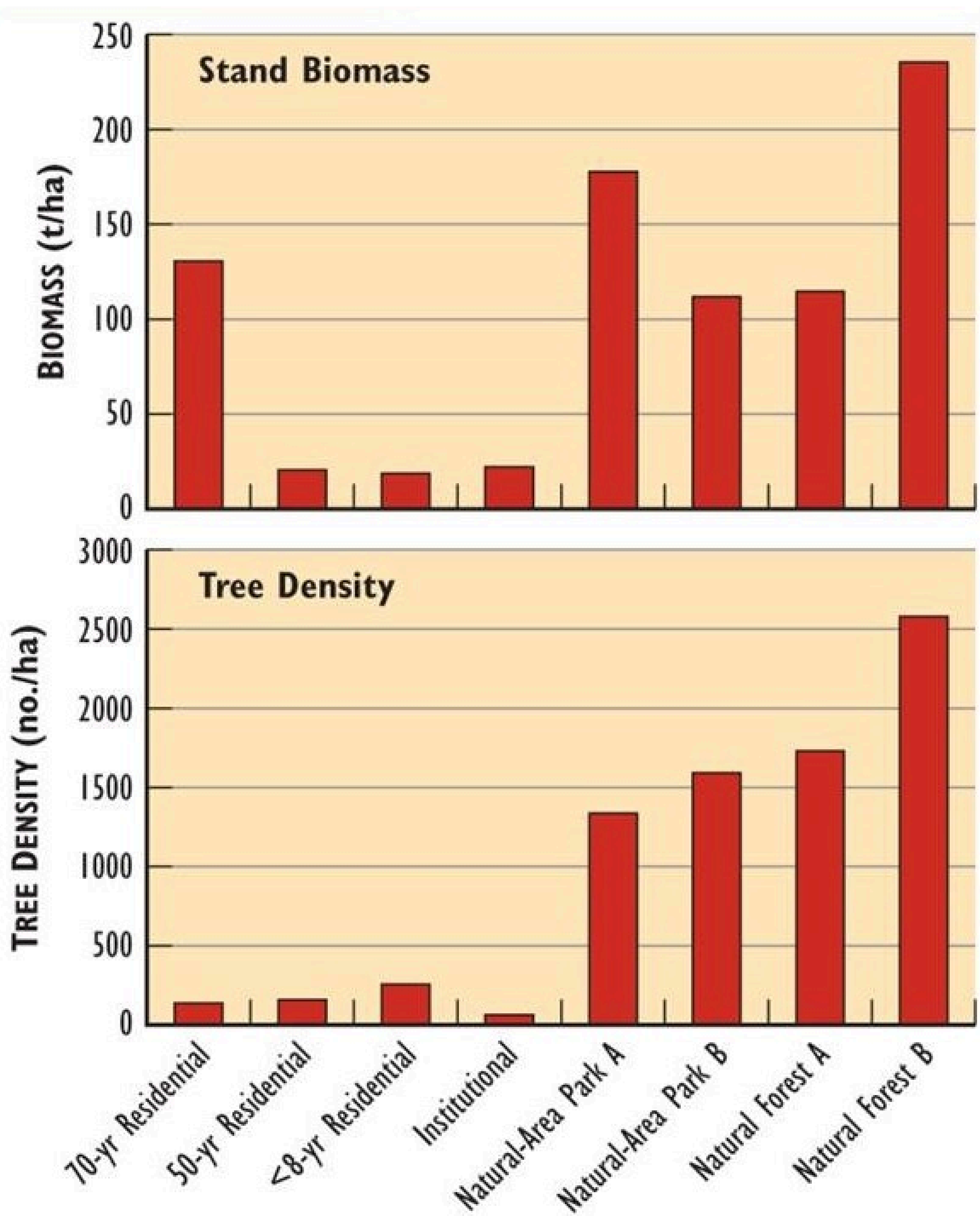
The characteristics of various urban ecosystems have been studied in Canada. Many urban habitats are highly disturbed and are managed to keep them in an early stage of succession. Urban lawns, for example, are mown frequently to prevent their vegetation from developing beyond a stage that is dominated by low-growing, herbaceous plants. Moreover, because most lawn-growers want a monoculture of only one or two species of grasses, they may apply herbicide to kill unwanted dicotyledonous plants, such as clovers, dandelion, and other "weeds."

The most commonly grown grass in lawns in temperate-zone countries is the Kentucky blue grass (Poa pratensis), which, despite its common name, is actually a Eurasian species. Also cultivated in some regions are ryegrass (Lolium perenne), red fescue (Festuca rubra), and bent grasses (Agrostis species); these are also aliens. Other aspects of the intensive management of lawns include the use of fertilizer, insecticide, and irrigation. Some ecologists recommend less-intensive systems of lawn management, including tolerance of such non-grass plants as red clover (Trifolium pratense), black medic (Medicago lupulina), and other legumes, which fix atmospheric nitrogen and so reduce the need for fertilizer. Even such species as dandelion and buttercup (Ranunculus acris) can be tolerated in lawns and viewed as attractive “wildflowers” rather than as “weeds.”

The urban forest is another prominent habitat in cities and towns, although it does not always support native species. Neighbourhoods with abundant trees can be studied using the same methods that are used to examine natural forest. One study looked at the urban forest in residential, institutional, and parkland areas of Halifax (Figure 25.8). Older residential neighbourhoods had a tree biomass similar to that of natural forest in the region, although the stem density was considerably less (many trees in the mature urban forest are relatively large). Younger neighbourhoods had a smaller tree biomass but a higher density, suggesting a pattern of succession in the urban forest. Even an institutional neighbourhood, consisting mostly of several hospitals and a university, had a substantial population of trees.

Image 25.6. Streets with large numbers of mature trees are relatively pleasant, compared with places in which the urban forest is sparse or missing. This residential street in Halifax is mostly forested with alien trees, such as Norway maple (Acer platanoides) and linden (Tilia cordata). Source: B. Freedman.

Figure 25.8. Characteristics of the Urban Forest in Halifax. Tree density and biomass are shown for stands of urban forest in different kinds of neighbourhoods. The data for natural forest are for rural mature hardwood stands. Source: Freedman et al. (1996).



The majority of trees in urban forests are alien species (Table 25.2). In the oldest residential area sampled in Halifax, 72% of the trees were non-native, the most common being Norway maple (Acer platanoides), linden (Tilia europaea), European ash (Fraxinus excelsior), Scotch elm (Ulmus glabra), and rowan (Sorbus aucuparia). An eight-year-old residential neighbourhood had a much larger percentage of native trees (about 92%), which had survived the clearing of the natural forest when the suburb was developed. However, most of the local homeowners were choosing alien species for their horticultural plantings, so their prominence will increase rapidly as the neighbourhood ages.

Table 25.2. Prominent Street Trees in Selected Canadian Cities. The data show the frequency of the seven most abundant species growing in urban forests of four cities. Frequency is given as the percentage of the total number of trees, and Origin is: (N) native to North America or (I) introduced. Source: Data compiled from municipal governments.

City	Prominent Species	Frequency	Origin
Vancouver	Japanese cherry (*Prunus serrulata*)	11	I
	sour cherry (*Prunus cerasus*)	9	I
	Norway maple (*Acer platanoides*)	6	I
	red maple (*Acer rubrum*)	4	N
	linden (*Tilia cordata*)	4	I
	weeping birch (*Betula pendula*)	3	I
	hornbeam (*Carpinus betulus*)	2	I
Winnipeg	white elm (*Ulmus americana*)	25	N
	poplar (*Populus spp.*)	15	N
	Manitoba maple (*Acer negundo*)	10	N
	green ash (*Fraxinus pennsylvanica*)	10	N
	bur oak (*Quercus macrocarpa*)	10	N
	basswood (*Tilia americana*)	10	N
	black ash (*Fraxinus nigra*)	5	N
London	silver maple (*Acer saccharinum*)	20	N
	Norway maple (*Acer platanoides*)	15	I
	honey-locust (*Gleditsia triacanthos*)	8	N
	sugar maple (*Acer saccharum*)	5	N
	green ash (*Fraxinus pennsylvanica*)	5	N
	linden (*Tilia cordata*)	5	I
	red oak (*Quercus rubra*)	2	N
Halifax	Norway maple (*Acer platanoides*)	30	I
	linden (*Tilia cordata*)	20	I
	white elm (*Ulmus americana*)	15	N
	Scotch elm (*Ulmus glabra*)	5	I
	European ash (*Fraxinus excelsior*)	5	I
	red oak (*Quercus rubra*)	5	N
	horse chestnut (*Aesculus hippocastanum*)	5	I

The displacement of native plants by alien ones results in important ecological damage, especially if the foreign ones become invasive. Some ecologists believe that horticulturists should place much greater emphasis on the use of native plants, rather than risk the serious problems associated with biological "pollution" by aliens.

The urban forest provides many useful ecological services. For example, large amounts of carbon are stored in urban trees, which helps offset some emissions of CO_2 from the combustion of fossil fuels. Urban parks and well-treed residential areas can store as much carbon in tree biomass as can a natural forest (Table 25.8). In addition, well-placed trees reduce the wind speed near buildings, which decreases the air-infiltration rate and thereby helps to conserve heat during cold weather. Trees can also shade buildings, reducing the energy needed for air conditioning during warm weather. Transpiration from tree foliage also helps to cool the ambient urban atmosphere, as does the shading of streets, lawns, and other areas. Urban trees also absorb some air pollutants (such as SO_2 and particulates), help to reduce noise levels, and greatly improve outdoor aesthetics. A well-developed urban forest also provides habitat for lower-growing plants and for animals in built-up areas.

Another study in Halifax also examined the non-tree vegetation (Turner et al., 2005). In an older residential neighbourhood, 87% of the low-growing species were aliens as were 84% of the shrubs and trees. Even in a recent suburban development, which still had remnants of native habitat, 77% of the low vegetation and 69% of the woody plants were aliens. These observations are not particularly surprising in light of the results of surveys of commercial horticultural businesses in the study area, which offered few or no native plants for sale.

Image 25.7. Urban biodiversity can be pleasant, but it is often managed in a highly contrived manner and is dominated by alien plants and animals. Almost none of the species in this cemetery in Toronto are native to Canada. Source: B. Freedman.

A study of birds in various Toronto neighbourhoods found that even commercial and industrial habitats sustained some species. However, about 97% of the birds in those habitats were aliens such as rock dove, starling, and house sparrow (Table 25.3). These introduced species also dominated the bird fauna of residential neighbourhoods, accounting for 64-94% of the birds present. However, the residential areas had a significant amount of habitat with abundant trees, shrubs, and other plants, which allowed some native birds to live in small numbers, including American robin (Turdus migratorius), blue jay (Cyanocitta cristata), and cardinal (Cardinalis cardinalis). Of all the habitats surveyed, only a natural-area park had a relatively low fraction of alien birds (25%). The mostly forested habitat of that park sustained

26 species of birds, most of which were not seen in the highly anthropogenic habitats. Not surprisingly, this study found that the more natural the vegetation in an urban habitat, the larger the number of native birds that was supported. Even relatively small areas of natural habitat in urban areas could sustain breeding by native birds.

Table 25.3. Density of Birds in Various Urban Habitats in Toronto. The data are the average numbers of birds observed per kilometre2 during censuses in May and June. Only the most abundant species are included. An asterisk (*) indicates a non-native species. Source: Data from Savard (1978).

Species	Downtown Commercial	Downtown Industrial	Mature Residential A	Mature Residential B	Younger Residential	Grassy Park	Natural Park
Rock dove*	106	188	247	131	3	94	0
Chimney swift	0	13	14	3	2	8	19
Flicker	0	0	0	0	2	9	19
Blue jay	0	0	6	19	18	0	7
Common crow	0	0	0	13	3	5	38
American robin	0	0	28	87	174	73	25
Starling*	72	196	426	116	285	427	89
House sparrow*	87	167	517	353	487	121	65
Common grackle	4	7	18	25	120	24	81
Cardinal	0	0	0	12	5	0	15
TOTAL BIRDS	277	566	1256	778	1223	788	609
No. of species	5	5	7	11	15	10	26
% Non-native	96	97	94	77	64	80	25

Waterfowl are also abundant in urban areas with aquatic habitat, such as beside an ocean or near a lake or river. For example, many cities have wild breeding populations of "giant" Canada goose (Branta canadensis maxima), which are descended from birds that were released in those places since the 1950s. The geese find that grassy lawns near water provide suitable feeding habitat, and their population in some cities has increased enormously. However, many of these geese have lost the habit of migrating, and some people consider their abundance and year-round presence to be a nuisance. Some cities have attempted to alleviate their "over-population" of geese by capturing animals and shipping them to willing host cities elsewhere. Some cities are culling the geese by killing part of the population.

During the spring and fall migrations, some cities with aquatic habitat support large numbers of native waterfowl and other birds. Some waterfowl may remain during the winter if open water is present. Urban birders from Victoria to St. John's often spend time viewing the numerous native ducks, geese, swans, gulls, shorebirds, and other migrating and wintering birds in local aquatic habitats. Each autumn, for example, the Toronto waterfront provides habitat for thousands of long-tailed ducks (Clangula hyemalis) that are migrating from their arctic breeding grounds. St. John's is the only city in the world where ivory gulls (Pagophila eburnea) can be regularly seen.

Some native mammals also occur in urban habitats. Grey (black) squirrels (Sciurus carolinensis) and raccoons (Procyon lotor) may even inhabit downtown neighbourhoods as long as there is some open forest available. Urban areas with extensive shrubby and forested habitat may sustain white-tailed deer (Odocoileus virginianus), red fox (Vulpes vulpes), striped skunk (Mephites mephites), and coyote (Canis latrans). The key to sustaining populations of native animals in urban areas is to maintain as much relatively natural habitat as possible, dominated by indigenous plants. If this is done, even inner-city backyards can provide habitat for some native animals. This function is enhanced by the deliberate naturalization of urban habitats by growing native plants in horticulture (see In Detail 25.2).

In Detail 25.2. Urban Naturalization. Urban naturalization is a "new" horticultural practice that favours the use of native plants to achieve pleasing aesthetics in gardening. It is a more natural alternative to conventional horticulture, in which there is a very strong preference for the cultivation of alien plants. Naturalization avoids many of the ecological problems that are associated with growing aliens, which can become invasive and damage natural habitats and may be vectors of deadly diseases of native species (see Chapter 26).

But what is meant by terms such as "native" and "natural"? In the sense intended here, and in the context of the Americas, a native (indigenous) species is one that was present in an ecoregion before about 1500 (that is, in pre-Columbian times). If a species was introduced afterward, either deliberately or accidentally, and then developed self-maintaining populations, it would be considered "naturalized" but not indigenous (they may also be "invasive aliens" if they cause ecological damage). "Natural communities" are considered to be self-organizing, co-evolved assemblages of native species that occur in habitats that are appropriate for their survival.

Because many native plants are beautiful and can grow well in habitats provided by gardens, they can be easily used in horticulture. In fact, they may do very well because they are pre-adapted to local climate, soil, and other aspects of the habitat. They may be grown in contrived but pleasing arrangements of flowering plants, shrubs, and trees, as is commonly done in horticulture, or they may be managed to create a facsimile of a natural community.

If naturalization is used to replace conventional horticultural habitats, such as lawns and gardens that are dominated by alien species, it will result in areas being better suited to support native birds and other animals. This kind of gardening can create beautiful spaces, but it has a much softer ecological footprint. Although naturalized gardens are still uncommon, they are attracting increasing attention from people seeking to express a more natural view of their world.

Conclusions

Urban ecosystems sustain humans, associated non-native organisms, and some native species and remnants of natural habitats. However, urban ecosystems are ecological "islands" that draw upon the surrounding region to continuously supply immense quantities of natural resources and to assimilate wastes. A great challenge for urban ecologists is to develop a better understanding of the structure and function of the urban–industrial techno-ecosystem, including the exchanges of materials and energy and the factors that affect biodiversity. This knowledge can help to identify ecologically pathological relationships, which can then be mitigated to reduce the urban–industrial footprint. If this is done, then modern cities can become more ecologically sustainable than is now the case.

Questions for Review

1. What changes were important in the development of urban places during the socio-cultural evolution of our species?
2. What is an ecological footprint? What are its key components?
3. Characterize the urban ecosystem of your community in terms of its structural (such as species and habitats) and functional (resource use, waste generation) attributes.
4. What are major differences between urban and rural biodiversity?

Questions for Discussion

1. Make a list of factors that are important in the ecological footprint of your community. How might these be changed in order to decrease the size of the footprint?
2. Why do so few people use a bicycle as their routine means of transportation, in spite of its mechanical efficiency and low cost?
3. How does your lifestyle contribute to pollution of your environment?
4. Define the following terms: dumping (disposal), incineration, recycling, composting, reuse, and waste production and prevention. What role does each of these play in waste management in your community?
5. What are the major practices used to treat urban sewage? Why have some cities chosen to treat their sewage in an environmentally responsible way, while others have not?
6. Characterize the principal elements of urban biodiversity in your neighbourhood. How could habitats be naturalized in order to support more indigenous species?
7. Use the footprint calculator provided by the Global Footprint Network (an environmental organization) to calculate your ecological footprint. (Go to http://www.footprintnetwork.org/en/index.php/GFN/page/personal_footprint/) Try doing a "virtual experiment" by varying aspects of your lifestyle in the calculator to see what effect it has on your personal footprint. For example, see what happens if you ride a bike, use public transit, or fly in an airplane.

Exploring Issues

1. Your municipal government has hired you to provide advice as it seeks ways to make the community function in a less damaging, more sustainable manner. What studies would you undertake to determine ways by which urban functions (such as transportation, sewage treatment, and management of solid materials and wastes), land-use patterns, and biodiversity can be improved to contribute to the goal of sustainability? What do you think your recommendations would be?

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Chapter 26 ~ War

Learning Outcomes

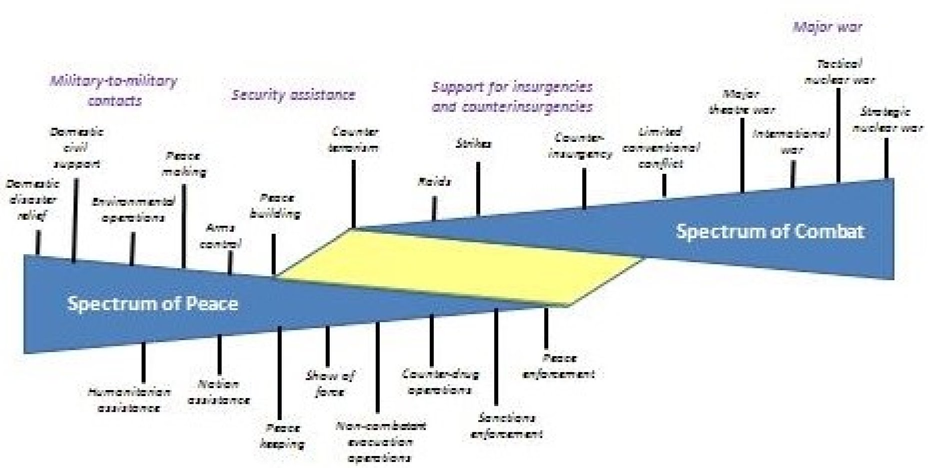
After completing this chapter you will be able to:

1. Explain the causes of wars and other violent conflicts.
2. Describe the costs of militarism and warfare in terms of human lives, economic costs, and environmental damage.
3. Outline the economic and environmental damage that would potentially be caused by the use of nuclear weapons.
4. Outline the influences and mechanisms that help to promote disarmament and avoid warfare.

Causes of Extreme Conflict

War (or warfare) might be defined as a period of organized deadly conflict between human societies, countries, or another defined group. War is waged to achieve political objectives, or as stated by the German military theorist, Carl von Clausewitz (1780-1831) in his famous book On War (1832): "War is the continuation of national policy by other means." In modern times, the adversaries in warfare are typically well-armed with lethal weaponry. The results of a conflict often include the widespread destruction of the infrastructure of the warring parties, much loss of human life, a great disruption of society, and severe environmental damage. Militarism refers to a belief of people or governments in the need to maintain a strong military capability to defend or promote national interests. The implementation of war-oriented policies results in enormous amounts of resources being diverted to building and maintaining a martial capability in the form of armed forces and their equipment and other infrastructure. The absence of war is referred to as peace, during which time society typically has a focus on improving socioeconomic and environmental conditions, rather than on preparing for conflict. In reality, however, the conditions of peace and war may each vary enormously and even overlap to some degree (Figure 26.1).

Figure 26.1. The spectrum of peace and combat. This conceptual diagram shows the ways that armed forces might be engaged in operations during both war and peacetime. The intensity of warfare increases to the right of the diagram, and that of peace to the left. Modified from Johnsen (1998).



The intensity of combat may range from a calamitous exchange of nuclear weapons to local actions that are taken to control an insurgency. The intensity of peace can vary from utter civil and international tranquility to policing actions that are needed to maintain civil order. The engagement of military forces during peacetime can range from a deployment to assist civil authorities during a natural disaster such as major flooding, actions needed to prevent domestic terrorism, or international operations sanctioned by the United Nations to keep or enforce the peace among other warring countries.

Certainly, war has long been an enterprise of organized groups of people. It is referred to in some of the earliest records of civilization. One of the earliest historical references is in the second book of the Judeo-Christian Bible: “The Lord is a warrior,” (Exodus 15, 3-18), a phrase that refers to a belief that God intervened with violent actions against the army of the Egyptian Pharaoh, who was trying to prevent the Jewish tribes led by Moses from leaving his realm.

Moreover, humans may have a genetically based predisposition to engage in violent behaviour, with sometimes lethal consequences. This suggests that when stimulated in certain ways by environmental circumstances, humans may be hard-wired to become viciously aggressive, and such a response may be an integral aspect of our biology.

Interestingly, many other species also appear to be like this, including our closest living relative, the chimpanzee (Pan troglodytes). Biologists studying the behaviour of these animals in the wild have observed instances of groups of related male individuals deliberately engaging in violent and sometimes lethal raids against a neighbouring troop, particularly against other males. This activity could be likened to non-human warfare, albeit at a small scale. Interestingly, the closely related Bonobo (Pan paniscus) is much less aggressive; rather, this chimp appears to diffuse societal tension in non-violent ways, including a matriarchal group structure and sexual promiscuity.

Many species of ants are also war-like in their sociology. For example, the Amazon ant (Polyergis) makes raids on colonies of the wood ant (Formica) in order to capture slaves that are then used to tend their broods of eggs and pupae, killing any individuals that do not submit to detention. One additional example of lethal aggression between species might involve a pack of wolves (Canis lupus) attacking coyotes (Canis latrans) that are observed to trespass on their territory.

However, these are somewhat unusual examples of violence committed by groups of non-human animals. It is much more common for animals to engage in violent behaviour when in competition for sexual reproduction, as when male deer of various species, such as elk (Cervus canadensis), aggressively joust with their antlers for access to females in their herd, or when rams of bighorn sheep (Ovis canadensis) act similarly by whacking their heads together. Animals may also compete in violent ways to secure access to scarce food or other resources.

However, if these aggressive behaviours are occurring as contests between particular individuals they would not be considered to represent warfare, a term that should be limited to acts engaged in by organized groups having a common purpose. Von Clausewitz (1832) defined war in this way: “War is thus an act of force to compel our enemy to do our will.”

In our own species, it is likely that the earliest pre-historic conflicts were between extended family groups (or clans) that were engaged in a subsistence economy of hunting and gathering, who may have fought over access to food or other resources. However, because of low population densities those conflicts may have been rather infrequent. Interestingly, there is no actual evidence in ancient archaeological records of such aggression occurring amongst hunting-and-gathering people, such as the in the cave paintings of Lascaux, France and elsewhere, which instead focus on depictions of animals being hunted as food. Nevertheless, it is hard to imagine that conflicts between neighbouring bands of people did not sometimes occur.

As human cultural evolution progressed, the clashes between small groups of people would have progressed to bigger conflicts involving neighbouring communities and cultures. By 10-12-thousand years ago, many archaeological sites include remains of relatively advanced weapons such as bow and arrow, mace, and sling, all of which could have been used in human conflicts as well as for hunting.

Of course, the scale and intensity of warfare have increased enormously since those early days. Wars progressed into conflicts between city-states, and then between nation-states and often their coalitions. Cumulative improvements of technology have resulted in the development of increasingly destructive and sophisticated weapons, and the rapid growth of both populations and economies during the past several centuries have resulted in a gigantic scale of military capability.

Today, modern warfare potentially involves a contest with the potential to achieve an equivalent of Armageddon, a Biblical metaphor for a conflict so destructive that it represents the end of civilization. In the Abrahamic religions, Armageddon was a place mentioned in Revelation 16:16 where there was an enormous battle that resulted in the end of the world. Indeed, any enthusiastic use of the arsenals of advanced weaponry of today, and particularly the nuclear arsenals of several countries, could result in an end-of-times outcome.

Of all the possible damages that humans might cause to their own civilization and to the biosphere, an all-out nuclear war would certainly result in the worst possible destruction. To paraphrase the poet T.S. Eliot (1888-1965): this is the way the world could end, not with a whimper but a bang.

Causes of War and Other Hot Conflicts

Wars occur because one party decides that its goals are best (or only) secured through the use of force rather than through other means (such as diplomacy), and because the other party is prepared to employ force to resist. Those goals may involve vital national interests, or they may be inspired by some combination of politics, socioeconomic circumstances, or beliefs founded in culture or religion. The causes of war are always complex, but they may be understood by briefly looking at some examples, which are presented below in chronological order.

Disputes between nation-states (countries) or their coalitions have been the most common reason for the “conventional wars” that are fought by regular armies. These wars are typically fought over national interests, such as conflicts over territorial boundaries, the imperial ownership of colonies, or rights of access to certain regions for trading or transportation. The examples below were selected as being relevant to conflicts in which Canada or its colonial progenitors were engaged.

- The Seven Years’ War was an international conflict that occurred between 1756 and 1763 and involved European powers organized into coalitions led by Britain-Prussia or France-Spain. The war was mostly about the control of foreign colonies, but the personal aggrandisement of heads of state was also an important factor. The conflict occurred in Europe and in various international theatres. In North America it resulted in the British securing colonial ownership of New France, a region now consisting of the Maritime Provinces and southern Québec, as well as Spanish Florida and some Caribbean islands.
- The War of 1812, which actually took place during 1812 to 1815, was fought between Britain and its proto-Canadian colonies and the United States aided by France. It was an offshoot of the Napoleonic Wars of 1796-1815, a series of conflicts that occurred mostly in Europe and were fought between France and its allies and Britain and its own confederates. The War of 1812 was declared by the U.S. for a number of political and economic reasons – to lift trade restrictions imposed by the Royal Navy, to stop the forced impressing of American sailors into British naval service, to end British support of Amerindian tribes that were resisting American westward expansion, and to expand its national territory into what is now the southern regions of the Prairie Provinces.
- The First World War (or Great War) of 1914-1918 was a conflict between two large coalitions: the Allies (western European countries led by France and Britain, plus Canada and other countries of the British Commonwealth, Russia, and later in the conflict Italy and the United States) and the Central Powers (a German-led group that included Austria-Hungary and Turkey). This war was triggered by the assassination of the Archduke Franz

Ferdinand of Austria, but the ultimate causes are remarkably complex. They are linked to tensions arising from the aspirations of Germany for hegemony (a kind of imperial leadership) in Europe, for the Austro-Hungarian empire to eliminate threats to its survival, for national security of all of the participating nations, and for the permanence of colonial empires.

- The Second World War of 1939-1945 was an even more widespread conflict between two enormous coalitions. On one side was the Allies, consisting of western European countries ultimately led by Britain, plus France, Belgium, Canada and other Commonwealth countries, and beginning in 1941, the Soviet Union and the United States. On the other side was the Axis Powers led by Germany and Japan, but also including Italy, Romania, and some other countries of eastern Europe. The conflict in Europe was precipitated mostly by aggressive German aspirations to politically dominate Europe and beyond, a goal that was partly instigated by lingering frustration with the humiliation and crushing reparations imposed on that country as a consequence of its defeat in the First World War. The German intent was to politically dominate western Europe, and to colonize eastern Europe with large numbers of Germanic settlers. The fever for war was also fuelled by profound differences in socio-political systems between democracies and dictatorships, and between capitalism and socialism-communism. A more minor cause was disgust felt by many people in the Allied countries about political and social policies imposed by the Nazi dictatorship in pre-war Germany and Austria. Those policies were resulting in severe losses of civil liberties by ethnic groups, other social minorities, and the political opposition, including their seclusion in concentration camps, where many were forced to work as slaves under starvation conditions, or were mass-murdered.
- The First Gulf War of 1990-1991 was instigated when Iraq unexpectedly invaded and took over Kuwait in August, 1990. The invasion was ostensibly rationalized on the basis of Kuwait once being controlled by Iraq. However, the real reason for the invasion was Iraq seeking relief from huge debts associated with its recent war with Iran of 1980-1988. Those debts were mostly owed to nearby Arab countries, and a substantial part could be relieved by taking over the government and rich oil fields of Kuwait. Almost immediately, however, the invasion of Kuwait was opposed by a coalition of nations led by the United States and sanctioned by the United Nations. The public justification for the subsequent war of liberation was based on preserving the sanctity of sovereign states – in particular, that of Kuwait prior to the Iraqi invasion. However, the key underlying reason was a compelling desire to safeguard the reliability of supply of Middle Eastern petroleum to Europe, North America, and Japan. At the time, about 63% of the known recoverable reserves of petroleum in the world were in the Middle East (WRI, 1995). Iraq held 11% of the global reserve and when it added the Kuwaiti stocks it would have controlled 21%, while also threatening an additional 29% in Saudi Arabia and the United Arab Emirates. The oil-dependent industrial nations considered it an unacceptable economic threat to have so much of the world's petroleum controlled by a capricious Iraqi dictatorship led by Saddam Hussein. In addition, the governments of various Middle Eastern countries felt threatened by their own potential invasions by Iraq.

Wars between differing cultures are fought because of deep animosities associated with different religions or political ideologies. These kinds of wars may involve the armies of nation-states or they may occur as rebellions or insurrections within a country. Examples include the following:

- The American War of Independence (1775-1783), also known as the American Revolution, was fought between the Imperial forces of Great Britain and an insurgency of many people who were living in what is now the eastern United States. The main cause of the war was an intense difference in political ideology – many of the colonial Americans were dissatisfied at being governed and taxed by a foreign parliamentary government without having an effective representation in that administration. In essence, the revolutionaries were seeking the freedom to govern themselves, and they fought to win that right, in the process founding the United States of America. However, many other Americans of the time did not seek liberation from direct rule by Britain, and after the war most of them left the nascent United States, many of them immigrating as United Empire Loyalists to what is now eastern Canada.

- The French (1789-1799) and Russian (1917) Revolutions were broadly comparable in the sense that both started as rebellions undertaken with the intent of replacing an absolute monarchy with a system of governance that was more broadly based on the will of the populace. The monarchs that were replaced were King Louis XVI of France and Tzar Nicholas II of Russia. However, both of these revolutions ushered in periods of profound social and political upheaval that resulted in unstable governments of various kinds, ranging from temporary re-institution of a monarchy, to dictatorship, to the liberal democratic systems that exist in those countries today. Essentially, these revolutions were socio-political in their nature.
- The Korean War of 1950-1953 and the Second Indochina War of 1960-1975 were separate conflicts fought for similar reasons – irreconcilable differences in the socio-political systems of capitalism and communism, and the desire to replace one with the other. The Korean conflict began when communist North Korea, later aided by China and Russia, invaded capitalist South Korea, later aided by the U.S., Canada, and other western countries. The war in Indochina began as an insurgency in South Vietnam by a communist Viet Kong guerrilla force, later joined by regular troops of North Vietnam supported logistically by China and Russia. These communist forces were resisted by the capitalist government of South Vietnam as well as the United States and several other western countries (Canada did not fight in this war).
- "The Troubles" was a period of ethnic and political conflict in Northern Ireland that also spilled over into violence in England and the Republic of Ireland. This conflict began in the late 1960s and ended in 1998, although sporadic violence still occurs. This was a low-grade war between radical factions that differed in two main attributes: (a) in religion and associated cultural traits (Roman Catholic versus Protestant) and (b) in politics, with the nationalist (or republican) Catholics striving to have Northern Ireland join with the Republic of Ireland, and the unionist (or loyalist) Protestants wanting to remain one of the four countries that make up the United Kingdom (along with England, Scotland, and Wales). The fighting consisted mostly of urban terrorism such as bombings and assassinations by paramilitary organizations of both sides, while the police and armed forces of the United Kingdom and Republic of Ireland tried to contain the violence and maintain social order.
- The violence between Hutu and Tutsi peoples in Rwanda, Burundi, and neighbouring countries of central Africa was essentially a result of intense ethnic conflict between these tribal groups. The distinction between Hutu and Tutsi is mostly one of self-identified cultural affiliation – people view themselves as being one or the other, based mostly on their family lineage. Other than that, the groups speak the same language and are physically similar (the Tutsi tend to be taller and leaner, but this is not a consistent difference). Regardless of the real or presumed differences, many people in each cultural group had developed an intense prejudice against the other, a situation that was made worse by asymmetric power structures in government and other forms of tribal competition. In 1994 this state of affairs culminated in a mass murder in Rwanda of more than 500-thousand Tutsis by Hutus over a 3-4-month period. Tutsi forces from Burundi then invaded Rwanda, and although there are ongoing conflicts in that region of Africa, the genocidal mass killings were ended.
- The Kurds are a distinct people of the Middle East, but they do not have a home country. Instead, they live in adjoining regions of Iraq, Iran, Syria, and Turkey, where the national governments have tended to suppress the Kurdish culture in an attempt to assimilate them into that of the mainstream. However, many Kurds have nationalist aspirations and these people have engaged in long-running insurgencies with the intent of secession to form their own homeland. The Kurds have achieved a substantial degree of self-determination in northern Iraq, but not elsewhere.
- The state of Israel was founded in 1948 as a result of a decision by the United Nations to partition the land of Palestine, at the time a British protectorate, into Jewish and Arabic states. Essentially, this was done to provide a country for Jews in their ancestral homeland following a genocide during the Second World War during which about six million were killed (a genocide is the mass killing of an identifiable group as an attempted extermination). However, the division was resisted by many of the indigenous Palestinians as well as surrounding Arabic countries. This resulted in a series of wars between Israel and surrounding countries, as well as hot conflicts with Palestinian guerrillas associated with several political factions. The causes of this long-running conflict are complex, but they include reciprocal prejudice and hate between adversarial groups based on religion and other cultural differences.

- The final example of extreme conflict between cultural groups is an on-going one between radical Islamic fundamentalists (Islamists) and “Western” sociocultural influences. The Islamists are organized into a number of trans-national paramilitary organizations, such as Al-Qaeda, Islamic State in Iraq and Syria (ISIS), and the Taliban, who are fighting to oppose western influence in countries where the dominant religion is Islam, while also seeking an ascendancy of the Sunni version of Islam over the Shia and other ones. The opposing forces include the national governments of all countries where the Islamists are active, heavily supported by the “West,” which consists of relatively developed countries governed by liberal democracies and epitomized by the United States, and including Canada. The conflict mostly involves terrorist actions such as assassinations and bombings of public places, including the catastrophic attacks using hijacked jetliners on September 11, 2001, on the World Trade Towers in New York and the Pentagon in Washington. In addition, however, the conflict involves organized Islamist armies fighting against governmental forces, the latter often aided by international expeditionary forces.

These various examples of wars, chosen from a multitude of possible cases, show that a lethal conflict may be caused by a variety of triggers, some operating over longer periods of time and others on a shorter-term basis. In all cases, however, the decision to engage in extreme violence against other people and their culture or economy is based on a logical interpretation of the existing circumstances, as they are understood by one or both of the opposing sides. The logic itself may seem twisted and irrational to an independent observer, perhaps one who is less sympathetic to judgements based on racism, xenophobia, and other intolerances. Nevertheless, all acts of extreme violence make a kind of sense to their perpetrators, and that is the fundamental reason why they are undertaken. As we will learn in the rest of the chapter, the results of warfare can include mayhem and murder at extraordinary scales, causing misery to many people and also to the broader environment.

Image 26.1. The World Trade Towers burning on September 11, 2001. The two World Trade Towers were the tallest buildings in New York and a global symbol of both international commerce and western-influenced capitalism. They were attacked by hijacked commercial jetliners flown by Al-Qaeda aligned terrorists. The fires caused by the attacks weakened the buildings enough that they then collapsed. The total mortality associated with these attacks, another at the Pentagon in Washington on the same day, and a fourth hijacked jetliner that crashed into a field in Pennsylvania, was 2,996 people, and at least $10 billion in property damage was caused. Source: Image from U.S. Library of Congress, LCCN2002717279 LC-A05-A11.tif; http://commons.wikimedia.org/wiki/Category:Library_of_Congress_images_of_September_11_attacks#mediaviewer/File:September_11th_terrorist_attack_on_the_World_Trade_Center_LCCN2002717279_LC-A05-A11.tif

Social and Economic Impacts

Wars can have enormous and damaging socioeconomic impacts. The most obvious damages are associated with the killing and injuring of people, sometimes in unfathomable numbers, as well as an awful disruption of the lives of the survivors. In a more general sense, the economies of nations become transformed by their conversion into a focus on the production of goods and services that are needed to support a war effort. This is especially the case of the largest conflicts, for which a "total-war economy" may be deemed necessary to avoid defeat.

Mortality during war

The most terrible conflicts in history, in terms of causing mortality, were the two so-called "world wars" of the twentieth century. The conflicts received those names because the wars occurred on several continents and so many countries were involved in the fighting.

The First World War (1914-1918) was fought throughout much of Europe. The greatest battlefields were in the lowlands of Belgium and France where there were relatively static and long-lasting confrontations between enormous armies that were well dug-in with extensive trenchworks. Additional large conflicts occurred in eastern Europe, the Middle East, and the North Atlantic Ocean. The total number of military deaths was about 8.5 million (8.5M), of which the Central Powers lost 5M and the Allies the rest (including 67-thousand (67k) Canadians) (White, 2010). Most of the deaths occurred during combat, either directly in action or afterward because of grievous or infected wounds, but many others were a result of epidemic diseases such as cholera that were promoted by poor sanitary conditions.

In addition, there were 7-13M deaths of non-combatants during the First World War. Most of these resulted from starvation or disease, which were a consequence of severe disruption of the economy and of the functioning and infrastructure of civilization in affected regions. As in other wars, the estimates of civilian deaths are not based on direct counts but rather on calculations of so-called "excess mortality", or differences in the death rate before and during the war. The worst losses of civilians were in Turkey at about 2.2M, Russia at 1.5M, Italy 1.0M, Austria-Hungary 700k, Germany 692k, France 500k, Serbia 450k, Romania 430k, and Britain 230k. The data for Turkey include the victims of a genocide directed against Armenians in that country, which itself may have killed 1M people.

Because of the unprecedented mortality, the First World War was labelled as "the War to end all wars", in the expectation that people would never again allow such an avoidable catastrophe to take place. To prevent such a re-occurrence, the leading countries of the world created an international security organization called the League of Nations whose mission was to maintain world peace, essentially by providing a forum in which countries could work out their differences. Unfortunately, that body was not successful and only two decades after the end of WWI there was an even more extensive conflict, with a loss of life more than twice as large.

This was the Second World War (1939-1945), whose two main battle theatres were throughout most of Europe and in eastern Asia, with additional areas including the western Pacific Ocean, the North Atlantic Ocean, northern Africa, and the Middle East. The total number of military deaths was about 20 million, of which the Allies lost 13M (10M of whom were of the Soviet Union) and the rest from the Axis nations (White, 2010; Canada lost 45k). Most of the military deaths occurred during combat or as a later result of wounds, but especially in the eastern front many soldiers died of cold, starvation, or epidemic diseases.

The toll of civilian deaths during this extensive conflict was even more extraordinary, totalling about 30-46 million (the global population in 1945 was about 2.3 billion, so the larger mortality number represents about 2%). Most of the mortality was caused by starvation and disease, but there were also "death camps" where large numbers of civilians were exterminated by the Nazis. In addition, both sides directed intensive military actions against cities in an attempt to instil terror and loss of hope in the civilian populations. The countries suffering the worst civilian mortality were Russia at about 17 million, China 8M, Poland 6M, and the East Indies 4M.

The worst episodes of civilian mortality caused by direct military actions involved the mass-bombing of cities by the German, Japanese, and Allied air forces (including that of Canada). In essence, the intended goals of these attacks on civilian targets were to demoralize the population and wreck the war economy. The most destructive cases included the bombing of cities in Britain during the so-called "Blitz", which occurred during a nine-month period beginning in September, 1940. More than 20k people were killed in London and about 1M buildings were destroyed or damaged (Wikipedia, 2014a). London was the most heavily targeted city, but others were also hit hard and in total more than 40k people were killed during this aerial offensive directed mostly at civilian targets.

It is important to recognize, however, that Allied air forces also engaged in mass-bombing of German cities, especially after they gained command over the airspace of Europe. This involved flights sometimes of more than one-thousand bomber aircraft dropping huge "blockbuster" explosives of 1.8-5.4 tonnes (these were nominally capable of devastating an entire city "block") and incendiary devices to ignite great firestorms. The worst cases of civilian mortality during those massed Allied operations occurred in Hamburg with about 45k killed, and Dresden with 25-35k deaths (Wikipedia, 2014b). Berlin, the capital of Nazi Germany, was subjected to at least 363 air raids, which killed more than 20k people, rendered about 1/3 of the buildings unusable, and created about 16 km^2 of rubble-filled bombed-out zones (Wikipedia, 2014c).

In the Pacific war, the American bombing of Tokyo in March, 1945, killed about 100k people and injured at least as many, making it the most destructive event of conventional bombing in history (Wikipedia, 2014d). The U.S. also dropped atomic bombs on Hiroshima and Nagasaki in August, 1945, to end that war, killing 90-166k and 60-80k people, respectively (Wikipedia, 2014e).

Moreover, the Nazi government of Germany targeted certain ethnic groups for genocide, and killed at least 5.5 million Jews in extermination and work camps, and 0.5 million Gypsies (or Roma; proportional to their initial population, this ethnic group suffered the most grievous loss during the war). The victims of the genocides died from outright murder, starvation, and disease. Other groups targeted for extermination by the Nazis were homosexuals, people with physical or mental disabilities, and political dissidents. There were also immense massacres of prisoners of war, including about 3M soldiers captured by the Germans from Soviet armies, and perhaps more than 1M Germans captured by the Soviets.

For context and additional information, here are some estimates of the numbers of fatalities associated with other wars of the past several centuries, again with an emphasis on those in which Canada has been involved to some degree (White, 2014):

- Seven Years' War (1756-1763), during which about 1.3M people died, more than half by non-combat means, especially from epidemic diseases such as cholera
- American War of Independence (1775-1783), about 37k deaths from combat and 96k from non-combat
- War of 1812 (1812-1815), about 13k military deaths and 15-17k non-combat
- U.S. Civil War (1861-1865), about 600k deaths (1/3 in battle and the rest non-combat)
- World War I (1914-1918), about 8.5M military deaths and 7-13M civilians
- Second World II (1939-1945), about 20M military deaths and 30-46M civilians
- Korean War (1950-1953), 2-3M military deaths and 2-3M civilians
- Second Indochina War of 1960-1975, about 1.3M military deaths and 0.3-1.5M civilians
- Iraq (2003-2014), about 150k deaths, mostly civilians in war-related violence
- Afghanistan (2001-2014), about 50k deaths, mostly civilians in war-related violence

Warfare and other kinds of extreme violence result in enormous social damages to affected populations. Large numbers of people are killed or injured, afflicted by epidemic diseases, displaced from their homes, or suffer from immediate and post-traumatic psychological stress.

Huge economic costs are also associated with warfare. They include outlays for the wages of military personnel and their upkeep, expenditures on hardware and consumables, and the destruction of buildings and other manufactured capital (including weapons). Moreover, these costs are also relevant to non-war times, because huge expenditures must be made to support a military capacity that is deemed necessary to provide an appropriate level of defence against potential aggression.

Of course, these various costs of war and militarism are diverted from other spending options, such as those needed for health and educational programs. In Canada and all other countries there are political tensions between people who argue that a high level of military preparedness is needed to provide for national security, and others who believe that a more socially responsible course is to expend a larger fraction of limited resources on improved health and educational outcomes in the general population. To a large degree, the extreme positions along this spectrum of political views are irreconcilable, and the prudent way forward is a pathway somewhere in the middle of the controversy.

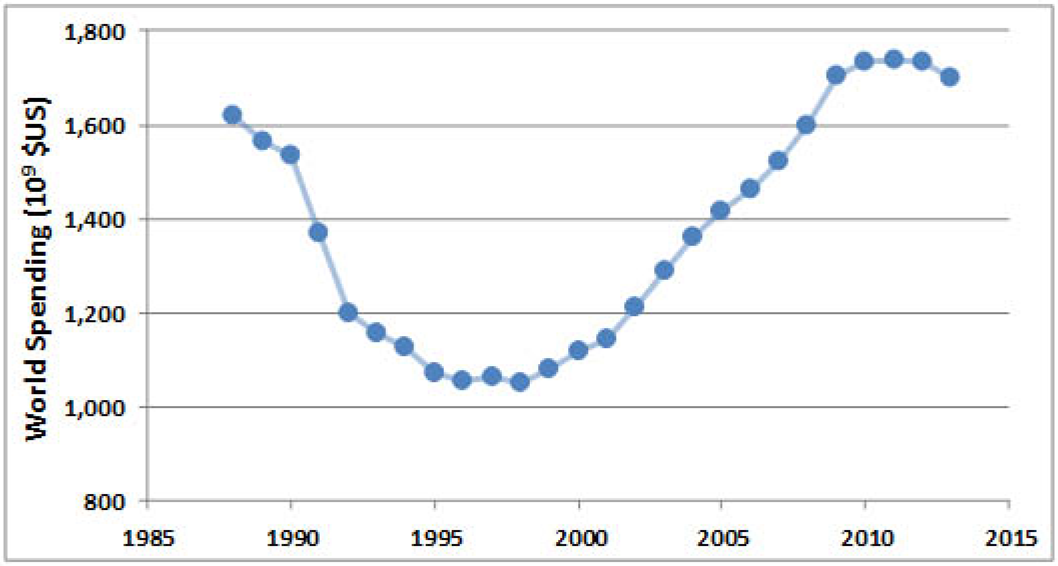
In any event, in the real world in which we live, immense amounts of social and economic capital are expended to prepare for military actions, and if necessary to engage in them. Enormous amounts of money are spent to construct a military infrastructure of buildings and other structures, to manufacture specialized vehicles and weapons, to pay for military personnel, and to purchase consumables such as munitions, fuel, and food.

Figure 26.2 shows the history of global military spending over the period 1987 to 2013. The peak of expenditures in the late 1980s reflects the enormous military outlays that were made during the height of the "Cold War," when U.S.-aligned liberal democracies and other allies were engaged in a persistent confrontation with communist nations allied with the USSR and China. The Cold War did not involve significant direct conflicts between the nuclear-armed protagonist groups, although there were destructive proxy wars that involved some of their allies. The largest and most devastating of the proxy wars were the Korean War (1950-1953), the Second Indochina War (or Vietnam War; 1960-1975), and the Soviet Invasion of Afghanistan (1979-1989).

The large reduction of military expenditures beginning in 1990-1991 mostly reflects two key changes in the strategic military milieu:

1. The USSR economy collapsed at that time and that Soviet entity devolved into the Russian Federation, and then into separate countries such as Russia, Ukraine, and others. Between 1988 and 1990 its annual military spending averaged $299 billion, but in 1992 that deflated to $62B and then further to $21B in 1998 (all in constant 2011 $US; SIPRI, 2015). Spending has increased considerably since then, to $85B in 2013.
2. There was greatly reduced military spending by the U.S. and its allies as a "peace dividend" associated with the end of the Cold War. Between 1988 and 1990 the annual U.S. military spending averaged $546 billion, but this was reduced to an average of $386B during 1996-2000 (constant 2011 $US). However, since 2001 the U.S. spending has almost doubled as it ramped up expenditures for its "War on Terror" (to $720B in 2010, although it since decreased somewhat to $619B in 2013).

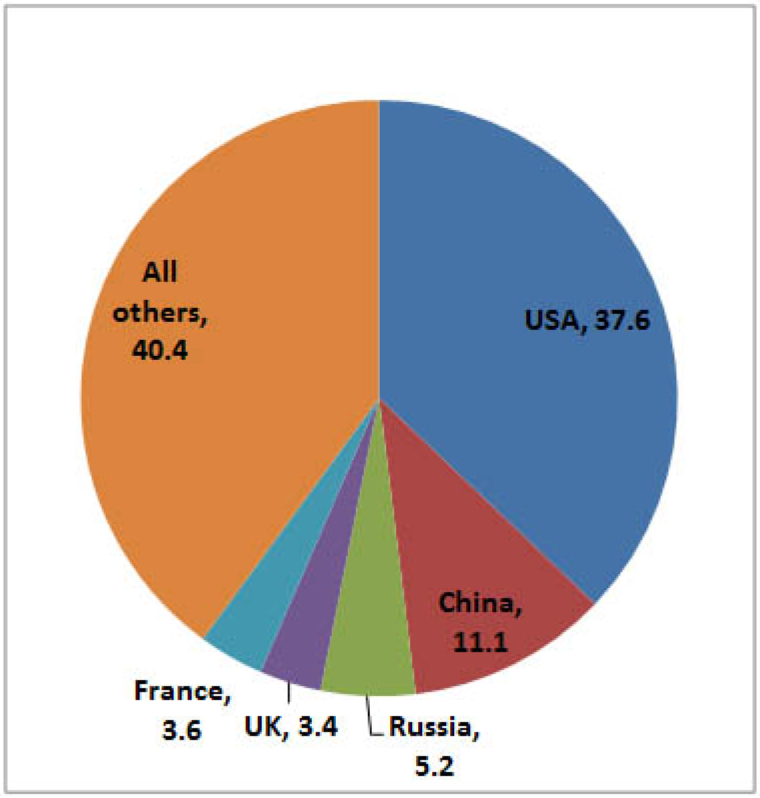
Figure 26.2. Global military spending from 1987 through 2011. The data are in units of billions of constant-2011 U.S. dollars, meaning they are corrected for inflation. Source: Data from SIPRI (2015).



The total global spending for military purposes in 2013 was US$1,747 billion (or US$1.747 trillion; in year-2013 dollars; SIPRI, 2015). This was equivalent to about 2.4% of the total global Gross National Income (GNI) in that year, which had a value of US$73.9 trillion (World Bank, 2015). (GNI, also referred to as Gross National Product (GNP), is the sum of the values of all products and services that are generated within a country in one year. For any country, GNI is equivalent to the Gross Domestic Product or GDP plus any net income received from other countries). For comparison, the global spending on education and health were each equivalent to about 10% of the GNI (World Bank, 2015).

Figure 26.3 shows the relative amounts of recent (2013) military spending by various countries. The United States, which accounts for about 4.6% of the world population, is responsible for about 38% of global military spending. This far outpaces the second-largest spender, China, which is home for 20% of the people in the world. These data reflect the fact that, at the present time, the U.S. is the world's only military "superpower". However, an enormous national burden is associated with the fiscal policies that are required to attain and sustain this strategic position. To do this, the U.S. has accumulated an enormous public debt to finance its military capability. There are important socioeconomic consequences of diverting such a large fraction of the limited resources of the country to military-related spending instead of on health, education, and other social priorities.

Figure 26.3. Military spending by various countries in 2013. The data are expressed as a percentage of the total global spending of US$1,705 billion in year-2013 dollars. Source: Data from SIPRI (2015).



Although Canada is a wealthy country on a per-capita basis, it is a relatively small player in the global military stage. Total military spending in 2013 was $18.5 billion, which is equivalent to about 1% of our GDP (compared with 4% for the U.S.; SIPRI, 2015).

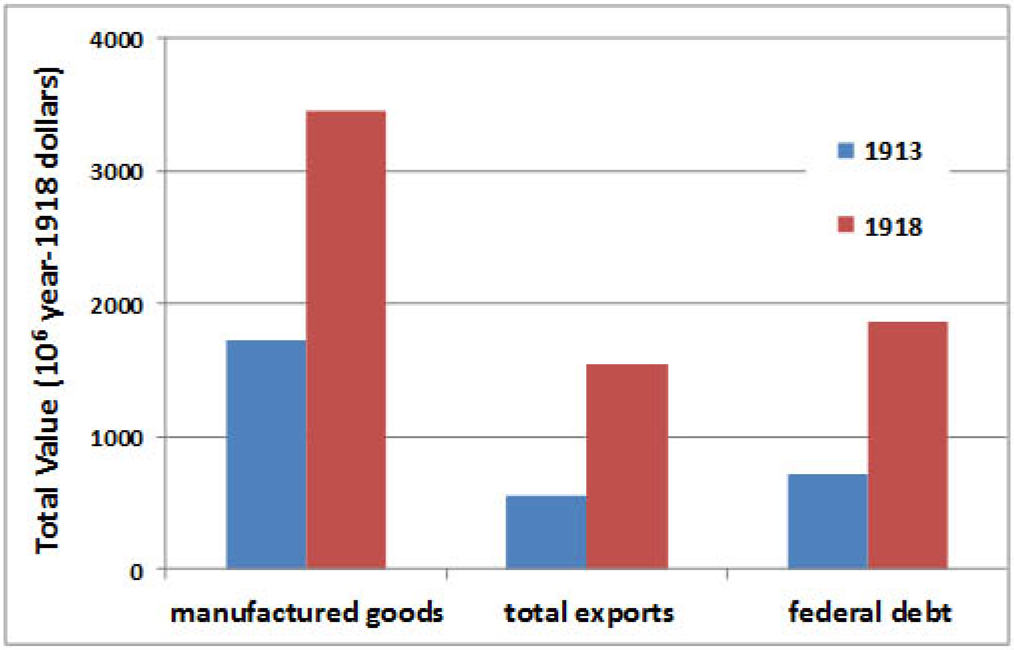
Nevertheless, Canada has been involved in many international conflicts, the biggest of which were previously noted. Our country's largest expenditures for military purposes occurred during the First and Second World Wars, when all of the Dominions of the British Empire were called upon to fight on the Allied aide. During those conflicts the Canadian armed forces were relatively large and had to be equipped with transportation, weapons and other materiel, and consumable supplies. To supply those goods and service a large fraction of the nation's economy was diverted to military purposes.

Prior to WWI, the armed forces of Canada amounted to just over 3-thousand personnel, but more than 620k military personnel became engaged in that conflict, suffering casualties of 67k killed and 173k wounded (Wikipedia, 2014f). The build-up of economic activity to support the war effort is suggested by changes in selected indicators between 1913, just before the start of the war, and 1918, when spending was at about a peak (Figure 26.4). Compared with 1913, the value of manufactured goods in 1918 was 101% larger (data are adjusted for inflation; note that a 100% increase is the same as a doubling), which was due to the manufacturing of machines and other goods needed for the war effort. The value of all exports from Canada increased by 180%, again reflecting the need to send food, weapons, and other goods to Europe to support Canadian military personnel as well as the economies of allied countries, particularly Britain.

To pay for the immense wartime expenditures the federal government increased its revenues in various ways. This included the imposition of what at the time was said to be a "temporary" tax on the income of working Canadians, although that levy was never repealed (its legacy is our system of personal income tax). However, the increase in federal revenues was grossly insufficient to pay for the actual expenditures on the war effort, and so the debt of the

Government of Canada increased by 162% between 1913 and 1918. The total direct expenditure on the war by the federal government over 1915 to 1920, including the demobilization, was about $1,670 million (year-1918 dollars; Government of Canada, 1921).

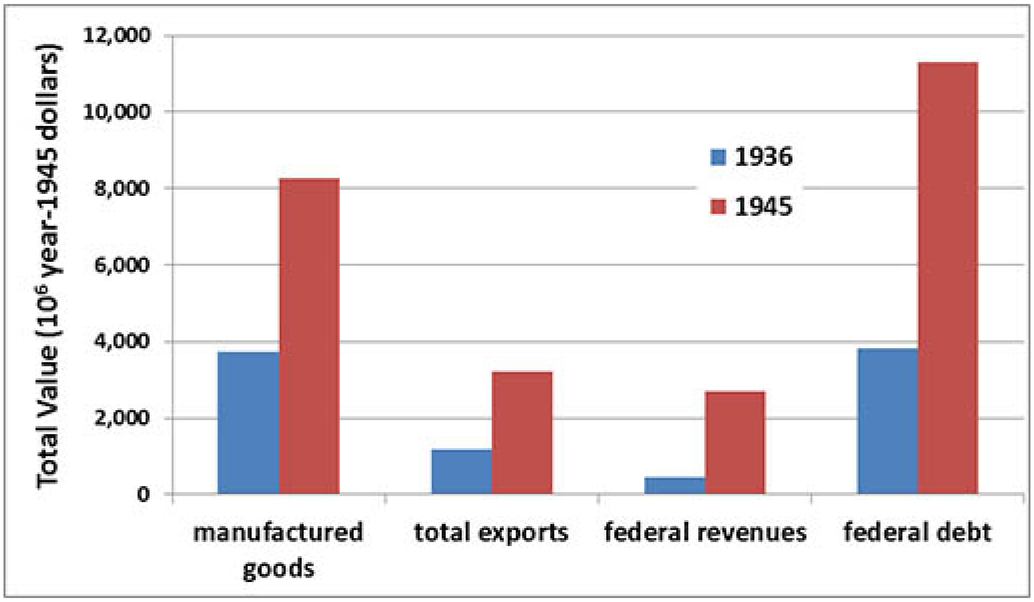
Figure 26.4. Changes in selected economic indicators of Canada relevant to expenditures during the First World War. The data are in millions of year-1918 dollars, and so are adjusted for wartime inflation. Source: Data from Government of Canada (1917, 1921), corrected for inflation using Bank of Canada (2011).



The economic effects on Canada of WWII were even larger than those of WWI. About 1.1 million people served in the armed forces of Canada during that war, suffering casualties of 45k killed and 54k wounded. The cost of the war effort is suggested by changes in selected economic indicators between 1936 before the start of the war, and 1945 when spending was at about a peak (Figure 26.5). Compared with 1936, the value of manufactured goods in Canada was 120% larger, mostly because of the need to manufacture weapons, machines and other goods for the war effort. The value of all exports increased by 175%, again reflecting the need to send food, weapons, and other goods to Europe and Asia to support Canadian military personnel as well as allied countries, especially Britain. To pay for the wartime expenditures the federal government increased its revenues by 478%, mostly by raising taxes. Nevertheless, the revenue increase was insufficient to pay for all expenditures on the war effort, and so the federal debt increased by 195% between 1936 and 1945. The total direct expenditure by the Government of Canada on the war over the years 1940 to 1946, including the demobilization, was about $18,943 million (year-1945 dollars; Government of Canada, 1947).

Figure 26.5. Changes in selected economic indicators of Canada relevant to expenditures during the Second World War. The data are in millions of year-1945 dollars. Source: Data from Government of Canada (1947),

corrected for inflation between 1936 and 1945 using Bank of Canada (2011).



The armed forces are also important employers in many countries. Globally, about 92.6 million people have military employment, including 20.6M in the active armed forces, 42.9M in reserve forces, and 29.1M in paramilitary organizations (Wikipedia, 2015). The largest forces (active forces + reserves + paramilitary; 2012 data) are held by North Korea (7.7M), India (4.8M), China (3.9M), South Korea (3.7M), Russia (3.4M), and the United States (2.2M). Canada has about 65,700 active military personnel and 34,000 reservists.

Even larger numbers of people are employed in civilian industries that service military interests, ranging from the manufacturing of weapons and vehicles to the provision of food and fuels.

Canadian Focus 15.1. The Armed Forces of Canada Prior to Confederation in 1867, military forces in Canada consisted of regular troops of Britain that were assigned to the colony (or prior to 1758, those of France), supported by local militias of armed civilians, and sometimes by allied Aboriginal nations (Granatstein, 2002; Wikipedia 2015r). Those forces were intended for use in defense against aggression by other European powers, Aboriginal groups, or American forces (the latter particularly during the American Revolutionary War of 1775 to 1783, the War of 1812 of 1812-1814, and the Fenian Raids of 1866 to 1871). Even for some time after 1867 the responsibility for military command in Canada was vested in the British Crown and its commander-in-chief for North America. This was the case until the final removal of British army and navy units from Canada in 1906.That withdrawal led to the formation of the Royal Canadian Navy, Canadian Army, and Royal Canadian Air Force. However, even today, the nominal head of command is still the reigning monarch of Canada, Queen Elizabeth II, as represented by the Governor General.

The first overseas deployment of Canadian military forces was to support Britain during the Second Boer War (1899-1902) in southern Africa. A much larger international commitment occurred in Europe during the First World War (1914-1918), and then again during the Second World War (1939-1945). There were also significant participations in the Korean War (1950 to an armistice in 1953) and in Afghanistan (2001-2014). Other foreign engagements have included the First Gulf War (1991), the Kosovo War (1998-1999), and various UN-sanctioned peace-keeping missions such as those in Suez (1956-1967) and Cyprus (1954-present). In total, the Canadian forces have participated in 75 international operations since 1947.

Canadian defence policy is established by elected political leaders of the Government of Canada, led by the Prime Minister and the Minster of National Defence. Since the end of the Second World War, that policy has had three broad objectives: (1) the defence of Canada; (2) the defence of North America in cooperation with the U.S.; and (3) contributing to international security. During the era of the Cold War of 1946 to 1991, much of the defence policy was intended to contribute to a collective security of Western Europe and North America in the face of military threats from the Soviet bloc of communist nations. During that period substantial ground and air forces were based in Western Europe and operated within the command structure of the North Atlantic Treaty Organization (NATO). Following the end of the Cold War, however, the focus of NATO has been extended to international security operations in other parts of the world, especially in Afghanistan, the Balkan region, and Libya.

The present defence policy of Canada was established in 2006 by a new Conservative Government. The Canadian military is now being oriented and equipped to fulfill six core missions:

- to conduct routine national operations, including in the Arctic regions of Canada, as well as continental ones through the auspices of the North American Aerospace Defence Command (NORAD)
- to respond to a major terrorist attack
- to support civilian authorities during a crisis caused by a natural disaster in Canada
- to conduct a major international operation for an extended period
- to deploy forces for a shorter period in response to military or natural crises elsewhere in the world
- to provide support to major international events in Canada

The Canadian forces are funded at an annual level of about $22.6 billion (in 2013), which ranked 14th in the world (Wikipedia. 2015r,s). However, in some years the base funding is augmented to support non-baseline expenses of new missions, such as those recently occurring in Afghanistan and Libya. The number of regular personnel is about 68-thousand, and there are an additional 51-thousand in reserve forces, with the total number ranking 74th in the world.

The Government of Canada has embarked on initiatives to build the stocks of military equipment and further to improve them with advanced technologies. This program included the acquisition of equipment needed for the mission in Afghanistan, such as battle tanks, armoured personnel carriers, artillery, and unmanned air drones. There are also initiatives to replace or build the air fleet, including the acquisition of C-130 Hercules and C-17 Globemaster III transport aircraft, CH-47 Chinook heavy-lift helicopters, and F-35 Lightning II Joint Strike Fighter jets. A process is also being implemented to renew the naval fleet, including the construction of 15 new warships to replace the existing 15 frigates and destroyers, plus 2-3 new support vessels and 6-8 smaller vessels to patrol coastal and arctic waters.

Environmental Damage

All wars result in some amount of carnage (deaths) and mayhem (destruction). Of course, this varies tremendously depending on the scale of the conflict and the ways that the fighting is conducted. Obviously, relatively small clashes may not cause a lot of environmental damage. At the other end of the spectrum, the largest possible wars, which could involve the use of existing stockpiles of nuclear weapons, would potentially obliterate the biosphere. This would happen as a consequence of the immense explosions as well as the resulting catastrophic fires and climatic consequences of the release of enormous amounts of particulates and gases to the atmosphere.

The environmental effects of warfare can be organized into a number of topic areas, including the following major ones:

- the depletion of non-renewable resources such as metals and fossil fuels, and renewable ones such as agricultural soil capability and forest cover
- environmental and ecological damage by air, soil, and water pollution
- the destruction of biodiversity by habitat damage and uncontrolled hunting
- damage caused to the infrastructure of society and its economy However, the environmental consequences of warfare are exceedingly complex and so they cannot be generalized. Moreover, there have been remarkably few studies of environmental damages caused by warfare, even though they can be devastating. In this section we will examine the subject area by looking at information and examples from selected conflicts, including potential scenarios for a nuclear war.

In fact, a deliberate strategy of war may be to cause intense environmental damage in order to destroy the economic capacity of an enemy. This might be referred to as ecocide – an attempt to cause severe environmental destruction as a tactic of warfare. An early such action was undertaken by Scipio Africanus the Younger (185-129 BCE), a Roman consul who defeated the Carthaginians in the Third (and final) Punic War of 146 BCE. Having achieved victory, he then ordered his troops to utterly raze the city of Carthage (in Tunisia) and is also said to have devastated the surrounding agricultural land by spreading large amounts of salt to poison the soil (Wikipedia, 2015h).

Conventional Munitions

Tremendous amounts of conventional munitions are used in warfare – the explosive potential of this weaponry is based on very rapid, energy-releasing, chemical reactions. The intent of their use is mostly to blow up buildings, equipment, and people, but damage is also caused to other components of the environment, such as forests and other habitats. In this section we examine environmental and other damages caused by the use of conventional munitions. In a later section we will examine nuclear explosives, whose immense power is based on fission or fusion reactions.

During the Second World War about 21 million tonnes (Mt) of conventional explosives was used, 36% of them by U.S. forces, 42% by Germans, and the rest by other combatants (Westing, 1985a). During the Korean War, the total use of munitions was 2.9 Mt, 90% by U.S. and its allied forces. In the Second Indochina War the expenditure was 14.3 Mt, more than 95% by U.S. and allied forces.

Although subsequent wars have been extremely violent, their total use of explosive munitions has been much smaller than in the ones just noted. This was because the conflicts were relatively brief and much of the bombing was highly focussed on well-defined targets. This has been especially the case for the U.S.-led Gulf War of 1990-1991, and then from 2001 the U.S.-led invasions of Iraq and Afghanistan during the still on-going "War on Terror." Much of the bombing during those conflicts involved "smart weapons" that were accurately guided to their targets by lasers devices, pre-programmed geographic information systems, and/or battlefield technicians remotely monitoring the pathway of bombs and missiles to their targets on video screens. For instance, in the brief but intense Gulf War to liberate Kuwait, about 0.12 Mt were exploded, almost all by the U.S.-led coalition forces (Barnaby, 1991).

In the following sections we examine some of the environmental damages associated with the use of explosive munitions, beginning with the First World War. Although enormous quantities of munitions were exploded during these conflicts, there have been remarkably few studies of the non-human environmental damages. Rather, the focus of research has been on the misery caused to people through deaths and injuries, and the destruction of buildings and other infrastructure. Nevertheless, severe environmental damage was caused in many affected regions, and it is useful to look at some of the obvious indicators of those effects.

The World Wars

The First and Second World Wars are the most prominent conflicts ever waged, particularly in terms of the loss of human lives. Both conflicts occurred over widespread areas and caused terrible mortality, destroyed cities, and disrupted civilization in many other ways. Although the ecological damages were also severe they were never much studied and so are poorly quantified. They also have not been commonly thought of as important impacts of these wars, in comparison with the human tragedies that were caused. Despite that perception, awful environmental damage was associated with those wars.

To some degree the ecological effects of these conflicts can be gained from literary images of the time, a number of which describe the devastation caused to forests and other ecosystems. This is especially true of some of the literature emerging from the First World War. The Western Front was located in the coastal-plain lowlands of Belgium and France where for years huge armies fought back-and-forth over terrain webbed with elaborate trenchworks. Offensives gains were small, hard-won, and required the wastage of many people and copious materiel. The intense and long lasting confrontations devastated the agricultural terrain and woodlands of the battlefields.

Some of the worst effects occurred in flat and poorly drained lowlands of the Flanders region of Belgium. The city and vicinity of Ypres were devastated and were described like this: "In this landscape nothing existed but a measureless bog of military rubble, shattered houses, and tree stumps. It was pitted with shell craters containing fetid water. Overhead hung low clouds of smoke and fog. The very ground was soured by poison gas." (Wolff, 1958). The deep clay soil of Flanders was churned into a sticky, glutinous morass by artillery explosions and the movements of hordes of men and machinery: "Because of the impervious clay, the rain cannot escape and tends to stagnate over large areas … the low-lying, clayey soil, torn by shells and sodden with rain, turned to a succession of vast, muddy pools … the ground remains perpetually saturated … gluey, intolerable mud … liquid mud … molasses-like topsoil."

The devastation of forests can be appreciated from excerpts from literature of the time based on field observations: "The scene in No Man's Land … was indeed a chilling one … Woods were empty fields masked by what seemed to be a few short poles stuck in the ground. … Gaunt, blackened remnants of trees drip in the one-time forests. … Houthulst Forest, shelled day and night throughout six hundred acres of broken tree stumps, wreckage, and swamps – the acme of hideousness, a Calvary of misery." (Wolff, 1958). Another passage describes how a forest was dismembered by a bombardment: "When a copse was caught in a fury of shells the trees flew uprooted through the air like a handful of feathers; in a flash the area became, as in a magicians trick, as barren as the expanse around it."

Beyond the battle zones forests were being frantically harvested to supply an unconstrained war effort (Freedman, 1995). Belgium lost almost all of its forested area, while France lost about 10%. In Britain the timber harvesting rate was increased by more than 20-fold and about half of the existing forest was cut during the Great War. The most important need for timber was for use as shaft props to help prevent cave-ins of underground coal mines, because there was a tremendous demand for that strategic fuel. Great increases in the rates of forest harvesting also occurred in Europe during the Second World War.

It must have seemed perverse to many of the observers at the time, but during the growing season some kinds of birds and wildflowers could be abundant in the seemingly devastated battle zones of the Western Front and elsewhere. There were observations of birdlife as being "almost normal" within a short distance of front-line trenches (Gladstone, 1919). The house sparrow (Passer domesticus) was described as "plentiful and unconcerned in half felled orchards and ruined houses." Many anecdotes described how some birds nested in the midst of apparent devastation, and how they sang and otherwise went about their lives during bombardments and assaults.

One of the most famous poems to come out of the Great War, written by John McCrae, a Canadian physician and Lieutenant Colonel, makes note of abundant red-flowered poppies (Papaver rhoeas) and the songs of Skylarks (Alauda arvensis) in a graveyard in Flanders:

"In Flanders fields the poppies blow
Between the crosses, row on row,

That mark our place; and in the sky
The larks, still bravely singing, fly
Scarce heard amid the guns below."   (In Flanders Fields; 1915)

Even today, on Remembrance Day, which occurs in November 11 to commemorate the end of the War, many Canadians and other people wear an artificial red poppy on their chest as a tribute to the many people of the armed services who died in that and subsequent wars.

A number of species have been rendered endangered as a consequence of warfare. The last wild Père Doavid's deer (Elaphurus diavidianus) were killed by foreign troops during the Chinese Boxer Rebellion of 1898-1900, although the species survives in captivity (Westing, 1980). The European bison (Bison bonasus) was almost made extinct during the First World War by hunting to provide food for troops, and was again decimated during the Second World War, although it was afterward protected and has since recovered somewhat in forested areas of central and eastern Europe. In Africa, various species of large animals have become increasingly endangered as a consequence of widescale and lingering wars and insurrections, during which a lax enforcement of hunting laws results in much illegal killing of wild animals for bushmeat and valuable body parts. The monetary incentives for poaching endangered rhinos (Ceratotherium simum and Diceros bicornis) are especially great because of the value of their horns, and for African elephant (Loxodontia africana) because of their ivory tusks.

There have also been instances of certain wild animals increasing in abundance as an indirect consequence of warfare, usually because of decreased commercial hunting. During the First and Second World Wars, the abundance of gamebirds such as grouse and pheasants increased markedly in Britain and some other countries because of less hunting pressure (Gooders, 1983). The populations of some raptorial birds such as falcons and hawks also increased because most gamekeepers had been recruited into military service and so they were not culling these supposedly injurious predators of gamebirds. During the Second World War, the stocks of fish increased in the North Atlantic, as did whales in the Southern Ocean, and fur-bearing mammals in northern and eastern Europe, all because of less hunting (Clark, 1947; Westing, 1980; Freedman, 1995).

Second Indochina War

Enormous amounts of munitions were also exploded during the Second Indochina War of 1961-1975. The quantity used by U.S. forces alone was more than 14.3 Mt, about double that used by the U.S. during World War II (Martin and Hiebert, 1985; Westing, 1976, 1985a). About half of the explosive tonnage was delivered by aerial bombardment, half by artillery, and less than 1% from ship-borne artillery. The U.S. forces dropped about 20 million aerial bombs, fired 230M artillery shells, and used more than 100M grenades and millions of rockets and mortar shells.

This vast outpouring of high explosives caused tremendous damage to the landscape of Indochina (Orians and Pfeiffer, 1970; Westing, 1976, 1982). About 2.5 million craters were formed in 1967 and 1968 alone by the explosion of 225- and 340-kg bombs dropped in saturation patterns from high-flying B-52 bombers, each sortie of which produced a bombed-out area of about 65 ha. The craters had a typical diameter of about 15 m, depth of 12 m, and usually filled with water and then provided habitat for mosquitoes and other aquatic biota. In agricultural areas, some of the water-filled craters were eventually developed for use in aquaculture. In addition, explosions and the use of napalm (incendiary bombs made of a gelled petroleum) often started forest and grassland fires, which often affected extensive terrain. The total area affected in these ways was about 8.1 million ha or 11% of the landscape of Indochina, including 26% of South Vietnam, the main battlefield. One military observer offered the following impression: "The landscape was torn as if by an angry giant. The bombs uprooted trees and scattered them in crazy angles over the ground. The tangled jungle undergrowth was swept aside around the bomb craters." (Westing, 1976).

The Gulf and Afghanistan Wars

The first Gulf War was fought by an anti-Iraq coalition led by the United States (Canada participated in the aerial war). The war began with an extensive 37-day bombardment of Iraqi military and infrastructure targets, followed by a 9-day ground war. An estimated 120-thousand tonnes of explosives were expended during the conflict, almost all by coalition forces (Barnaby, 1991). The coalition bombardment was relatively "efficient" in the sense that one tonne of explosive caused about one enemy-military death, compared with about 2t per death in in the Vietnam War and 4t in Korea. The higher kill rate by bombardment in the Gulf War was partly due to the frequent use of "smart" weapons that could be accurately guided to their targets, along with the open exposure of many Iraqi military units in desert terrain.

A second Gulf War occurred in 2003 when a U.S.-led "coalition of the willing" invaded Iraq to depose its government led by Saddam Hussein (this action was not sanctioned by the U.N. and Canada did not participate). The main reasons given to justify that war by its main advocates, the United States and Britain, were: (1) the presumption that Iraq had assisted Islamist terrorists in the airplane-bombing of the World Trade Towers in New York and the Pentagon in Washington, both on September 11, 2001, and (2) the accusation that Iraq was developing weapons of mass destruction and so was a grave threat to its neighbouring states. However, the evidence for both of those allegations was weak and no proof was ever provided for either of them. This war began with a 3-week bombardment of military and infrastructure targets, mostly with smart weapons, followed by a 3-week ground war that defeated the Iraqi military forces. A provisional Iraqi government was soon put in place, and later an elected one. Unfortunately, however, Iraq is still wracked by deadly sectarian violence, mostly between Shia and Sunni branches of Islam, and well as a bloody insurgency intended to create a fundamentalist Islamic State in the region.

A related war began in Afghanistan two years earlier, in 2001. The goal of that conflict was to replace an Islamist Taliban regime with a more western-friendly government. This war involved an invasion of Afghanistan by U.S. and U.K. forces, greatly assisted by an anti-Taliban alliance of northern Afghanis called the United Front (or Northern Alliance). The initial conflict involved a brief aerial bombardment of Taliban military concentrations followed by a ground war conducted mainly by the United Front. Once the Taliban were deposed, a coalition of U.N.-sanctioned forces (with Canadian participation) was deployed to provide military support for a provisional Government of Afghanistan and later an elected one.

The western coalition has tried to re-build civilian infrastructure of the country, which had been devastated by several decades of conflict associated with an earlier invasion by Russia to support a then-Communist government, followed by several rounds of sectarian conflicts and civil war. However, the brief war to depose the Taliban has been followed by on-going sectarian violence and guerrilla conflict with Taliban forces based out of neighbouring Pakistan.

In both the Afghan War and the Second Gulf War most of the mortality occurred during the insurgency periods rather than during the "major conflict" to depose the previous government. Although there were brief periods in these wars during which the coalition forces engaged in intensive bombing, much of that involved "smart weapons" and so the tonnage of explosives used was considerably smaller than during the First Gulf War, and enormously less than in the other conflicts examined in this section.

Legacy Munitions

Explosives that remain in place after a conflict has ended are referred to as legacy munitions or unexploded ordinance (UXOs). There are several kinds: (1) large numbers of unexploded bombs that may yet be deadly if dug up, (2) fields of land mines, and (3) unused artillery munitions that can be easily made into improvised explosive devices (IEDs) and planted as mines beside roadways.

Conflicts that involved a great deal of artillery fire and aerial bombing leave abundant remnants of (UXOs) that are lingering hazards on the landscape (Westing, 1984a, 1985b; Martin, and Hiebert, 1985). In fact, in older UXOs the detonator and main charge may become more unstable, which may increase the risk to bomb-disposal experts or anyone else that disturbs the ordinance. Many civilians have been killed by UXOs, often years after the end of the conflict. In Poland, about 90-million explosive items have been discovered and removed since the end of the Second World War, and the cleansing is still on-going. There are similar problems in all theatres of that war, and in all conflicts of the past century-and-a-half. For instance, at least 10% of U.S. ordnance did not explode in the Second Indochina War, resulting in a deadly legacy of about 2-million unexploded aerial bombs, 23-million artillery shells, and tens of millions of grenades. Laos was the most heavily bombed country during that war, in terms of bombs per unit-area. More than half a million aerial bombing missions by the U.S. dropped about 5Mt of ordnance on Laos. This included huge numbers of anti-personnel cluster bombs, each of which scattered hundreds of bomblets the size of a tennis ball (Wikipedia, 2015i). An estimated 288-million cluster bomblets and 75-million unexploded bombs remained across Laos after the end of the war, resulting in a deadly legacy that still kills or wounds many people; between 1996 and 2009 more than 1-million UXOs were destroyed in Laos, freeing up 23-thousand hectares of mostly agricultural land.

The use of explosive mines adds to the lingering hazards, because many of the devices are not recovered after the hostilities are over. Almost all are weight-triggered land mines that are buried in fields as anti-personnel weapons or in roads to blow up vehicles, but some are marine mines used to damage military vessels or commercial shipping. Modern anti-personnel mines can be extremely difficult to find and remove because they are constructed almost entirely of plastic and so cannot be magnetically detected. Land mines may be laid in enormous numbers – even in the brief First Gulf War about 6-million were used, and their remnants will pose an explosive hazard for many years (McKinnon and Vine, 1991).

During a long-running civil war in Cambodia from the 1970s to the early 1990s, land mines killed many civilians and injured even more – by the end of that conflict about 35-thousand people had undergone leg amputations because of accidental mine injuries, and even at the end in 1990 the rate was 6-thousand per year (Stover and Charles, 1991). In 2006, 15-20-thousand people, almost all of them civilians, were being killed world-wide by accidental explosions involving land mines (UN News Center, 1997). This was about half the mortality rate of ten years previously, when a United Nations treaty prohibiting the manufacturing of the devices went into effect. Afghanistan is another heavily mined country, with as many as 10 million having been deployed since a series of conflicts began there in 1979 (ICBM, 2011). About 80% of the mines are anti-personnel devices and 20% were targeted against military vehicles.

Chemical Weapons

Weapons that cause deaths or injuries through exposure to toxic chemicals are referred to as chemical weapons. Large-scale chemical warfare began during World War I, when both sides of that conflict used more than 100-thousand tonnes of lethal anti-personnel agents (Westing, 1977). These were deadly gases and vapours that caused devastating injuries to the lungs, such as chlorine, chloropicrin, phosgene, and trichloromethyl chloroformate, as well as the skin-blistering agent called mustard gas. These chemical weapons caused about 1.3-million casualties, including 85-thousand deaths. Chemical-weapon UXOs are still a dangerous legacy of that war in Belgium and France, where most of the chemical weapons were used.

Gaseous weapons were also used by Iraqi forces against those of Iran during the 1981-1987 war between those countries. Those weapons killed about 20-thousand Iranian soldiers and injured another 80-thousand, plus many civilian casualties. The Iraqis also used chemical weapons when fighting an Iranian-supported rebellion in its northern region of Kurdistan, the best-known case being an aerial attack in 1988 on the town of Halabja, using the nerve gases sabin and tabun, and killing about 5-thousand and injuring 10-thousand, almost all of whom were civilians (McKinnon and Vine, 1991; Wikipedia, 2015j). This was the largest attack with chemical weapons ever directed against a civilian population.

The United States military used a non-lethal “harassing agent” called CS during the Second Indochina War. About

9-million kg of CS were aerially sprayed onto more than one-million ha of South Vietnam, rendering treated areas uninhabitable by people for 15-45 days (Westing, 1977). Much of the CS was sprayed over wild habitats, so there must also have been tremendous damage caused to wildlife in those places, although no studies were ever made of that likely effect.

Although not strictly speaking a tactic of warfare, the Nazi government of Germany used toxic gases in their mass-murder of civilian and military prisoners during the Second World War (Wikipedia, 2015k). The murders mostly occurred as industrial-scale killings in specially designed extermination camps. However, they were also a routine practice in many of the more numerous concentration camps where slave-labourers were incarcerated to contribute to the war effort in manufacturing. A disproportionately large fraction of the deaths was of Jews, who were the target of a genocide, but large numbers of other ethnic and political groups and prisoners of war were also killed. The total mortality in the death camps was about 4-million. Much of the killing was done in specially built gas chambers, the largest of which could be used to murder several thousand people at a time. In the use of the larger chambers, the victims would be herded inside, ostensibly for a communal shower to cleanse them after an awful trip to the camp by a cattle train. Instead, they were gassed with a fast-acting nerve poison called zyklon-B, which is a cyanide-based insecticide. The bodies were mostly burnt in fire pits or in specially constructed crematoria.

Herbicides in Vietnam

An unprecedented tactic used by the U.S. military during the Second Indochina War was to spray herbicide extensively to deprive their enemy of food production and forest cover (Boffey, 1971; Westing, 1984b; Freedman, 1995). This was a massive program that resulted in more than 1.4- million ha being sprayed, equivalent to one-seventh the area of South Vietnam. Most of the spraying involved wild habitats such as tropical forest, but about 14% was directed against cropland. The herbicide spraying began in 1961, reached a peak in 1967, and was terminated in 1971. The herbicide used most frequently was a half-and-half mixture of 2,4-D and 2,4,5-T that was known as Agent Orange, with more than 46-million kg being used. Because the intention was to cause severe damage to ecosystems, the spray rates were quite high – about 25 kg/ha or 10-times that with the same herbicides to promote the growth of conifer trees in forestry by reducing the abundance of competing vegetation.

The ecological damage caused by the defoliation program was so severe that opponents of the spraying labelled it as ecocide, which in this case was the intentional use of anti-environmental actions over a large area as a tactical component of a military strategy (Westing, 1976). Because herbicides are poisonous to plants, extensive tracts of vegetation were directly poisoned by the sprays. However, animals were indirectly affected by the extensive destruction of habitats, although that damage was never documented in any detail.

The most intensive ecological damage was caused to coastal mangrove forest, of which 110-thousand ha were sprayed, or 36% of its area in South Vietnam. Because the dominant tree species of mangrove forest are extremely sensitive to herbicides, the spraying devastated the ecosystem and created large areas of muddy barrens. By the early to mid-1980s, the sprayed areas of mangroves had substantially revegetated. However, the habitats were degraded in species composition, with the more valuable red mangrove (Rhizophora apiculata) being less abundant than originally. To some degree this problem was alleviated by planting seedlings of red mangrove over extensive areas.

Severe damage was also caused to various kinds of upland tropical forest, which were extensively devastated by the herbicide spraying. The spraying of croplands caused great damage to food production in areas controlled by enemy forces, and there were reports of illness or death of domestic livestock.

One of the most controversial aspects of the herbicide spraying was the contamination of the 2,4,5-T by a dioxin known as TCDD (2,3,7,8-tetrachlorodibenzo-p-dioxin). (Dioxins are is a range of compounds that are characterized by the presence of a heterocyclic 6-membered ring, in which two carbon atoms are substituted by oxygen atoms. TCDD is considered the most toxic compound in the dioxin series. It is most famous as a contaminant in Agent Orange and in the context of a large industrial release in 1976 at Seveso, Italy.) The TCDD in the 2,4,5-T was an inadvertent by-product of the process by which the herbicide was manufactured, and it occurred in a concentration as high as 45 ppm but averaging 2.0 ppm (Westing, 1982; Freedman, 1995). As much as 170 kg of TCDD was sprayed with herbicide onto Vietnam.

TCDD is known to be extremely toxic to many kinds of animals, and even at small doses it causes birth defects and miscarriages in laboratory mammals. However, the toxicity of TCDD to people is less well understood. The most commonly reported symptom of an intense exposure is a skin condition known as chloracne, which appears similar to severe adolescent acne but is more severe and persistent. Other than chloracne, however, there is ongoing debate about whether TCDD causes cancer, birth defects, or other severe diseases in people, and even if any human mortality has been caused by exposures to this chemical.

Nevertheless, because most of the Agent Orange herbicide used in Vietnam was grossly contaminated with TCDD, there has been much concern and debate over the potential effects on people exposed to these chemicals. Even today the controversy has not been resolved, although after a complex series of lawsuits and other legal actions, in 1985 the U.S. government began to compensate military personnel who claimed to have suffered health effects as a result of work they did in the herbicide spraying in Vietnam. No compensation was ever paid to any other people, including the many citizens of Vietnam who were exposed to the herbicides and their aftermath conditions.

Image 26.2. Spaying herbicide in Vietnam. The image shows a group of four aircraft spaying a herbicide formulation (likely Agent Orange, a 50:50 mixture of 2,4-D and 2,4,5-T) over tropical forest in South Vietnam in the late 1960s. Source: National Museum of the U.S. Air Force, photo 071002-F-1234P-022; http://en.wikipedia.org/wiki/Agent_Orange#mediaviewer/File:%27Ranch_Hand%27_run.jpg

The largest-ever marine oil spill was a tactic of “environmental warfare” during the war to liberate Kuwait in 1991. The spill was deliberate and it occurred when Iraqi forces released about 800-thousand tonnes of petroleum into the Persian Gulf from several tankers and storage tanks at a coastal ship-loading facility (Holloway and Horgan, 1991). The apparent military purpose of the deliberate spill was to prevent amphibious landings of Allied forces. Compared with spills during peacetime, not much effort was expended on recovering the spilled petroleum or treating the ecological damage, although care was taken to protect the seawater intakes of desalinization plants in Saudi Arabia because they supply most of the fresh water used in that country and so have great strategic value. Eventually, about 770 km of coast were polluted by tarry residues of this spill, mostly in Saudi Arabia. This immense spill killed 20-30-thousand seabirds and perhaps 260-thousand shorebirds (sandpipers and plovers) that forage on beaches. Marine mammals, sea turtles, and sea snakes were also killed in large numbers.

An even larger petroleum spill occurred on land when 788 Kuwaiti oil-wells were sabotaged and ignited by Iraqi forces, essentially as an act of economic terrorism (Earle, 1991). At the peak of the spill the emissions of oil were 2-6-million tonnes per day. As soon as that brief war ended a massive effort was undertaken to cap the blow-outs, and about half were capped within six months and the last one a year after the spill began. Much of the petroleum and its associated gases burned in the atmosphere, but huge amounts of oil also accumulated in oil-lakes up to 7 m deep on the land. The plumes of oily smoke from the burning wells typically rose to 3-5-thousand m in the atmosphere and sometimes could be detected more than one thousand km away. The smoke and fumes caused intense local pollution, could result in cool weather by blocking the sun, and blackened rain and snow up to several thousand kilometres away. Near the burning wells there were appalling scenes of fire, smoke, and surrounding lakes of petroleum. William Reilly, at the time the Administrator of the U.S. Environmental Protection Agency, said: “If hell had a national park, it would be those burning oil fires. … I have never seen any one place before where there was so much compressed environmental degradation.” (Popkin, 1991). There are still persistent tarry residues in the vicinity of the blowouts.

> Image 26.3. Burning wellheads in Kuwait. The image shows a number of petroleum wellheads that were ignited by Iraqi forces as an act of economic terrorism at the end of the brief way to liberate Kuwait in 1991. Source: United States Army, Technical Sergeant Perry Heimer; http://commons.wikimedia.org/wiki/

File:BrennendeOelquellenKuwait1991.jpg

Nuclear War

Nuclear weapons have an immense destructive capability – it is massively larger than that of conventional munitions. Although the global inventory of nuclear weapons is considerably smaller today than when the Cold War ended in 1990, their large-scale use in a war would nevertheless cause almost unfathomable damage. The potential scale of the destruction was suggested by U.S. President John F. Kennedy (1917-1963) in a speech to the United Nations in 1961: "Mankind must put an end to war, or war will put an end to mankind." His speech was given at a time of intense tensions about communism in Cuba, when the U.S. and Soviet Union did come perilously close to fighting a nuclear conflict. A nuclear war would also be an immense threat to the natural world, because it would potentially be capable of destroying ecosystems over much of the planet. The damage would initially be caused by the tremendous blasts and conflagrations that would be associated with nuclear explosions, followed by poisoning of many of the survivors by exposure to radioactive fallout and ionizing gamma radiation. These effects would likely be followed by a longer-term deterioration of climatic conditions as a result of global changes in atmospheric chemistry. The ecologist Arthur Westing (1987), who has specialized in research on the environmental effects of warfare, described a nuclear war as having the potential to be "the ultimate insult to nature."

Nuclear Arsenals

The global nuclear arsenal reached a peak around 1985, when it totalled about 70-thousand warheads with an explosive yield of 11-20-thousand megatonnes (Mt) of TNT-equivalent (Grover and White, 1985; Westing, 1985; Sivard, 1989). (TNT is 2,4,6-trinitrotoluene, which is the key ingredient in dynamite, a commonly used explosive. The ginormous explosive yield of nuclear explosions is indicated by its equivalence in terms of megatonnes of TNT; 1 Mt = 109 kg).) This was at least one-thousand times more than the aggregate yield of conventional explosives (11 Mt) used in the Second World War (6.0 Mt) plus the Korean War (0.8 Mt) and Second Indochina War (4.1 Mt). On a per-capita basis that zenith of the global nuclear arsenal represented 3-4 tonnes of TNT per person on the planet.

Nuclear weapons can be divided into two categories based on the ways that that they are caused to explode (Freedman, 1995). So-called atom bombs (or fission bombs) are based on the "splitting" of certain fissile isotopes of uranium and/or plutonium, two heavy metals. (By definition, all atoms of an element must have the same numbers of protons in their nucleus, but the number of neutrons may vary and so therefore the atomic weight. In nuclear chemistry, an isotope is a variant of an element with a particular number of neutrons. For example, uranium may have from 141 to 146 neutrons present and so there are six isotopes, the most abundant being 235uranium and 238uranium, of which 235U is the more radioactive and so useful in nuclear power and fission bombs. For plutonium, the isotope Pt235 is the one used in fission bombs.)

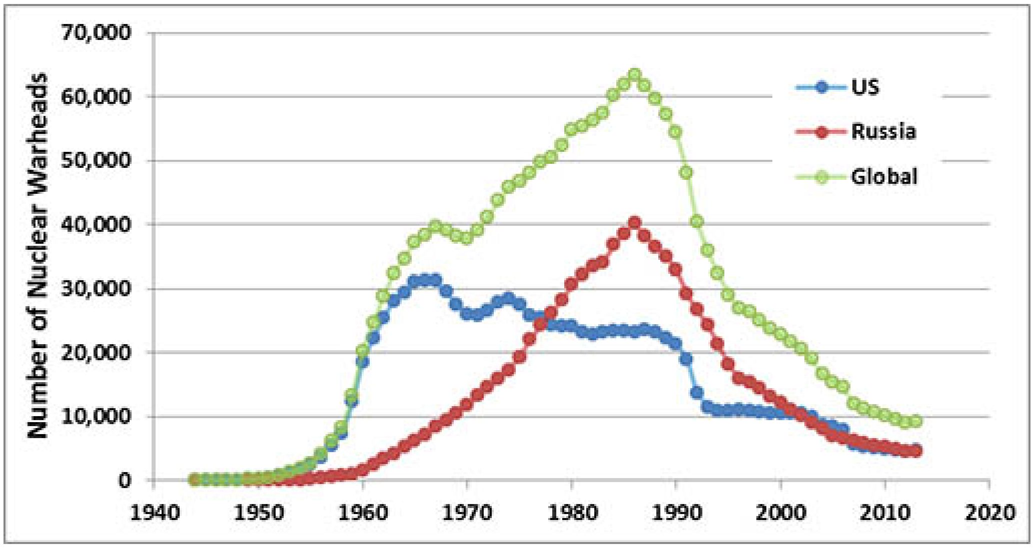
In a fission bomb a chemical explosion forces a mass of enriched U235 or Pt235 to reach a critical density that causes nuclei to split into smaller units, and in the process release an enormous amount of nuclear energy as a massive explosion. Fission reactions are also used as an energy source in nuclear-fuelled power plants, but in that application the reactions are carefully controlled. Fission bombs range from relatively small devices with a yield equivalent to less than one tonne of TNT to others as large as 0.5 Mt.

The other kind of nuclear weapons are fusion bombs (or hydrogen bombs) that are based on the fusion of nuclei of deuterium and tritium, two isotopes of hydrogen. Nuclear fusion also fuels the extraordinary energy production in stars, but no technology exists to control the reaction for commercial energy production. In a hydrogen bomb, a fission explosion is used to create such enormous heat and density that the conditions are sufficient to cause hydrogen nuclei to fuse into helium, a slightly heavier element, and in the process release immense energy as a gigantic explosion. Fusion bombs have an extremely high yield, ranging up to 50 Mt of TNT equivalent.

The largest nuclear bombs are referred to as strategic weapons; they have an explosive yield of 0.60 Mt or more and are designed to be delivered by a missile or airplane over a distance of thousands of kilometres. So-called tactical weapons are much smaller and more numerous; they are intended to be used in a local battlefield, have a yield of less than 0.20 Mt, and are delivered by smaller missiles, artillery, aircraft, or torpedoes. The aggregate nuclear arsenal peaked in 1985 when there were about 70,000 nuclear weapons, including 4,300 strategic-delivery vehicles (mainly missiles but also long-range aircraft) with each carrying about six warheads (Wikipedia, 2015l). Almost all of these weapons were owned by the U.S. and the USSR, with Britain, China, and France having much smaller inventories. At that peak the global nuclear arsenal had an aggregate yield of more than 11-thousand Mt.

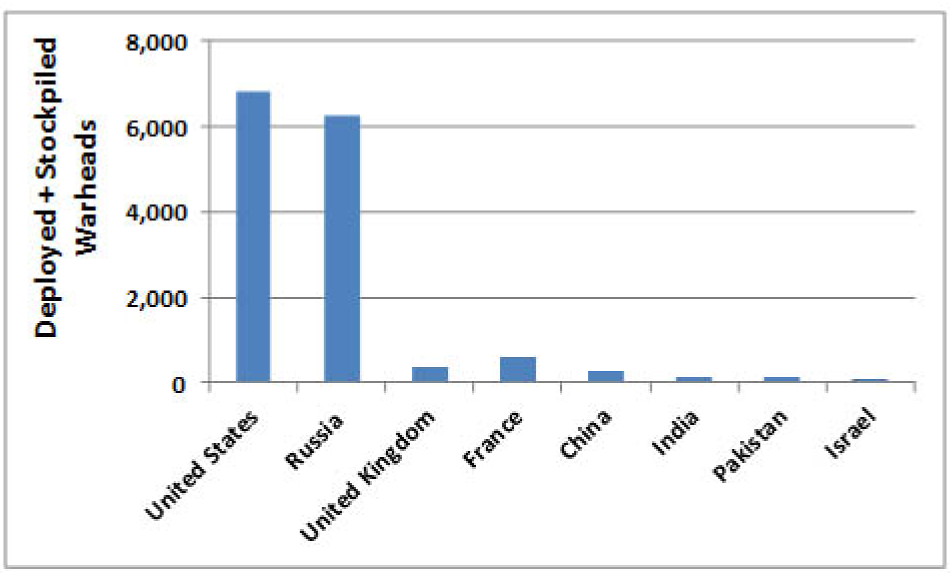
Fortunately, the global inventory of nuclear weapons has been substantially reduced from the mid-1980s peak. This has occurred partly because of a series of international treaties that were brokered by the United Nations, beginning with the Limited Test Ban Treaty in 1963, then the Nuclear Non-proliferation Treaty in 1968, and the Comprehensive Nuclear-Test-Ban Treaty in 1996 (note, however, that not all countries with nuclear weapons have signed on to, ratified, or respected these various treaties) (Wikipedia, 2015m). Even more important, however, beginning in 1972 there have been a series of bilateral nuclear-reduction agreements signed between the U.S. and Russia (representing the former Soviet Union), most recently the New Strategic Arms Reduction Treaty of 2010, that have resulted in large and verified reductions in the weapons held in their arsenals. The changes in nuclear arsenals are shown in Figure 26.6. Between 1985 and 2013 the global nuclear arsenal decreased by about 72%, almost entirely because of large reductions by the U.S. and Russia.

Figure 26.6. Changes in global nuclear arsenals. Source: Data from Kristensen and Norris (2015).



As of 2015, 163 states had ratified the Comprehensive Nuclear-Test-Ban Treaty and another 20 states had signed but not ratified it (Wikipedia, 2015m). Of the countries that are known or thought to have nuclear weapons, China, Israel and the United States have signed but not ratified the Treaty, and India, North Korea and Pakistan have not signed it. Israel is signatory to the Treaty although it has never acknowledged its nuclear weapons, which are believed to number about 80 (Figure 26.7). South Africa once had nuclear weapons but they have been decommissioned, while those of Belarus, Kazakhstan, and Ukraine have been passed to Russia for storage and eventual retiring. Among other countries, only Iran is thought to recently be seriously engaged in developing its own nuclear weapons (although its programs may have been suspended because of intense international pressure and economic sanctions),.

Figure 26.7. Countries holding nuclear weapons. The data are for warheads that are deployed plus those held in stockpiled reserves. Source: Data from Kristensen and Norris (2015).



To summarize this section: the world now has many fewer nuclear weapons than several decades ago, but the ones that still exist amount to an enormous and exceedingly destructive arsenal should they ever be used. Moreover, the number of countries with nuclear weapons is increasing, a fact that poses additional risks of them being used in a war.

Hiroshima and Nagasaki

There has never been a nuclear war, but there are two instances in which nuclear bombs were used in a war. These fission bombs were used by the U.S. against Japan during the Second World War, and within a few days of their use the war in the Pacific ended with an unconditional surrender. The bomb dropped on the city of Hiroshima on August 6, 1945, caused an explosion with a yield of about 0.015 Mt of TNT, and that on Nagasaki several days later 0.021 Mt (Barnaby and Rotblat, 1982; Pittock et al., 1985). Although these nuclear bombs caused immense explosions in comparison with any made by a conventional device, they were small compared with recent strategic bombs that are typically about 0.6 Mt but can range up to 50 Mt.

The bombs dropped in Japan were exploded in the atmosphere at a height of about ½ km, in order to further spread their destructive impact compared with a ground-burst. The Hiroshima bomb killed about 140-thousand people or 40% of that city's population (estimates of the mortality range from 90k to 166k), while the Nagasaki device killed 74-thousand or 26% of the population (60k-80k). Most of the deaths and destruction were caused by the combined effects of immense blasts and thermal (heat) energy. About half of the explosive energy induced a blast wave that travelled at the speed of sound (about 11 km in 30 sec) and caused severe damage to buildings as far as 2-3 km from the epicentre of the explosions. Thermal energy accounted for another third of the energy and created a fireball that was intense enough to vaporize people near the epicentre, to ignite wood as far as 2 km away, and to cause skin burns in people up to 4 km distant. The firestorms resulted in burnt-out areas of 13 km^2 at Hiroshima and 7 km^2 at Nagasaki. In total, about 2/3 of the buildings in Hiroshima were destroyed and 1/4 of those in Nagasaki.

About 15% of the explosive energy of those atomic bombs was expressed as ionizing radiation, of which 1/3 was released within one minute of the explosions and 2/3 more gradually by radioactive decay of fallout material. Ionizing radiation has am energy content that is high enough to remove an electron from an atom or molecule. This produces ionized free radicals with unpaired electrons that make atoms or molecules highly chemically reactive. Various kinds of highly energetic subatomic particles are ionizing, including alpha and beta particles, neutrons, and cosmic rays. The high-energy photons of short-wavelength portions of the electromagnetic spectrum are also ionizing, especially ultraviolet, X-rays, and gamma radiation. The free radicals produced by ionizing radiation disrupt biological systems by damaging DNA and other vital biochemicals, thereby disrupting genetic and physiological systems and potentially resulting in mutations, diseases including cancer, radiation sickness, and ultimately death. There are natural sources of ionizing radiation in the environment, such as solar ultraviolet radiation, while anthropogenic sources include exposure to X-ray or radioactive medical procedures, or to gamma radiation and radioactive fallout from nuclear explosions.

The enormous fires caused by the explosions induced upward-flowing convective air-masses that cooled as they rose high in the atmosphere, condensing their moisture into a "black rain" that was heavily laden with soot and radioactive particles. Among other effects, the ionizing radiation caused many survivors of the explosions to experience "radiation sickness" whose symptoms included weakness, nausea, diarrhoea, vomiting, fever, hair loss, blood poisoning, and bleeding from the bowels, gums, nose, and genitals. Some of the follow-up studies of longer-term survivors of the explosions have found higher incidences of eye diseases, blood disorders, and certain cancers, but other studies did not confirm those results.

> Image 26.4. Aftermath of the nuclear explosion at Nagasaki in August, 1945. The image shows an extensive area of devastated urban terrain, including a Buddhist temple in the foreground. Source: Photo by Corporal Lynn P. Walker, Jr., U.S. Marine Corps, NARA FILE #: 127-N-136176; http://en.wikipedia.org/wiki/

Atomic_bombings_of_Hiroshima_and_Nagasaki#mediaviewer/File:Nagasaki_temple_destroyed.jpg

Nuclear Test Explosions

The development of nuclear weapons was accompanied by large numbers of test explosions, the first series of which were above-ground and subsequent ones within the ground. The first test of a nuclear weapon happened in 1945 in New Mexico and involved a fission device with a yield of 0.02 Mt, while the first hydrogen bomb was exploded in 1952 at Enewetak atoll in the south Pacific, and the largest-ever was a 50 Mt blast at Novaya Zemlya in 1961 in northern Siberia (Wikipedia, 2015n).

The Limited Test Ban Treaty of 1963 resulted in a ban of signatory nations undertaking any testing of nuclear weapons in the atmosphere, underwater, or in outer space, although underground test blasts were still allowed. However, France did not ratify the treaty until 1974 and continued atmospheric testing until then, and China until 1980. The Soviet Union conducted its last underground test blast in 1990, the U.K. in 1991, the U.S. in 1992, and China and France in 1996. These countries pledged to not conduct any further nuclear tests when the Comprehensive Test Ban Treaty was enacted in 1996. However, non-signatory India and Pakistan have conducted test-blasts as recently as 1998 and North Korea in 2009. In total, there have been about 2,083 nuclear test explosions, 42% of them by the U.S., 34% by Russia, and 10% by France.

A limited amount of information about environmental impacts is available for some of the above-ground test explosions conducted by the U.S. during the 1950s. Those detonations caused severe damage to surrounding ecosystems, with the intensity of the effects rapidly decreasing with distance from the epicentre. After the explosions, the affected habitats gradually recovered. For example, an area in the Mohave Desert of Nevada was used to test 89 above-ground devices with a yield up to 0.07 Mt (Shields and Wells, 1962; Shields et al., 1963). The explosions cleared core areas of 73-204 ha of all obvious life and caused severe damage to vegetation on an additional 400-1375 ha, but no obvious damage was observed beyond an area of 3,255 ha. The damaged areas were invaded by pioneering species of plants, which were later replaced by longer-lived species to establish relatively stable communities.

A few studies were also made of above-ground tests on islands in the South Pacific. One researcher studied plants on Belle Island, located 4.3 km from a 1952 blast on Elugelab Island (Palumbo, 1962). The island was obliterated by the blast and transformed into a water-filled crater. Although the vegetation on Belle Island suffered radiation damage after the detonation, an apparently complete recovery was made within only six months. This observation suggests that at least some biota that survives a nearby above-ground nuclear explosion may have considerable resilience and an ability to recuperate from the disturbance.

Consequences of a Nuclear War

To some degree the destruction that would be caused by nuclear bombs can be predicted based on observations made during test explosions of various magnitude, and also on the results of computer-based models of physical processes. When a nuclear bomb is exploded, about 40-54% of the enormous release of energy typically occurs as a blast wave, 30-50% as thermal radiation, and 5-7% as ionizing radiation (Westing, 1977; Wikipedia, 2015o). To maximize the damage caused, strategic weapons would likely be exploded in the lower atmosphere, at a height less than 1,000 m, which results in less of the energy being absorbed by the ground.

In a large-scale exchange of strategic nuclear weapons not all of the arsenal of the warring parties would be successfully delivered. This is mostly because much of the arsenal would be destroyed by pre-emptive strikes or would be intercepted in flight. In the mid-1980s, studies were made of a range of damage scenarios caused by the likely scale of nuclear explosions during a hypothetical conflict. One representative estimate used for the purposes of modelling was for the detonation of 5 6-thousand megatons of nuclear weapons (Grover and White, 1985; Harwell and Grover, 1985). That study was made during the "Cold War" and almost all of the bombs were presumed to be targeted on the Northern Hemisphere, especially on the United States and Soviet Union, who were the most dominant potential adversaries. However, countries allied with either of those countries would also be heavily targeted. This would have included various "western capitalist" nations such as Canada, France, Germany, Great Britain, and Japan, as well as those of the "communist bloc" such as China, Czechoslovakia, East Germany, and Poland. It was presumed that military installations would be the primary targets of the nuclear assaults. However, cities would also be attacked because they commonly host military infrastructure and in any event are the economic heart of any country.

The scenario of a 5-6-thousand Mt exchange was predicted to cause the deaths of about 20% of the global population, including 75% of the people living in the United States (the mortality would relatively less in Canada, although some of our major cities would have been targeted). However, a large fraction of the survivors would have suffered from terrible injuries or radiation sickness, and with so much of the infrastructure of civilization destroyed they would not have been able to access much in the way of medical treatment. Most of the deaths and injuries would be caused by thermal radiation, but blast, fire, ionizing radiation, and falling buildings and other built structures would also be exceedingly dangerous.

Clearly, the immediate consequences of an all-out nuclear war would be dreadful. It would involve a crushing loss of human life, physical devastation, and incapacitation of social systems. This terrible misery would essentially destroy the civilization of the affected countries, and a fast recovery would be impossible. Nevertheless, people would probably survive in some places remote from the explosions, although they would then have to deal with extremely degraded environmental conditions in the aftermath of a nuclear war.

Extensive damage would also be caused to ecosystems. The scale of damage that would be caused to forested terrain by individual air-bursts of three sizes was estimated by modelling studies (Table 18.1). Close to the epicentre, most damage would be caused by the force of the blast, and to a lesser degree by ionizing radiation. It is likely, however, that much larger areas would be consumed by fires ignited by the thermal radiation, and those conflagrations would account for most of the damage. Vertebrate animals would mostly be killed by thermal radiation, but many would die later on from radiation sickness caused by exposure to ionising radiation.

Table 26.1. Damage caused by nuclear air-bursts of various sizes in forested terrain. The data are estimates of the areas that would be affected by various kinds of damage, ranging from trees being blown down to poisoning by ionizing radiation. Note that these estimates do not include damage that would be caused by the spread of wildfires ignited by the explosion, the extent of which would largely be determined by weather following the blast, especially the windspeed and direction. Source: Data from Westing (1977).

Kind of damage (km^2)	**Size of bomb**		
	18 kt	**0.91 Mt**	**9.1 Mt**
>90% of trees are knocked down by blast wave	5.7	141	820
trees are killed by ionizing radiation	1.3	6.5	12
biomass is ignited by thermal radiation	12	333	1,830
vertebrate animals are killed by blast wave	0.4	5.9	27
vertebrate animals are killed by ionizing radiation	3.2	11	18
vertebrate animals are killed by thermal radiation	16	420	2,350

Climatic Effects

The immense explosions and fires resulting from a large-scale exchange of nuclear weapons would cause massive amounts of tiny particulates, soot, and greenhouse gases to be injected high into the atmosphere. These materials would have a lingering effect on the absorptive and reflective qualities of the atmosphere, which would result in changes in large-scale climatic regimes. Studies of the potential consequences of a nuclear war for global climate have been made using computer models of atmospheric properties that were initially developed to do research on global warming (Chapter 17). Instead of using the models to study the climatic effects of increases of greenhouse gases, they were modified to examine the likely consequences of the injection of fine inorganic particulates and carbonaceous smoke into the upper atmosphere (Crutzen and Birks, 1982; NRC, 1985; Pittock et al., 1985; Stephens and Birks, 1985; Robock et al., 2007; Toon et al., 1990, 2007; 2008).

One mid-1980s scenario examined an exchange of 6.5k Mt of nuclear weapons. It was predicted that the explosions and fires would result in the injection of 330-825 million tonnes of fine particulates and 180-300 Mt of sooty smoke into the atmosphere, much of which would enter the stratosphere and so would be extremely persistent ((NRC, 1985; Stephens and Birks, 1985). These materials would have a substantial cooling effect. The inorganic dust would do this by increasing the albedo (reflectivity) of the atmosphere, which would decrease the penetration of sunlight to the surface and result in a cooling of the lower atmosphere. The smoke would absorb sunlight at a high altitude and then re-radiate much of that energy back to space, while also creating a stable upper layer of warm air that would retard the processes by which particles are removed from the atmosphere. These various mechanisms could reduce the energy received at the surface of the planet by more than 90%. If this were to occur, there would be severe consequences for climate, including persistent cold or even freezing temperatures, a phenomenon that has been labelled as a "nuclear winter" or if less severe, a "nuclear autumn."

Another study was done in 2006 with updated computer models of the global climate system (Robock et al, 2007). Two scenarios were examined for a large-scale war – one involved the use of the entire nuclear arsenal of the time, and the other one-third of it. The study predicted that about 150 Mt of smoke would be released to the atmosphere by the larger war, and 50 Mt by the lesser one. In the 150 Mt war, the prediction was for a global average surface cooling of -7 to -8°C that would persists for years, and even after a decade would be -4°C. In view of the global average cooling during the most recent ice age being about -5°C, the speed and magnitude of the nuclear influence would represent an immense deterioration of the global climate. Moreover, the cooling would be most intense on the continents, because the oceans are thermally buffered to a much greater degree. The study predicted that the cooling could reach as low as -20°C in large areas of North America and more than -30°C over much of Eurasia.

There would be severe ecological consequences if a nuclear winter were to occur (Grover and Harwell, 1985; Harwell and Hutchinson, 1985; Grime, 1986; Westing, 1987). Both agricultural and natural vegetation would be injured or killed by prolonged chilling and freezing, especially if these stressors occurred during the growing season. This would have devastating effects on agricultural production and on natural ecosystems. The effects of cold temperatures in the oceans might be less because those massive waterbodies have a great deal of thermal buffering. Of course, regardless of the cooling, the productivity all ecosystems would be decreased as a result of the persistent blocking of incoming sunlight, which is needed to drive photosynthesis.

Further injuries to vegetation and animals would be caused by a predicted increase in the penetration of solar ultraviolet radiation as a result of damage caused to the stratospheric ozone layer, and also by the presence of large amounts of toxic gases in the lower atmosphere, such as ozone and sulphur dioxide. These lingering effects of the aftermath conditions of a nuclear conflict would add to the enormous ecological damage that was immediately caused by the explosions through blast, thermal radiation, ionizing radiation, and wildfires.

Although the environmental consequences of a large-scale nuclear war cannot be predicted with much accuracy, it is clear that they would be horrific. There would be a bleak post-holocaust future for humans and the biosphere. It is vital that people have a broad understanding of the terrible consequences of a nuclear war, and of all kinds of warfare, so that they will support the necessary actions to prevent them from occurring.

In fact, optimism for a world devoid of extreme conflicts is quite widespread in society. Moreover, it is embedded in the teachings of major religions. This is exemplified by the following quotation from the Old Testament of the Bible (Isaiah 2, 4; New American Standard Bible):

> And He will judge between the nations, And will render decisions for many peoples; And they will hammer their swords into plowshares and their spears into pruning hooks. Nation will not lift up sword against nation, And never again will they learn war.

This passage suggests that conflicts amongst people can be resolved by fair and impartial judgements, and if this is done there is no need for weapons or for war. While the quotation suggests that an omnipotent power such as God can be such an arbiter, in the modern world it is more likely that international organizations will play that role, as we examine in the following section.

Avoiding War

Probably all wars have begun with the proponents and most of their supporters having optimistic and enthusiastic beliefs of triumph. Nevertheless, such conflicts result in misery to many of the people who become involved, while also causing terrible damage to the environment. This has been especially true of wars of the past century, which have been characterized by increasingly sophisticated and destructive weapons that are commonly directed against civilians in addition to enemy combatants. Because of an increasingly widespread recognition of the dreadful consequences of wars, powerful social forces have become engaged in doing what is possible to prevent conflicts from occurring.

These anti-war forces operate within all countries, but are especially powerful in liberal democracies because people and organizations under that political system are allowed to freely express their views, so long as they do so in ways that are non-violent and otherwise legal. In this sense, liberal democracy may itself be regarded as a force for peace, because it fosters an open discourse about the health and ills of society, including whether it is necessary to engage in violent conflicts to resolve issues that could potentially be resolved by a negotiated settlement.

In fact, because of wide recognition of the appalling consequences of warfare, governments have worked together to institute various international mechanisms for resolving conflicts among nations. Some of these are binational or multinational treaties and other agreements among particular countries, while others are global in scope and have been implemented under the auspices of the United Nations. Key international agreements relative to the prevention or mitigated conduct of war include the following (Wikipedia, 2015p): 1919 – Covenant of the League of Nations (this was the founding of the League of Nations, which in 1945 was replaced by the United Nations) 1929 – Third Geneva Convention relative to the Treatment of Prisoners of War (updated in 1949) 1945 – Charter of the United Nations (the founding of the United Nations) 1949 – Fourth Geneva Convention relative to the Protection of Civilian Persons in Time of War (a UN treaty) 1951 – Convention on the Prevention and Punishment of the Crime of Genocide (UN) 1963 – Limited Test Ban Treaty (UN) 1968 – Nuclear Non-proliferation Treaty (UN) 1972 – Anti-Ballistic Missile Treaty (UN) 1972 – Biological and Toxin Weapons Convention (UN) 1991 – Treaty on Conventional Armed Forces in Europe (nations of the North American Treaty Organization and the Warsaw Pact) 1991 – Strategic Arms Reduction Treaty (U.S. and Russia) 1993 – Chemical Weapons Convention (Organization for the Prohibition of Chemical Weapons) 1996 – Comprehensive Nuclear-Test-Ban Treaty (UN) 1996 – Anti-Personnel Mine Ban Convention (UN) 2002 – Strategic Offensive Reductions Treaty (U.S. and Russia) 2010 – New Strategic Arms Reduction Treaty (U.S. and Russia)

In addition to these sorts of international agreements, the United Nations and other organizations sometimes undertake actions to prevent or end local or regional conflicts. Within that context, peace-making refers to the enforced resolution of an active or potential conflict, often by establishing a balanced power relationship among the parties while also imposing a process to achieve a negotiated settlement. Peace-making may proceed through negotiations involving the parties in conflict, but if that does not work it may require military action to create a more symmetrical power structure so that neither side has a strong advantage.

Examples of peace-making actions include several imposed settlements of conflicts that arose after the break-up of the Socialist Federal Republic of Yugoslavia beginning in 1991, which eventually resulted in the formation of a number of countries: Bosnia and Herzegovina, Croatia, Kosovo, Macedonia, Montenegro, Serbia, and Slovenia. The wars of secession associated with the break-up resulted in several peace-making actions to stop the violence. For example, when the relatively powerful armed forces and militias of Serbia engaged in war measures to prevent the secession of the province of Kosovo, the North Atlantic Treaty Organization (NATO) engaged in a selective bombing campaign that forced a kind-of peace (Canada was a participant in that mission). Kosovo is now a self-proclaimed republic, although its governance is controlled by the United Nations and its independence is not recognized by Serbia.

Peace-keeping is an action that occurs after a hot conflict has stopped through a cease-fire agreement, but the conditions for a lasting peace are not yet in place so various means must be used to keep the antagonists apart. Peace-keepers may do their work by monitoring the movement and actions of armed forces in post-conflict areas and by otherwise assisting in the implementation of peace agreements, sometimes by enforcing provisions of a cease-fire. The UN has a peace-keeping program that has been active in various conflict zones in Africa, eastern Europe, and the Middle East (Canada participated in several of these missions, which are characterized by personnel wearing helmets or berets of a light-blue colour). Some peace-keeping actions have been remarkably long-lasting, such as the one that has been in place in Cyprus since 1964. These various international mechanisms have all been extremely helpful in preventing wars, or in making them less widespread or destructive.

There are also powerful social movements against war. These involve non-governmental organizations that protest against militarism or the engagement of their own or other countries in specific conflicts. There are also less-organized movements that conduct protest marches, hold sometimes large public assemblies, and undertake other kinds of anti-war advocacy. For example, the Greenpeace organization was formed in Vancouver in 1971to protest against a U.S. nuclear-weapon test on the Aleutian island of Amchitka. Soon afterward, Greenpeace developed a broader interest in environmental issues and its programs and actions became international in scope. Today, many anti-war NGOs operate internationally and in most countries (Wikipedia. 2015q), including the Canadian Peace Alliance and Ceasefire Canada.

There are also more broadly based forces for peace, which operate at a grander societal level to make deadly conflicts less likely:

- Democracy is a political system with numerous faults, but if properly implemented it assures the basic freedoms of people and so helps to avoid many of the kinds of discrimination that can result in the extreme discontent that may lead to insurrection or revolution. Democracy also allows for an open discussion about the size, capabilities, role, and purposes of the military sector of society.
- Equitable opportunities of people living within a society, and also among countries, help to diffuse tensions associated with gross and unfair inequalities of wealth, lifestyle, and access to health services, education, and cultural and recreational amenities. All people, including those living in poor countries, have a right to expect a decent standard of living and quality of life. It is difficult to build a prosperous and peaceful world if there are gross inequalities among people.
- Open and respectful communications are essential to helping parties understand opposing views and to find ways of accommodating differences of opinion or aspiration that may exist between nation-states, cultures, and other groups. Helpful exchanges of information include liaisons among cultural and national groups of people, politicians, and even the leadership of military forces.
- Reduced militarism is related to modifying the attitude of the political leaders of nations about the degree to which their society must be prepared for potential conflicts, and the amount of spending that is necessary for such purposes. If governmental priorities resulted in fewer resources being expended to maintain armed forces, arsenals, and other military infrastructure, then more would be available to support social programs related to health, education, culture, and other needs of society. However, such approached must be balanced against the degree of militarism exhibited by other countries within the community of nations.
- Anti-war cultural attributes also help to foster a widespread antipathy against violent conflicts. This is accomplished by documentaries, movies, novels, paintings, poems, sculptures, songs, websites, and educational curricula that take anti-war stances and help people to understand that peace is a desirable alternative to violent conflict.
- Empowerment of a comprehensive United Nations potential for peace-making and peace-keeping would mean that only the most determined antagonists would be able to escalate tensions to outbreaks of war. The UN is limited to authorizing those functions, which must then be carried out by willing member-nation. However, with improved funding and a stronger mandate the UN could be empowered to prevent more conflicts than it is now possible for it to do.
- Cooperative security is an idea that is not yet sufficiently recognized by the nation-states and cultures of the world, all of whom have a large stake in avoiding warfare and should collaborate more effectively to avoid it.
- Ecological sustainability is another force for peace. If it is attained then economic and environmental difficulties associated with non-sustainability would place fewer strains on the internal and international relations of countries, which are often a prelude to conflict. In essence, the global economy must be balanced against the capability of the world to provide flows of resources, while also maintaining the ability of the biosphere to sustain other species and natural ecosystems. We usually think of warfare as an activity that only occurs among people, but in a sense the human economy is presently at war with the biosphere. If that conflict with the natural world can be resolved, then wars among human cultures and nation-states will be easier to avoid.

Image 26.5. Peacekeepers patrolling the boundary between Eritrea and Ethiopia. This peacekeeping mission of the United Nations ran from 2000 to 2008, and it was intended to separate the warring parties until a peace agreement could be reached. Source: Dawit Rezenè, http://www.world66.com/africa/eritrea/lib/gallery/showimage?pic=africa/eritrea/soldiers_eritrea ; http://commons.wikimedia.org/wiki/File:UN_Soldiers_in_Eritrea.jpeg

Canadian Focus 15.2. Lester Pearson – A Nobel Prize for Peace-keeping Lester B. Pearson (1897-1972) was a distinguished Canadian who worked as a professor, historian, diplomat, civil servant, and politician, including serving as the 14th Prime Minister of Canada from 1963 to 1968 (Wikipedia, 2015t). In 1957, he was awarded the Nobel Peace Prize in recognition of ground-breaking work he did to organize a United Nations Emergency Force to resolve the Suez Canal Crisis.

That conflict occurred in 1956. It involved a coordinated attack against Egypt by armed forces of Britain, France, and Israel (Wikipedia, 2015u). The main intent was to seize the Suez Canal, which had been constructed during 1859-1869 by the French-owned Suez Canal Company, and which provides a vital shipping link between the Mediterranean Sea and the Indian Ocean. The canal had been nationalized by Egypt several months previously under the direction of its president, Gamal Nasser. That unilateral act had been undertaken to patriate ownership of the strategic shipping channel and its considerable economic benefits. The situation was, however, more complicated than a nationalistic seizing of a vital commercial asset. A larger context was the refusal of western powers to fund the construction of the Aswan High Dam on the Nile River, a project that Egypt considered to be vital to its economic development. That refusal had been precipitated by the increasing growth of economic and political ties between Egypt and communist nations, especially the Soviet Union and China, of which the former eventually provided most of the funding for the dam project.

In any event, the joint offensive to seize the canal from Egyptian control turned out to be enormously more controversial than its protagonists had anticipated. The attack was widely condemned by many nations, including the United States and the Soviet Union, as well as by the United Nations. The conflict was stopped when the UN General Assembly adopted a U.S.-sponsored resolution that called for an immediate ceasefire, a withdrawal of forces to behind armistice lines, an arms embargo on the adversaries, and reopening of the Suez Canal, which had been blocked by scuttled vessels. This was followed by additional UN resolutions, which established the first United Nations Emergency Force (UNEF), a multi-national military corps that would police the borderlands of Israel and Egypt in order to prevent hostilities from again breaking out.

The proposal for the cease-fire and the emergency UNEF force was primarily developed through the efforts of Lester Pearson, then serving as the Secretary of External Affairs of Canada and a front-line player at the UN. However, behind the scenes Pearson was being urged to lead this initiative by U.S. diplomats, because an American-led effort through the UN would have been resisted by a large bloc of countries, particularly the communist states. The proposal from Pearson received immediate support from Dag Hammarskjöld, the Secretary-General of the UN, and from other key world leaders, and it was quickly implemented.

In 1957, Lester Pearson was awarded the Nobel Peace Prize in recognition of his efforts to resolve the Suez Crisis and for the creation of a mandate for the UN Emergency Force. Pearson is now considered the “father” of the concept of peace-keeping. The Nobel selection committee proclaimed that Pearson had “saved the world” through his efforts to quickly end the crisis, which had the potential to spread into a regional and perhaps even global conflict of the superpowers of the time.

Canadian military personnel have since contributed to a number of UN peace-keeping operations (Wikipedia, 2015v). They served in that inaugural UNEF group from 1956 to 1967, which was placed on Egyptian territory on the Sinai Peninsula. The mandate of that force was terminated in 1967 by another outbreak of hostilities known as the Six-Day War, which was fought between Israel and its neighbouring Arab countries. Canada has also served in 32 additional UN peace-keeping operations (to 2015).

Image 26.6. Lester B. Pearson photographed in 1944. Source: Star Newspaper/The Ottawa Journal/Library and Archives Canada, e002505448 (Copyright is expired; http://en.wikipedia.org/wiki/File:Lester_B._Pearson_with_a_pencil.jpg).

Questions for Review

1. What are the root causes of violent conflicts? Use that conceptual framework to explain the causes of a particular war.
2. Write a brief essay on the economic costs of militarism and war.
3. What are the potential consequences of a nuclear war?
4. What is a nuclear winter, and what might cause it to occur?
5. Explain the social forces and international mechanisms that are helping to prevent wars from occurring.

Questions for Investigation

1. In view of the awful damage that is associated with war, why do these conflicts occur? What are the reasons that differences among people cannot always be settled using non-violent means.
2. During the Second Indochina War (Vietnam War), the U.S. forces dropped enormous quantities of bombs and also sprayed extensive regions with herbicide. Of these two classes of action, there had been more public controversy

over the herbicide spraying. Does this seem to be a reasonable public response to these actions of warfare, in view of the kinds of damage they are capable to causing to people and the broader environment?

Exploring Issues

1. The Government of Canada has assigned you to a team to which the United Nations has given the responsibility of ending a conflict in a foreign country. Outline the steps that you would promote for ending the conflict, including negotiations between the hostile parties, and peace-making and peace-keeping if necessary.
2. An anti-war NGO has hired you to lead a seminar in which options would be discussed for decreasing the level of military preparedness in Canada, including reasonable ways to lessen the expenditures for that purpose. How would you organize the seminar in order to encourage the participants to have an open discussion of the need for a balanced level of military preparedness in the face of competing uses of funding for health care, schools, and other social programs.

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Chapter 27 ~ The Biodiversity Crisis

Key Concepts

After completing this chapter, you will be able to

1. Outline how humans are causing the modern crisis of extinction and endangerment.
2. Give examples of species that have been made extinct through human activities, including cases from Canada.
3. Explain how a system of protected areas is essential to the preservation of biodiversity.
4. Outline the roles of governments, non-governmental organizations, scientists, and citizens in conserving species and other elements of biodiversity.

Introduction

Earlier, we defined biodiversity as the total richness of biological variation and examined reasons why it is important (see Chapter 7). In this chapter, we examine the many threats to biodiversity that are associated with the human economy. The emphasis is on severe damage that is being caused, especially that associated with losses of species and of natural ecosystems.

Extinction refers to the loss of a species or another named biological entity (referred to as a taxon) over all of its range on Earth. Extirpation is a more local disappearance, with the taxon surviving elsewhere. Extinction represents an irretrievable loss of a unique portion of the biological richness of Earth, whereas it may be possible to re-establish an extirpated taxon from a surviving population.

Extinctions have always occurred as a result of natural influences. These include random catastrophes as well as the longer-term effects of environmental change, such as in climate or in biological factors such as disease or predation (Chapter 7). In modern times, however, and even for the past 10-thousand years or so, almost all extinctions have been caused by anthropogenic influences, particularly by over-harvesting and the destruction of natural habitats. In fact, an enormous increase in the rate of extinctions has been one of the most important consequences of humans becoming the dominant species on Earth. Species are now disappearing so quickly that we refer to the phenomenon as an extinction crisis (or a biodiversity crisis).

Every species is unique, a fact that gives them great intrinsic value – this is a central tenet of the biocentric world view (see Chapter 1). Therefore, from an ethical perspective, any irretrievable loss of biodiversity is a shameful consequence of the ways that people are using their power to exploit other species and ecosystems. This is also a foolish way for humans to administer their global empowerment, because unique species are disappearing before they have been investigated for their potential usefulness in medicine or agriculture, and before we understand their importance as components of ecosystems. Human actions that result in extinctions can only be regarded as ecologically dangerous behaviour.

In this chapter, we examine the modern biodiversity crisis – the reasons why it is happening, ways of repairing at least some of the damage already caused, and how to prevent further losses.

Natural Extinctions

Life has existed on Earth for about 3.5 billion years. Almost all of the species that have lived during that period of time are now extinct, having disappeared "naturally" for some reason or other. (The survivors are referred to as extant, or still living today.) In many cases, the extinct species could not adapt to changes that occurred in their environment, such as shifts in climate or increases in disease, predation, or competition with other species. Many species, however, disappeared during brief episodes of mass extinction, which may have been caused by unpredictable catastrophes, such as a meteorite hitting Earth.

The geological record clearly shows that many species and groups of organisms (such as genera, families, and phyla) have appeared and disappeared over time (see Chapter 6). For example, many phyla of invertebrate animals evolved relatively quickly during an evolutionary proliferation that occurred around the beginning of the Cambrian era, about 570 million years ago. Subsequently, most of those phyla and their many species became extinct. About 20 extinct phyla from that period were discovered in a renowned fossil deposit known as the Burgess Shale, located in Yoho National Park in southeastern British Columbia. In an evolutionary sense, each of those extinct phyla represented a novel "experiment" in the form and function of invertebrate animals. We only know that these ancient creatures existed because their fragile body structures became fossilized under extraordinary geological circumstances (Gould, 1989).

The fossil record is replete with many other examples of ancient extinctions. However, the rate of extinction, and of the subsequent evolutionary radiation of new species, has not been uniform over time. The geological record clearly shows that relatively low and uniform rates of extinction have typically persisted for extremely long periods of time, but those tranquil eras were punctuated by about nine catastrophic events of mass extinction.

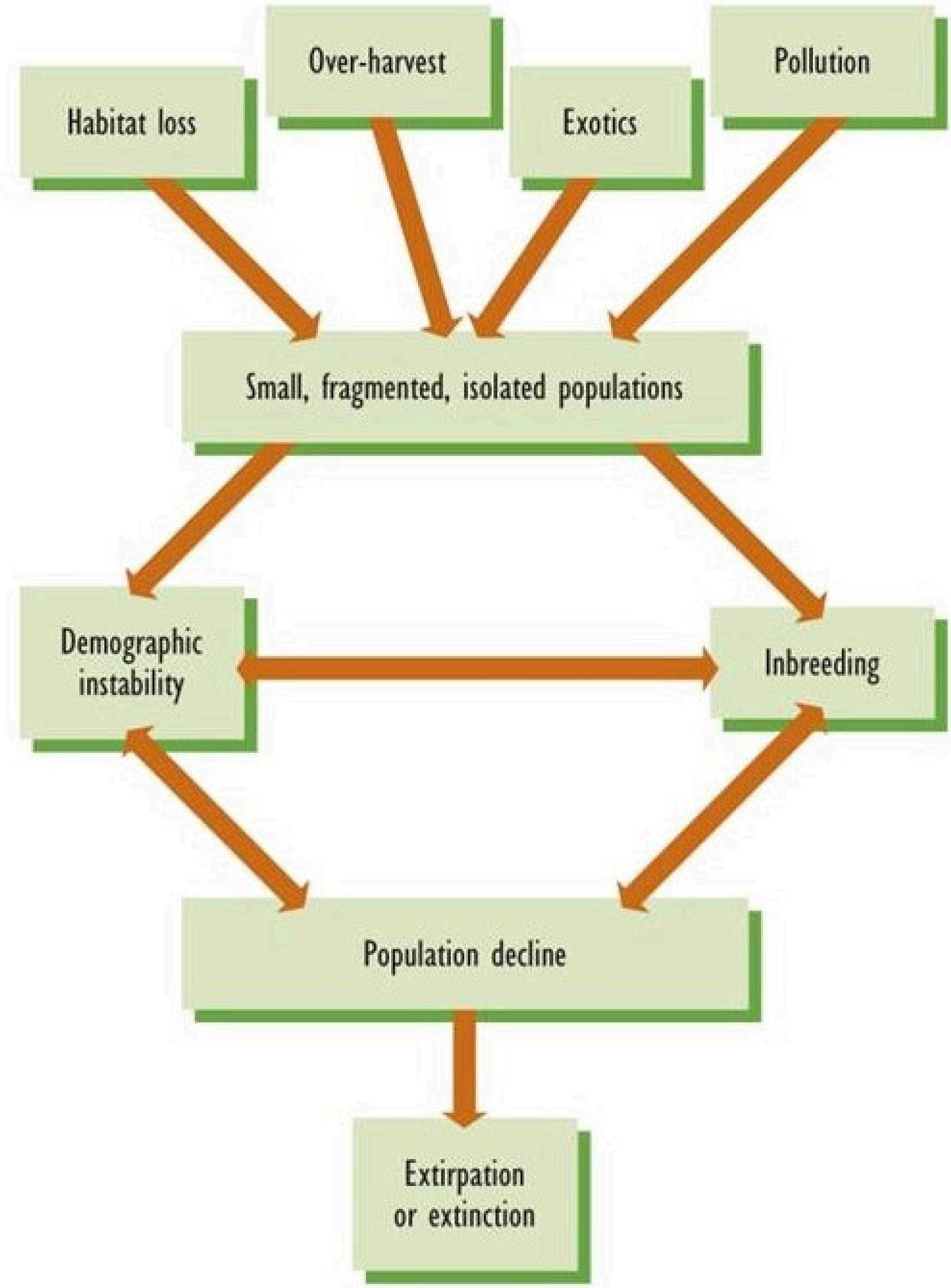
The most intense event occurred at the end of the Permian era, about 245 million years ago. This natural catastrophe resulted in the loss of about 54% of the existing families of marine animals, including 84% of the genera and 96% of the species (Erwin, 1990). Another mass extinction occurred at the end of the Cretaceous period, about 65 million years ago. This famous event involved the last of the dinosaurs and pterosaurs (flying reptiles), along with many other taxa, totaling perhaps three-quarters of the species living at the time. Many scientists believe that this crisis of paleobiodiversity was caused by a meteorite hitting the Earth, likely in the vicinity of the Yucatan peninsula of Mexico. Such a catastrophe would have caused a deadly tsunami, while also ejecting enormous quantities of dust into the atmosphere, likely resulting in a cooling of the climate that most species were unable to tolerate.

During the past several centuries, Earth's existing heritage of biodiversity has been buffeted by another mass extinction. This is an ongoing catastrophe, and it will certainly intensify into the foreseeable future. This ecological calamity is not a natural phenomenon. Rather, it is being caused by the influences and economic activities of modern humans.

Extinctions Caused by Humans

Many kinds of human activities are causing species to become endangered or extinct. (A species is considered endangered if, because of a small population or loss of habitat, it has a high risk of becoming extirpated or extinct.) The most important cause is the destruction of natural ecosystems and their conversion into habitats that are unsuitable for the original species, a problem that is especially acute in tropical countries. Excessive harvesting of some species is also significant, as is damage caused by introduced predators, diseases, and competitors. Any of these stressors can cause populations to become increasingly small and fragmented, a circumstance that results in much greater risks of extirpation or extinction (Figure 27.1).

Figure 27.1. The Extinction Vortex. Extinction can be caused by various influences and activities of humans, such as habitat loss, excessive harvesting, and the introduction of alien diseases, predators, and competitors. As a result of these stressors, large and continuously distributed populations may fragment into small isolated units that are highly vulnerable to the deleterious effects of inbreeding, population instability, and random catastrophes. These can cause endangered populations to decline further and may ultimately result in extirpation or extinction. Conservation biologists refer to this accelerating spiral of endangerment as the extinction vortex.



Because of these anthropogenic influences, the past several centuries have witnessed huge increases in the global rate of extinction and in the number of species that are threatened with this catastrophe. Not surprisingly, our knowledge of recently extinct and endangered species is relatively complete for large and conspicuous species such as vertebrate animals, especially those that live in temperate and higher-latitude countries, where most biologists also live.

In fact, there have been at least 842 known extinctions, including 746 animals and 96 plants (many of these are distinct subspecies and varieties; IUCN, 2014). The losses include 71 species of mammals, 135 birds, 22 reptiles, 34 amphibians, and 80 fishes. All of these extinctions were caused by human influences. Much larger numbers of species are at grave risk of suffering extinction (1,199 species of mammals are at risk, as are 1,373 birds, 927 reptiles, 1,957 amphibians, and 2,222 fishes).

Unfortunately, we know much less about extinctions among less conspicuous groups of organisms. This is particularly true of the enormous diversity of relatively small, poorly known species that live in tropical ecosystems, especially in old-growth rainforest. Undoubtedly, huge numbers of tropical species, particularly plants and invertebrates, have become extinct during the past several centuries as their natural forest habitat was converted into agricultural and other land-uses. We can refer to these losses as "hidden extinctions" because so few of the lost species had been discovered and named by taxonomists. Moreover, these hidden extinctions continue to occur rapidly, in fact at an accelerating rate, because their poorly explored tropical habitats are being destroyed so quickly.

In the following sections we will examine selected case studies of species that have been rendered extinct by humans and their activities.

Prehistoric Extinctions

Many species are useful as "resources" that humans can harvest and use as a source of food, medicine, timber, fuel, or some other purpose. In many cases, the exploitation of these potentially renewable resources has been so insatiable that their "mining" has culminated in extinction. These once-valuable species now occur nowhere on Earth (Freedman, 1995).

We previously examined extinctions that were caused by prehistoric hunters as they over-hunted populations of large, naive animals in newly discovered lands (see Global Focus 12.2). In North America, it appears that paleohunters exterminated many species of large mammals soon after people discovered the continent by migrating across a Beringean land bridge more than 12 millennia ago, at the end of the most recent ice age. Known extinctions occurring around that time include 77 species of mammals, such as 10 species of horse, a giant ground sloth, four kinds of camels, two bison, the mastodon, several mammoths, and the sabre-toothed tiger. Other large animals became extinct when South America was colonized somewhat later.

The colonization of "new" land masses by humans also caused prehistoric mass extinctions in other places. Australia and New Guinea were discovered about 50-thousand years ago. Soon after, many species of marsupials, large flightless birds, and tortoises became extinct, likely because of over-hunting.

New Zealand was colonized less than one-thousand years ago. Within two centuries, 30 large birds were extinct, among them a goose, a swan, and 26 species of large flightless birds known as moas. The extinctions proceeded as an anthropogenic wave that began in northern North Island, which was the initial point of colonization, to southern South Island. Many of the moas were herded by the hunters and their dogs to convenient butchering sites, where the great piles of bones were later used by early European farmers as a source of phosphate fertilizer.

In a similar fashion, the human colonization of Madagascar, about 1,500 years ago, resulted in the extinction of 14 species of lemurs, 6-12 flightless elephant birds, and various other big and edible animals. Other well-known prehistoric mass extinctions occurred on Hawaii, New Caledonia, Fiji, and the West Indies. In fact, this phenomenon likely occurred whenever a previously inhabited island was discovered and colonized.

The endemic (local) species that existed only on small islands are particularly vulnerable to extinction. The key reasons for this were:

- island species occur in small, isolated populations, which are especially vulnerable to extinction
- many birds of remote islands had not experienced intense predation during their recent history, and as a result they had evolved to be flightless, relatively large, and unafraid of predators, so they were extremely vulnerable to hunting by people once their islands were colonized
- most island species did not co-occur with closely competing organisms, so they were easily displaced when more capable species were introduced
- islands also became ecologically degraded by introduced plants, animals, and diseases
- finally, the human colonization of remote islands, particularly by Europeans, resulted in extensive destruction of natural habitats as the islands were cleared for agricultural, urban, and tourism developments.

For these reasons, the species of remote islands have suffered particularly high rates of extinction. For example, at one time, each of the approximately 800 islands of the southern Pacific Ocean may have had several endemic species of flightless rails (a family of marsh birds known as Rallidae), plus other unique birds and reptiles. As these islands were discovered and colonized by prehistoric Polynesians, perhaps thousands of these endemic species became extinct through over-hunting and habitat damage. For instance, a study of bird bones recovered at an archaeological site on the island of Ua Huka found that 14 of the 16 original birds no longer occur there, including 10 endemic species that had been rendered extinct. The extinctions worsened when Europeans secondarily colonized these and other oceanic islands, because of the extensive habitat losses that occurred during "development." In fact, of the 135 taxa of birds (including 95 species) around the world that are known to have become extinct since 1600, all but nine lived on islands.

The problem of extinction-prone island biotas can be further illustrated by the case of the Hawaiian Islands, an ancient, remote archipelago of volcanic outcroppings in the central Pacific Ocean. When these islands were first discovered by Polynesian seafarers, there were at least 86 species of birds, including 68 that occurred nowhere else. Of those 68 endemics, 24 are now extinct and 29 are endangered. Similarly, the native flora at the time consisted of as many as two thousand species of flowering (angiosperm) plants, of which as many as 98% were endemic. During the past several hundred years, more than 100 of the endemic plants became extinct, and more than 500 are threatened or endangered. The extinction and endangerment of Hawaiian species has been caused by the widespread conversion of natural habitats into agricultural and urbanized land-uses, coupled with introductions of alien predators, competitors, virulent diseases, and destructive herbivores such as goats.

Historic Losses by Over-Harvesting

Unsustainable harvesting during historic times has caused some of the most famous cases of extinction and endangerment, in some instances involving species that were initially extremely abundant. We will illustrate this phenomenon by referring to the dodo, great auk, passenger pigeon, and other notable cases. These are examples of the devastating effects that insatiable killing can have on vulnerable populations of wild creatures.

The dodo (Raphus cucullatus) was a turkey-sized, flightless bird that disappeared in 1681, making it the first documented extinction of the historical era. The loss of this species is immortalized in everyday language by the phrase "dead as a dodo," which is used as a metaphor for an irrevocable loss. The word "dodo" is also sometimes used to indicate an old-fashioned or stupid person. This etymology derives from the dodo's apparent inability to adapt to threats posed by the human colonists of Mauritius, the only place where this bird lived. Mauritius is a small island in the Indian Ocean, discovered by Portuguese sailors in 1507. In 1598 it was colonized by the Dutch, who hunted the dodo for meat, gathered its eggs, and cleared its habitat for agriculture. They also released cats, pigs, and monkeys that preyed on dodos and destroyed their ground-level nests. These stressors caused the dodo to decline rapidly and become extinct.

The great auk (Pinguinus impennis) , a flightless seabird, was the first documented anthropogenic extinction of a species whose range included North America. Early mariners knew it as the original "pennegoin," although it belonged to a different family of birds (Alcidae) than the outwardly similar penguins (Spheniscidae) of the Southern Hemisphere. The great auk lived throughout the north Atlantic region, breeding on a few islands off eastern Newfoundland, in the Gulf of St. Lawrence, around Iceland, and north of Scotland. This large seabird was initially abundant in its breeding colonies. Because it was flightless, it could be easily killed. Consequently, the great auk had long been exploited by Aboriginal people inhabiting what is now known as Newfoundland, and also by Icelanders and European fishers, as a source of meat, eggs, and oil. Unfortunately, the great auk developed into a valuable commodity when its feathers became sought after for stuffing mattresses in the mid-1700s. This resulted in a relentless slaughter that quickly caused the great auk to become extinct.

One of the largest breeding colonies of great auks was on Funk Island off eastern Newfoundland. In 1785, an observer described the harvest of great auks and other seabirds on Funk Island (Nettleship and Evans, 1985):

> "It has been customary of late years, for several crews of men to live all summer on that island, for the sole purpose of killing birds for the sake of their feathers, the destruction of which they have made is incredible. If a stop is not soon put to that practice, the whole breed will be diminished to almost nothing, particularly the penguins."

The great auk was, in fact, extirpated from Funk Island in the early 1800s. The last two individuals seen alive were killed in 1844 by several Icelanders who were searching for specimens to sell to a bird "collector" of natural-history specimens. Because of their extreme rarity at the time, great auks and their eggs were precious to collectors – they were, unfortunately, too valuable to let live.

The passenger pigeon (Ectopistes migratorius) may have numbered as many as 5-billion individuals three centuries ago, when it may have been the most populous landbird in the world. It bred in mature forests of oak, beech, hickory, and chestnut in southeastern Canada and the northeastern United States. These trees produce large seeds known as "mast," which were a key food for this bird. In the autumn, passenger pigeons migrated in enormous flocks to the southeastern United States. Their immense flocks were described as being so dense as to obscure the sun, and taking hours to pass. The birds roosted communally during winter nights, often in such large numbers that they would kill trees by an excessive deposition of guano (bird feces), and would break stout limbs under their weight.

The naturalist John Lawson described an impressive passage of these birds in the Carolinas (Feduccia, 1985):

> "I saw such prodigious flocks of these pigeons . . . in 1701-2 . . . that they had broke down the limbs of a great many trees all over these woods, whereupon they chanced to sit and roost . . . These pigeons, about sun-rise . . . would fly by us in such vast flocks, that they would be near a quarter of an hour, before they were all passed by; and as soon as that flock was gone, another would come; and so successively one after another, for the rest of the morning."

The seemingly unlimited abundance of passenger pigeons, and their habit of migrating and breeding in large and dense groups, made them an easy target for market hunters who sold their carcasses in cities and towns. During the early 1800s there was a well-organized hunt of passenger pigeons to supply urban markets with cheap meat. During seasons when the hunt was on, "wagon loads of them . . . poured into the market . . . and pigeons became the order of the day at dinner, breakfast, and supper, until the very name became sickening" (A. Wilson in 1829; quoted in Feduccia, 1985).

The sizes of the harvests were staggering. For example, about one-billion pigeons were taken in 1869 in breeding colonies in Michigan alone. The intensity of the commercial hunting far exceeded sustainability, and this, along with destruction of much of the breeding habitat, caused the passenger pigeon to decline rapidly in abundance. The last known attempt at nesting was in 1894, and the last known individual died a lonely death in the Cincinnati Zoo in 1914.

The Carolina parakeet (Conuropsis carolinensis) once bred widely in the southeastern United States. This parakeet was a fairly common, brightly plumaged, fruit- and seed-eating bird that foraged and roosted in groups, especially in mature hardwood forest. Carolina parakeets were not hunted as a valuable commodity. Rather, they were exterminated because they were regarded as an agricultural pest, because of damage they caused while feeding in orchards and grain fields. Unfortunately, Carolina parakeets were an easy mark for eradication because they nested and fed communally. Also, they tended to assemble around wounded colleagues, which allowed an entire flock to be easily wiped out by a hunter. The last record of a flock of these parakeets was in 1904, and the last known individual died in a zoo in 1914.

The Steller's sea cow (Hydrodamalis stelleri) was a mammal related to the manatees. It lived in subarctic waters around the Aleutian Islands in the Bering Sea and was hunted by Aboriginal people of that region. Soon after this shy and inoffensive species was "discovered" by Russian explorers in 1741, it was hunted as a source of food and hides and was rendered extinct after only 26 years of exploitation.

The Caribbean monk seal (Monachus tropicalis) lived in the Caribbean Sea and Gulf of Mexico. This species was encountered, and eaten, on the second voyage of Christopher Columbus to the Americas in 1494. Populations of this seal were depleted by an eighteenth-century market hunt for its meat and blubber. The last survivors were exterminated by the subsistence hunting of local fishers.

The Eskimo curlew (Numenius borealis) is a large sandpiper that was still abundant as recently as 150 years ago. It was exploited by market hunters during its migrations through the prairies and coasts of Canada and the United States, and also on its wintering grounds on the pampas (grasslands) and coasts of South America. The uncontrolled hunting caused this bird to become rare by the end of the nineteenth century. The last observed nesting attempt was in 1866, and the last specimen was "collected" (by shooting) in Labrador in 1922. For some decades the Eskimo curlew was thought to be extinct, very small numbers of this perilously endangered bird may have recently been seen by expert birders.

The right whale (Balaena glacialis) once ranged over all temperate waters of the Northern Hemisphere. Because if its rich oil content, habit of swimming at a relaxed speed in coastal waters, and the fact that it floated when dead, early whalers considered this the "right" whale to hunt. Due to commercial over-hunting of right whales for their blubber, which was rendered into oil to fuel the lamps of Europe and America, its populations collapsed over its entire range. This whale has been extirpated from the eastern Atlantic off Europe, and it is critically endangered in the western Pacific off Korea and Japan. Only about four hundred right whales survive in the northwest Atlantic Ocean. Most of these animals spend much of the summer and autumn in the mouth of the Bay of Fundy and off southwestern Nova Scotia. They migrate south to spend the winter along the southeastern United States and eastern Caribbean. Although not hunted for decades, the population of right whales has been slow to recover, largely because of mortality caused by collisions with ships and entanglement in fishing gear.

Image 27.1. The Labrador duck (Camptorhynchus labradorium) used to winter on the Atlantic coast of Canada and the United States and probably nested in Labrador. Because of excessive hunting, it became extinct around 1875. This is a photograph of carved models of a pair of Labrador ducks, replicated from old stuffed specimens that had been "collected" in Nova Scotia by a nineteenth-century naturalist. Source: B. Freedman.

Losses by Habitat Destruction

Many species have been rendered endangered or extinct because their natural habitats were converted to agricultural or other land-uses or were damaged by invasive alien species. We will first examine several examples of this phenomenon, and then assess the modern destruction of tropical forest, which is the human activity that is most important in causing extinctions today.

The American ivory-billed woodpecker (Campephilus principalis principalis) lived in the southeastern United States, where it bred in extensive tracts of mature, bottomland, hardwood forest and cypress swamp. Most of this habitat was heavily logged or converted to agriculture by the early 1900s, which drove the population of ivory-billed woodpeckers into a rapid decline. There had been no sightings of this woodpecker since the early 1960s, but astonishingly, in 2005, one individual was photographed in a remote forest tract in Arkansas, prompting hope that the species might yet be recovered. A closely related subspecies, the critically endangered Cuban ivory-billed woodpecker (Campephilus principalis bairdii), may still occur in tiny numbers in mountain forests in Cuba.

The black-footed ferret (Mustela nigripes) was first "discovered" in the prairies of North America in 1851. Because of habitat loss, this predator became extirpated in Canada and endangered in the United States. Extensive areas of its habitat of short-grass and mixed-grass prairie were converted into agricultural use. Also, its principal food, the prairie dog (Cynomys ludovicianus), has declined in abundance. The prairie dog has been relentlessly poisoned as a perceived pest of rangeland. With little habitat or food, the black-footed ferret is unable to survive over most of its former range. Nevertheless, a cooperative recovery program of the U.S. Fish and Wildlife Service and the Canadian Wildlife Service has resulted in the release of captive-bred ferrets into places where suitable habitat still exists, and they appear to be increasing in abundance in those places. A small population is now present in Grasslands National Park in southern Saskatchewan.

The Furbish's lousewort (Pedicularis furbishiae) is an herbaceous plant that grows only along a 230-km stretch of the Saint John River valley in New Brunswick and Maine. This species had been considered extinct, but in 1976 it was "re-discovered" by a botanist doing field studies of the potential environmental impacts of a proposed hydroelectric reservoir on the upper Saint John River in Maine. That industrial development would have obliterated the only known habitat of the lousewort. For that, and other environmental and economic reasons, the dam was not constructed.

> Canadian Focus 27.1. Alien Invaders During the past five centuries, and at an accelerating pace, Canada has become host to an enormous number of alien plants, animals, and microorganisms. Many of them were introduced intentionally, and others accidentally. Some have caused severe damage by invading natural ecosystems and displacing native species or by becoming serious predators or pathogens of native biota. Others are causing awful economic damage as pests in agriculture, forestry, horticulture, or in the home. Canada is not unique in this circumstance – all countries are suffering grave ecological and economic damage from invasive aliens. In fact, this syndrome is one of the biggest environmental problems facing the planet. There is a litany of examples of invasive aliens in Canada. The following cause some of the most important ecological damage: Invaders of Natural Habitats
>
> - Garlic mustard (Alliaria petiolata) is a Eurasian plant that was accidentally introduced to America, possibly as a contaminant of crop seed or by hitchhiking in soil carried as ballast on sailing ships. This herbaceous plant invades bottomland forests of southern Ontario and Quebec, where it crowds out native plants, some of which are rare.
> - Gorse (Ulex europaea) is a European shrub that was introduced as a horticultural plant. It is invasive in coastal British Columbia, where it displaces at-risk plants that live in dry forests of Garry oak (Quercus garryana) and Douglas-fir (Pseudotsuga menziesii).
> - Purple loosestrife (Lythrum salicaria) is a herbaceous Eurasian plant that was introduced as an ornamental species or with ship ballast. It can degrade wetland habitat for native plants and animals.
> - Leafy spurge (Euphorbia esula) was accidentally introduced as a contaminant of crop seed. It invades prairie and displaces rare native species.
> - The brown spruce longhorn beetle (Tetropium fuscum) is a Eurasian insect that arrived in Halifax in the 1990s, probably carried in wood used to secure ship cargoes. It is attacking and killing native spruce trees, especially red spruce (Picea rubens), and it may be a threat to the entire boreal forest.
> - Chestnut blight (Endothia parasitica) and Dutch elm disease (Ceratocystis ulmi) are Asian fungal pathogens that were brought to North America with horticultural stock of alien trees. These diseases have wiped out native chestnut and elms wherever encountered, causing terrible damage to natural forests. A similar recent case introduced through horticulture is the butternut canker (Sirococcus clavigignenti), which is now killing butternut trees (Juglans cinerea).
> - The common carp (Cyprinus carpio) is a Eurasian fish introduced as a source of food and sport. It damages shallow-water habitats by uprooting aquatic plants and disturbing sediment while feeding and nesting.
> - The zebra mussel (Dreissenia polymorpha) arrived to the Great Lakes in ballast water of ships from Europe. It causes damage by displacing native mollusks and by fouling water pipes and other structures.
> - The green crab (Carcinus maenas) arrived in ballast water in the mid-nineteenth century and is now firmly established on the East Coast. It feeds broadly and has caused declines of many native invertebrates.
> - The green fleece (Codium fragile) is a marine alga from Eurasia that recently (about 1990) established on the Atlantic and Pacific coasts. It displaces native seaweeds, particularly in the Atlantic. Invaders of Anthropogenic Ecosystems:
> - The starling (Sturnus vulgaris), English sparrow (Passer domesticus), and rock pigeon (Columba livea) are Eurasian birds that were introduced to America by "homesick" European immigrants. They are now extremely abundant and displace native birds from breeding sites, compete with them for food, and foul urban areas with their excrement.
> - The common rat (Rattus norvegicus), house mouse (Mus musculus), and cockroach (Blatta orientalis) are alien animals that are pests in many homes.

- The dandelion (Taraxacum officinale), crabgrass (Digitaria sanguinalis), and plantain (Plantago major) are among many alien plants that were introduced to North America, mostly by accident, and are now considered pests of horticulture.
- Bull thistle (Cirsium vulgare), groundsel (Senecio jacobea), and St. John's wort (Hypericum perforatum) are among many invasive aliens that degrade pastures by crowding out more nutritious plants or by being distasteful or poisonous to livestock.

Tropical Deforestation

Tropical forest is most biodiverse ecosystem on Earth – its richness of species is unparalleled. Moreover, this poorly explored biome is thought to contain millions of as-yet-unnamed species, particularly of insects (Chapter 7). Because so many tropical-forest species have a local distribution, the destruction of this ecosystem causes a disproportionate number of extinctions (in comparison with those by the clearing of other kinds of natural ecosystems).

It is well known that the rate of deforestation in most tropical countries has increased alarmingly during the past century, particularly in the past several decades. This is in marked contrast to the situation in most higher-latitude countries, where forest cover has been relatively stable (see Chapter 14). In North America, for example, there has been little net change in forest cover in recent years (Table 27.1). In contrast, most countries of Central and South America had substantial losses of forest cover during that period, as did most tropical countries of Africa and Asia. Overall, the developing world lost 138 million hectare of forest between 1990 and 2005 (5.8% overall), and most of that was tropical forest (WRI, 2008). Globally, the rate of clearing of tropical rainforest during the 1980s and 1990s was equivalent to more than 1% of that biome per year—a rate that, if maintained, would imply a half-life for that biome of less than 70 years.

Most tropical deforestation is caused by the conversion of forest into subsistence agriculture by poor families. This agricultural conversion is greatly increased whenever access to the forest interior is improved. When roads are constructed for timber extraction or mineral exploration, deforestation often follows rapidly. The complex social causes of deforestation include population growth, inequality of land ownership, and the displacement of poor families by mechanization and the global commercialization of agriculture. Because of these factors, enormous numbers of poor families are seeking arable land in most of the less-developed countries. These people need land on which they can grow food for subsistence and for some cash income.

The forest conversion often involves a system of shifting cultivation, in which the trees are felled, the woody debris burned, and the land used to grow mixed crops for several years. By that time, fertility has declined and weeds have become abundant. The land is then abandoned for a fallow period of several decades. This allows a secondary forest to regenerate, while nearby patches of forest are cleared to provide new land for cultivation.

A more intensive system of subsistence agriculture, known as slash-and-burn, results in a permanent conversion of the land into crop production. Slash-and-burn also involves cutting and burning the forest. After the forest is gone, however, the land is used continuously, without a fallow period during which a secondary forest may regrow and site fertility regenerate.

Much tropical forest is also affected by commercial logging, or is being cleared to provide land for industrial agriculture, such as oil-palm plantations, sugar-cane fields, and cattle pasture. Tropical deforestation is also caused by flooding during the development of hydroelectric reservoirs, by the cutting of wood to manufacture charcoal, and by the harvesting of fuelwood, especially near towns and cities. Wood is the predominant cooking fuel in many tropical countries, especially for poorer, rural families – for most of the world's people, the energy crisis involves fuelwood, rather than fossil fuels (see Chapter 14).

Because so many species live in tropical forest, the modern rate of deforestation of this biome is having catastrophic consequences for global biodiversity. This damage will become increasingly important in the future, assuming the present relentless pace of tropical deforestation continues.

Table 27.1. Changes in Forest Area in Selected Countries and Regions. Forest area is for 2011 (in 10^6 km^2), and change in forest cover is presented as percent of the original cover and as the percentage change from 2005 to 2010. Source: Data from WRI (2008) and UNEP (2015).

Country	Forest Area	% of Original Forest	Recent Change (%)
North America	6.15	77.3	0.2
Canada	3.1	91.2	-0.4
United States	3.04	60.2	0.6
Central America	0.839	54.5	-2.4
Honduras	0.051	51.6	-11.8
Nicaragua	0.03	44.3	-11.5
Mexico	0.646	63.4	-12
Cuba	0.029	28.8	6
Costa Rica	0.026	34.9	4.4
South America	8.61	69.1	-2.1
Venezuela	0.46	83.6	-3.1
Bolivia	0.569	77.2	-2.7
Brazil	5.17	66.4	-2.1
Columbia	0.604	53.5	-0.8
Peru	0.678	86.6	-1.1
Argentina	0.292	59.5	-4.1
Europe	10.19	58.4	0.4
Sub-Saharan Africa	5.8	–	-2.9
WORLD	39.55	53.4	-0.4

Image 27.2. The greatest modern threats to biodiversity are associated with deforestation in tropical countries. This area in West Kalimantan in Indonesian Borneo was, until recently, covered in old-growth tropical rainforest. The forest was logged to recover its largest trees, which were used to manufacture timber and plywood for export. A secondary harvest was then made of smaller trees for local use, after which the area was converted to agricultural land-use through a practice known as slash-and-burn. At the time the photo was taken, people had just moved into the area and were engaging in subsistence agriculture. Few native species

can survive in this ecologically degraded habitat. Source: B. Freedman.

Fortunately, a widespread awareness and concern has developed about this important ecological problem. This has stimulated a great deal of research into the conservation and protection of tropical forests, and governments have started to set aside substantial areas as national parks and other kinds of protected areas. Thousands of sites, comprising hundreds of millions of hectares, have now received some sort of "protection" in tropical countries.

However, the effectiveness of the protected status varies greatly. It depends on factors that influence governmental commitments to conserving forest and other natural ecosystems and to protecting biodiversity more generally. Social stability and related political priorities are important considerations – these are critical to addressing the economic causes of the destruction of tropical ecosystems. Societal factors include poverty, population growth, inequities in the distribution of wealth and land, industrial timber harvesting to earn foreign exchange, and corruption. More directly, political stability and priorities determine whether enough money is available to support a system of protected areas and to find effective means to control the poaching of animals and timber and to prevent other encroachments.

Poaching (illegal harvesting) of endangered wildlife is a terrible problem for species that have economic value on the international black market (see Global Focus 27.1). This can be illustrated by the black rhino (Diceros bicornis) and the elephant (Loxodonta africana) in a game reserve in Zambia, Africa. In the early 1970s, the Luangwa Valley contained about 100-thousand elephants and as many as 12-thousand black rhinos (Leader-Williams et al., 1990). Unfortunately, these relatively large populations quickly collapsed because of poaching, which resulted from the extremely high prices paid for rhino horns and elephant tusks on the black market. Even though Zambian park wardens made courageous efforts under difficult circumstances, it proved impossible to control the poaching. The astronomical value of horn and ivory has spawned a well-organized and profitable chain of illegal poaching, smuggling, and sale.

In spite of these sorts of problems, some tropical countries are developing a real commitment to the protection of their threatened biodiversity. In Central America and the Caribbean, for example, Belize has given protected-area status to 37% of its landbase, while Costa Rica had allocated 27%, and the Dominican Republic 19% (World Bank, 2015).

For perspective, we should note that the relative areas of protected land in those Latin American nations are greater than in Canada (8.6%) or the United States (14%), in spite of their comparative poverty (these data are for IUCN categories I–V; see Global Focus 27.2). Such vigorous conservation activities are badly needed in the region: Costa Rica retains only about 35% of its original forest and the Dominican Republic 25%.

In other Latin American countries, conservation efforts have been disrupted by civil war and other political instabilities, and also by indifferent governmental and social priorities. For example, in 2006, the percentage of the national territory with status as IUCN I–V protected areas was only 0.1% in Jamaica, 0.2% in El Salvador, 0.3% in Haiti, 0.6% in Mexico, and 5.5% in Trinidad and Tobago (WRI, 2008).

> Global Focus 27.1. Categories of Protected Areas The International Union for the Conservation of Nature (IUCN) and the World Commission on Protected Areas (WCPA) recognize six categories of protected areas. Categories I, II, and III represent particularly strong commitments to maintaining natural ecosystems within the protected area, while the other categories allow some degree of resource management or extraction. The following explains the salient features of the various categories: I. Strict Nature Reserves and Wilderness Areas include ecological, nature, and wilderness reserves. These are managed to preserve their natural condition, although use by scientists for research and monitoring may be allowed. II. National Parks and Equivalent Reserves consist of national, state, and provincial parks, plus areas under Aboriginal or other traditional ownership. These areas are managed primarily to protect ecosystems, although non-consumptive recreation is usually permitted. III. Natural Monuments include geological phenomena and archaeological sites and are intended to protect features of aesthetic or cultural importance. IV. Habitat and Species Management Areas consist of wetlands and wildlife sanctuaries. These are intended to conserve through the protection and management of habitats. Hunting and other consumptive uses may be allowed. V. Protected Landscapes and Seascapes include landscapes, marine areas, scenic rivers, recreational areas, and conservation areas in which the varied interactions of people and nature have produced areas of distinct character. These areas are managed to sustain use by both people and wild species and ecosystems. VI. Managed Resource Protected Areas contain areas of primarily natural ecosystems. These are managed to conserve biodiversity, while also providing sustainable harvests of renewable resources and ecological services.

The world's greatest expanses of tropical rainforest occur in equatorial Africa, south and southeastern Asia, Central America, western South America, and the basin of the Amazon River. The latter region, known as Amazonia, contains the most extensive rainforest and may support half of the biodiversity of Earth (Mongabay, 2008). This rich tropical region is still extensively covered by primary old-growth rainforest that has been little affected by modern agriculture, lumbering, or other influences of industrial society (although all of Amazonia has supported indigenous cultures for thousands of years).

However, the exploitation and devastation of the Amazonian forest is proceeding rapidly. Great expanses of rainforest are being converted into industrial-scale cattle ranches and soybean farms. In addition, large areas have been deforested by poor farmers who have migrated from heavily populated regions of Amazonian countries in search of "new" agricultural land. Extensive areas of Amazonian forest have also been degraded by hydroelectric developments, lumbering, mining, and timber harvesting to manufacture charcoal as a fuel for the production of iron.

Most of Amazonia lies in northern Brazil. The population in that region has increased enormously in recent decades to several million people, mostly through the migration of landless peasants from other parts of Brazil. This, along with the development of industrial agriculture, has resulted in rapid deforestation in Amazonian Brazil. Between 1970 and 2013, a total of 759-thousand km^2 of tropical forest was cleared, equivalent to about 19% of Amazonia in Brazil (Butler, 2015). In total, Brazil has accounted for 80% of the deforestation in Amazonia. The peak of deforestation was in 2004, when about 28-thousand km^2 of primary forest was cleared in Brazil. Fortunately, the rate of deforestation has slowed since then, to 6-thousand km^2 in 2013. Most of the continuing deforestation is done to develop additional acreage for cattle ranching and soybeans, for which huge export markets have developed in China and Europe.

For various reasons, including pressures exerted by international environmental organizations, the governments of Brazil and other Amazonia countries have committed themselves to conserving their natural heritage, even while vigorously “developing” the economy of the region. Up to 2012, the government of Brazil had designated about 2.0-million km^2 of Amazonia as protected areas or Indigenous reserves, while Peru had set aside 365-thousand km^2, Venezuela 325k km^2, Colombia 309k km^2, and Bolivia 220k km^2 (Butler, 2015). The protected areas are mostly national parks, while the Indigenous reserves are intended to protect the homelands and cultures of aboriginal peoples. However, as with protected areas everywhere, these ones often suffer from poaching, illegal mining and agricultural settlement, and other prohibited activities that degrade their ecological values, while also threatening Aboriginal cultures and land tenure.

Global Focus 27.2. Trade in Species-at-Risk Some endangered species are valuable for one reason or another. They may be sought by private collectors or by zoos or botanical gardens, which may be willing to pay a large price for a living specimen. Some animal and plant tissues are valuable, which may result in endangered species being killed for their fur, horn, or ivory, or for their finely grained or colourful wood. For example, rhinoceros horn is precious is Yemen for crafting dagger handles, while in eastern Asia tiger bones, the rhizome of ginseng, and bile from the gallbladder of bears are used in traditional medicine. Elephant ivory is valued for carving, and rare furs of cheetah, jaguar, leopard, and tiger are used in expensive clothing.

A global treaty called the Convention on International Trade in Endangered Species (CITES) obliges signatory nations to control the trade in threatened species within their national jurisdiction. CITES was established in 1973 under the United Nations Environment Programme (UNEP). Its key function is to monitor the international trade in endangered species and to control or prevent it as much as possible. For these purposes, species are assigned status as being extinct, endangered, vulnerable, or rare by an allied organization called the World Conservation Union (IUCN). The actual international trade in species is monitored by the “Traffic” network of the IUCN and the World Wildlife Fund (WWF). The global headquarters of CITES, IUCN, and WWF are all in Switzerland.

International trade in 630 species of animals and 301 plants is prohibited by CITES (these are so-called Appendix I species; CITES, 2015). In addition, the trade in 4,827 animals and 29,592 plants (Appendix II) requires a CITES permit and is monitored by the World Conservation Monitoring Centre (WCMC) of Cambridge, UK. WCMC also publishes a series of “red books” that summarize the status and commerce of about 8,300 plant and 7,200 animal species. Canadian species listed by CITES include 49 species of mammals, 57 birds, 4 reptiles, 9 fish, and 85 plants (the latter are mostly native orchids; Environment Canada, 2015). However, the importing of a much larger number of non-Canadian species listed by CITES is also monitored and regulated by Environment Canada.

One of the responsibilities of Canada under the CITES treaty is to report on its international trade in species that fall under the purview of WCMC. In 2013, for example, the Government of Canada issued 1,097 permits to export CITES species or their parts (CITES, 2015). Many of the permits are for species that are listed by CITES, but are not native to Canada but may be bred here, such as parrots, cacti, and orchids. Table 1 shows a selection of native Canadian species for which CITES export permits were given in 2013.

Table 27.2. Selected species for which CITES trade certificates were given in 2013. Source: Data from CITES

(2015).

Species	Permits	Type of Export
peregrine falcon (*Falco peregrinus*)	24	live animals
gyrfalcon (*Falco rusticolus*)	106	live animals
golden eagle (*Aquila chrysaetos*)	2,264	feather & foot specimens
bald eagle (*Haliaeetus leucogaster*)	2,591	feather & other specimens
wolf (*Canis lupus*)	3,614	skins & other trophies
orca (*Orcinus orca*)	115	specimens
lynx (*Lynx lynx*)	16,200	skins & other trophies
bobcat (Lynx rufus)	38,669	skins & other trophies
mountain lion (*Puma concolor*)	425	skins & other trophies
sandhill crane (*Grus canadensis*)	2,272	skins & other trophies
beluga whale (*Delphinapterus leucas*)	272	specimens
narwhal (*Monodon monoceros*)	69	tusks & carvings
river otter (*Lontra canadensis*)	7,549	skins & other specimens
black bear (*Ursus americanus*)	61,332	skins, trophies, meat, specimens
grizzly bear (*Ursus arctos*)	1,280	skins, trophies, meat, specimens
polar bear (*Ursus maritimus*)	1,267	skins, trophies, specimens
walrus (*Odobenus rosmarus*)	487	skins, trophies, specimens

Of course, these data refer only to the legal trade of species listed by CITES. There is also an illegal trade in Canada, particularly of bear gallbladders, caribou antlers, and certain furs. There is also an illegal trade in some living animals and plants such as certain orchids, and gyrfalcons and peregrine falcons that are valuable in the Middle East for the sport of falconry. Most of the illegal trade involves animals and plants that were hunted or collected by poachers. In addition, there are large illegal imports of banned products into Canada, such as rare parrots, reptiles, and fish for the pet trade. There is also a burgeoning illicit trade of animal parts used in traditional medicine, particularly to service a large market in traditional Chinese medicine.

The illegal trade in rare and endangered species is responsible for an enormous international economy of as much as several billion dollars per year (reputedly second only to the illegal drug trade). This is the reason why this kind of illegal commerce is flourishing in so many countries, including Canada. To some degree, governments can deal with the problem by more rigidly enforcing their laws governing the illegal trade and by imposing severe penalties on convicted offenders. Ultimately, however, the illicit commerce is driven by a wealthy and enthusiastic marketplace. Obviously, for the sake of the endangered biodiversity, it is crucial that the demand be curtailed as soon as possible. Ultimately, people's attitudes must be changed, and severe penalties must be imposed for the illegal possession of species or body parts banned by CITES.

Species Declines

Numerous species of certain groups of organisms have been suffering intense and widespread declines in their populations, with many of them becoming endangered and even extinct. These include large carnivores, reptiles, amphibians, predatory birds, and migratory songbirds. We will examine the problem of species declines using the example of North American songbirds.

Within the past two decades or so, ecologists and birders have been reporting alarming declines in the populations of many species of so-called neotropical migrants (these are birds that spend most of the year in tropical habitats but migrate to higher-latitude regions to breed). Most of the declining species breed in mature temperate and boreal forest. Although the reasons for the songbird declines are not totally understood, the most important factors are probably the following:

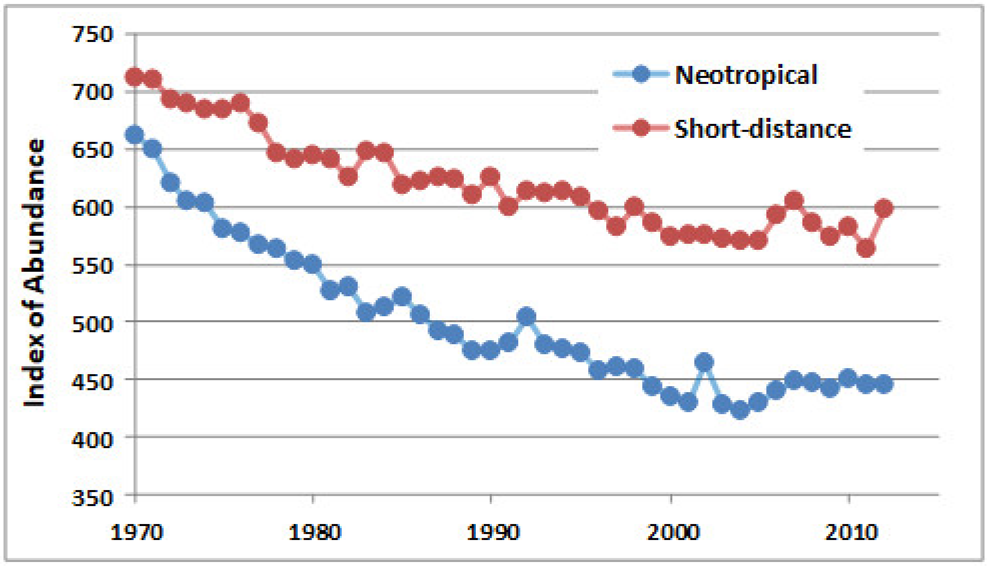
- extensive deforestation in their tropical wintering range
- disturbance of mature-forest habitat in the northern breeding range
- fragmentation of the breeding habitat into "islands" that are too small to sustain populations over the long term, and that are easily penetrated by forest-edge predators and nest parasites (such as cowbirds – to be discussed later)
- loss of critical habitats for staging and migration
- effects of pesticides and other toxic chemicals
- possibly also new introduced diseases, such as the West Nile virus

Bachman's warbler (Vermivora bachmanii) appears to have become extinct because of the loss of its tropical wintering habitat. This songbird used to breed in mature hardwood forest in the southeastern United States. Although suitable habitat remains in that region, this warbler has not been seen since the mid-1950s and is undoubtedly extinct. This loss was probably caused by the clearing of its critical wintering habitat, believed to have been humid tropical forest in Cuba that was converted into sugar-cane plantations.

Much of the evidence suggesting that populations of many other neotropical migrants are declining is anecdotal – skilled birders are not seeing as many individuals of many species as they once did, even in places where the local habitat has not changed much. Unfortunately, only a few studies have closely monitored bird populations for many years in mature forest habitat. One of the best long-term studies is for a tract of forest in West Virginia, where the breeding birds, particularly the migrants, declined substantially over a 37-year period. From 1947 to 1953, 25-28 species bred at that site, of which 14-16 were neotropical migrants. This decreased to only 15 species and 8 migrants breeding over the period of 1973-1983 (Terborgh, 1989). During that same period, the total abundance of birds decreased by 16%, and that of neotropical migrants by 37%. In another important census of forest birds, made at Hubbard Brook, New Hampshire, 70% of the breeding species declined between 1969 and 1984 (Holmes et al., 1986).

An important data set has been compiled by the Canadian Wildlife Service, based on information from a large number of breeding bird surveys, which are made annually at many locations using a common methodology. Because so many widely spaced areas contribute to the database, it provides an indication of synoptic trends in the abundance of birds. The analysis in Figure 27.2 shows that the abundance of neotropical migrants breeding in Canada has declined markedly, while that of species that spend the winter in North America has not decreased to the same degree.

> Figure 27.2. Changes in Abundance of Neotropical Migrants. The index of abundance is based on an annual analysis of a large number of breeding-bird surveys coordinated by the Canadian Wildlife Service across our country. The index for neotropical migrants is based on data for 88 species that spend the winter in Central or South America, while that for short-distance migrants is based on 81 species that winter in North America. Source: Data from CWS (2015).



The causes of the declines of migratory landbirds include the reduction of their breeding habitat due to timber harvesting and conversion into agricultural and urbanized areas. The amount of high-quality habitat has declined, while much of the remainder has been fragmented into small islands of natural forest. This change is important because birds have less success when breeding in small fragments of habitat. In part, this is because their nests are more vulnerable to predators such as crows, jays, magpies, skunks, and foxes.

Many migratory species have also been affected by nest parasitism by the brown-headed cowbird (Molothrus ater), which lays its eggs in the nests of other species. The foster parents raise the voracious cowbird chick, while their own young are neglected and usually die. The cowbird has greatly expanded its range and abundance in North America, mostly because humans have provided it with suitable habitat by disturbing the formerly extensive forest. Cowbirds feed in open areas and are particularly efficient at parasitizing nests near forest edges.

Many bird species in the northern and eastern parts of the modern range of the cowbird are extremely vulnerable to nest parasitism (Freedman, 1995). They have only recently come in contact with this parasite and have not evolved an effective defense. For example, Kirtland's warbler (Dendroica kirtlandii), an endangered species, may suffer a parasitism rate of 70%, and each incidence leads to reproductive failure. A study in Illinois found that two-thirds of 75 nests of various host species were parasitized by cowbirds, including 76% of 49 nests of neotropical migrants. The rate of nest parasitism of white-crowned sparrows (Zonotrichia leucophrys) in California increased from 5% in 1975 to 40-50% in 1990-1991, much more than the 20% rate that the population could face without declining.

The cowbird problem is a dilemma. This is because the only obvious way to help the threatened birds is to kill large numbers of cowbirds, itself a native species. Although distasteful, that action is required if people wish to deal with the severe damage that this parasite is inflicting on other birds, as an indirect consequence of anthropogenic changes to its habitat.

Back from the Brink

Fortunately, dismal stories about extinctions and other grievous losses do not make up all the news about biodiversity.

There are also some uplifting successes of conservation. These involve species that were taken perilously close to the brink of extinction, but have since recovered because they were given effective protection. In some cases, the recoveries have been vigorous enough that the species are no longer in imminent danger. Although these success stories are a distinct minority (the number of endangered species is increasing much more rapidly), they are nevertheless instructive. They illustrate that positive actions can yield great benefits, both for the species in question and for the people that may now be able to exploit them as a potentially renewable resource. (Historical data in this section are from Freedman, 1995.)

The Northern Fur Seal

The northern fur seal (Callorhinus ursinus) lives in the northern Pacific Ocean. It was relentlessly exploited for its fur, and by 1920 had been reduced from a population of several million to only about 130-thousand. Because this fur seal was believed to be in danger of extinction, an international treaty was signed to strictly regulate its harvest. Its population responded vigorously to the conservation measures and rebounded to almost 1-million individuals, abundant enough to again support a commercial hunt for its fur, leather, and oil. However, its numbers have declined again and now there is only a subsistence hunt, equivalent to about one-thousand animals per year since 2000 (NMFS; 2007). The northern fur seal has been suffering considerable non-hunting mortality from entanglement in fishing gear, over-fishing of its food, poaching, and oil spills.

Some other seals were also hunted excessively, but then rebounded in abundance after the exploitation was stopped, or at least sensibly regulated. Two Canadian examples are the harp seal (Phoca groenlandica) of the north Atlantic Ocean, which now numbers about 7-million animals (Chapter 14), and the grey seal (Halichoerus grypus) of temperate Atlantic waters. The grey seal numbered only about 5-thousand animals as recently as the mid-1960s and was considered endangered. Since then, however, this seal has had remarkable population growth and now numbers more than 0.5-million animals.

The Whaling Industry

Many populations of large whales were severely depleted during several centuries of unregulated hunting (Chapter 14). Following protection, some populations have substantially recovered. The best example of this is the grey whale (Eschrichtius robustus) of the Pacific coast of North America, which was protected in the 1930s when its population numbered as few as one-thousand animals. It now numbers about 19-thousand, roughly comparable to its pre-exploitation abundance (IWC, 2015). Although the grey whale of the eastern Pacific is no longer endangered, it was extirpated in the eastern Atlantic several centuries ago, and a tiny stock in the western Pacific is critically endangered.

Other large whales were also heavily depleted by commercial hunting. With few exceptions, they have been protected from exploitation since an international moratorium on whaling in 1986. Their populations are slowly recovering, although not yet to the degree achieved by the grey whale. The sperm whale (Physeter catodon), for example, had a global pre-whaling abundance of about 2-million, but now numbers fewer than 1 million (IWC, 2015). Similarly, the finback whale (Balaenoptera physalus) initially numbered about 200-thousand, but now numbers 50-thousand. The blue whale (B. musculus), initially numbering 200-thousand, now numbers only 6.5-thousand. The humpback whale (Megaptera novaeangliae) was about 120-thousand and is now 89-thousand. These species will continue to recover their abundances as long as they remain protected from commercial hunting. There is intense pressure, however, for the moratorium to end for the most abundant species, particularly the minke whale (Balaenoptera acutorostrata), which numbers about 600-thousand.

Image 27.3. Populations of humpback whales (Megaptera novaeangliae) were heavily exploited worldwide by commercial whaling. However, this species is now protected and its numbers are increasing. Humpback whales, such as this animal off Brier Island, Nova Scotia, spend much of the summer feeding on small fish in northern latitudes. Source: B. Freedman.

Several other species of whales remain badly depleted and are recovering extremely slowly. One of these is the population of right whales (Balaena glacialis) of the western Atlantic, which numbers only about 500 individuals. Another is the right whale of the eastern Pacific Ocean, with only a hundred or so animals. Yet another is the bowhead whale (Balaena mysticetus) of the Arctic, with a population of about 14-thousand. Bowhead whales are still subjected to an Aboriginal hunt in northern coastal Alaska (no more than 67 can be struck per year; several are also taken off Baffin Island in Canada and Greenland). The most important causes of mortality of Atlantic right whales appear to be collisions with ships and entanglement in fishing nets.

The American Bison

Before the American bison (or buffalo; Bison bison) was subjected to an intensive commercial hunt, its population was about 60 million. At that time, bison was the most abundant large wild animal in North America, ranging over most of the continent.

The eastern subspecies (B. b. pennsylvanicus) was an animal of forests and glades that ranged over much of the eastern United States. It was hunted to extinction by the mid-1800s. The plains bison (B. b. bison) ranged throughout the prairies and was by far the most populous subspecies. They migrated in enormous herds – one was described as being 80 km long and 40 km wide, another as 320 km long, and another as moving over a 160 km front! The plains bison were subjected to an intensive market hunt during the nineteenth century and were nearly exterminated. Apart from the money that was made by selling meat and hides, the eradication of these bison was encouraged by governments, especially in the U.S., likely for two reasons. First, the development of prairie agriculture was being disrupted by the bison herds, especially during their mass migrations. Second, because the bison were critical to the subsistence economy of the Plains Indians, extermination of these abundant animals made it easier to displace the Aboriginal tribes in favour of European colonists.

The most famous buffalo hunter was William F. Cody, or "Buffalo Bill," who was contracted in 1869 to provide meat for workers constructing the Union Pacific Railroad through the U.S. prairie. Cody reportedly killed 250 bison in a single day and more than four-thousand during an 18-month period. Once the railways were built, tourist excursions were organized during which a train would stop near a herd of migrating buffalo, which allowed passengers to shoot them in a leisurely fashion through windows of the coaches. Some of the tongues (a delicacy) would be cut from the dead animals, and perhaps some hides, but otherwise the carcasses were left to rot. Such actions were a wanton destruction, but the worst damage was caused by market hunts that were made feasible by the new railroad, because it allowed the meat to be quickly shipped to urban consumers. Between 1871 and 1875, market hunters killed about 2.5 million bison per year. In addition, the Plains Indians had acquired rifles and horses by this time and were also able to hunt bison much more effectively than before.

The unregulated hunting of the plains bison was unsustainable, and the species declined precipitously. By 1889 there were fewer than one-thousand bison left in the United States, and only small herds survived in the Canadian prairies. Almost too late, a few closely guarded preserves were established, and some wild animals were captured for breeding programs. These and later actions have allowed the numbers of plains bison to increase to their present abundance of more than 50-thousand animals. Of course, almost all of their original habitat is gone, having been converted into agriculture, so this animal will never recover its former abundance. However, the plains bison is no longer endangered.

The wood bison (B. b. athabascae) of the southwestern boreal forest is a third subspecies. When this animal became endangered by over-hunting, its only remaining wild population was protected in and around Wood Buffalo National Park in northern Alberta and the adjacent Northwest Territories. Unfortunately, the genetic integrity and health of this population has been degraded by interbreeding with plains bison, which were introduced to the area by misguided wildlife managers in the late 1920s. However, a previously unknown population of wood bison was discovered in 1960 in a remote area of Wood Buffalo National Park, which appears not to have suffered from interbreeding with the plains subspecies. Some of these "pure" wood bison were used to establish another isolated population, northwest of Great Slave Lake. Regrettably, many of the wild-ranging wood bison have been exposed to introduced diseases of cattle, most notably tuberculosis and brucellosis. These, along with predation by people and wolves, have taken their toll, and the long-term viability of their population is cause for concern.

Remarkably, agricultural interests within the federal government have proposed to exterminate virtually all of the bison in the vicinity of Wood Buffalo National Park, except for the "pure" wood bison occurring in isolated populations known to be free of bovine diseases. That slaughter would be intended to prevent the spread of brucellosis and tuberculosis from bison to cattle herds that are spreading northward in Alberta. A secondary reason for the proposed slaughter is to protect the genetic integrity of the wood bison subspecies, because hybrid wood/plains animals would be targeted for extermination. This would leave the more isolated, non-diseased, pure wood bison to repopulate the cleared habitat. This proposal is highly controversial and, even if permitted, would probably not be successful. An enormous effort would be required to find each and every hybrid bison in the target area, which is an immense wilderness of boreal forest and muskeg.

Some Other Recoveries

The sea otter (Enhydra lutris) lives on the west coast of North America. This marine mammal was subjected to a devastating 18th- and 19th-century hunt for its dense and lustrous fur. In fact, it had been thought to be extinct, until small residual populations were discovered in the 1930s. The sea otter has now recovered its abundance over much of the west coast. This resurgence was aided by re-introductions into areas from which it had been extirpated, such as the Pacific coast of Vancouver Island. Sea otters now number more than 100-thousand individuals, but the Canadian population is still small enough to be designated as a threatened species.

Image 27.4. The sea otter (Enhydra lutris) was decimated by hunting for its fur. Its populations have since recovered over much of the range, including parts of western Vancouver Island. Although no longer hunted, sea otters are still threatened by oil spills, habitat change caused by fishing, and illegal shooting by fishers who perceive that otters are eating "too many" valuable crustaceans and shellfish. Source: C. Harvey-Clark.

The pronghorn antelope (Antilocapra americana) of the western plains was severely over-hunted during the nineteenth century, and its population was reduced to about 20-thousand individuals. Fortunately, strong conservation measures were implemented, and this species now numbers more than 500-thousand, and it again sustains a sport hunt.

The trumpeter swan (Cygnus buccinator) used to breed extensively in western North America, but its populations were devastated by hunting for its meat and skin, with perhaps fewer than 100 surviving. However, this swan is now protected and has recovered in abundance, now numbering more than 24-thousand individuals.

The wild turkey (Meleagris gallopavo) was widely extirpated from its natural range by hunting and habitat loss (of course, domestic varieties are abundant in agriculture). Because of conservation measures and re-introductions to areas from which the species had disappeared, populations of wild turkeys have recovered substantially, for example in southern Ontario and Quebec. Many stocks of this large gamebird can again sustain a sport hunt.

The wood duck (Aix sponsa) was over-hunted for its beautiful feathers and as food. It also suffered from losses of habitat due to lumbering and wetland drainage. The recovery of the wood duck has been aided by the widespread provision of nest boxes in wetlands used by this cavity-nesting species. Nest-box programs also benefit several other relatively uncommon cavity-nesting ducks, particularly the hooded merganser (Lophodytes cucullatus) and common goldeneye (Bucephala clangula). An unrelated program of providing terrestrial nest-boxes has helped to increase the abundance of eastern and western bluebirds (Sialia sialis and S. mexicana), which had been declining because of habitat loss.

The American beaver (Castor canadensis) was one of the most sought-after species in the fur trade, a commercial activity that stimulated much of the early exploration of Canada and the United States. Beavers were over-harvested almost everywhere, which caused the species to be extirpated from most of its natural range. However, conservation measures and decreased demand for its fur have allowed the beaver to recover its populations over most of its range where the habitat is still suitable. In fact, they are now considered to be a "pest" in some recolonized habitats because of the flooding they cause.

The whooping crane (Grus americana) is, it is hoped, an incipient success story of conservation. The whooping crane was never very abundant (likely around 1,500 individuals), even before its populations were devastated by the combined effects of hunting, loss of its breeding habitat of prairie wetlands to agriculture, deterioration of its wintering habitat along the Gulf of Mexico, and egg and specimen collecting. These stressors drove the wild population down to a perilously small level of only 15 individuals (in 1941). Fortunately, since then, the whooping crane has been vigorously protected from hunting, while its major breeding habitat in Wood Buffalo National Park and its wintering habitat in coastal Texas have been conserved. These measures, along with a program of captive breeding and release, have allowed the population of whooping cranes to increase to more than 600 animals (in 2011; almost one-third are in captivity, 279 in the Wood Buffalo population, and the rest in newly established breeding populations in Wisconsin and Florida). There is cautious optimism for the survival of this species, although it is still endangered.

Canadian Biodiversity at Risk

The conservation status of species in Canada is assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). COSEWIC is a consultative body with expert representatives from governments (federal, provincial, territorial, and Aboriginal), universities, and non-governmental organizations. It makes recommendations to the federal, provincial, and territorial governments, whose responsibility it is to actually designate conservation status.

Once a species is listed as endangered or threatened in Canada, a parallel body known as RENEW (REcovery of Nationally Endangered Wildlife) is mandated to prepare a plan that would ensure the recovery of its population to a safer level. However, because of a lack of funding, as of 2014 only about 40 recovery plans had been completed, although many others were in various stages of development.

COSEWIC recognizes five categories of risk, each of which has a specific meaning in terms of imminent threats to the future survival of species (COSEWIC, 2015).

- Extinct refers to any species of wild life that was formerly indigenous to Canada but no longer exists anywhere in the world. Canadian examples of extinct species are the great auk (Pinguinus impennis), passenger pigeon (Ectopistes migratorius), Labrador duck (Camptorhynchus labradorium), sea mink (Mustela macrodon), deepwater cisco (Coregonus johannae), longjaw cisco (Coregonus alpenae), and eelgrass limpet (Lottia alveus). Extinct subspecies are the Queen Charlotte caribou (Rangifer tarandus dawsoni), blue pike (Stizostedion vitreum glaucum), and Banff longnose dace (Rhinichthys cataractae smithi). As of 2014, 15 Canadian taxa (species, subspecies, or distinct populations were extinct.
- Extirpated refers to any species or subspecies that was formerly indigenous to Canada but now only survives in the wild or elsewhere, usually in the neighbouring United States. Examples include the black-footed ferret (Mustela nigripes), Atlantic grey whale (Eschrichtius robustus), Northwest Atlantic walrus (Odobenus rosmarus),

greater prairie chicken (Tympanuchus cupido), pygmy short-horned lizard (Phrynosoma douglassi), paddlefish (Polyodon spathula), and blue-eyed mary (Collinsia verna). As of 2014, 23 taxa were extirpated in Canada.

- Endangered refers to indigenous species that are faced with imminent extinction or extirpation throughout all or a significant portion of their Canadian range. As of 2014, 312 taxa were considered to be endangered. Examples include the Vancouver Island marmot (Marmota vancouverensis), bowhead whale (Balaena mysticetus), right whale (Balaena glacialis), whooping crane (Grus americana), Eskimo curlew (Numenius borealis), burrowing owl (Speotyto cunicularia), piping plover (Charadrius melodus), Blanchard's cricket frog (Acris crepitans blanchardi), blue racer snake (Coluber constrictor foxii), eastern prickly pear cactus (Opuntia humifusa), small white ladyslipper (Cypripedium candidum), thread-leaved sundew (Drosera filiformis), and seaside centipede lichen (Heterodermia sitchensis)
- Threatened refers to any indigenous taxon that is likely to become endangered unless factors affecting its vulnerability are reversed. As of 2014, 167 taxa were considered threatened in Canada. Examples include the wood bison (Bison bison athabascae), sea otter (Enhydra lutris), Pacific humpback whale (Megaptera novaeangliae), marbled murrelet (Brachyramphus marmoratus), massasauga rattlesnake (Sistrurus catenatus), and American chestnut (Castanea dentata).
- Special concern refers to any indigenous species that is not currently threatened but is at risk of becoming so because of small or declining numbers, occurrence at the fringe of its range or in restricted areas, habitat fragmentation, or some other reason. As of 2014, 204 taxa or populations were considered to be of special concern. Examples include the grizzly bear (Ursus arctos), polar bear (Thalarctos maritimus), blacktail prairie dog (Cynomys ludovicianus), long-billed curlew (Numenius americanus), ivory gull (Pagophila eburnea), spotted turtle (Clemmys guttata), and eastern prairie fringed orchid (Platanthera leucophaea).

It must be recognized that the designation of species at risk is a continuing and always incomplete process. For instance, because the conservation status of only a few species of invertebrates has been investigated, endangered species in this group are enormously under-represented in the COSEWIC list. Unfortunately, more rapid progress is constrained by a shortage of funding for research and monitoring of endangered species, and by a lack of specialists with the necessary taxonomic and ecological skills and knowledge.

In addition to the work of COSEWIC, an intergovernmental group of federal, provincial, and territorial scientists is working to develop periodic science assessments of the status of Canadian biodiversity. Their most recent evaluation provides an excellent appraisal of the prospects and information needs of a wide swath of Canadian species, and is a valuable source of information (CESCC, 2014).

Of course, it is not sufficient merely to designate species as being at risk of extirpation or extinction. If their status is to be improved, the species and their habitats must also be protected. Remarkably, governments in Canada have not yet enacted effective legislation to protect endangered species and their habitat. However, this situation is starting to change. In 2002, the Government of Canada passed a Species at Risk Act, which provides some protection for species occurring on federal lands and otherwise within federal jurisdiction.

However, the federal legislation has little direct influence on the status of the many species-at-risk that are living on provincial, territorial, Aboriginal, or private land. Most importantly, the Act does not fully address the protection of habitat of endangered species off federal land. To some degree, this deficiency is covered by legislation that has been enacted by provinces and territories. However, their legislations are also not very effective, because they too do not specifically protect the habitat of species at risk, especially on private land. Such a piecemeal approach results in uneven levels of protection for species-at-risk, which is unacceptable from the conservation viewpoint.

The lack of effective protection of species-at-risk in Canada is raising controversy. Governments feel the need to demonstrate that they are making rapid progress toward sustainability, an important component of which involves the protection of native species and their habitats. Unfortunately, the progress to date has been lacking and is not yet effective in protecting our endangered biodiversity. Hopefully, the lobbying efforts of Canadian non-governmental organizations will result in appropriate changes to the currently weak legislation of all levels of government. Key national organizations in this regard are Nature Canada, Canadian Parks and Wilderness Society (CPAWS), Ecojustice, and World Wildlife Fund-Canada (WWF).

Some of the natural ecosystems of Canada now exist only as small remnants of their former extent. Because of this, they are as endangered as the species they support. The most endangered of our natural ecosystems are (see also Chapter 8):

- the tall-grass prairie of southwestern Ontario and southeastern Manitoba
- Carolinian forest of southern Ontario
- dry coastal Douglas fir and Garry oak forest types of southwestern British Columbia
- semi-desert of southeastern British Columbia
- various kinds of old-growth forest in all parts of forested Canada, but particularly in the east
- and many kinds of freshwater wetlands

Some of these ecosystems, particularly the tall-grass prairie and Carolinian forest, are also rich in endangered species. It is imperative that the remaining areas of these endangered ecosystems become preserved in parks and other kinds of protected areas.

Protected Areas

Protected areas are parks, ecological reserves, and other tracts of land or water that have been set aside from intensive development to conserve their natural values. The intent is usually to protect representative examples of widespread communities or ecoscapes, threatened ecosystems, or the habitat of endangered species. However, many protected areas also support human activities that do not severely threaten the ecological values that are being conserved. Such activities may include ecotourism, other kinds of non-consumptive outdoor recreation (such as skiing and golf), spiritual activities, education, scientific research, and sometimes even exploitative activities such as hunting, fishing, trapping, or timber harvesting (see Environmental Issues 27.1).

It is important to understand that protected areas should not be regarded as the only, or even as the most important way to conserve endangered species and ecosystems. To the degree possible, native species and other natural values should be accommodated in all areas that people are using for economic purposes, such as for agriculture, forestry, fishing, or mining. The role of protected areas is to ensure that species and ecosystems that are at risk in those “working” areas still have suitable refuges where they can maintain themselves.

Ideally, a national system of protected areas in Canada would involve lands and waters controlled by federal, provincial, and territorial governments, Aboriginal groups, and private interests. A perfect system would be designed to sustain all native species and natural ecosystems over the long term, including terrestrial, freshwater, and marine systems. To ensure that all elements of native biodiversity are adequately represented within a system of protected areas, all species and ecosystem types in the country or province must be identified, their abundance or extent determined, and their critical stressors understood. This information would allow all aspects of natural-ecological heritage to be accommodated within a comprehensive system plan for a network of protected areas.

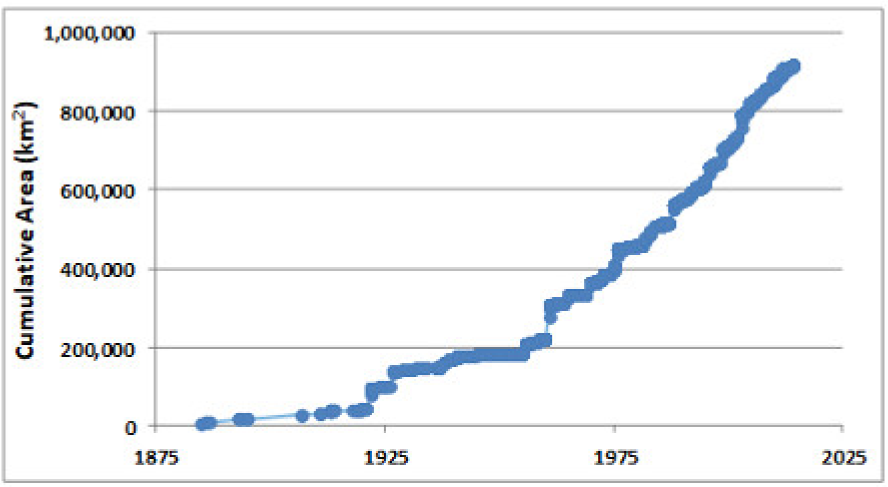
Of course, these are ideal criteria, and no country has yet designed and implemented a comprehensive network of protected areas that sustains all native species and natural ecosystems. Moreover, most existing protected areas are relatively small and are threatened by stressors originating within their boundaries or by degrading influences from the surrounding area. Because of these and other problems, it is doubtful whether many of the smaller protected areas will be able to sustain their present ecological values over the longer term. This will be especially true if a major environmental change occurs, such as global warming or a catastrophic disturbance (such as a devastating wildfire or disease epidemic).

The International Union for the Conservation of Nature (IUCN) recognizes six categories of protected areas (see Global Focus 27.2). In 2011, there were about 161-thousand terrestrial protected areas in the world, representing as much as 15% of the global land area (Protected Planet, 2015). There are many fewer marine protected areas, about 7-thousand and covering only 1% of the oceanic surface. Each year, however, additional protected areas are added to the tally, including in the marine realm, for which such initiatives are recent compared with the terrestrial realm.

Protected Areas in Canada

National parks, provincial parks, and similar places are the largest and most important protected areas in Canada. A summary of areas protected in Canada is provided in Figures 27.3 and 27.4. Note that the nationally protected area of about 10% is smaller than recommended by many conservation scientists, whose estimates range from 15-40% of the landmass.

Figure 27.3. Protected Areas in Canada. The data are the cumulative sums over time. The terrestrial protected areas cover 10.4% of the land area of Canada, and 0.9% of the marine area under our national jurisdiction (in 2013). Source: Data for (a) are from CCEA (2015) and for (b) from Environment Canada (2015b).



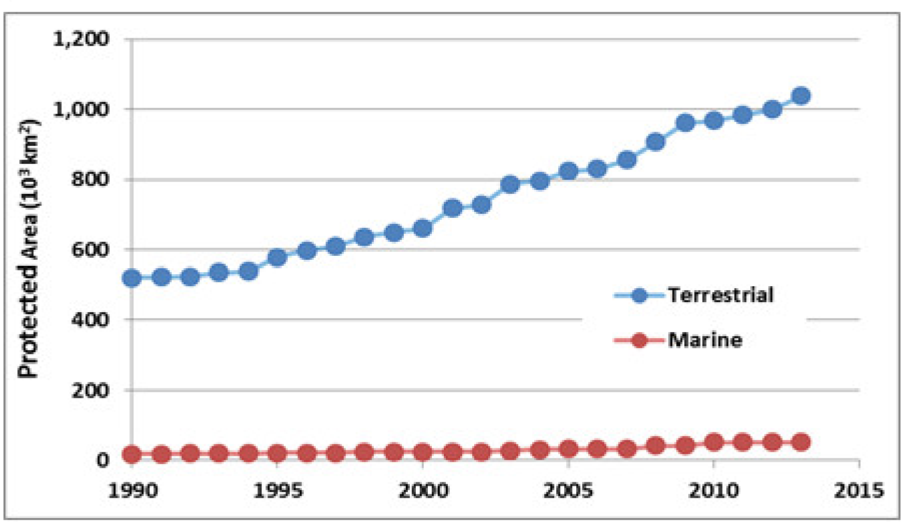
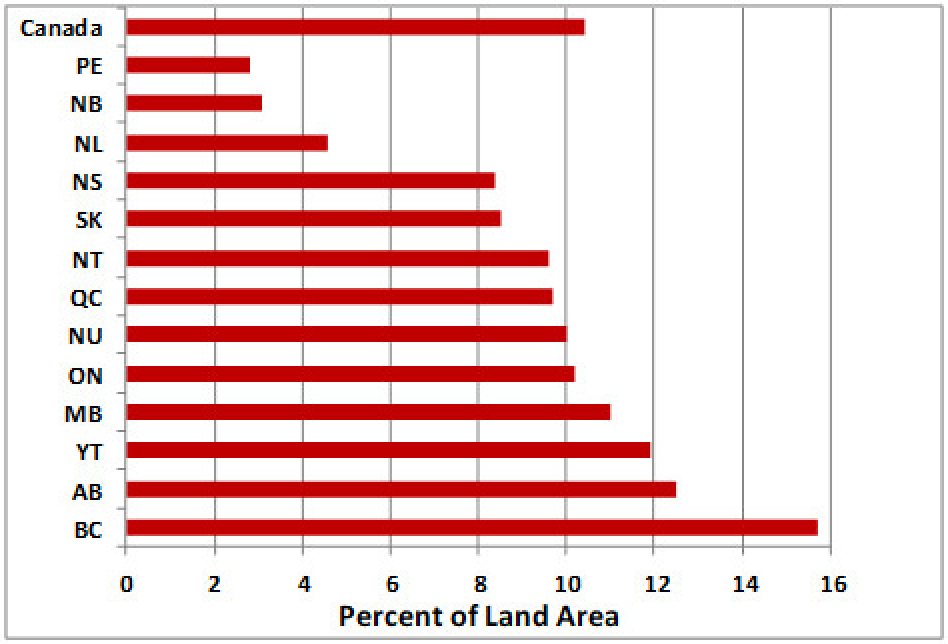


Figure 27.4. Protected Areas in the Regions of Canada. Source: Environment Canada (2015b).



In addition to their primary goal of conserving biodiversity, most parks serve additional purposes, including the support of economically important outdoor recreation and tourism. To some degree, the use of parks for these purposes is a challenge to their ability to function as ecological reserves. For example, strictly interpreted, the ecological values of national parks are not compatible with consumptive uses of their natural resources (such as sport fishing) or with the development of infrastructure to support recreation and tourism (such as campgrounds, golf courses, hotels, roads, ski facilities, and even interpretation facilities).

The ecological-reserve function of many protected areas is also threatened by land-use and management activities that are occurring in their surrounding area. Usually, the most important of the “external” stressors are associated with agriculture, forestry, mining, tourism, or hydroelectric development. In fact, all of the national parks in more southern regions of Canada are significantly threatened in this way. We can illustrate this problem with several well-known examples.

- Point Pelee National Park is a small, 15.5 km^2 park in southwestern Ontario. It contains some of the most important remnants of natural habitat left in the Carolinian zone (Chapter 8), most of which has been converted into agriculture or urbanized land-uses. Consequently, Point Pelee supports populations of many endangered species and ecological communities. However, this small park is used intensively for outdoor recreation, including birding, boating, hiking, and picnicking on its beaches. To support these culturally and economically important activities, much of the limited area of the park is maintained as paved roads, pathways, parking lots, campgrounds, information centres, lawns, and other land-uses that do not enhance the protection of ecological values. Moreover, the area next to the national park is almost entirely converted into agricultural lands, such as onion fields established on drained marshes, or into cottage and motel developments that support tourism. These land-uses have isolated the relatively natural ecosystems of Point Pelee, to the degree that it is an ecological “island” that is surrounded by incompatible uses of the landscape. For these and other reasons, the park is losing some of the natural features it is trying to protect. For example, it has lost 10 of its original 21 species of reptiles, and 6 of 11 amphibians. Some of its habitats are being badly degraded by invasions of alien plants (such as garlic mustard, Alliaria petiolata), which crowd out native species. In fact, 37% of the vascular plants in the park are non-native.
- Fundy National Park in New Brunswick is a similar case, although its ecological values are not as severely

threatened as those of Point Pelee. Fundy has an area of 206 km^2, but park ecologists believe that this is not large enough to sustain viable populations of certain wide-ranging species, such as black bear, pine marten, and pileated woodpecker, or certain natural ecosystems such as old-growth forest. To some degree, these and other natural values are being compromised by the development of tourism facilities within the park, including campgrounds, a golf course, a swimming pool, interpretive facilities, and extensive lawns and roads. Also important are industrial activities in the area surrounding the park, where forestry interests are extensively converting the natural forest into faster-growing conifer plantations
- Banff National Park in southwestern Alberta was the first national park to be established in Canada, in 1885. The original intent was to protect extremely scenic viewscapes and hot springs and to develop the area in support of the economic benefits of tourism. It was not until several decades later that the philosophical underpinning of national parks shifted toward the protection of natural values. In any event, the early development of Banff featured the enthusiastic construction of large hotels, golf courses, skiing facilities, major highways, a transcontinental railroad, several villages, and other structures. This pattern continues today with much ongoing construction, coupled with rapid development of the area east of the park for tourism, residential neighbourhoods, forestry, and other uses. These facilities severely threaten the long-term viability of the natural values of Banff. This economic development is engendering intense controversy and has been the subject of a commission of enquiry (see Environmental Issues 27.1).

Provincial and territorial governments also have a responsibility to protect natural values within their jurisdiction. These governments have designated many ecological reserves and wilderness areas, supplemented by natural areas that are protected in provincial parks and conservation areas, which are also well-used for recreation. Some municipalities also have natural-area parks that provide habitat for native species. An outstanding example is the city of Windsor, Ontario, which is protecting important remnants of tall-grass prairie and Carolinian forest, and their many species-at-risk.

Some environmental non-governmental organizations (ENGOs) are also active in the protection of natural areas. At the national level, the Nature Conservancy of Canada is the ENGO that most actively protects land to conserve its biodiversity, usually by purchasing or accepting donations of private property or land-use rights (see Canadian Focus 27.2). Ducks Unlimited Canada plays a similar role, but with a focus on wetland habitat. At provincial and more local levels, many private land trusts are also protecting natural areas.

Additional national ENGOs also play important roles in protecting the biodiversity of Canada. Prime examples include the Canadian Parks and Wilderness Society, the Canadian Wildlife Federation, Nature Canada, the Sierra Club, and the World Wildlife Fund (Canada). However, these organizations mostly do this work through advocacy – they lobby governments and the private sector to pursue more effective biodiversity agendas. They also engage in public campaigns and conduct research toward those ends. WWF-Canada, for example, was the prime mover behind the Endangered Spaces Campaign, which was effective in convincing governments to preserve representative areas of natural ecosystems within protected areas. The Canadian Council of Ecological Areas is an association of conservation experts in government, ENGOs, and universities, who are working toward a strategic plan for a national system of protected areas.

In spite of the diverse conservation-related activities of governments and private organizations, the existing network of protected areas is highly incomplete. There are four reasons for making this statement:

1. the full breadth of Canada's natural heritage is not yet represented in protected areas
2. there are many species at risk in Canada, many of which will have to be protected in ecological reserves that do not yet exist
3. most of the existing protected areas are too small to protect their ecological values over the long term
4. where species- and communities-at-risk occur in “working” landscapes outside of protected areas, their special

needs for critical habitats are often not being met

The third is important because small areas cannot usually sustain viable populations of some species of wildlife over the long term, even if they are protected. Small reserves also cannot sustain the ecological conditions that are required for certain communities to persist, especially old-growth forest. In such cases, a protected area must be managed within the context of its surrounding landscape as a single, integrated ecosystem. Management activities in such greater protected areas should be designed to ensure the long-term viability of populations of species at risk, as well as natural communities at risk.

> Environmental Issues 27.1. Ecological Integrity in the Bow Valley In 1885, Banff was the first national park to be proclaimed in Canada. Banff is also the most famous of our national parks, because of its spectacular scenery, easily viewed large animals, and superb infrastructure supporting world-class tourism and outdoor recreation. These values attract visitors from across Canada and many other countries.
>
> Banff National Park covers a large area (6,640 km^2) and thus plays an important role in protecting the natural ecological values of its region. This is enhanced by the fact that Banff is bordered by several other protected areas, namely Jasper, Yoho, and Kootenay National Parks and Peter Lougheed Provincial Park, which collectively comprise an area of 26-thousand km^2.
>
> Most of the native species and natural ecosystems of Banff are well protected within its boundaries and in surrounding lands. Some others, however, are not. These natural values are threatened by a variety of stressors, some of which exert their influence within the park while others make themselves felt outside its boundaries.
>
> Banff hosts more than 3 million tourists each year, generating more than $6 billion in economic activity. To service its many visitors, the park contains hotels, lodges, and campgrounds. To provide the tourists with interesting things to do, and to generate revenue and local employment, the park contains ski hills with associated lifts and lodges, golf courses, an extensive network of roads and trails, interpretation facilities, and two full-service settlements with more than 8-thousand residents – the villages of Banff and Lake Louise. In addition, the Canadian Pacific Railway passes through Banff, as does the Trans-Canada Highway. These various facilities are developed especially intensely in the so-called Banff-Bow Valley corridor, a region that encompasses the major transportation routes through the park as well as the main tourist areas.
>
> The tourism- and transportation-related infrastructure in the Banff-Bow Valley corridor provides support for big-business tourism and the national system of ground transportation. However, these facilities are stressors to the natural values of the park. In fact, local populations of grizzly bear, timber wolf, and other wide-ranging species are at risk in the greater Banff region, mostly because they suffer unsustainably high death rates. The mortality is a result of collisions with vehicles on the highways and railroad, hunting outside of but close to the park, and the killing of "problem" bears that become habituated to people near campgrounds and frequently used trails. One study of grizzly bears found that 90% of their deaths in Banff occurred within 0.5 km of human infrastructure, and only 2 of 73 deaths were due to natural causes. In addition, the wilderness values of extensive areas have become degraded by visual and noise pollution associated with traffic, highways, railroads, ski lifts, buildings, and large numbers of people.
>
> The various environmental challenges to the ecological integrity of Banff National Park are an increasingly serious problem. A Task Force of five independent experts, appointed by Parks Canada, studied these challenges (Page et al., 1996). The Task Force was given three objectives:
>
> 1. to develop a vision for the region that would integrate ecological, social, and economic values
> 2. to undertake an analysis of existing information, and to provide direction for monitoring programs
> 3. to recommend changes that would allow the Banff-Bow Valley region to be used for sustainable tourism and

recreation industries, while also protecting its heritage of ecological values

The Task Force reviewed a wealth of existing information, commissioned original research, and engaged in public consultations. Its final report concluded that intensive economic development in the Banff–Bow Valley region was quickly approaching an unsustainable level, and this was threatening the ecological integrity of the national park. The Task Force made numerous recommendations for specific actions and policies that would help to deal with the intensifying crisis. It strongly advised that the pace and intensity of development be strictly controlled, and in some cases reversed. In essence, the Task Force reasonably concluded that Banff National Park can be an effective protected area only if its use by people is kept within sustainable bounds.

The Task Force report was favourably received by the then-minister responsible for Parks Canada, who declared that all of its major recommendations would be followed. If this was to happen, however, Parks Canada had to take firm action against powerful economic interests that are determined to increase the amount of recreation and transportation infrastructure in the Banff-Bow Valley corridor. Since then, however, subsequent ministers and senior administrators in Parks Canada have not had the fortitude to resist many of the compelling calls for additional "development", and so Banff National Park is not yet being managed in ways that make its ecological integrity the bottom line, rather than additional economic development.

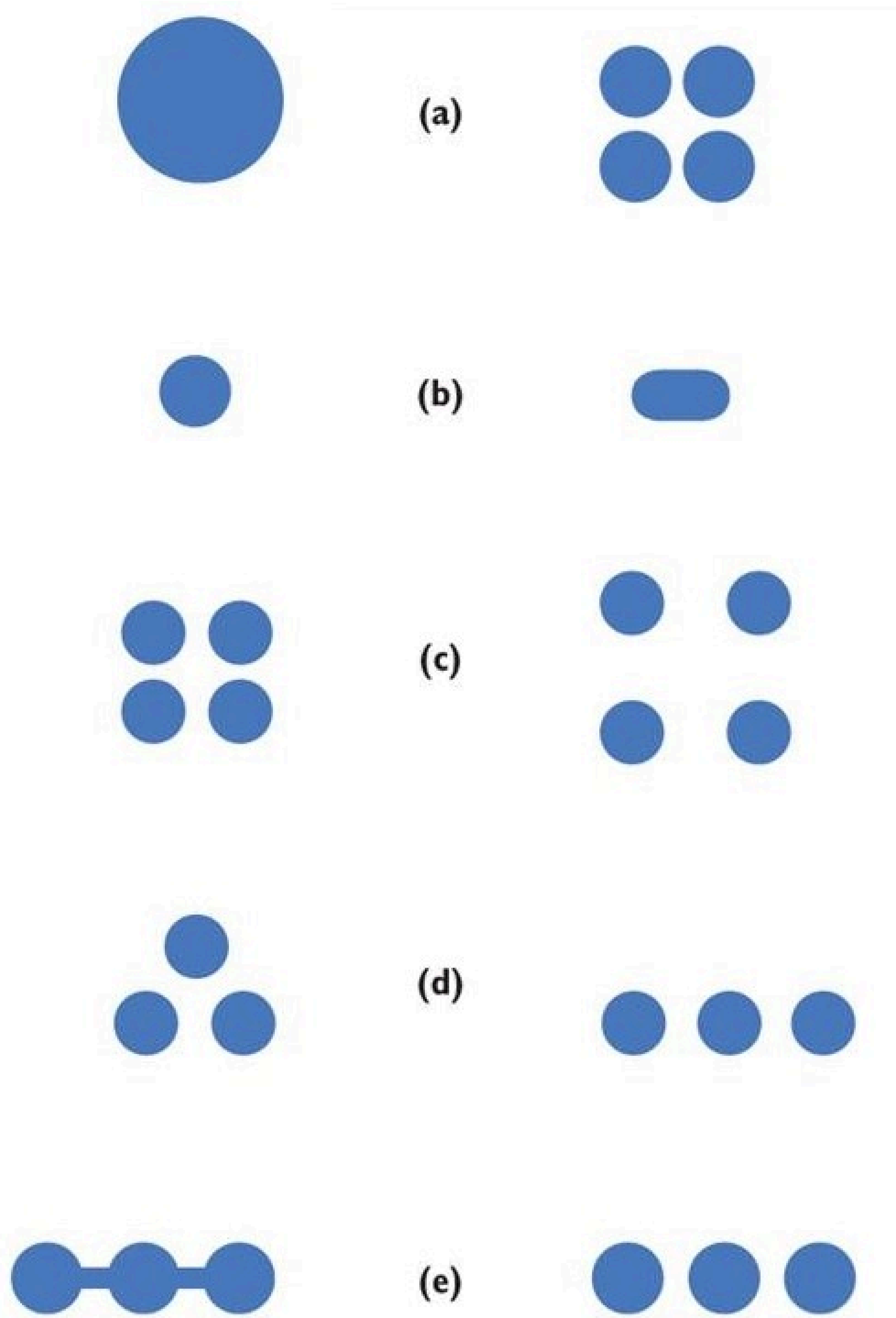
Design and Stewardship

The design of protected areas is an important field of research in conservation biology. The essential questions involve ways of determining the best size, shape, and positioning of protected areas in order to optimize their ability to protect biodiversity, while using limited funding as efficiently as possible. The least controversial recommendations of conservation biologists are that ecological reserves should be as large and as numerous as possible. Other aspects of the design of protected areas are being actively debated, and the discussion will not be resolved until more research is undertaken. These aspects of reserve design include the following:

- The choice between size and number of protected areas: Is it preferable to have one large reserve or several smaller ones with the same total area (Figure 27.5a)? Conservation biologists identify this question with the acronym SLOSS, for single large or several small. According to ecological theory, a population in a larger reserve is expected to have a lower risk of local extinction compared with one in a smaller area. However, if separate populations occur in different reserves (even if they are relatively small), the redundancy might protect against catastrophic loss of an endangered species in a larger reserve (even if it is relatively large).
- Larger reserves have more interior habitat: So-called "interior" habitat is not influenced by environmental conditions that occur at an ecotone (or a transition between habitat types, such as a forest edge). Ecotonal habitats may be penetrated by invasive species, predators, and parasites (such as cowbirds), which can be an important problem in protected areas. In addition, many species require interior habitat for successful breeding. Larger reserves have proportionately more interior habitat, a factor that contributes to the conservation of interior species (Figure 27.5a).
- Reserves should be clumped: Similar reasoning suggests that it is better to aggregate reserves than to arrange them in a linear fashion. This would reduce the average distance between protected areas, which may enhance their ecological connections (Figure 27.5d).
- The role of corridors: A system of reserves connected by corridors of suitable habitat may provide better opportunities for gene flow and re-colonization after extirpation (Figure 27.5e). Admittedly, however, corridors might also make it easier for diseases and invasive species to spread among reserves.
- Circular reserves are better: A circle has a smaller ratio of edge to area than any other two-dimensional shape. To avoid extensive edge habitat in the design of a protected area, a roughly circular shape may be preferable (Figure 27.5b).

- Reserves should be close together: If a population is extirpated in a protected area, the chances of natural re-colonization may be improved if the species survives in a nearby reserve. Consequently, it may be better to have unconnected reserves arranged relatively close to each other, rather than far apart (Figure 27.5c).

Figure 27.5. Design of Protected Areas. This figure summarizes basic principles of conservation biology for the design of protected areas. In each comparison, the design on the left is better than the one on the right (the total areas are assumed to be the same). See the text for additional explanation. Source: Modified from Simberloff (1988).



It is important to understand that the stewardship of biodiversity requires much more than a simple declaration that a tract of natural area is henceforth to be considered "protected." The ecological integrity of the reserves must also be monitored and management may be necessary to conserve any threatened values. For example, if a protected area supports a population of an endangered species, its abundance and habitats should be monitored. If any decline is observed, the environmental causes should be determined by research, and then, if possible, be mitigated to prevent or repair the damage. Management activities can include, among other actions, patrols to prevent the poaching of animals or timber, modification of habitats to keep them suitable for species at risk, and even captive breeding and release of endangered species.

Considered together, these stewardship actions represent an integrated program of monitoring, research, and management. The application of such a system can be illustrated by the case of the endangered Kirtland's warbler (Dendroica kirtlandii). Monitoring has shown that this rare bird has declined in abundance, and its global population is now only a few hundred breeding pairs. Research has revealed that its only breeding habitat consists of jack pine (Pinus banksiana) stands of a particular age and structure. Many such stands have now been protected in the breeding range of the warbler. However, as these stands get older, they are no longer suitable as breeding habitat. Consequently, management is actively developing appropriate breeding habitat by prescribed burning and the planting of jack pine. Additional research has shown that the endangered warbler is heavily parasitized by the brown-headed cowbird. Consequently, cowbird populations are being controlled in the breeding habitat of the warbler. Further research and monitoring are being directed to the environmental stressors that affect the warbler during its little-known migrations and on its wintering range. Of course, these integrated activities of monitoring, research, and management must continue as long as Kirtland's warbler remains endangered.

> Canadian Focus 27.2. The Nature Conservancy of Canada Governments throughout Canada have created many protected areas, but their actions are almost exclusively on so-called Crown land, which they already own. However, many of the most important properties of conservation value are privately owned by individuals or corporations. This is particularly the case of southern regions of Canada, where most species-at-risk and endangered ecosystems occur. Because of a lack of money and other priorities, governmental agencies are often reluctant to secure ecologically important habitat on privately owned lands. For this reason, conservation charities known as land trusts have formed for the purpose of raising funds to acquire private property in order to establish protected areas.
>
> At the national level, the largest of these organizations is the Nature Conservancy of Canada (NCC). The focus of NCC is on acquiring private property of high conservation value, which it does by purchasing or accepting donations of real estate, as well as rights of land-use. The latter involves a kind of private property called a conservation easement (or in Quebec, a servitude). If owned by NCC, a conservation easement can prevent current and future owners of the real estate from converting its natural habitat into residential lots or cultivated agriculture, or from engaging in other proscribed activities that might threaten the natural values of the property. There are many other land trusts that operate at local and provincial scales that also acquire private conservation lands and easements. However, NCC is the only national organization, and it is by far the biggest.
>
> Since its origin in 1962, NCC has contributed to the protection of 1.1-million hectares of natural habitat throughout Canada (Freedman, 2013; NCC, 2015). In 2013-14, NCC raised (and spent) more than $87 million to advance its conservation mission. In 2012, it met the goals of its five-year "Force for Nature" fund-raising campaign, which raised more than $546 million, from the private sector and all levels of government. More than 62-thousand Canadians contribute annually to support the work of NCC.
>
> The conservation actions of NCC are being guided by "ecoregional plans", also known as "conservation blueprints", which help to identify the most important places where private action can make the greatest difference in protecting native species and natural ecosystems. These plans are developed in close partnership

with governments, the U.S. Nature Conservancy, Ducks Unlimited Canada, provincial and local land trusts, industrial interests, and academic scientists. As of 2015, NCC had completed 15 “ecoregional plans”, all for southern parts of Canada, which are the most imperiled from the conservation perspective. Eventually, NCC intends to have ecoregional plans for all regions of Canada. The results of the plans are used to identify focal areas for land assemblies – there are now 77 of these key areas for action, which NCC refers to as “Natural Areas,” each of which is the focus of a “Natural Area Conservation Plan.”

Successful conservation action requires more than just acquiring properties – each project must also be properly stewarded to maintain or enhance its natural values. Stewardship actions range from posting signs at property boundaries, to innovative, science-based management actions that are needed to sustain particular species or ecological communities.

For example, NCC routinely subjects its tall-grass prairie reserves in southeastern Manitoba to prescribed burns, which prevents the endangered grassland from being degraded by incursions of shrubs and trees. At NCC reserves that protect imperiled Garry oak forest on southern Vancouver Island, stewardship volunteers spend many hours pulling alien weeds that threaten rare plants. One last example involves a protected area of rare Carolinian forest at Clear Creek in southern Ontario, where NCC is converting adjacent cornfields into natural forest in order to increase the size and enhance the viability of the conserved ecosystem. These kinds of stewardship activities must be advised by leading-edge scientific knowledge, which NCC develops by hiring ecologists and by working in partnership with other organizations.

The Nature Conservancy of Canada is only one example of the many highly motivated and effective non-governmental conservation organizations in Canada. Their work is crucial to sustaining the biodiversity-at-risk of our country. Of course, being charities, private organizations like NCC can only spend money that they can manage to raise, which is a good reason for all sectors of our society to support their important work of protecting natural habitats.

International Conservation

The conservation of wild species of plants and animals is now regarded by almost all societies as a worthwhile and important objective. As a result, in most countries, many people are becoming active in support of conservation. Evidence of these hopeful changes includes the fact that governments are becoming more engaged in the conservation of indigenous and global biodiversity, while large numbers of non-governmental organizations are becoming active at local, national, and international levels. In addition, more ecologists and other scientists are conducting biodiversity-related research and training in universities and other institutions. Most importantly, many citizens are working hard to conserve biodiversity, either by taking direct action on their own property, or by supporting the worthwhile initiatives of ENGOs, private companies, and governments.

All of these activities contribute to the greater agenda of biodiversity conservation, particularly by doing the following:

- identifying and protecting the habitats of rare and endangered species and communities, while also conserving representative areas of natural ecosystems
- working to control the illegal trade in the products of endangered species, such as elephant ivory, rhino horn, bear gallbladders, tiger bones and hides, and wild ginseng (see Global Focus 27.1)
- increasing the awareness of people about biodiversity issues and the need to conserve all species, ecosystems, and ecological sevices
- conducting necessary research into the biology and ecology of endangered species and ecosystems
- raising or providing funds for all of the above

Not surprisingly, the intensity of these conservation activities is greatest, and increasing most quickly, in relatively wealthy countries, such as Canada. Those countries can more easily afford to allocate significant funding and personnel to this worthwhile cause. Increasingly, however, signs of awareness of the importance of biodiversity issues, and actions to conserve those values, are also rapidly developing in less-developed countries. This reflects changes in the attitudes of people and governments and is reinforced by lobbying and funding provided by domestic and international aid agencies and ENGOs. These changes are critically important because a large fraction of Earth's threatened biodiversity occurs in tropical, less-developed countries.

Of course, a respect for nature has always been an integral component of major religions that developed in tropical countries, such as Buddhism, Hinduism, Jainism, and Taoism. Nevertheless, this respect has not necessarily been translated into a real-world conservation ethic among the peoples of those or any other nations. As a result, wildlife and natural habitats have suffered badly, mostly as a result of the extensive conversion of natural ecosystems into agricultural ones, but also from timber harvesting and other ways as well.

It is beyond the scope of this book to describe the many international agencies and organizations that are active in the protection of global biodiversity. Some of the most important of them are Conservation International, the International Union for the Conservation of Nature (IUCN), The Nature Conservancy (U.S.), the United Nations Environment Programme (UNEP), the World Resources Institute, the World Wildlife Fund, and the Worldwatch Institute. These organizations are active in conservation advocacy, in protecting species and natural habitat, in education and lobbying, in research and monitoring, and in raising funds for the protection of biodiversity.

To illustrate the rapid development of international conservation activities, we can examine a program known as the Global Biodiversity Strategy (Reid et al., 1992). This is a joint program of the International Union for the Conservation of Nature, the World Resources Institute, and the United Nations Environment Programme. Its broad objectives are to maintain essential ecological processes and life-support systems on Earth, to preserve biodiversity, and to ensure the sustainable development of natural resources. Although these are rather general goals, they are important because they link the conservation of biodiversity with the sustainable development of the human economy. One cannot occur without the other, a fact that must be acknowledged by any governments or agencies that support the Global Biodiversity Strategy.

Through this initiative, all nations can initiate meaningful actions to conserve and protect their biodiversity for the benefit of present and future generations of people, as well as for reasons of intrinsic value. To achieve this end, 85 specific actions are recommended for implementation by nations that have committed to the Strategy. The following five actions are considered essential:

1. ratification and implementation of the recommendations of the Convention on Biological Diversity, as presented in 1992 by UNEP at the United Nations Conference on Environment and Development, held at Rio de Janeiro, Brazil (the "Earth Summit")
2. implementation of the actions detailed in the Global Biodiversity Strategy, with a focus on efforts to conserve and protect the indigenous biodiversity of signatory nations
3. creation of an international administrative mechanism to ensure broad participation in decisions concerning global biodiversity, with representation from governments, the scientific community, citizens, industry, the United Nations, and non-governmental organizations
4. establishment of an international network, linked to the Convention on Biological Diversity, to monitor threats to biodiversity so that individuals and organizations can be alerted and take appropriate actions
5. integration of biodiversity considerations into planning processes for national development

The Convention on Biological Diversity is now the leading international treaty to advance the conservation of biodiversity, within the context of a comprehensive agenda for sustainable development (UNEP, 2015). The three key goals of the Convention are the conservation of biodiversity, the sustainable use of its components, and the equitable sharing of benefits from the use of genetic resources. The 194 ratified parties to the Convention are engaged in various co-operative initiatives and information and technology sharing, and are committed to identify and conserve their biodiversity.

A key action is to periodically undertake science assessments of the status of global biodiversity (SCBD, 2015). Broadly speaking, the most recent assessment found that the prospects of biodiversity were rapidly worsening in many parts of the world, although considerable progress was being made in co-operative planning and in the designation of protected areas and other conservation measures in many countries.

It is too soon to tell whether these international actions will be successful because the programs began only in the late 1970s (as an earlier program called the World Conservation Strategy). However, it is encouraging to know that this sort of comprehensive international effort exists and that almost all of Earth's nations are participating, including countries in all stages of economic development. Of course, it remains to be seen how effective the individual and collective actions will be. This is substantially because, although environmental and biodiversity issues are extremely important to sustainability of the human enterprise, their resolution does not yet have much political traction in many countries, including in Canada

Conclusions

If Earth's resources are to be used by people on an ecologically sustainable basis, rare and endangered species and threatened natural ecosystems must be protected. Clearly, an international program like the Global Biodiversity Strategy is needed to guide the process of sustainable development.

The modern predicament of extinction and endangerment of biodiversity is a critical element of the global environmental crisis, and its resolution is a key aspect of ecologically sustainable development of the human economy. Hopefully, the increasing intensity of conservation activities worldwide will be sufficient to turn the tide, so future generations will regard these ongoing actions as a "success story" of global conservation. Any alternative result would be catastrophic and tragic.

> The one process . . . that will take millions of years to correct is the loss of genetic and species diversity by the destruction of natural habitats. This is the folly that our descendants are least likely to forgive us. E.O. Wilson (cited in Reid et al., 1992)

Questions for Review

1. What are the greatest modern threats to global biodiversity?
2. What are the greatest threats to the native biodiversity of Canada?
3. List five examples of species that became extinct at any time during the past 500 years, and explain why they were lost.
4. List five examples of species that were endangered but have since recovered, and explain why this happened.

Questions for Discussion

1. How are the products of biodiversity important in your life? Compile a list of ways in which you routinely use products of biodiversity in your daily routine, such as foods, materials, and medicines. Are there substitutes for

these uses?
2. Do you know of any species that are rare or endangered in the region in which you live? Find several examples, and identify the habitat needs of those species. Do you think that these rare or endangered species are being adequately protected? What more could be done? How can you help?
3. Find several examples of endangered spaces (endangered ecosystems) in your region and decide whether they are being adequately protected. What more could be done? How can you help?
4. We learned in this chapter that the greatest modern threat to Earth's biodiversity is deforestation in tropical countries. Can you think of ways in which Canadians are economically linked with deforestation in the tropics? For example, do Canadian consumers provide a demand for tropical-forest products? Do Canadians hold some of the foreign debt of tropical countries? How might these circumstances contribute to tropical deforestation?
5. Everyone can help to protect endangered species and spaces. List some of the ways in which you can contribute to solving the problems of endangered biodiversity in the region where you live, in Canada, and internationally.

Exploring Issues

1. Your provincial government has committed itself to ensuring that its indigenous biodiversity will be conserved. Your services have been retained to provide advice on how to accomplish that goal. What would you tell the government to do in order to identify and conserve its indigenous species and ecosystems?

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PART VI: ECOLOGICALLY SUSTAINABLE DEVELOPMENT

Chapter 28 ~ Ecologically Sustainable Development

Key Concepts

After completing this chapter, you will be able to:

1. Outline the process of an environmental impact assessment, and describe several Canadian examples.
2. Discuss how monitoring and research are necessary to understanding the causes and consequences of environmental damage.
3. Explain how environmental reporting and literacy are crucial to dealing with the environmental crisis.
4. Outline the roles of governments, non-governmental organizations, scientists, and citizens in designing and implementing an ecologically sustainable economy.

Introduction

The previous parts of this book allowed us to learn the subject matter of environmental science by examining key ideas and by analyzing a body of supporting information. In this final chapter, we bring many of these topics together in an interdisciplinary fashion.

In the first sections of the chapter, we will examine topics related to environmental management and protection at the broader societal level. These topics include environmental impact assessment, monitoring and research, environmental literacy, and sustainability. All of these are necessary for maintaining an acceptable level of environmental quality and healthy ecosystems—two necessary objectives for a truly sustainable socio-economic system. We will also examine a range of actions that each of us can undertake to help resolve environmental problems.

In the concluding section of this chapter, we will briefly discuss the future prospects for advanced economies, such as that of Canada, and for spaceship Earth.

Environmental Impact Assessment

An environmental impact assessment (EIA) is a planning process that is used to help prevent environmental problems. Environmental impact assessments do this by identifying and evaluating the potential consequences that a proposed development may have for environmental quality. Because it can consider ecological, physical-chemical, and other environmental effects, as well as socio-economic consequences, an EIA is a highly multidisciplinary and interdisciplinary activity.

An EIA may be conducted to examine various kinds of activities, or planned developments, that could affect environmental quality, such as the following:

1. an individual project, such as a proposal to construct an airport, dam, highway, incinerator, mine, or power plant
2. an integrated scheme, such as a proposal to develop an industrial park, a pulp or lumber mill with its attendant wood-supply and forest-management plans, or other complex developments that involve numerous projects
3. a governmental policy that carries a risk of substantially affecting the environment

The scale of an environmental assessment can vary greatly, from the examination of a relatively small proposal to construct a building near a wetland, to a megaproject associated with natural-resource development.

In Canada, environmental impact assessments for proposals that involve federal funding or jurisdiction are regulated under the Canadian Environmental Assessment Act (CEAA), which was enacted in 1992. The Act is a law that requires federal decision makers, referred to as "responsible authorities," to consider the predicted environmental effects of a proposed project before it is allowed to go ahead. If significant adverse effects are predicted, the project is not allowed to proceed until the damages have been addressed by a change in design or through some other mitigation.

Initially, the CEAA required that EIA studies be done on a wide range of projects involving jurisdiction of the federal government. However, in 2012 the Act was greatly weakened by requiring that only big projects are considered (CEAA, 2013). Provinces and territories also have legislated requirements for EIA, as do some local levels of government, such as municipalities and First Nations.

EIA is based on the reasonable premise that all proposed projects, programs, and policies carry risks for human welfare and for other species and ecosystems. For example, a proposed project may emit toxic chemicals into the environment. In such a case, it is necessary to determine if the anticipated emissions might exceed the regulated levels. The most stringent standards and guidelines are related to the maximum exposures that humans can tolerate without suffering risks to their risks, while criteria to protect other species and ecosystems are less exacting. For example, the guideline for uranium in drinking water is 0.02 mg/L (Health Canada, 2008), but that for the protection of aquatic life is 40 mg/L for a short-term exposure (<1-4 days) and 5.5 mg/L for a long-term exposure (CCME, 2009).

In addition, a project might cause disturbances to natural habitats during its construction or operation, which could result in ecological damage. These effects should be identified and quantified, and the potential environmental damages evaluated, before permission is granted to start the project.

The process of environmental impact assessment is intended to predict these potential damages and to suggest ways of avoiding or mitigating them as much as possible. However, this does not necessarily mean that no damage will be caused by a proposed development. In almost all cases, some damage is inevitable.

Because most developments potentially affect a great variety of species and ecosystems, EIAs are limited to predicting the effects on only a selection of so-called valued ecosystem components (VECs). These components are valued because society perceives them to be important for one or more of the following reasons:

1. They are an economically important resource, such as an agricultural crop, a commercial forest, or a stock of fish, mammals, or birds
2. They are a rare or endangered species or ecological community
3. They are of cultural or aesthetic importance

The initial phase of the process of environmental impact assessment is known as a screening. The screening determines the level of assessment that a proposed activity will undergo, such as whether a minor review or a full assessment is appropriate. In fact, the great majority of environmental assessments in Canada are restricted to the screening level – in general only larger projects require a more extensive, comprehensive assessment. The decision about whether to proceed to a more comprehensive assessment is made by a responsible authority of the relevant level of government (such can be federal, provincial, territorial). Usually, the responsible authority is a department or agency with a mandate or experience that is relevant to the proposed project. The decision is based on the likelihood that the proposed development will cause significant adverse environmental effects, but expressions of public concern are also an important consideration.

A full EIA requires the proponent to prepare an environmental assessment report, which is a series of documents that describe the proposed undertaking, as well as studies of its likely environmental and socio-economic effects. The proponent must also inform the public of its detailed plans, which is usually done by holding meetings in local communities and making planning documents available for review by individuals and concerned organizations. For the largest projects, a review panel of experts may be appointed by the federal Minister of the Environment to hear submissions from the proponents, as well as from individuals and organizations that have been given permission to intervene in the process. Once the panel has considered all written and verbal submissions, it delivers a summary report and a list of recommendations to the responsible authority and the Minister of the Environment, who make the report public. The federal government must then decide whether to allow the development to proceed as proposed, or with required mitigations that would avoid or lessen environmental effects that are deemed unacceptable. A follow-up program may also be required, such as environmental monitoring and the mitigation of unanticipated damages.

Once the level of assessment is decided, a scoping exercise is undertaken. This identifies potentially important interactions between project-related activities on the one hand and human welfare or VECs on the other. In essence, the scoping compares the predicted spatial (space) and temporal (time) boundaries of stressors that are associated with the proposed development with the areas where people and VECs are found. If potential interactions are identified, the assessors must determine whether significant damage is likely to be caused.

Sometimes an impact assessment is not well funded or it has to be completed relatively quickly. In such cases, ecologists, sociologists, toxicologists, and other professionals may have to provide expert opinions about the likely importance of interactions between project-related stressors and human welfare or VECs. These professional opinions should be based on the best-available scientific information and understanding, while recognizing that such knowledge is incomplete and differences of opinion may arise among qualified specialists. When sufficient time and funding are available, it is possible to conduct field, laboratory, and/or computer-based (simulation) research to investigate the potential interactions identified during the screening process. It must be understood, however, that even well-funded, properly designed, and well-executed research may yield uncertain results, particularly about damage that might occur at low intensities of exposure to project-related stressors.

Planning Options

If potentially important risks to human welfare or VECs are identified, a number of planning options must be considered. There are three broad choices.

- Prevent or Avoid: One option is to avoid the predicted damage by ensuring that there are no significant exposures of people or VECs to damaging stressors related to the project. This can be done by modifying the characteristics of the project, or in cases of severe conflicts with human welfare or ecological values, by choosing to cancel it entirely. Because prevention and avoidance may involve substantial costs, they are sometimes considered to be less desirable options by the proponents of a development. Politicians and regulators may also dislike this option since it may involve intense controversy and substantial economic opportunities may be cancelled. Nevertheless, there is always public and regulatory pressure to take as many precautions as possible before undertaking a proposed development.
- Mitigation: Another option is the mitigation of any predicted damages, or to repair or offset them as much as possible. Because any direct damage to people is considered unacceptable (and therefore to be rigorously avoided), mitigation is mainly relevant to damage inflicted on VECs or to indirect, low-level risks to people. For instance, if the habitat of a valued species is threatened, it may be possible to move the population at risk to a suitable habitat elsewhere, or to create or enhance a habitat at another place so that no net damage is caused. For example, a wetland may be unavoidably destroyed by a proposed development, but the damage may be offset through the creation of a comparable wetland elsewhere. Mitigations are a common way of dealing with potential conflicts between project-related stressors and VECs. However, it is important to understand that mitigations are never

complete, and there is often residual damage.

- Accept the Damages: The third option is for decision makers to choose to allow a project to cause some or all of the predicted damages to human welfare or VECs. This choice is often considered tolerable by the proponents of a project and by politicians (although such a preference would rarely be explicitly stated). Their rationale is due to their perception that the socio-economic benefits gained by proceeding with a threatening project are likely to be much greater than the costs of environmental damage. From an environmental perspective, however, this choice might not be viewed as being acceptable, usually because the environmental "costs" are being grossly undervalued.

Environmental impact assessments generally find that a proposed development carries risks of causing some degree of environmental damage. Usually, the development is allowed to proceed in some form, with the predicted damage being avoided or mitigated to the degree that is considered technologically and economically feasible. As noted previously, however, there are always residual risks that cannot be avoided or mitigated. Any damage that does occur represents some of the environmental costs of development, which are real even if there is financial compensation or other kinds of offsets.

Once a project has begun, compliance monitoring is usually necessary to ensure that regulatory criteria for pollution or health hazards are not being exceeded. It is extremely useful, although not always required, to also monitor the ecological effects of a project. This tests the predictions of the impact assessment and identifies unanticipated effects or "surprises." Ideally, a monitoring program for ecological effects is begun before a project actually starts, in order to establish the baseline conditions. The monitoring should then continue for some years after the project is completed, until it is determined that important damage is not being caused. If unanticipated damage is shown by the monitoring, it may be prevented, avoided by an adaptive change in the project design, mitigated in some way, or accepted as an ecological "cost" of development.

Examples of Impact Assessments

EIAs have been conducted in all regions of Canada, examining projects that varied widely in both scale and potential effects. Each of these unique cases is instructive, in the sense of illustrating the environmental implications of development projects and the role played by impact assessment. In the following sections, we briefly examine selected elements of some environmental impact assessments in Canada.

Diamond Mines in the Northwest Territories

This proposal involved the development of mines to extract diamonds from five deposits discovered about 300 km northeast of Yellowknife. A variety of potential environmental damages were identified with this project. First, some of the diamond-bearing rock lies beneath lakes that would have to be drained to develop a mine. These aquatic ecosystems would be destroyed.

In addition, large amounts of gravel are needed to construct roads and other infrastructure. Much of this material would be obtained from long, sinuous features known as eskers, which provide critical denning habitat for grizzly bear, wolf, and other high-profile species.

Further, large numbers of caribou traverse the region during their seasonal migrations. These are potentially affected by the mine and its network of roads. Substantial damage to the caribou would harm the Aboriginal people in the region, who engage in a subsistence hunt for these animals. Those people might also suffer from interference with their commercial harvest of fur-bearing mammals.

Finally, the proposed mines are located in a region that was a huge, roadless wilderness. Conservationists, led by the World Wildlife Fund, objected to the approval of the mine before a system of protected areas was set up in the region for the preservation of natural ecosystems and native species, including large carnivores such as grizzly bear, wolf, and wolverine.

The diamond-mine proposal passed its environmental impact assessment and was allowed to proceed. It was subject to stringent requirements, however, such as the implementation of acceptable methods of disposal of mining and milling wastes and the protection of waterbodies and rivers (other than those that must unavoidably be damaged to develop the mines and dispose of tailings). A ban was imposed on local hunting by project personnel. As well, a monitoring program was to be undertaken to ensure that unanticipated damage is not caused to air or water quality or to wildlife. The mine must also meet socio-economic criteria, including several that deal with employment opportunities and other ways of engaging local people (including Aboriginals) in the development. As a measure outside the scope of the formal impact assessment, the government of the Northwest Territories committed to establishing protected areas in the larger region, although this has not yet been followed through in its entirety.

Destruction of Diseased Bison: Agriculture Canada proposed to slaughter almost all the bison in the southern region of Wood Buffalo National Park and its vicinity. Some of these animals are infected with bovine tuberculosis and brucellosis, and there are concerns over the potential spread of these diseases to herds of cattle to the south and west of the area. The bison targeted for slaughter are hybrids between the indigenous wood bison and plains bison that were introduced to the region during the late 1920s. The proposal did not include the elimination of small populations of genetically "pure" wood bison living farther to the north, and in fact, these were predicted to receive a measure of protection from the potentially harmful effects of interbreeding with hybrid animals.

This proposal was made in support of commercially important livestock interests, but it quickly engendered intense controversy. It was opposed by virtually all conservationists and by local Aboriginal people. Although this project successfully passed the impact assessment process, it was later suspended by the federal Minister of the Environment, largely in recognition of the intense opposition from conservation and First Nation interests.

The Hibernia Offshore Oil Development: Several decades of exploration resulted in the discovery of large reservoirs of petroleum in undersea geological formations on the Grand Banks, east of Newfoundland. An EIA examined a proposal from a consortium of companies to develop this valuable resource. A system of underwater wells was proposed that would feed to a central collecting system on a huge platform located in 80-m deep water. The petroleum would be delivered periodically to onshore refineries using tanker ships.

The offshore waters of the Hibernia field sometimes experience intense wind, and immense icebergs pass through the region during most years. Some icebergs are large enough to scour the ocean floor. These natural forces pose risks to the production and storage facilities. As well, accidents may result from equipment failure or human error. Alone or in combination, these factors could cause a massive petroleum spill. Such an accident would result in enormous damage to the fishery, to marine mammals and seabirds, and to other ecological and economic values. The Hibernia development includes a sophisticated system of weather and iceberg monitoring, coupled with stringent spill-prevention and control technologies. These measures have been accepted by regulators and politicians as providing an acceptable degree of environmental safety. Consequently, the Hibernia development passed the impact assessment process, and it began producing petroleum in 1997.

Grande-Baleine Hydroelectric Complex: Some regions of Canada have an enormous potential for the development of hydroelectricity. One area in which this renewable source of energy is being vigorously developed is northwestern Quebec. Several large rivers flowing into James and Hudson Bays have been dammed, allowing the storage of immense reservoirs of water. Electricity is generated at times when consumer demand is greatest.

The Grande-Baleine Complex was a proposal to add to the hydroelectricity capacity of Quebec by constructing three generating stations, with a total capacity of 3,212 MW, on the Grande Baleine River. The associated dams would have flooded 1,667 km^2 of terrestrial habitat. Other disturbances would have included the construction of roads and transmission lines to deliver the electricity to southern markets.

This development would have had important environmental impacts. The most critical of these was the ecological damage associated with the creation of such enormous reservoirs, including the loss of terrestrial and wetland habitat, changes in flow regimes, damage to the ecology of rivers, and effects on water quality and ecosystems in the affected riverine estuaries of Hudson Bay. In addition, the local populations and movements of caribou and fur-bearing mammals would have been affected, with consequences for the livelihood of Aboriginal people living in the region.

These and other potential effects were considered during a detailed environmental impact assessment, and plans were made to avoid or mitigate the damage to the degree that was possible. Ultimately, however, the proposed development did not proceed, not so much because of environmental concerns, but as a result of insufficient commitments to purchase the electricity in the northeastern United States. Without access to that foreign market, the estimated $13 billion cost of the project's construction was not considered economically feasible. Since then, in 2014, the project is being re-considered due to improved prospects for selling the electricity in New York State and Ontario.

A Municipal Incinerator: This was a proposal to construct a facility to incinerate large quantities of municipal waste from metropolitan Halifax, Nova Scotia. Some of the heat produced would have been used to generate about 16 MW of electricity (this is also known as a waste-to-energy facility). The incinerator would have been fitted with advanced technologies to control the emissions of potentially toxic chemicals, such as metals, gases, and organic particles and vapours, the latter including polycyclic aromatic hydrocarbons, dioxins, and furans. Such emissions can never be totally eliminated, however, and there is controversy about the risks to human health inherent in even minute exposures to some chemicals, particularly dioxins and furans. As it turned out, the proposal to build the incinerator was turned down by the provincial Minister of the Environment, partly because it was considered too costly in comparison with alternative methods of disposal of municipal waste, but also for environmental reasons.

A Peat Mine: Peat mined from bogs is used as a horticultural material, and it can also be burned as a source of energy. This proposal would have developed a mine on a bog in Nova Scotia to provide peat as an industrial fuel. The EIA focused on the fact that the bog in question provides habitat for several rare species, including a carnivorous plant called the thread-leaved sundew (Drosera filiformis). This species is endangered in Canada and also in much of the rest of its range in the eastern United States. Because the bog harbours the largest of only four known populations of the sundew in Canada, the provincial Minister of the Environment did not allow a mine to be developed on that site. This was a controversial decision because it cancelled a local development initiative in a region in which the economy is chronically depressed.

> Image 28.1. The thread-leaved sundew (Drosera filiformis) and its bog habitat. The largest known population of this carnivorous plant in Canada occurs on a site in southwestern Nova Scotia that was proposed for a peat mine. An environmental impact assessment predicted that the mining would obliterate the most important population of this endangered species, and as a consequence the government of Nova Scotia did not allow the mine to proceed. Source: Bill Freedman.

In Detail 28.1. Cumulative Environmental Effects Environmental impact assessment (EIA) is a planning activity that is used to identify and evaluate environmental problems that may be caused by a proposed economic activity. According to the Canadian Environmental Assessment Act, this includes the need to evaluate cumulative environmental impacts, or those resulting from the effects of a proposed undertaking within some defined area, in addition to those caused by any past, existing, and imminent developments and activities. The concept of cumulative effects recognizes that the environmental effects of separate anthropogenic influences will combine and interact to cause changes that may be different from those occurring separately. It is sensible and precautionary to consider all of the anthropogenic influences when examining the potential effects of a newly proposed project or activity.

Assessment of cumulative impacts requires knowledge of both the likely effects of a proposed development, as well as those of other anthropogenic activities in a study area, plus additional ones that are likely to occur. If all of this is known, then the incremental effects of a proposed undertaking can be evaluated for their relative importance. Cumulative effects can result from multiple pathways, and they may be manifested in physical, biological, and socioeconomic damages.

There are a number of examples of cumulative environmental effects that are primarily ecological and have occurred in Canada:

- aggregate damage caused to populations of migratory salmon in the Fraser River watershed in British Columbia as a result of commercial fishing in the open Pacific or in the river itself, along with sport and subsistence fishing, plus degradation of freshwater habitat through such influences as the dumping of sewage, agricultural erosion and pesticides, warmer temperatures and woody debris in streams caused by forestry operations, risks of sea-louse infection from aquaculture in coastal waters, and warming oceanic waters caused by climate change
- incremental losses of wetlands in the Prairie provinces caused by various agricultural practices, such as drainage, excessive fertilization with nutrients, toxicity caused by pesticides, and trampling by cattle, along with drying caused by periodic droughts whose frequency may become exacerbated by anthropogenic climate change
- losses of biodiversity throughout Canada, but particularly in southern regions, caused by deforestation to develop land for urbanized and agricultural uses, fragmentation by roads and transmission corridors, disturbances by forestry and mining, and various kinds of pollution
- ecological damage in a region of boreal forest in northern Alberta in which there are diverse anthropogenic stressors associated with timber harvesting, exploration and mining for oil and gas, oil-sand extraction and processing, and pipelines and roads to service all of those economic activities
- threats to the ecological integrity of national parks that are associated with the internal development of infrastructure to support tourism, such as campgrounds, interpretation centres, roads and trails, golf courses, and skiing facilities, along with economic activities in the surrounding area such as forestry and agriculture, as well as regional influences such as acid rain and climate change. A requirement that environmental impacts be studied in a cumulative manner acknowledges the complexity of ecosystems and the fact that all aspects of their structure and function are affected by a diverse array of influences.

Environmental Legislation

Many activities that could potentially degrade environmental quality are regulated by legislation passed by various levels of government. In addition, Canada has signed a number of international treaties and protocols that deal with important environmental issues.

Environmental law in Canada is made extremely complex by jurisdictional overlaps and other factors. One problem is that of harmonization of related pieces of legislation among the provinces/territories and the federal government. In 1998, these governments adopted the Canada-Wide Accord on Environmental Harmonization, which was intended to achieve progress in this direction. However, that action was resisted by certain interest groups, including the Canadian Environmental Law Association (CELA). CELA views the accord as a mechanism for devolving federal environmental roles and responsibilities to the provinces and territories. Nevertheless, the subsequent years has witnessed a considerable devolution of federal authority in the environmental realm, particularly since 2006 during the tenure of the Conservative government.

Environmental law in Canada is changing rapidly as new legislation is passed and older laws are modified or more specifically interpreted by the courts. One important interpretive decision of the Supreme Court of Canada affecting environmental impact assessments (described in Chapter 20) was the Rafferty decision of 1989, which made it clear that an EIA was needed for any undertakings involving the federal government.

In addition, in 1999, the Supreme Court's Marshall decision involved a case in which an Aboriginal person had been convicted of catching fish out of season, without a licence and for commercial sale. This conviction was overturned on the basis of treaty rights, negotiated in 1760-1761, that guaranteed Mi'kmac and Maliseet Indians the right to commercially harvest natural resources at any time of year within an extensive treaty area in the Maritime Provinces. The Supreme Court interpreted the modern resource-harvesting rights of those Aboriginal nations as being sufficient for individuals to earn a "moderate living." The Marshall decision restored to Aboriginal people a legal right to engage in fish and timber harvests that are not subject to the same seasonal and geographical restrictions as for non-Aboriginals. The Marshall decision resulted in controversy and conflict with non-Aboriginal fishers and government agencies.

In 2003, the Supreme Court extended aspects of the Aboriginal resource-access rights to Métis in Canada, ruling that those persons could also freely hunt and fish for subsistence purposes. Some key issues were left unresolved, such as the definition of a Métis person as well as restrictions that might be imposed for the purposes of safety and resource conservation. These aspects are being resolved through ongoing negotiations of interest groups with federal, provincial, and territorial governments. The social and economic repercussions of these decisions by the Supreme Court of Canada will take years to work out.

Subsequent decisions of the Supreme Court in 2013 and 2014 have clarified Aboriginal rights to land tenure and resource rights in British Columbia. These cases involved proposals to build mines and oil pipelines in areas where First Nations has not signed land-claim agreements with the provincial government and as such had never ceded their rights to property in areas where large industrial developments were being proposed. In essence, the Supreme Court affirmed those Aboriginal rights. Although the implications of that decision are not yet fully appreciated (it is likely that additional legal actions will be needed to accomplish this), it appears that substantial negotiations will be needed to gain Aboriginal approval for industrial projects being proposed within their domain.

The settlement of comprehensive land claims with indigenous nations in Canada (in effect, the modern equivalent of "treaties") includes the formulation of suites of environmental laws. For example, such settlements include provisions that govern many aspects of resource harvesting and management, waste management, and protected areas within the settlement regions.

An important example of the need for effective legislation concerns the protection of species at risk and their habitat. That sort of legislation has existed in the United States since 1973 as the Endangered Species Act (ESA) administered by the Fish and Wildlife Service (2015). As of 2014, 1,330 species of animals and 889 of plants were listed as endangered or threatened under the ESA (685 of the listed animals occur in the United States and 645 in other countries, while 886 of the plants grow in the United States and three elsewhere). In addition, approved recovery plans were in place for 479 of the listed U.S. animals and 676 of the plants.

In Canada, the conservation status of species is designated by a group of experts from government, conservation organizations, and academia known as COSEWIC (the Committee on the Status of Endangered Wildlife in Canada; see Chapter 27). As of 2014, COSEWIC had assigned at-risk status to 721 indigenous species and other taxa (such as subspecies; only native taxa are designated). Moreover, in 2002, a federal Species at Risk Act (SARA) became law. SARA has toughened the legal provisions in support of the protection of species listed by COSEWIC. Its provisions are particularly strong with respect to at-risk species and their habitat occurring on lands owned by the federal government or otherwise falling within its jurisdiction.

However, the SARA legislation is much weaker with respect to species and critical habitat on lands beyond direct federal jurisdiction, such as areas owned by provincial, territorial, municipal, Aboriginal, or private interests. Although there are provisions in SARA for the federal government to intervene in such cases, and to provide compensation to affected landowners, it is not bound to do so. Many such interventions would inevitably be expensive and controversial, and so far this mechanism has not been used much to protect at-risk species in Canada. Most of the provinces and territories have also passed laws related to the protection of species at risk within their own jurisdictions, or they are preparing such legislation.

Of course, it is not sufficient to simply pass good laws that are intended to regulate actions that might degrade the quality of the environment – it is also necessary to enforce them. Between 2011 and 2015, there were 95 successful prosecutions (that is, with a conviction) under the Canadian Environmental Protection Act (CEPA) or the Fisheries Act (Environment Canada, 2015). There are, however, a much larger number of cases that can be resolved with softer regulatory actions, such as writing a warning letter to a non-compliant party.

Several non-governmental organizations have taken on the mandate of advocating improvements to environmental law and policy in Canada, while ensuring that the existing laws are rigorously applied. The most prominent of these are the Canadian Environmental Law Association and Ecojustice. These organizations lobby politicians and suggest specific changes to existing or proposed legislation. In some cases they also take government agencies to court in order to force them to enforce the existing laws or to seek interpretation from a higher court such as the Supreme Court of Canada.

Environmental Monitoring and Research

There are widespread and well-founded concerns about severe damage being caused to the quality of the environment. In response, many nations are implementing programs to monitor changes in environmental quality over time. Most of these programs are intended to document changes that are occurring over large regions or entire countries and to help predict future variations. These efforts are much larger in scale and scope than programs that monitor whether a particular industrial facility is complying with regulations and guidelines. Most large-scale monitoring is conducted by governmental agencies, or in some cases, by non-governmental organizations. The resulting data and knowledge are used to guide decision making in government, to enhance the work of NGOs, and to provide material for environmental research and education.

In the sense meant here, environmental monitoring involves repeated measurements of factors that are related to either the inorganic environment, the structure and functioning of ecosystems, and any intersections with human welfare. Because not everything can be monitored, successful monitoring programs depend on the careful choice of a limited number of representative indicators and on the collection of reliable data. If a monitoring program detects important changes, the possible causes and consequences of those changes are usually researched.

An environmental indicator is a relatively simple measurement that is used to represent a complex aspect of environmental quality. Indicators are usually sensitive to changes in the intensity of stressors. For example, the level of chemical residues in species high in the food web is often used as an indicator of contamination of its larger ecosystem. This is why residues of chlorinated hydrocarbons (such as DDT and PCBs) are routinely monitored in herring gulls and cormorants on the Great Lakes, and in marine mammals in coastal waters of the Pacific, Atlantic, and Arctic Oceans (Chapter 22). Similarly, many lichens are known to be sensitive to gaseous pollutants and so are monitored as indicators of air quality over large regions, including cities.

Other indicators include species that are considered to represent the general health of the ecosystem of which they are a component. For instance, the population status of grizzly bears is considered a good indicator of the quality of their extensive ecosystem, as are populations of spotted owls for western old-growth rainforest, pileated woodpecker and pine marten in some other forests, salmon and trout in certain aquatic ecosystems, and orca and other cetaceans in the marine realm.

Sometimes, composite indicators are monitored to track changes in environmental quality. These are environmental analogues of the composite indexes that are used to monitor complex trends in finance and economics, such as the Consumer Price Index (CPI) and the Toronto Stock Exchange (TSE) index. Because they allow complex changes to be presented in a simple manner, composite indictors are especially useful for reporting to the general public.

Composite indicators of air and water quality have been developed using data for various kinds of important pollutants, such as major gases, vapours, and particulates in the atmosphere. However, composite indicators of environmental quality (or of ecosystem health or ecological integrity; see In Detail 28.1) are not yet well developed. This is mostly because scientists have not yet agreed on what the component variables should be.

When a change in indicators is measured in an environmental monitoring program, or when one is predicted, it is necessary to understand its causes and consequences. This is generally done by using the accumulated knowledge of effects of environmental stressors on ecosystems, along with research that is designed to address important questions that are not yet understood. We can examine the linkages between environmental monitoring and research by considering several examples.

Suppose that environmental monitoring has detected that precipitation has become acidified in some large region (Chapter 19). The cause(s) of the acidification might be understood by determining the concentrations of chemicals in the precipitation and by investigating local emissions of gases and particulates to the atmosphere. Researchers must also understand the consequences of an increased deposition of acidifying substances to freshwater and terrestrial ecosystems, as well as the implications for buildings and other urban features. At first, the research would examine the existing knowledge of the causes and ecological effects of acidification in various kinds of habitats. However, that knowledge is always incomplete and therefore it must be augmented with new research examining risks of acidification that are not yet understood. The accumulated information helps society to understand whether the causes of acidification can be controlled, and if so, to assess the potential environmental and economic benefits.

In another example, monitoring might indicate that the ecological character of a region is changing because the natural forest is being extensively converted into plantations through industrial forestry. The ecological consequences would initially be interpreted in the light of existing knowledge of the effects of forestry, supplemented by additional research that investigates poorly understood issues. Specific research questions might address effects of the ecological conversions on biodiversity, forest productivity, watershed hydrology and chemistry, and global environmental change through effects on carbon storage (Chapters 17 and 23). This information is needed to help decision makers evaluate whether they should permit further conversions of natural forest into plantations.

Environmental monitoring and research in Canada are carried out by various agencies. Environment Canada is the most active agency at the federal level. In addition, the Department of Fisheries and Oceans deals with fisheries and oceanic environments, Natural Resources Canada provides data about non-renewable and some renewable resources, the Canadian Forest Service provides information relevant to commercial forests, Parks Canada examines changes in national parks, and Health and Welfare Canada deals with influences of environmental quality on human health. Statistics Canada plays a key role in compiling information and making it available to governments, companies, and the public. All of the provincial and territorial governments of Canada also have comparable agencies that deal with environmental issues within their jurisdiction.

A few non-governmental organizations also undertake a considerable amount of environmental monitoring and research. For instance, the WWF-Canada has programs that fund work on endangered species and ecosystems. The Nature Conservancy of Canada is active in work associated with conservation planning and stewardship. Universities also have considerable technical expertise in environmental issues. University personnel are not necessarily involved in long-term monitoring programs, but many professors and graduate students undertake research into the causes and consequences of environmental changes.

Environmental monitoring programs provide society with crucial information and knowledge. Both are necessary for the implementation of effective programs to prevent further degradation of environmental quality and the health of ecosystems, and to repair existing damage. These actions are necessary if society is to conduct its economy in a truly sustainable manner.

> In Detail 28.1 Notions of Environmental Quality Environmental quality, ecosystem health, and ecological integrity are important notions that help us understand the importance of changes in environmental conditions. However, like other notions, these ones cannot be precisely defined, although it is possible to develop a general understanding of what they mean.
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> Because they integrate changes in many components of ecosystems and environments, these concepts involve complex phenomena. Environmental quality, for example, is related to the concentrations of potentially toxic chemicals and other stressors in the environment, to the frequency and intensity of disturbances, and to the effects of these on humans, other species, ecosystems, and economies. Of particular concern are stressors associated with human activities, because these have become so important in the modern world.
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> Ecosystem health and ecological integrity are similar to each other and, in many respects, to environmental quality. However, these indicators focus on changes that may be occurring in natural populations and ecosystems, rather than on effects on people and their economy. All of these notions involve many variables that are related to stressors and socio-economic or ecological responses. As a result, they are sometimes measured using composite indicators, which integrate many possible changes that are thought to be important. Composite indicators are not exact measurements of environmental quality, ecosystem health, or ecological integrity, but they do allow society to determine whether conditions are getting worse or better.
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> These ideas can be explained by using ecological integrity as an example. Obviously, most stressors associated with human activities will enhance some species, ecosystems, and ecological processes, while at the same time damaging others. However, ecological theory suggests that systems with higher values for any or all of the following characteristics will have a greater degree of ecological integrity:
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> - The ecosystem is resilient and resistant (see Chapter 9) to changes in the intensity of environmental stressors
> - The system is rich in indigenous biodiversity values
> - The ecosystem is complex in its structure and function
> - Large species are present
> - Top predators are present
> - The ecosystem has controlled nutrient cycling, meaning it is not "leaking" its nutrient capital
> - The ecosystem has a "natural" character and is self-maintaining, as opposed to being strongly affected by human influences and management
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> These sorts of criteria for ecological integrity are off particular relevance to managing protected areas. IF ecological integrity is being maintained or enhanced, then a protected areas is doing its job of maintaining biodiversity and ecological functions.

Some Challenges and Successes

As we noted earlier, programs of monitoring and research should be capable of detecting changes in environmental quality, while also helping to predict future effects. Well-designed programs should deal with the most important known stressors or potential threats to the environment. They should measure or predict the effects on people and on sensitive ecosystems and species, particularly those that are economically or ecologically important.

These are the simple requirements of a sensible program for monitoring and investigating environmental problems. Unfortunately, these criteria are not well met by many existing programs, and as a result some important environmental problems are not yet well understood. Consequently, they are not being addressed effectively, and they could become worse in the future. The following are some examples selected from preceding chapters.

- What constitutes an acceptable exposure of humans to potentially toxic chemicals? Some toxins, such as metals and many biochemicals, occur naturally. How much can anthropogenic emissions be allowed to increase exposures beyond the natural background? Is any increase in exposure acceptable for non-natural toxins, such as dioxins, furans, PCBs, synthetic pesticides, and radionuclides? Or are there acceptable thresholds of exposure to those substances?
- Is a widespread decline of migratory birds occurring? If so, what are the causes, and how can we manage the responsible stressors to repair the damage and prevent further losses of these native birds?
- Anthropogenic emissions of CFCs (chlorofluorocarbons) may be causing a depletion of stratospheric ozone, resulting in increased ground-level exposures to ultraviolet radiation. What risks does this change have for human health and for wild species and ecosystems? How can the damage be prevented and repaired?
- What are the dimensions of the global extinction crisis? How is biodiversity important to the health of the biosphere and to human welfare? Which Canadian species and ecosystems are most at risk, and why? Should Canada expend more effort to help conserve tropical biodiversity, or should we focus on problems within our own boundaries? How are Canadians linked to biodiversity-depleting stressors in tropical countries?
- Extensive declines and diebacks of forests have been reported in various parts of the world, including Canada. Is that damage being caused by natural environmental changes or by stressors associated with human activities? If anthropogenic stressors are important, how can they be managed to prevent and repair the forest damage?
- What are the environmental consequences and costs of conventional and nuclear warfare? The effects of war are devastating to people, their economy, and ecosystems. If these effects were better known, this inherently destructive behaviour might be avoided.
- Is it possible to valuate the worth of species, communities, and ecological services (that is, to measure their worth in dollars) so that these can be integrated into economic cost-benefit models?
- How intensively can renewable resources be harvested and managed without causing unacceptable risk to their long-term sustainability and without inflicting damage to other species and ecosystems?

To deal properly with these and many other important issues, we must improve our understanding through better monitoring and research. We can illustrate the achievable benefits by examining a few “success stories” in which monitoring, research, and effective actions helped to resolve important environmental problems.

- Eutrophication of fresh water was identified as an important environmental problem during the 1960s and early 1970s. Research discovered that phosphate was the primary cause and that the damage could largely be avoided by constructing sewage-treatment facilities and by using low-phosphorus detergent.
- Contamination with persistent chlorinated hydrocarbons, such as DDT, dieldrin, and PCBs, was found to be widespread in the 1960s and 1970s. Research showed that some species, such as predatory birds, were being seriously harmed and that there were possible effects on humans. The toxicological evidence convinced decision makers to ban these chemicals in most countries, to the great benefit of the environment.

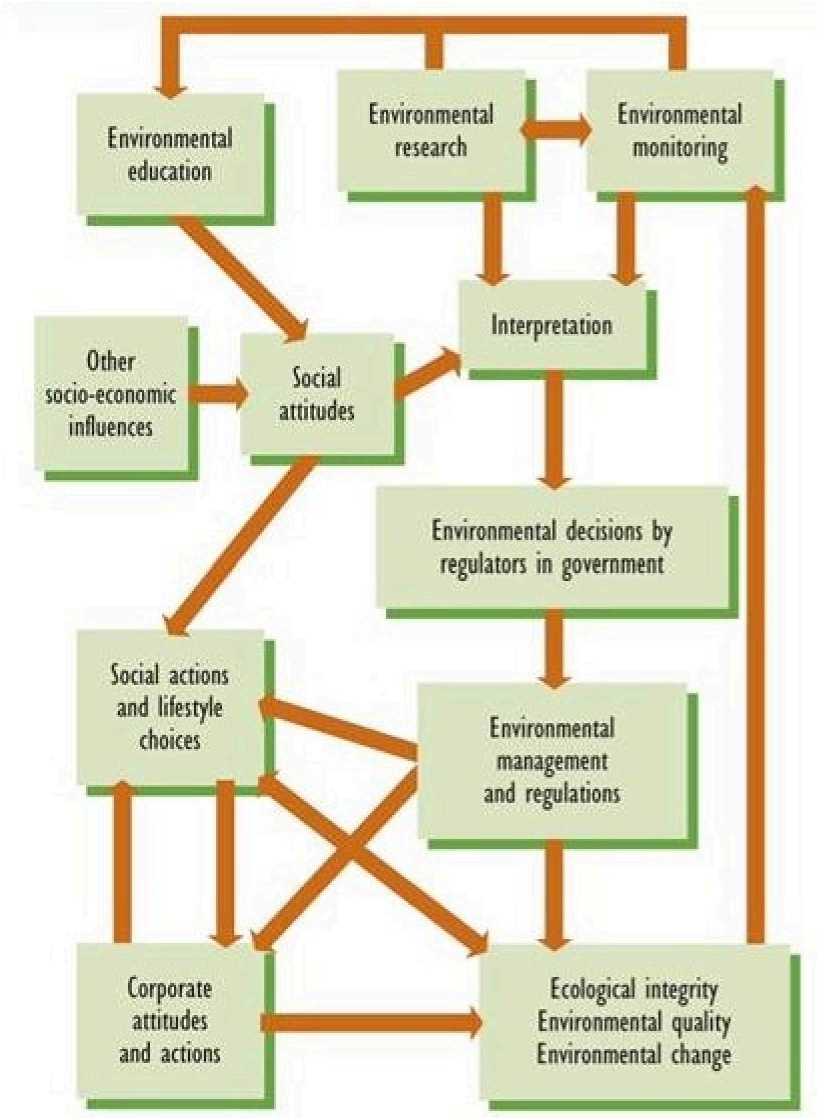
- Acidification was recognized during the late 1970s and the 1980s as an extensive phenomenon causing many ecological damages. Research showed that the problem was largely due to the atmospheric deposition of sulphur and nitrogen compounds. This convinced decision makers to require reductions of industrial emissions, and that action led to some improvements.

Environmental Literacy and Reporting

Environmental literacy refers to a well-informed understanding of environmental issues, and it is an important societal goal. Knowledge about the causes and consequences of environmental damage can influence the decisions and choices made by politicians, regulators, corporations, and individual citizens. If appropriate, those decisions and choices can influence environmental quality in a positive way (Figure 28.1). People acquire this knowledge in various ways, the most important of which are environmental reporting and other forms of education.

> Figure 28.1. Influences on Environmental Quality. This is a conceptual model of the many influences on environmental quality, including the roles of monitoring, research, regulation, and literacy. Environmental monitoring and research provide an understanding of the causes and consequences of changes in conditions. Ideally, this understanding is based on objective information from monitoring and research programs, interpreted by environmental scientists and other qualified specialists (although their explanations may be conditioned by social and cultural influences). This knowledge is communicated to decision makers in government, who may implement regulations and undertake management activities that affect environmental quality.
>
> Knowledge about environmental and ecological changes is also communicated to the general public, through state-of-the-environment reporting, the educational system, activities of non-governmental organizations, and the mass media. Social attitudes regarding the environment are affected by environmental literacy, and they may result in more appropriate choices of lifestyle and a public influence on the policies and actions of

governments and corporations. Source: Modified from Freedman (1995).



Environmental literacy has a pervasive influence on the attitudes that people develop. Individuals who are knowledgeable about environmental issues are more likely to make appropriate lifestyle choices and to influence decision makers to ensure that sensible policies are implemented. In contrast, poorly informed public opinion encourages less-appropriate environmental choices, such as rampant consumerism and a wasteful use of natural resources. Environmental illiteracy also fosters the development of controversial "red herrings", or illogical beliefs that mislead or distracts from important issues.

An example of an environmental red herring is the common misunderstanding that many people have of the differences between contamination and pollution. Related unhelpful syndromes are known as NIMBY (not in my backyard), LULU (locally unacceptable land use), BANANA (build absolutely nothing anywhere near anybody), and NIMTO (not in my term of office). NIMBY, LULU, and BANANA are common views that many people have about proposed developments that may affect their local environment, while NIMTO is a frequent political response. These attitudes can result, in part, from a lack of credible information about the risks that may be associated with developments in the neighbourhood. Alternatively, NIMBY, LULU, and BANANA may result when planners and developers are insensitive to the legitimate concerns of local people.

In addition to affecting the siting of commercial and industrial facilities, NIMBY, LULU, BANANA, and NIMTO cause huge problems for planners who are attempting to build certain kinds of environmental management facilities that society wants and needs. For example, even though all voters recognize that their community needs facilities for the disposal of solid wastes and the treatment of sewage, not many people wish to have such works located in their own neighbourhood.

Decision makers in government and industry need objective cost-benefit analyses when dealing with environmental problems. These people have the responsibility of making societal-level choices to avoid, mitigate, or accept environmental damage. Their choices are often based on their perceptions of the costs associated with environmental damage, offset by economic benefits promised by the activity that is causing the degradation. Unfortunately, the perspective of many decision makers is that of conventional, short-term economics rather than ecological economics (see Chapters 1 and 12). Because many social controversies have resulted from seemingly non-balanced choices, the role of decision makers is changing in many countries. In addition to, or even instead of, actually making choices, these people are increasingly being expected to create an appropriate climate for multilateral consultation and consensus-driven decision making.

Environmental reporting is one process that is used to communicate information about environmental changes to various interest groups. Such reporting should involve clear and objective presentations of information about changes in environmental quality, and should also offer unbiased interpretations of the causes and consequences of those changes.

Environmental reporting is delivered to the broader public by various agencies, including government departments, educational institutions, non-governmental organizations, and the mass media. A governmental instrument that has been prominent since the mid-1980s is known as state-of-the-environment reporting. For a time, the federal government released well-regarded, comprehensive reports on the state of the Canadian environment (in 1986, 1991, and 1997). Most of the provinces have also released periodic state-of-the-environment reports. Unfortunately, Environment Canada has now largely abandoned this function, and in 1996 it closed down its division responsible for the preparation of comprehensive state-of-the-environment reports. Nevertheless, various federal agencies continue to make useful information about the environment available to the public. One excellent example is Statistics Canada, which makes available a wide range of useful information.

Of course, most people become informed about environmental issues through the mass media, such as the internet, newspapers, and television. These can be effective means of environmental education, but there are drawbacks. Often, media presentations of issues are biased, and sometimes they are inaccurate. The focus is often on controversy, especially when there are unresolved issues that are characterized by scientific uncertainty. This can result in high-profile disputes dominating the environmental agenda, which can detract from efforts to deal with some other important problems whose causation and resolution are better known.

To some degree, this approach can be counterbalanced by providing the broader public with more objective information and by fostering a better understanding of the issues. One means of accomplishing this is to ensure that environmental issues are dealt with, adequately and objectively, in the education system. Ideally, this exposure would occur throughout the system – from primary and high schools, through colleges and universities, to continuing education for the working public.

Within all of these contexts (but particularly in schools, colleges, and universities), there are two broad ways of delivering environmental education:

1. The first involves discrete, interdisciplinary classes in environmental studies and environmental science. Arguably, environmental issues are important enough to social literacy to justify their treatment as a primary subject area, comparable to biology, languages, literature, mathematics, music, physics, and other disciplinary subjects.
2. The second way of delivering environmental education is to integrate appropriate case material across the

curriculum. Environment-related elements can be used to assist the teaching of all disciplinary subjects, ranging from the physical sciences, through the other natural sciences and medicine, to the social sciences.

Measures to ensure that citizens are environmentally literate are a necessary part of any strategy that is designed to resolve environmental problems. If people understand these critical issues, they will be more willing to make personal choices in support of the protection of environmental quality, biodiversity, and natural ecosystems.

Sustainability

We previously defined sustainable development as progress made toward an economic system that is ultimately based on the wise use of renewable resources (Chapters 1 and 12). Therefore, a sustainable economy would not deplete its capital of natural resources, and so would not compromise the availability of those necessities for use by future generations of humans. We also noted that ecologically sustainable development would allow the human enterprise to continue, but without causing unacceptable damage to other species or natural ecosystems.

By these criteria, the so-called "advanced" economies of modern times (such as that of Canada, the United States, countries of Western Europe, Japan, and Australia) are clearly non-sustainable. There are two major reasons for this alarming conclusion:

1. The first is the obsession that politicians, economists, and other managers of national and international economies have for rapid economic growth, both to keep up with an expanding population and to increase the standard of living.
2. The second reason involves the likelihood that the present size of advanced economies is already too large to be sustained for long. The rationale for these two statements is briefly explained in the following paragraphs (and is further supported by more detailed examination in earlier chapters).

Economic growth is typically achieved by forcing both non-renewable and potentially renewable resources through an economy, thereby making the economy larger. Since about 1990, nations with advanced economies have been achieving economic growth rates of about 1-3% per year, which, if maintained, would double the size of their economies in only 26 to 70 years. Rapidly developing economies, such as those of Brazil, China, Chile, India, Mexico, and Thailand, have been growing even faster (but from a much smaller per-capita base), at up to 5-10% in some years, which is sufficient to double their economies in only 7 to 15 years.

As we learned earlier, this sort of rapid economic growth can be achieved only as long as resources continue to be readily available. In Chapters 13 and 14, we examined many examples of rapidly depleting stocks of both non-renewable and potentially renewable resources. Such examples suggest that modern economic growth rates cannot be sustained and, in fact, will reverse themselves when crucial resources become depleted. Moreover, many scientists and environmentalists believe that the present sizes of advanced economies (such as that of Canada) are already too large to be sustained. The arguments in support of that assessment are similar to those just noted – the large, "developed" economies are maintained by the forced throughput of mined resources, the supplies of which are rapidly becoming depleted.

It is common today for politicians, corporate spokespeople, and resource managers to assert publicly that they support efforts to make progress toward sustainable development. However, almost all of these people are confusing genuine sustainable development, as it was defined at the beginning of this section, with "sustainable economic growth." In a resource-constrained world, unlimited economic growth can never be sustained over the long term. This is why ecologists and environmentally astute economists believe that further growth is undesirable: "Economic growth as it now goes on is more a disease of civilization than a cure for its woes" (Ehrlich, 1989).

It is important to understand that, although they are pushing society in an ill-advised direction, advocates of economic growth are not a malevolent force. These people hope that growing economies will allow larger numbers of people to be productively employed and thereby enjoy the benefits of an advanced, material society. These are highly desirable goals.

However, is it prudent to seek to achieve a gigantic economy that would only temporarily support a large number of people? Or would it be better to limit the scale of the human enterprise to a level that can be supported by Earth's biosphere and resources over the longer term? Fundamental considerations in a sustainable human economy are:

- the numbers of people that must be supported
- the total intensity of their resource use
- the equitability of standards of living among the world's peoples
- and the environmental damage that is caused

Ultimately, an ecologically sustainable economy is limited by the carrying capacity of planet Earth for our species and its enterprise. Vital elements of a sustainable economy must include control over:

- the population sizes of people and our mutualistic species (such as cows and other domestic animals)
- and per-capita and total-population resource consumption

In part, the resolution of resource dilemmas will require a more equitable sharing of wealth among people living in poorer and richer countries. This would moderate the importance of poverty as a key factor in causing environmental degradation.

> Canadian Focus 28.2. Speaking for the Fishes Many fisheries are collapsing, and the reason is that these potentially renewable bio-resources have been subjected to irresponsibly high rates of harvesting. People are deeply concerned about the ruination of vital marine resources, and about the collateral ecological damage caused by industrial methods of harvesting. The ecological damages include effects on native species, natural communities, and ecosystem functions such as productivity and clean-environment services. A number of Canadian ecologists have devoted their careers to documenting the causes and consequences of these ecological tragedies, and in finding ways to recover the degraded stocks.
>
> These people are environmental heroes because they are champions of both resource sustainability and the need to maintain healthy ecosystems. These ecologists work in universities, environmental organizations, and governmental research laboratories and policy divisions. These scientists are many, and only some are profiled here. All are professors who have devoted their great opportunity of academic freedom to engage in research to document and understand calamities of aquatic bio-resources. They are also engaged in honest and effective public advocacy to ensure that society moves toward a more sustainable use of its limited stocks of bio-resources, and of its natural heritage of indigenous biodiversity.
>
> Ransom Myers was a population ecologist who worked on ocean fisheries, initially as a scientist with the federal Department of Fisheries and Oceans (DFO) and then as a professor at Dalhousie University. He and his students undertook highly regarded research that documented collapses of fish stocks, as well as global declines of other marine bio-resources. A special contribution was to bring these important issues to the attention of politicians and regulators, as well as to the broader public. Myers was a leader in outreach from the academic community, and he helped to focus attention on the vital need to conserve both marine bio-resources needed as food as well as the biodiversity of the oceans. Fortune magazine nominated Myers as one of its "10 people to

watch" globally because of his powerful influence on marine policy. Unfortunately, Myers died suddenly of cancer in 2007, a shocking event for his family and many colleagues. However, there are valuable lessons to be learned from his work, including the value of high-quality research, enthusiastic support of students and colleagues, scientific integrity, and the need for at least some professors to be engaged in public discussions of issues of the day that fall within the domain of their expertise.

Jeff Hutchings, a colleague of Myers and also a professor at Dalhousie, engaged in research that documented the causes of the collapse of cod stocks in the northwest Atlantic, a bio-resource tragedy that had awful economic consequences. At the time, Hutchings and Myers were working for DFO, where bureaucratic interests were profiling the collapse of cod as a somewhat natural phenomenon from which the stocks would quickly recover. Hutchings and Myers publicly opposed those views, because their interpretation of the ecological data clearly showed that the damage had been caused by overfishing. They also showed that the damage had mostly occurred within the context of quotas set by DFO that were too large to be sustainable, and that were often over-ruled by politicians who used their authority to set permissible catches that were even larger than what DFO was recommending. Hutchings won a prize as a "whistle blower" for the effectiveness with which he communicated evidence about the cod calamity to both scientists and the public.

Daniel Pauly is a French-born fishery ecologist at the University of British Columbia. He takes an international approach to his research, being engaged in projects around the world, all with the common thread of studying marine bio-resources, documenting threats to their sustainable use, and proposing management and policy solutions to those problems. Pauly is the leader of a collaborative international venture known as the Sea Around Us Project, which is using GIS (geographic information systems) to map global fisheries catches to help document and mitigate the damaging effects of this industrial activity. His work has focused on collapses of fishery resources, on risks to critical marine habitats (such as reefs, seamounts, and upwellings), and on damage caused to marine biodiversity. Pauly has won many professional awards, is an advisor to governments, and a frequent commentator in the media on issues related to the marine realm.

Boris Worm and Heike Lotze are part of a younger cohort of professors whose enterprise is focused on identifying, and then repairing, damage that the human economy is causing to the marine realm. They work at Dalhousie University, and both are interested in Canadian and international marine issues, particularly collapsing stocks of bio-resources and damage caused to biodiversity. Like the others noted above, Lotze and Worm are engaged with a broad network of collaborators, including scientists in universities and governments from around the world, as well as many graduate students. Worm and Lotze have similar motivations in their professional life. They have a love and fascination with science and with the natural world, and a deep concern about terrible damage that is being caused to vital resources and to biodiversity.

But neither they nor the other ecologists mentioned in this section are just complainers about these important problems – they are leading the charge to find ways to fix these problems, and are demanding that those fixes be rapidly implemented.

Environment and Society

All levels of society have a responsibility to protect the quality of our common environment. These obligations are a central aspect of the social contract by which enlightened communities function.

The role of government is an overarching one, because it is empowered to regulate the activities of itself, the private sector, non-governmental organizations, and individuals. Of course, many activities of government and the private sector carry risks of causing environmental damage, and there is always an obligation to avoid or mitigate damage as much as possible.

The role of environmental non-governmental organizations (ENGOs) is to lobby government and industry about issues, to raise public awareness, and increasingly (because of shortages of governmental capability), to raise funds that can be used to prevent and repair environmental damage. Finally, all individual citizens have an obligation to live their lives in an environmentally responsible manner.

In the following sections, we will briefly examine the roles and activities of key environmental organizations.

International Organizations

The United Nations Environment Programme (UNEP) is the principal international organization that deals with environmental matters. UNEP is responsible for coordinating global environmental efforts with other agencies of the United Nations, national governments, and non-governmental organizations. UNEP also coordinates the development of multinational treaties and other agreements and periodically hosts global conferences on environmental themes.

Other agencies of the United Nations also have mandates that involve environmental issues. These include the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), the United Nations Educational, Scientific, and Cultural Organization (UNESCO), the United Nations Population Fund (UNPF), the World Health Organization (WHO), and the International Labour Organization (ILO).

A wide range of non-governmental environmental organizations are also active on the international stage:

- ENGOs involved in the international conservation of biodiversity include Conservation International, the Cousteau Society, the International Union for Conservation of Nature and Natural Resources, the Nature Conservancy (U.S.), the Smithsonian Institution, and the World Wildlife Fund.
- Those dealing with population issues include the Population Institute, the Population Reference Bureau, and Zero Population Growth.
- Those with general mandates concerning resources and other environmental issues include the Earth Island Institute, the Environmental Policy Institute, Friends of the Earth, Greenpeace International, Resources for the Future, the Sierra Club, the World Resources Institute, and the Worldwatch Institute.

Canadian Organizations

At the federal level, Environment Canada plays a central role in preserving and enhancing environmental quality. Its mandate includes the protection of water, air, and soil quality, renewable resources, and biodiversity. Its institutional objective is to foster a national capacity for sustainable development, in co-operation with international, provincial, territorial, municipal, and Aboriginal governments, as well as other departments of the federal government, the private sector, and non-governmental organizations.

Other agencies of the federal government also have important environmental mandates:

- Natural Resources Canada deals with mineral and forest resources, including aspects of the environmental impacts of mining, the use of fossil fuels, and forestry
- Health and Welfare Canada deals with environmental issues related to human health and also has primary

jurisdiction over pesticide registrations
- Agriculture and Agri-Food Canada deals with issues involving agricultural practices, including sustainability and pesticide-use registrations
- Fisheries and Oceans Canada has a mandate to promote understanding, conservation, and beneficial use of aquatic bio-resources.
- The Canadian Coast Guard helps to protect the marine environment by preventing marine pollution
- Parks Canada manages national parks
- Aboriginal Affairs and Northern Development Canada is responsible for environmental and resource issues in extensive northern regions
- The Canadian Environmental Assessment Agency conducts environmental assessments of projects involving the federal government
- Statistics Canada compiles environment-related data and makes them available to other agencies and the public

All of the provincial and territorial governments have agencies similar to those listed above for dealing with environmental responsibilities under their jurisdiction.

Canada also has a wealth of non-governmental organizations that deal with environmental issues. National organizations that focus on the conservation of biodiversity include the Canadian Parks and Wilderness Society, the Canadian Wildlife Federation, Nature Canada, the Nature Conservancy of Canada, and the World Wildlife Fund of Canada. Organizations with general mandates concerning resources and other environmental issues include the Canadian Arctic Resources Committee, Canadian Ecology Advocates, Ducks Unlimited Canada, Energy Probe Research Foundation, Friends of the Earth, Greenpeace Canada, Pollution Probe, the Royal Society of Canada, the Sierra Club (Canada), the Tree Canada Foundation, and Wildlife Habitat Canada. In addition, all of the provinces and territories have non-governmental organizations that deal with environmental issues on a more regional basis.

Image 28.2. The Nature Conservancy of Canada is an ENGO whose activities focus on acquiring land or land-use rights for the protection of natural values. This project involved the purchase of property on an island in Nova Scotia that provides habitat for several rare plants, including the best known locale in Canada of the eastern mountain avens (Geum Peckii). Source: B. Freedman.

Environmental Citizenship

Although each of us individually has a relatively small effect on the environment, our collective influence is enormous. If all Canadians were to pursue a lifestyle that has softer environmental effects, there would be great benefits for all of us, for future generations, and for other species.

Environmental citizenship involves actions that are taken by people and families to lessen their impact on the environment. Individual acts of environmentalism involve making lifestyle choices that include having a small family, using less energy and material resources, and causing fewer damages to the natural world. In addition to the many "green" actions that people can undertake, they can give moral and financial support to ENGOs that deal with environmental issues at international, national, and regional levels.

Libraries, bookstores, and web sites stock many so-called "green" handbooks and pamphlets. These list hundreds of specific actions that people and families can take to lessen their effect on the environment. The diverse possibilities include shutting off the lights when leaving a room, turning the thermostat down to 15° or less during the winter (while wearing warm slippers and a sweater!), avoiding wasteful travel habits (such as commuting alone in a car), avoiding the use of pesticides in lawn and garden care, planting native trees to store carbon on one's property and to provide wildlife habitat, becoming a vegetarian, and giving money and volunteer time to environmental charities (see In Detail 27.2).

Image 28.3. Each of us can choose to adopt a lifestyle that is less intensive in terms of its environmental impact. Being a "green" person involves many appropriate choices, such as commuting by bicycle instead of by automobile. Source: B. Freedman.

However, few individual Canadians will make all of the green choices that are possible. To do so would be to voluntarily adopt an austere lifestyle, and most people are unwilling to choose this. Instead, most will undertake some positive actions, perhaps including recycling of many household wastes, riding a bicycle to school or work, not worrying about a weedy lawn, and favouring several environmental organizations. This would be selective environmentalism rather than a fully green lifestyle. However, if selective environmentalism is substantial enough, and is adopted by many people, there will be huge benefits. Each of us is responsible for demonstrating our environmental citizenship by making as many green choices as possible and by encouraging relatives, friends, and acquaintances to do the same.

If the citizens of Canada and other countries do not make these sensible, environmentally astute choices, the results will eventually be tragic.

In Detail 27.2. Environmental Choices Each of us is confronted by many choices on how to live our lives, and how to influence our family, friends, and society at large. Many of our choices have significant environmental consequences, in terms of resource use, pollution, and the conservation of biodiversity. In this box, we examine a selection of "green" choices that can contribute to making our lifestyles and economy more sustainable by consuming and wasting less. Consider each of the suggested choices, and think about the environmental benefits that would result if large numbers of Canadians were to adopt them. **Environmental Themes:** Reduce:

- Do not purchase more than you really need
- Avoid disposable or over-packaged products
- Buy products that are durable and long-lasting
- Do not discard items until they are truly worn or cannot be fixed.

Reuse:

- Be practical and creative in finding uses for disused goods to avoid discarding them
- Use empty glass and plastic containers to store bulk food and odds and ends
- Reuse shopping bags at the grocery store and for other purposes
- Save cardboard, paper, string, and rubber bands for reuse
- Pass along disused clothing, toys, furniture, books, and magazines to family or friends, donate them to social service organizations, or sell them

Recycle:

- Discover what materials can be recycled in the area where you live, and then do so as fully as possible
- Purchase products manufactured from recycled materials; this helps to develop a market for the goods

Avoid:

- Do not purchase any goods or services that are produced at an unacceptable cost in terms of the destruction of natural habitat or excessive pollution or resource consumption

Support Environmental Initiatives:

- If you think that a company, government bureaucracy, or politician is not supporting environmentally sound initiatives or policies, complain regularly by writing letters or e-mail, or in other ways –if you think they are doing a good job, let them know that also
- Support environmental organizations (ENGOs) with your money and/or time (as a volunteer)

Lifestyle Choices:

- Become a naturalist by learning to identify wild plants and animals and to understand their habitat needs and ecological relationships
- Become a vegetarian, which allows you to feed lower in the food web and be less involved in the economy of

industrial livestock rearing and slaughter
- Live more simply by consuming fewer resources

Some Specific Actions: Water and Sewage:

- Use a flow-reducing attachment on faucets and shower heads to decrease the use of water
- Turn off taps to reduce dripping, and ensure they are in good repair
- Do not run water continuously when hand-washing dishes, brushing your teeth, washing, or shaving
- Only wash full loads in a dishwasher or washing machine, and use the energy-saver or shortest possible cycle
- Keep a container of drinking water in the refrigerator, instead of running the tap until the water gets cold
- Put food scraps into the compost bin or discard them as garbage; using an in-sink disposal unit wastes water and adds excess organic matter to the sewage system
- Reduce water use by about 20% by placing two 2-litre plastic bottles filled with water into the toilet reservoir, or install a low-flush toilet
- Insulate your water heater and pipes to obtain hot water more quickly and reduce energy wastage
- Do not flush anything down the toilet that was not previously eaten (plus toilet paper) – cigarette butts, disposable diapers, dental floss, tampon holders, and condoms create problems at sewage treatment facilities and litter the environment.
- Use cleaning products that cause little environmental damage and avoid the use of bleach and fabric softener
- If you are not hooked up to a central sewer system, use a composting toilet, which saves water and results in much less organic waste

Energy Use:

- Turn off lights, television, stereo, and other appliances when you leave a room
- Use energy-efficient lights; compare these efficiencies for comparable amounts of lighting:

	incandescent	compact fluorescent	light-emitting diode
Lighting	60 watts	13-15 watts	6-8 watts
Lifespan	1,200 hr	8,000 hr	50,000 hr
Annual cost	$11.95	$2.56	$1.10
CO_2 emissions	68 kg/yr	15.9 kg/yr	2.6 kg/yr

- Where possible, use a pressure cooker or microwave instead of a regular oven; they cook food faster and use much less energy
- In winter, set your thermostat to the lowest comfortable temperature and wear a sweater
- Also in winter, turn down the heat at night and when you are away during the day
- If you use air conditioning in the summer, set your thermostat to the highest comfortable temperature
- Ensure that storm windows and doors fit their frames snugly, and that any crevices are caulked – these actions greatly reduce heat loss during winter and prevent cooling loss in summer
- Install solar panels to produce heat and/or electricity for your house or office
- If you are burning wood in a stove or furnace: only use well-seasoned fuel dried for at least six months, use a high-efficiency burner but do not excessively dampen the combustion because a smoldering burn pollutes the atmosphere, and do not burn painted wood, plastic, or garbage

Use of Household Products:

- Avoid using hazardous cleaning products; instead, use “old fashioned” alternatives such as baking soda, borax, and vinegar
- To clean windows, mix 10 mL of vinegar into 1 L of water, and wipe with newspaper, which can then be composted
- Clean sink drains with hot water containing 60 mL of baking soda and 60 mL of vinegar per L
- Clean your oven with a pasty mixture of water and baking soda or pour salt onto fresh grease spots and wipe clean minutes later
- Clean the toilet with baking soda and a mild detergent using a toilet brush
- Clean sinks and counters with a pasty mixture of baking soda and water
- Polish varnished furniture with a mixture of one part lemon juice and two parts olive or vegetable oil; for unvarnished furniture use 15 mL lemon oil in 1 L mineral oil
- If you must use hazardous household products, inquire about appropriate waste depots and hazardous-waste collection days in your community
- Always store hazardous products in their original containers, so that handling and disposal instructions on labels can be followed
- Store hazardous products in closed containers and in well-ventilated places, and do not store bleach close to acid or ammonia (if mixed, deadly chlorine gas is emitted)
- Use curtains, carpets, furniture, and other household items that contain minimal or no hazardous chemicals and materials, such as formaldehyde
- Use low-toxic paints, stains, varnishes, solvents, waxes, glues, adhesives, and cleaners

In the Garden:

- Water your garden only when necessary, in the coolest part of the day (early morning or late evening), while avoiding over-watering and watering on windy days (to avoid excessive loss by evaporation)
- Cut the lawn to a height of about 6-7 cm, because taller grass holds water better
- Recycle your lawn clippings by leaving them in place for in situ composting
- Use a push mower, which saves fuel, avoids pollution, and provides exercise
- Use a mulch of tree leaves, grass clippings, or wood chips to reduce water evaporation around garden plants, shrubs, and trees
- Avoid using synthetic fertilizer and pesticides, instead fertilize using compost and use alternative pest-control products such as insecticidal soap and manual methods of control (such as digging weeds by hand and hand-picking pest insects)
- Rotate species of vegetables and flowers in your garden from year to year and between locations, to discourage soil diseases and pest insects
- Plant basil, chives, chrysanthemums, garlic, horseradish, marigolds, mint, and thyme amongst garden plants, because their natural odors and root secretions repel many pest insects
- Maintain bird feeders, as birds contribute to natural insect control
- Naturalize your garden by cultivating native plants instead of alien species and let commercial horticultural businesses know that this is what you want to buy
- Compost as much of your organic discards as possible, which greatly reduces the garbage put out for collection and provides an excellent organic fertilizer and soil conditioner
- To avoid pollution, use sand instead of salt to deal with ice on your sidewalk or driveway
- Home gardeners can be efficient and productive food producers, and even if you do not have a backyard you can obtain a plot in your community’s allotment site
- Plant as many trees as possible to offset some of your CO_2 emissions
- Plant well-positioned trees to cool your house instead of using air conditioning
- Collect and use rainwater for watering the garden

When Shopping:

- Patronize small local businesses and farmers' markets instead of large chain stores, which helps to avoid products that have been transported long distances and keeps money in the local economy
- Buy products that are not over-packaged and are in returnable or recyclable containers
- Buy storable products in bulk rather than in over-packaged smaller sizes, and store them in containers that you have saved
- Avoid fruit or vegetables that are sold in blister or plastic packages
- Use a cloth-diaper cleaning service instead of buying disposable diapers
- Buy products in paper containers instead of plastic or polystyrene ones
- Buy unbleached, non-coloured, recycled paper products
- Use fabric shopping bags that can be re-used, or re-use plastic shopping bags

Getting Around:

- Use a bicycle whenever possible
- If you must drive a car or truck, own one that is as small as possible because fuel consumption and overall resource use are strongly related to vehicle weight
- Drive at moderate speeds – a car uses about 10% less fuel when driven at 90 km/h rather than 100 km/h
- Turn off the engine when waiting in your vehicle
- Avoid carrying unnecessary weight, as it causes your vehicle to burn more fuel
- Combine errands to reduce your total mileage
- Keep your vehicle well serviced so it works efficiently
- Use alternatives to the personal motor vehicle as often as possible, such as public transit, car or van pools, walking, or bicycling

In the Office:

- A tablet or laptop computer uses considerably less energy than a desktop computer
- Ink-jet printers use up to 95% less energy than laser printers
- Make two-sided copies when photocopying and printing, and use a machine that has an automatic "stand by" or "sleep" mode

Image 28.4. Ecotourism is an economically important activity that depends on the local availability of high-quality natural habitats. This is a view of part of a jungle lodge in southeastern Peru known as Explorer's Inn. It is a famous destination for naturalists because of the extraordinary richness of tropical birds and vegetation that can be seen there. Source: B. Freedman.

Prospects for Spaceship Earth

It is crucial that people understand how human activities cause damage to our common environment, in both direct and indirect ways. We must also design ways to prevent or effectively mitigate that damage. Over the long term, our society can prosper only if it institutes a sensible limitation on its population and ensures that its use of natural resources is ecologically sustainable.

The coupling of population control with sensible strategies of environmental management will be decisive in attaining a sustainable prosperity for humans, while accommodating other species and their natural communities on the only planet in the universe that is known to sustain life and ecosystems.

> *Try not to see things as they are, but rather as how they should be.* (A principle of Buddhist thought)

Questions for Review

1. What are the circumstances that would trigger an environmental impact assessment, and how would the VECs (valued ecosystem components) be chosen for examination?
2. Define the following terms: economic growth, sustainable development, and ecologically sustainable development.

3. Give an example of environmental legislation in Canada, describe the problem it is intended to address, and clarify the roles and responsibilities of governments, the private sector, and individuals.
4. Make a list of 10 important choices that a Canadian student might consider making in order to soften her or his environmental impact.

Questions for Discussion

1. There has not yet been a full assessment of the environmental impacts of a broad governmental policy, such as entering into a free trade agreement with another country. Does this mean that important environmental considerations are not being adequately considered when Canada's trade policies are developed?
2. Imagine that a large industrial development (such as a power plant, sewage-treatment plant, incinerator, pulp mill, or mine) is being proposed for the area where you live. Make a list of the important environmental considerations that you think should figure in an EIA of the proposed development.
3. Consider a landscape that is being managed for the harvesting of timber for a pulp mill. What economic and ecological values would have to be accommodated by an ecologically sustainable system of land-use in that wood-supply area?
4. Considering all you know about environmental science, do you believe that there is a crisis in the region where you live, or in Canada, or on Earth? If you do believe that there is an environmental crisis, what are the core elements of a societal strategy that would alleviate the damage?

Exploring Issues

1. Make a list of actions that you and your family could easily take in order to become less damaging in your environmental impact. For each action, consider the environmental benefits that would result, as well as the implications for your lifestyle.
2. You have just been elected to the position of "Benevolent Dictator" of Canada. You will have this position of power until you decide you no longer want it, and you have the responsibility to quickly make the national economy operate according to the principles of ecological sustainability. What would be the central elements of such an economy? How would you choose to implement any changes necessary to achieve such a sustainable economy?

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Glossary

accuracy: The degree to which a measurement or observation reflects the actual value. Compare with precision.

acid rain: The wet deposition only of acidifying substances from the atmosphere. See also acidifying deposition.

acid shock: An event of relatively acidic surface water that can occur in the springtime when the snowpack melts quickly but the ground is still frozen.

acid sulphate soil: Acidic soil conditions caused when certain wetlands are drained and sulphide compounds become oxidized.

acid-mine drainage: Acidic water and soil conditions that develop when sulphide minerals become exposed to the atmosphere, allowing them to be oxidized by Thiobacillus bacteria.

acid-neutralizing capacity: The quantitative ability of water to neutralize inputs of acid without becoming acidified. See also buffering capacity.

acidification: An increasing concentration of hydrogen ions (H^+) in soil or water.

acidifying deposition: Both the wet and dry deposition of acidifying substances from the atmosphere.

acute toxicity: Toxicity associated with short-term exposures to chemicals in concentrations high enough to cause biochemical or anatomical damages, even death. Compare with chronic toxicity.

aerobic: Refers to an environment in which oxygen (O_2) is readily available. Compare with anaerobic.

aesthetic pollution: Substantially a matter of cultural values, this commonly involves images that are displeasing to many (but not necessarily all) people.

afforestation: Establishment of a forest where one did not recently occur, as when trees are planted on agricultural land.

age-class structure: The proportions of individuals in various age classes of a population.

agricultural site capability: See site capability.

agroecosystem: An ecosystem used for the production of food.

agroforestry: The cultivation of trees in plantations, typically using relatively intensive management practices.

algal bloom: An event of high phytoplankton biomass.

ammonification: Oxidation of the organically bound nitrogen of dead biomass into ammonium (NH_4+).

anaerobic: Refers to an environment in which oxygen (O_2) is not readily available. Compare with aerobic.

angiosperm: Flowering plants that have their ovules enclosed within a specialized membrane and their seeds within a seedcoat. Compare with gymnosperm.

anthropocentric world view: This considers humans as being more worthy than other species and uniquely disconnected from nature. The importance and worth of everything is considered in terms of the implications for human welfare. Compare with biocentric world view and ecocentric world view.

anthropogenic: Occurring as a result of a human influence.

applied ecology: The application of ecological principles to deal with economic and environmental problems.

aquaculture: The cultivation of fish and other aquatic species.

aquifer: Groundwater resources in some defined area.

artificial selection: The deliberate breeding of species to enhance traits that are viewed as desirable by humans.

artificial wetland: An engineered wetland, usually constructed to treat sewage or other organic wastes.

aspect: The direction in which a slope faces.

assimilation efficiency: In an animal, the percentage of the energy content of ingested food that is absorbed across the gut wall. In plants, the percentage of solar visible light that is fixed by photosynthesis. The term may also be used to refer to the percentage assimilation of ingested inorganic nutrients (such as nitrate or phosphate) by plants or animals, or of drugs by animals.

atmosphere: The gaseous envelope surrounding the Earth, held in place by gravity.

atmospheric inversion (temperature inversion): A relatively stable atmospheric condition in which cool air is trapped beneath a layer of warmer air.

atmospheric water: Water occurring in the atmosphere, in vapour, liquid, or solid forms.

atom bomb: An explosive device that is based on the uncontrolled "splitting" of certain fissile isotopes of uranium and/or plutonium.

autecology: The field within ecology that deals with the study of individuals and species. Compare with synecology.

autotroph: An organism that synthesizes its biochemical constituents using simple inorganic compounds and an external source of energy to drive the process. See also primary producer, photoautotroph, and chemoautotroph.

available concentration: The concentration of metals in an aqueous extract of soil, sediment, or rocks, simulating the amount available for organisms to take up from the environment. Compare with total concentration.

baby boom: A period of high fecundity during 1945–1965 that occurred because of social optimism after the Second World War.

background concentration: A presence or concentration of a substance that is not significantly influenced by either anthropogenic emissions or unusual natural exposures.

binomial: Two latinized words that are used to name a species.

bioaccumulation (bioconcentration): The occurrence of chemicals in much higher concentrations in organisms than in the ambient environment. Compare with food-web magnification.

biocentric world view: This considers all species (and individuals) as having equal intrinsic value. Humans are not considered more important or worthy than any other species. Compare with anthropocentric world view and ecocentric world view.

bioconcentration: See bioaccumulation.

biodegradation: The breakdown of organic molecules into simpler compounds through the metabolic actions of microorganisms.

biodiversity: The richness of biological variation, including genetic variability as well as species and community richness.

biodiversity crisis: The present era of high rates of extinction and endangerment of biodiversity.

biogeochemical prospecting: Prospecting for metal ores using observations of high metal concentrations in plants, soil, or surface rocks.

biological control: Pest-control methods that depend on biological interactions, such as diseases, predators, or herbivores.

biological oxygen demand (BOD): The capacity of organic matter and other substances in water to consume oxygen during decomposition.

biomagnification: See food-web magnification.

biomass energy: The chemical potential energy of plant biomass, which can be combusted to provide thermal energy.

biome: A geographically extensive ecosystem, occurring throughout the world wherever environmental conditions are suitable.

biophilia: An innate love of people for nature

bio-resource: A renewable resource that is biological in character.

biosphere: All life on Earth, plus their ecosystems and environments.

birth control: Methods used to control fertility and childbirth.

BOD: See biological oxygen demand.

bog: An infertile, acidic, unproductive wetland that develops in cool but wet climates. Compare with fen.

boreal coniferous forest: A northern forest dominated by coniferous trees, usually species of fir, larch, pine, or spruce. See also boreal forest.

boreal forest (taiga): An extensive biome occurring in environments with cold winters, short but warm growing seasons, and moist soils, and usually dominated by coniferous trees.

broad-spectrum pesticide: A pesticide that is toxic to other organisms as well as the pest.

broadcast spray: A pesticide treatment over a large area.

browse: Broad-leaved shrubs that are eaten by herbivores such as hares and deer.

bryophyte: Simple plants that do not have vascular tissues nor a cuticle on their foliage.

by-catch: Inadvertent harvesting of a non-target species.

buffering capacity: The ability of a solution to resist changes in pH as acid or base is added.

calorie: A standard unit of energy, defined as the amount of energy needed to raise the temperature of one gram of pure water from 15°C to 16°C. Compare with joule.

carbon credits: Actions that help reduce the atmospheric concentration of CO_2, such as fossil-fuel conservation and planting trees.

carbon credits: See carbon credits.

carnivore (secondary consumer): An animal that hunts and eats other animals.

carrying capacity: The abundance of a species that can be sustained without the habitat becoming degraded.

chaparral: A shrub-dominated ecosystem that occurs in south- temperate environments with winter rains and summer drought.

chemical weapons: Weapons that cause deaths or injuries through exposure to toxic chemicals.

chemoautotroph: Microorganisms that harness some of the potential energy of certain inorganic chemicals (e.g., sulphides) to drive their fixation of energy through chemosynthesis. Compare with photoautotroph.

chemosynthesis: Autotrophic productivity that utilizes energy released during the oxidation of certain inorganic chemicals (such as sulphides) to drive biosynthesis. Compare with photosynthesis.

chromosome: Subcellular unit composed of DNA and containing the genetic information of eukaryotic organisms.

chronic toxicity: Toxicity associated with exposure to small or moderate concentrations of chemicals, sometimes over a long period of time. The damages may be biochemical or anatomical, and may include the development of a lethal disease, such as cancer. Compare with acute toxicity.

clear-cutting: The harvesting of all economically useful trees from an area at the same time.

climate: The prevailing, long-term, meteorological conditions of a place or region, including temperature, precipitation, wind speed, and other factors. Compare with weather.

climate change: Long-term changes in air, soil, or water temperature; precipitation regimes; wind speed; or other climate-related factors.

coal: An organic-rich, solid fossil fuel mined from sedimentary geological formations.

coal washing: See fuel desulphurization.

coarse woody debris: Logs lying on the forest floor.

coevolution: This occurs when species interact in ways that affect their reciprocal survival, and so are subject to a regime of natural selection that reinforces their mutual evolutionary change.

collective properties: This term is used in reference to the summation of the parts of a system. See also emergent properties.

commensalism: A symbiosis in which one of the species benefits from the interaction, while the other is not affected in either a positive or negative way.

commercial energy production: The use of solid, liquid, and gaseous fuels, plus all electricity. Does not include the use of traditional fuels. See also total energy production and traditional fuels.

commercial extinction: Depletion of a natural resource to below the abundance at which it can be profitably harvested.

common-property resource: A resource shared by all of society, not owned by any particular person or interest.

community: In ecology, this refers to populations of various species that are co-occurring at the same time and place.

community-replacing disturbance: A disturbance that results in the catastrophic destruction of an original community, and its replacement by another one. Compare with microdisturbance.

compaction: A decrease in the pore space of soil (or increased bulk density) caused by the passage of heavy machinery.

compartment: A reservoir of mass in a nutrient or material cycle.

competition: A biological interaction occurring when the demand for an ecological resource exceeds its limited supply, causing organisms to interfere with each other.

competitor: A species that is dominant in a habitat in which disturbance is rare and environmental stresses are unimportant, so competition is the major influence on evolution and community organization.

compost: Partially decomposed, well-humified organic material

composting: The processing of discarded organic material by encouraging decomposition processes under warm, moist, oxygen-rich conditions. The product, known as compost, is a useful fertilizer and soil conditioner.

conservation: Wise use of natural resources. Conservation of nonrenewable resources involves recycling and other means of efficient use. Conservation of renewable resources includes these means, in addition to ensuring that harvesting does not exceed the rate of regeneration of the stock.

contamination: The presence of potentially damaging chemicals in the environment, but at concentrations less than those required to cause toxicity or other ecological damages. Compare with pollution.

control (control treatment): An experimental treatment that was not manipulated, and is intended for comparison with manipulated treatments.

conventional economics: Economics as it is commonly practised, which includes not accounting for costs associated with ecological damages and resource depletion. Compare with ecological economics.

conventional munitions: Explosive devices that are based on chemical reactions, such as cordite and dynamite.

convergence (evolutionary conversion): This occurs when unrelated species with similar niches and living in comparable environments are subjected to parallel regimes of natural selection, resulting in their evolution to be similar in morphology, physiology, and behaviour.

conversion: See ecological conversion.

core: Earth's massive interior, made up of hot molten metals.

Coriolis effect: An influence of Earth's west-to-east rotation, which makes winds in the Northern Hemisphere deflect to the right and those in the Southern Hemisphere to the left.

creationist: A person who rejects the theory of evolution in favour of a literal interpretation of Genesis, the first book of the Old Testament of the Bible. See also scientific creationist.

critical load: A threshold for pollutant inputs, below which it is thought ecological damages will not be caused.

crude oil: See petroleum.

crude oil washing (COW) method: A method of washing a tanker's oil-storage components with a spray of crude oil before the next cargo is loaded. This eliminates the use of wash-water and avoids an important cause of marine oil pollution.

crust: The outermost layer of Earth's sphere, overlying the lithosphere and composed mostly of crystalline rocks.

cultural eutrophication: Eutrophication caused by anthropogenic nutrient inputs, usually through sewage dumping or fertilizer runoff. See also eutrophication.

cultural evolution: Adaptive evolutionary change in human society, characterized by increasing sophistication in the methods, tools, and social organizations used to exploit the environment and other species. Compare with evolution.

cultural identity: A complex of self-identified characteristics and values that a group of people considers important in defining their distinct quality.

culture: The shared beliefs, values, and knowledge of a defined group of people.

cumulative environmental impacts: Environmental impacts that result from a proposed undertaking, in addition to those caused by any past, existing, and imminent developments and activities.

decay: The decomposition or oxidation of dead biomass, mostly through the actions of microorganisms.

decomposer: See detritivore.

deductive logic: Logic in which initial assumptions are made and conclusions are then drawn from those assumptions. Compare with inductive logic.

deep drainage: Soil water that has drained to below the lower limits of plant roots.

deforestation: A permanent conversion of forest into some other kind of ecosystem, such as agriculture or urbanized land use.

demographic transition: A change in human population parameters from a condition of high birth and death rates to one of low birth and death rates.

denitrification: The microbial reduction of nitrate (NO_3^-) into gaseous N_2O or N_2.

desert: A temperate or tropical biome characterized by prolonged drought, usually receiving less than 25 cm of precipitation per year.

desertification: The increasing aridity of drylands; an environmental change that can make agriculture difficult or impossible.

detritivore: A heterotroph that feeds on dead organic matter.

developed countries: Countries with a relatively well-organized economic infrastructure and a high average per-capita income. See also high-income countries and compare with less-developed countries.

development (economic development): An economic term that implies improving efficiency in the use of materials and energy in an economy, and progress toward a sustainable economic system. Compare with economic growth.

discipline: A specific area of study, such as mathematics or music.

disturbance: An episode of destruction of some part of a community or ecosystem.

DNA: The biochemical deoxyribonucleic acid, the main constituent of the chromosomes of eukaryotic organisms.

domestication: The genetic, anatomic, and physiological modification of crops and other species from their wild, progenitor species, through the selective breeding of preferred races (or cultivars).

dose-response relationship: The quantitative relationship between different doses of a chemical and a biological or ecological response.

doubling time: The time it takes for something to increase by a factor of two (as in population growth).

drift: Movement of applied pesticide off the intended site of deposition through atmospheric or aquatic transport.

dry deposition: Atmospheric inputs of chemicals occurring in intervals between rainfall or snowfall. Compare with wet deposition.

dumping: The long-term disposal of disused material, for example, by placing solid waste into a sanitary landfill, or by discarding liquid waste into a waterbody.

earthquake: A trembling or movement of the earth, caused by a sudden release of geological stresses at some place within the crust.

ecocentric world view: This incorporates the biocentric world view but also stresses the importance of interdependent ecological functions, such as productivity and nutrient cycling. In addition, the connections among species within ecosystems are considered to be invaluable. Compare with anthropocentric world view and biocentric world view.

ecofeminism: A philosophical and political movement that applies feminist ideas to environmental concerns.

ecological conversion: A long-term change in the character of the ecosystem at some place, as when a natural forest is converted into an agricultural land use.

ecological economics: A type of economics that involves a full accounting of costs associated with ecological damages and resource depletion. Compare with conventional economics.

ecological footprint: The area of ecoscape (i.e., landscape and seascape) required to supply a human population with the necessary food, materials, energy, waste disposal, and other crucial goods and services.

ecological integrity (ecosystem health): A notion related to environmental quality, but focusing on changes in natural populations and ecosystems, rather than effects on humans and their economy. See also environmental quality.

ecological justice: A worldview in which all species (i.e., not just humans) have a right to equitable access to the necessities of life and happiness. See also social justice.

ecological pyramid: A model of the trophic structure of an ecosystem, organized with plant productivity on the bottom, that of herbivores above, and carnivores above the herbivores.

ecological service: An ecological function that is useful to humans and to ecosystem stability and integrity, such as nutrient cycling, productivity, and control of erosion.

ecological stress: See stressors.

ecological sustainability: See ecologically sustainable development.

ecological values: Broader utilitarian values that are based on the needs of humans, but also on those of other species and natural ecosystems.

ecologically sustainable development: This considers the human need for resources within an ecological context, and includes the need to sustain all species and all components of Earth's life-support system. Compare with sustainable development.

ecologically sustainable economic system: An economic system that operates without a net consumption of natural resources, and without endangering biodiversity or other ecological values. Ultimately, ecologically sustainable economic systems are supported by the wise use of renewable resources.

ecologically sustainable economy: An economy in which ecological goods and services are utilized in ways that do not compromise their future availability and do not endanger the survival of species or natural ecosystems.

ecology: The study of the relationships between organisms and their environment.

economic development: See development.

economic growth: A term that refers to an economy that is increasing in size over time, usually due to increases in both population and per capita resource use. Compare with development.

ecoregion: See ecozone.

ecoscape: A general term for landscapes or seascapes.

ecosystem: A general term used to describe one or more communities that are interacting with their environment as a defined unit. Ecosystems range from small units occurring in microhabitats, to larger units such as landscapes and seascapes, and even the biosphere.

ecosystem approach: A holistic interpretation of the natural world that considers the web-like interconnections among the many components of ecosystems.

ecosystem health: See ecological integrity.

ecotone: A zone of transition between two distinct habitats.

ecotoxicology: Study of the directly poisonous effects of chemicals in ecosystems, plus indirect effects such as changes in habitat or food abundance caused by toxic exposures. Compare with toxicology and environmental toxicology.

ecotype: A population specifically adapted to coping with locally stressful conditions, such as soil with high metal concentrations.

ecozone: The largest biophysical zones in the national ecological classification of Canada.

electromagnetic energy: Energy associated with photons, comprising an electromagnetic spectrum divided into components, including ultraviolet, visible, and infrared.

emergent property: A used in reference to synergetic properties that are greater than the summation of the parts of a system. See also collective properties.

emissions trading: A system in which a company whose that has not exceeded its cap on emissions of a regulated substance, such as SO_2, can sell its "surplus" to another that is likely to exceed its cap.

endangered: In Canada, this specifically refers to indigenous species threatened with imminent extinction or extirpation over all or a significant portion of their Canadian range.

endemic: An ecological term used to describe species with a local geographic distribution.

energy: The capacity of a body or system to accomplish work, and existing as electromagnetic, kinetic, and potential energies.

energy budget: An analysis of the rates of input and output of energy to a system, plus transformations of energy among its states, including changes in stored quantities.

energy production: See total energy production.

entropy: A physical attribute related to the degree of randomness of the distributions of matter and energy.

environment (the): (1) Refers to influences on organisms and ecosystems, including both non-living (abiotic) and biological factors; (2) An indeterminate word for issues associated with the causes and consequences of environmental damage, or with the larger environmental crisis.

environmental citizenship: Actions taken by individuals and families to lessen their impacts on the environment.

environmental degradation: Refers to pollution, disturbance, resource depletion, lost biodiversity, and other kinds of environmental damage; usually refers to damage occurring accidentally or intentionally as a result of human activities (see also anthropogenic), but can also be caused by natural disasters or stressors.

environmental discrimination (environmental prejudice): Discrimination against any defined group that results in them suffering a disproportionate amount of degradation or pollution of their living or work environment. See also environmental racism.

environmental ecology: See applied ecology

environmental education: A way of fostering environmental literacy by incorporating environmental issues in educational curricula, both in specialized classes as well as across the curriculum, and also including the out-of-school public.

environmental ethics: These deal with the responsibilities of the present human generation to ensure continued access to adequate resources and livelihoods for future generations of people and other species.

environmental impact assessment (EIA): A process used to identify and evaluate the potential consequences of proposed actions or policies for environmental quality. See also socioeconomic impact assessment.

environmental indicators: Relatively simple measurements that are sensitive to changes in the intensity of stressors, and are considered to represent complex aspects of environmental quality.

environmental literacy: Refers to an objective understanding, by individuals and society-at-large, of the causes and consequences of environmental problems.

environmental monitoring: Repeated measurements of indicators related to the inorganic environment or to ecosystem structure and function.

environmental mutagen: A mutagenic influence that is encountered in the environment. See also mutagen.

environmental non-governmental organizations (ENGOs): Charities and other not-for-profit organizations that are working in the environmental field. See also non-governmental organizations.

environmental quality: A notion related to the amounts of toxic chemicals and other stressors in the environment, to the frequency and intensity of disturbances, and to their effects on humans, other species, ecosystems, and economies.

environmental racism: Discrimination against a group of people defined by racial attributes, which results in them suffering a disproportionate amount of degradation or pollution of their living or work environment. See also environmental discrimination.

environmental reporting: Communication of information about changes in environmental quality to interest groups and the general public.

environmental risk: A hazard or probability of suffering damage or misfortune because of exposure to some environmental circumstance.

environmental risk assessment: A quantitative evaluation of the risks associated with an environmental hazard.

environmental science: An interdisciplinary branch of science that investigates questions related to the human population, resources, and damages caused by pollution and disturbance.

environmental scientist: A scientist who is specialized in some aspect of environmental science.

environmental security: The protection of people and the public interest from environmental risks, particularly those associated with anthropogenic activities and accidents, but may also include natural dangers.

environmental stressor: See stressor.

environmental studies: An extremely interdisciplinary approach that examines the scientific, social, and cultural aspects of environmental issues.

environmental teratogen: A teratogenic influence that is encountered in the environment. See also teratogen.

environmental toxicology: The study of environmental factors influencing exposures of organisms to potentially toxic levels of chemicals. Compare with toxicology and ecotoxicology.

environmental values: Perceptions of the worth of environmental components, divided into two broad classes: utilitarian and intrinsic.

environmentalist: Anyone with a significant involvement with environmental issues, usually in an advocacy sense.

erosion: The physical removal of rocks and soil through the combined actions of flowing water, wind, ice, and gravity.

estuary: A coastal, semi-enclosed ecosystem that is open to the sea and has habitats transitional between marine and freshwater conditions.

ethics: The perception of right and wrong. The proper behaviour of people toward each other and toward other species and nature.

eukaryote: Organisms in which the cells have an organized, membrane-bound nucleus containing the genetic material. Compare with prokaryote.

eutrophic: Pertains to waters that are highly productive because they contain a rich supply of nutrients. Compare with oligotrophic and mesotrophic.

eutrophication: Increased primary productivity of an aquatic ecosystem, resulting from nutrient inputs.

evaporation: The change of state of water from a liquid or solid to a gas.

evapotranspiration: Evaporation of water from a landscape. See also transpiration.

evolution: Genetically based changes in populations of organisms, occurring over successive generations.

evolutionary ecology: The interpretation of ecological knowledge in terms of evolution, natural selection, and related themes.

experiment: A controlled test or investigation designed to provide evidence for, or preferably against, a hypothesis about the natural or physical world.

exposure: In ecotoxicology, this refers to the interaction of organisms with an environmental stressor at a particular place and time.

exposure assessment: An investigation of the means by which organisms may encounter a potentially toxic level of a chemical or other environmental stressor.

externality: A cost or benefit that is received, even though the affected party did not choose to incur it.

extant: A species that still exists. Compare with extinct.

extinct (extinction): A condition in which a species or other taxon no longer occurs anywhere on Earth.

extinction crisis: See biodiversity crisis.

extinction vortex: An accelerating spiral of endangerment and extinction caused by worsening environmental conditions.

extirpated (extirpation): A condition in which a species or other taxon no longer occurs in some place or region, but still survives elsewhere.

fact: An event or thing known to have happened, to exist, or to be true. See also hypothesis.

fen: A wetland that develops in cool and wet climates, but is less acidic and more productive than a bog because it has a better nutrient supply. Compare with bog.

first law of thermodynamics: A physical principle stating that energy can undergo transformations among its various states, but it is never created or destroyed; thus, the energy content of the universe remains constant. See also second law of thermodynamics.

First Nations: The Aboriginal people(s) originally living in some place. This term is often used in reference to the original inhabitants of the Americas, prior to the colonization of those regions by Europeans, and their modern descendants.

fission bomb: See atom bomb.

fission reaction: Nuclear reaction involving the splitting of heavier, radioactive atoms into lighter ones, with the release of large quantities of energy.

fitness: The proportional contribution of an individual to the progeny of its population.

flow-through system: A system with an input and an output of energy or mass, plus temporary storage of any difference.

flue-gas desulphurization: A process to remove SO_2 from the waste (flue) gases of a power plant or smelter, before they are discharged into the atmsophere.

flux: A movement of mass or energy between compartments of a material or energy cycle.

food chain: A hierarchical model of feeding relationships among species in an ecosystem.

food web: A complex model of feeding relationships, describing the connections among all food chains within an ecosystem.

food-web magnification (food-web accumulation, food-web concentration): The tendency for top predators in a food web to have the highest residues of certain chemicals, especially organochlorines. Compare with bioaccumulation.

forest floor: Litter and other organic debris lying on top of the mineral soil of a forest.

forestry: The harvesting of trees and management of post-harvest succession to foster the regeneration of another forest.

fossil fuel: Organic-rich geological materials, such as coal, petroleum, and natural gas.

frontier world view: This asserts that humans have a right to exploit nature by consuming natural resources in boundless quantities. See also sustainability world view and spaceship world view.

fuel desulphurization: A process that removes much of the sulphur content of coal before it is used as a fuel in a power plant.

fuel switching: The replacement of a high-sulphur fuel, such as coal, by an energy source that does not emit sulphur gases, such as hydroelectricity or nuclear power.

full-cost accounting system: An accounting system that considers all costs, including those of environmental damage.

fungicide: A pesticide used to protect crop plants and animals from fungi that cause diseases or other damages.

fusion bomb: See hydrogen bomb.

fusion reaction: Nuclear reaction involving the combining of light nuclei, such as those of hydrogen, to make heavier ones, with the release of large quantities of energy. Fusion reactions occur under conditions of intense temperature and pressure, such as within stars and in hydrogen bombs.

Gaia hypothesis: A notion that envisions Earth's species and ecosystems as a "superorganism" that attempts to optimize environmental conditions toward enhancing its own health and survival.

gaseous wastes: The gaseous products of combustion or industrial reactions.

gene: A region of a chromosome, containing a length of DNA that behaves as a particulate unit in inheritance and determines the development of a specific trait.

genocide: The mass killing of an identifiable group as an attempted extermination.

genotype: The genetic complement of an individual organism. See also phenotype.

geography: The study of the features of the surface of the Earth, including topography, landforms, soil, climate, and vegetation, as well as the intersections of these with the economic interests of humans.

geothermal energy: Heat in Earth's crust, which can sometimes be used to provide energy for heating or generation of electricity.

glaciation: An extensive environmental change associated with an extended period of global climatic cooling and characterized by advancing ice sheets.

glacier: A persistent sheet of ice, occurring in the Arctic and Antarctic and at high altitude on mountains.

greater protected area: A protected area plus its immediately surrounding area, co-managed to sustain populations of indigenous species and natural communities.

green manure: Living plant biomass that is grown and then incorporated into the soil by tillage.

green revolution: Intensive agricultural systems involving the cultivation of improved crop varieties in monoculture, and increased use of mechanization, fertilizers, and pesticides.

greenhouse effect: The physical process by which infrared-absorbing gases (such as CO_2) in Earth's atmosphere help to keep the planet warm.

greenhouses gases (GHGs): Atmospheric gases that efficiently absorb infrared radiation and then dissipate some of the thermal energy gain by re-radiation. Synonym: ** radiatively active gases.

gross domestic product (GDP): The total annual value of all goods and services produced domestically within a country. GDP is equivalent to gross national product minus net investment income from foreign countries. See also gross national product (GNP).

gross national product (GNP): The total annual value of all goods and services produced domestically by a country, including net foreign investment income. See also gross domestic product (GDP).

gross primary production (GPP): The fixation of energy by primary producers within an ecosystem. See also respiration, net primary production, and autotroph.

groundwater: Water stored underground in soil and rocks.

groundwater drainage: The drainage of water to storage places in the ground, occurring under the influence of gravity.

growth: Refers to an economy or economic sector that is increasing in size over time. Compare with development.

gymnosperm: Vascular plants such as conifers, which have naked ovules not enclosed within a specialized membrane, and seeds without a seedcoat. Compare with angiosperm.

habitat: The place or "home" where a plant or animal lives, including the specific environmental factors required for its survival.

harvesting effort: The amount of harvesting, which is a function of both the means (such as the kinds of fishing gear) and the intensity (the number of boats and the amount of time each spends fishing).

harvesting mortality: Anthropogenic mortality, especially that due to the harvesting of a bio-resource. Compare with natural mortality.

hazardous waste: Wastes that are flammable, explosive, toxic, or otherwise dangerous. See also toxic waste.

herbicide: A pesticide used to kill weeds. See also weed.

herbivore (or primary consumer): An animal that feeds on plants.

heterotroph: An organism that utilizes living or dead biomass as food.

hidden injury: A reduction in plant productivity caused by exposure to pollutants, but not accompanied by symptoms of acute tissue damages.

high-income countries: Countries with a relatively high average per-capita income. See also developed countries and compare with low-income countries.

hormone: A biochemical produced in an endocrine gland (and transported by the blood) that functions to regulate a metabolic process. Some chemicals in food may mimic the function of hormones produced naturally in the body.

hormonally active substance: A hormone or another chemical that has an effect on the regulation of biochemistry. See also hormone.

humidity: The actual concentration of water in the atmosphere, usually measured in mg/m^3. Compare with relative humidity.

humus: Amorphous, partially decomposed organic matter. An important and persistent type of soil organic matter, it is very important in soil tilth and fertility.

hydrocarbons: Molecules composed of hydrogen and carbon only.

hydroelectric energy: Electricity generated using the kinetic energy.

hydrogen bomb: A nuclear weapon that is based on the fusion of nuclei of deuterium and tritium, two isotopes of hydrogen.

hydrologic (water) cycle: The movement between, and storage of water in, various compartments of the hydrosphere. See also hydrosphere.

hydrosphere: The parts of the planet that contain water, including the oceans, atmosphere, on land, in surface waterbodies, underground, and in organisms.

hyperaccumulator: A species that bioaccumulates metals or other chemicals to extremely high concentrations in their tissues. See also bioaccumulation.

hypereutrophic: Extremely eutrophic waters; usually considered to be a degraded ecological condition. See also eutrophic.

hypersensitivity: An extreme sensitivity to exposure to some environmental factor, resulting in a biological response such as asthma, disease, or even death. It may be expressed at the species or individual level, and it involves responses at relatively low intensities of exposure that the great majority of species or individuals could tolerate.

hypothesis: A proposed explanation for the occurrence or causes of natural phenomena. Scientists formulate hypotheses as statements, and test them through experiments and other forms of research. See also fact.

igneous rock: Rock such as basalt and granite, formed by cooling of molten magma.

impoundment: An area of formerly terrestrial landscape that is flooded behind a dam.

incineration: The combustion of mixed solid wastes to reduce the amount of organic material present.

indicator: See environmental indicator.

indigenous culture: A human culture existing in a place or region prior to its invasion, or other significant influence, by a foreign culture.

individual organism: A genetically and physically discrete living entity.

inductive logic: Logic in which conclusions are objectively developed from the accumulating evidence of experience and the results of experiments. See also deductive logic.

inequitable: Not equitable or fair.

inherent value: See intrinsic value

inhumane: Reflecting a lack of pity or compassion; most commonly refers to the cruel treatment by humans of other animals.

insecticide: A pesticide used to kill insects that are considered pests. See also pesticide and pest.

instrumental value: See utilitarian value

integrated forest management: Forest management plans that accommodate the need to harvest timber from landscapes, while also sustaining other values, such as hunted wildlife, outdoor recreation, and biodiversity.

integrated pest management (IPM): The use of a variety of complementary tactics toward pest control, with the aim of having fewer environmental and health risks.

interdisciplinary: Encompassing a wide diversity of kinds of knowledge.

intrinsic population change: Population change due only to the balance of birth and death rates.

intrinsic value: Value that exists regardless of any direct or indirect value in terms of the needs or welfare of humans.

invasive alien: Refers to non-native species that survive in wild habitats and possibly aggressively out-compete native species or cause other kinds of ecological damage.

inversion: See atmospheric inversion.

invertebrate: Any animal that lacks an internal skeleton, and in particular a backbone.

joule: A standard unit of energy, defined as the energy needed to accelerate 1 kg of mass at 1 m/s2 for a distance of 1 metre. Compare with calorie.

K-selected: Refers to organisms that produce relatively small numbers of large offspring. A great deal of parental investment is made in each progeny, which helps to ensure their establishment and survival. Compare with r-selected.

keystone species: A dominant species in a community, usually a predator, with an influence on structure and function that is highly disproportionate to its biomass.

kinetic energy: Energy associated with motion, including mechanical and thermal types.

knowledge: Information and understanding about the natural world.

landscape: The spatial integration of ecological communities over a large terrestrial area.

landscape ecology: Study of the spatial characteristics and temporal dynamics of communities over large areas of land (landscapes) or water (seascapes).

laws of thermodynamics: Physical principles that govern all transformations of energy. See also first law of thermodynamics and second law of thermodynamics.

leaching: The movement of dissolved substances through the soil with percolating rainwater.

legacy munitions: See unexploded ordinance.

lentic ecosystem: A freshwater ecosystem characterized by nonflowing water, such as a pond or lake. Compare with lotic ecosystem.

less-developed countries: Countries with a relatively well-organized economic infrastructure and a high average per-capita income. See also high-income countries and compare with developed countries.

life form: A grouping of organisms on the basis of their common morphological and physiological characteristics, regardless of their evolutionary relatedness.

life index (production life): The known reserves of a resource divided by its current rate of production.

liming: Treatment of a waterbody or soil to reduce acidity, usually by adding calcium carbonate or calcium hydroxide.

limiting factor: An environmental factor that is the primary restriction on the productivity of autotrophs in an ecosystem. See also Principle of Limiting Factors.

liquid waste: Variable urban wastes that include sewage and discarded industrial and household fluids.

lithification: A geological process in which materials are aggregated, densified, and cemented into new sedimentary rocks.

lithosphere: An approximately 80-km thick region of rigid, relatively light rocks that surround Earth's plastic mantle.

load-on-top (LOT) method: A process used in ocean-going petroleum tankers to separate and contain most oily residues before ballast waters are discharged to the marine environment.

long-range transport of air pollutants: See LRTAP.

lotic ecosystem: A freshwater ecosystem characterized by flowing water, such as a stream or river. Compare with lentic ecosystem.

low-income counties: Countries with a relatively small average per-capita income. See also less-developed countries and compare with high-income countries.

LRTAP: The long-range transport of atmospheric pollutants.

macroclimate: Climatic conditions affecting an extensive area. Compare with microclimate.

macroevolution: The evolution of species or higher taxonomic groups, such as genera, families, or classes. Compare with microevolution.

management system: A variety of management practices used in a coordinated manner.

manipulative experiment: An experiment involving controlled alterations of factors hypothesized to influence phenomena, conducted to investigate whether predicted responses will occur, thereby uncovering causal relationships. See also experiment and natural experiment.

mantle: A less-dense region that encloses Earth's core, and composed of minerals in a hot, plastic state known as magma.

marsh: A productive wetland, typically dominated by species of monocotyledonous angiosperm plants that grow as tall as several metres above the water surface.

mass extinction: An event of synchronous extinction of many species, occurring over a relatively short period of time. May be caused by natural or anthropogenic forces.

maximum sustainable yield (MSY): The largest amount of harvesting that can occur without degrading the productivity of the stock.

mechanization: The use of specialized machinery to perform work, instead of the labour of people or animals.

megacity: A large city, sometimes defined as having a population greater than 8 million people.

mesosphere: The layer of the atmosphere extending beyond the stratosphere to about 75 km above the surface of the Earth. See also stratosphere.

mesotrophic: Pertains to aquatic ecosystems of moderate productivity, intermediate to eutrophic and oligotrophic waters. Compare with eutrophic and oligotrophic.

metal: Any relatively heavy element that in its pure state shares electrons among atoms, and has useful properties such as malleability, high conductivity of electricity and heat, and tensile strength.

metamorphic rock: Rock formed from igneous or sedimentary rocks that have changed in structure under the influences of geological heat and pressure.

meteorite: An extraterrestrial rock-like object; very rarely, one may intersect with Earth's orbit and impact the planet.

microclimate: Climatic conditions on a local scale. Compare with macroclimate.

microdisturbance: Local disruptions that affect small areas within an otherwise intact community. Compare with community-replacing disturbance.

microevolution: Relatively subtle evolutionary changes occurring within a population or species, sometimes within only a few generations, and at most leading to the evolution of races, varieties, or subspecies. Compare with macroevolution.

middle-income countries: Countries with a rapidly increasing average per-capita income. See also high-income and low-income countries and compare with developed countries and less-developed countries.

militarism: A belief of people or governments in the need to maintain a strong military capability to defend or promote national interests.

mitigation: An action that repairs or offsets environmental damages to some degree.

monoculture: The cultivation of only one species while attempting to exclude others from the agroecosystem.

montane forest: A conifer-dominated forest occurring below the alpine zone on mountains.

MSY: See maximum sustainable yield.

mutagen: A chemical or physical agent (e.g., ultraviolet radiation) that is capable of inducing genetic mutations.

mutualism (mutualistic symbiosis): A symbiosis in which both partners benefit.

natural: Refers to a non-anthropogenic context, i.e., one that is not influenced by humans and is self-organizing and dominated by native species; see also nature.

natural capital: See natural resource

natural experiment: An experiment conducted by observing variations of phenomena in nature, and then developing explanations for these through analysis of potential causal mechanisms. See also experiment and manipulative experiment.

natural gas: A gaseous, hydrocarbon-rich mixture mined from certain geological formations.

natural mortality: Mortality due to natural causes. Compare with harvesting mortality.

natural population change: A change in population that is due only to the difference in birth and death rates, and not to immigration or emigration.

natural resource: A source of material or energy that is extracted (harvested) from the environment.

natural selection: A mechanism of evolution, favouring individuals that, for genetically based reasons, are better adapted to coping with environmental opportunities and constraints. These more fit individuals have an improved probability of leaving descendants, ultimately leading to genetically based changes in populations, or evolution.

nature: Refers to the entire system of physical and biological existence and organization, uninfluenced by humans; see also natural.

net ecosystem productivity: The amount of ecosystem-level productivity that remains after respiration is subtracted from gross productivity.

net primary production (NPP): Primary production that remains as biomass after primary producers have accounted for their respiratory needs. See also respiration and gross primary production.

niche: The role of a species within its community.

NIMBY: An acronym for "not in my backyard".

nitrification: The bacterial oxidation of ammonium (NH_4+) to nitrate (NO_3-).

nitrogen fixation: The oxidation of nitrogen gas (N_2) to ammonia (NH_3) or nitric oxide (NO).

noise pollution: When the level of ambient sound becomes distracting to the normal activities of people. At a higher intensity it can cause hearing impairment.

non-governmental organizations (NGOs): Charities and other not- for-profit organizations. See also environmental non-governmental organizations.

non-renewable resource (non-renewable natural resource): A resource present on Earth in finite quantities, so as it is used, its future stocks are diminished. Examples are metals and fossil fuels. Compare with renewable resources.

non-target damage: Damage caused by a pesticide to non-target organisms. See also broad-spectrum pesticide and non-target organism.

non-target organism: Organisms that are not pests, but which may be affected by a pesticide treatment. See also broad-spectrum pesticide and non-target damage.

not in my backyard: See NIMBY.

nuclear fuel: Unstable isotopes of uranium (^{235}U) and plutonium (^{239}Pu) that decay through fission, releasing large amounts of energy that can be used to generate electricity.

nuclear winter: A period of prolonged climate cooling that might be caused by a nuclear war.

null hypothesis: A hypothesis that seeks to disprove a hypothesis.

nutrient: Any chemical required for the proper metabolism of organisms.

nutrient budget: A quantitative estimate of the rates of nutrient input and output for an ecosystem, as well as the quantities present and transferred within the system.

nutrient capital: The amount of nutrients present in a site in soil, living vegetation, and dead organic matter.

nutrient cycling: Transfers and chemical transformations of nutrients in ecosystems, including recycling through decomposition.

ocean: The largest hydrological compartment, accounting for about 97% of all water on Earth.

old-growth forest: A late-successional forest characterized by the presence of old trees, an uneven-aged population structure, and a complex physical structure.

oligotrophic: Pertains to aquatic ecosystems that are highly unproductive because of a sparse supply of nutrients. Compare with eutrophic and mesotrophic.

omnivore: An animal that feeds on both plant and animal materials.

organic agriculture: Systems by which crops are grown using natural methods of maintaining soil fertility, and pest-control methods that do not involve synthetic pesticides.

orographic precipitation: Precipitation associated with hilly or mountainous terrain that forces moisture-laden air to rise in altitude and become cooler, causing water vapour to condense into droplets that precipitate as rain or snow.

outer space: Regions beyond the atmosphere of Earth.

over-harvesting (over-exploitation): Unsustainable harvesting of a potentially renewable resource, leading to a decline of its stocks.

oxidizing smog: An event of air pollution rich in ozone, peroxy acetyl nitrate, and other oxidant gases.

paradigm: A pattern or model; a collection of assumptions, concepts, practices, and values that constitutes a way of viewing reality, especially for an intellectual community that shares them.

parameter: One or more constants that determine the form of a mathematical equation. In the linear equation $Y = aX + b$, a and b are parameters, and Y and X are variables. See also variable.

parasitism: A biological relationship involving one species obtaining nourishment from a host, usually without causing its death.

peace: The absence of war.

peace-keeping: An action that occurs after a hot conflict has stopped through a cease-fire agreement, but the conditions for a lasting peace are not yet in place so various means must be used to keep the antagonists apart. Compare with peace-making.

peace-making: The enforced resolution of an active or potential conflict, often by establishing a balanced power relationship among the parties while also imposing a process to achieve a negotiated settlement. Compare with peace-keeping.

persistence: The nature of chemicals, especially pesticides, to remain in the environment before eventually being degraded by microorganisms or physical agents such as sunlight and heat.

pest: Any organism judged to be significantly interfering with some human purpose.

pesticide: A substance used to poison pests. See also pest, fungicide, herbicide, and insecticide.

pesticide treadmill: The inherent reliance of modern agriculture and public-health programs on pesticides, often in increasing quantities, to deal with pest problems.

petroleum (crude oil): A fluid, hydrocarbon-rich mixture mined from certain geological formations.

phenotype: The expressed characteristics of an individual organism, due to genetic and environmental influences on the expression of its specific genetic information. See also genotype.

phenotypic plasticity: The variable expression of genetic information of an individual, depending on environmental influences during development.

photoautotroph: Plants and algae that use sunlight to drive their fixation of energy through photosynthesis. See also chemoautotroph and photosynthesis.

photochemical air pollutants: Ozone, peroxy acetyl nitrate, and other strongly oxidizing gases that form in the atmosphere through complex reactions involving sunlight, hydrocarbons, oxides of nitrogen, and other chemicals.

photosynthesis: Autotrophic productivity that utilizes visible electromagnetic energy (such as sunlight) to drive biosynthesis.

phytoplankton: Microscopic, photosynthetic bacteria and algae that live suspended in the water of lakes and oceans.

plantation: In forestry, these are tree-farms managed for high productivity of wood fibre.

poaching: The illegal harvesting of wild life (plants or animals).

point source: A location where large quantities of pollutants are emitted into the environment, such as a smokestack or sewer outfall.

political ecology: This integrates the concerns of ecology and political economy to consider the dynamic tensions between natural and anthropogenic change, and also the consideration of damage from both natural and anthropogenic perspectives; the latter includes the broad range of concerns from individual people to all of society.

pollution: The exposure of organisms to chemicals or energy in quantities that exceed their tolerance, causing toxicity or other ecological damages. Compare with contamination.

population: In ecology, this refers to individuals of the same species that occur together in time and space.

potential energy: The stored ability to perform work, capable of being transformed into electromagnetic or kinetic energies. Potential energy is associated with gravity, chemicals, compressed gases, electrical potential, magnetism, and the nuclear structure of matter.

potentially renewable natural resource: An alternate phrase for renewable natural resource, highlighting the fact that these can be overexploited, and thereby treated as if they were nonrenewable resources. See also renewable resource.

ppb (part per billion): A unit of concentration, equivalent to 1 microgram per kilogram (μg/kg), or in aqueous solution, 1 μg per litre (μg/L).

ppm (part per million): A unit of concentration, equivalent to 1 milligram per kilogram (mg/kg), or in aqueous solution, 1 mg per litre (mg/L).

prairie: Grassland ecosystems occurring in temperate regions.

precautionary principle: An approach to environmental management, adopted by many countries at the 1992 Earth Summit, which essentially states that scientific uncertainty is not a sufficient reason to postpone control measures when there is a threat of harm to human health or the environment.

precipitation: Deposition of water from the atmosphere as liquid rain, or as solid snow or hail.

precision: The degree of repeatability of a measurement or observation. Compare with accuracy.

prevailing wind: Wind that blows in a dominant direction.

primary consumer: A herbivore, or a heterotrophic organism that feeds on plants or algae.

primary pollutants: Chemicals that are emitted into the environment. Compare with secondary pollutants.

primary producer: An autotrophic organism. Autotrophs are the biological foundation of ecological productivity. See also primary production.

primary production: Productivity by autotrophic organisms, such as plants or algae. Often measured as biomass accumulated over a unit of time, or sometimes by the amount of carbon fixed.

primary sewage treatment: The initial stage of sewage treatment, usually involving the filtering of larger particles from the sewage wastes, settling of suspended solids, and sometimes chlorination to kill pathogens.

Principle of Limiting Factors: A theory stating that ecological productivity (and some other functions) is controlled by whichever environmental factor is present in least supply relative to the demand.

production: An ecological term related to the total yield of biomass from some area or volume of habitat.

production life: See life index.

productivity: An ecological term for production standardized per unit area and time.

prokaryote: Microorganisms without an organized nucleus containing their genetic material. Compare with eukaryote.

protected area (reserve): Parks, ecological reserves, and other tracts set aside from intense development to conserve their natural ecological values. See also greater protected area.

r-selected: Refers to organisms that produce relatively large numbers of small offspring. Little parental investment is made in each offspring, but having large numbers of progeny helps ensure that some will establish and survive. Compare with K-selected.

radiatively active gases (RAGs): Atmospheric gases that efficiently absorb infrared radiation and then dissipate some of the thermal energy gain by reradiation.

rapidly developing countries: Countries with a quickly growing economic infrastructure and a rapidly increasing average per-capita income. See also high-income and low-income countries and compare with developed countries and less-developed countries.

reclamation: Actions undertaken to establish a self-maintaining ecosystem on degraded land, as when a disused industrial site is converted into a permanent cover of vegetation, such as a pasture. Compare with restoration and remediation.

recycling: The processing of discarded materials into useful products.

relative humidity: The atmospheric concentration of water, expressed as a percentage of the saturation value for that temperature.

remediation: Specific actions undertaken to deal with particular problems of environmental quality, such as the liming of acidic lakes and rivers to decrease their ecological damage. Compare with restoration and reclamation.

renewable resource (renewable natural resource): These can regenerate after harvesting, and potentially can be exploited forever. Examples are fresh water, trees, agricultural plants and livestock, and hunted animals. Compare with nonrenewable resources.

replacement fertility rate: The fertility rate that results in the numbers of progeny replacing their parents, with no change in size of the equilibrium population.

replication: The biochemical process occurring prior to cellular division, by which information encoded in DNA is copied to produce additional DNA with the same information.

reserve: (1) Known quantities of resources that can be economically recovered from the environment. (2) An alternative word for a protected area. See protected area.

residence time: (1) The time required for the disappearance of an initial amount; (2) The length of time that a stressor or other environmental influence remains active.

residue: Lingering concentrations of pesticides and certain other chemicals in organisms and the environment.

resilience: The ability of a system to recover from disturbance.

resistance: The ability of a population or community to avoid displacement from some stage of ecological development as a result of disturbance or an intensification of environmental stress. Changes occur after thresholds of resistance to environmental stressors are exceeded.

resource recovery facility: See waste-to-energy facility.

respiration: Physiological processes needed to maintain organisms alive and healthy.

response: In ecotoxicology, this refers to biological or ecological changes caused by exposure to an environmental stressor.

restoration: Establishment of a self-maintaining facsimile of a natural ecosystem on degraded land, as when abandoned farmland is converted back to a native prairie or forest. Compare with reclamation and remediation.

restoration ecology: Activities undertaken by ecologists to repair ecological damage, such as establishing vegetation on degraded habitat, increasing the populations of endangered species, and decreasing the area of threatened ecosystems.

reuse: Finding another use for discarded materials, usually with relatively little modification.

risk: See environmental risks.

risk assessment: See environmental risk assessment.

RNA: The biochemical ribonucleic acid, which is important in translation of the genetic information of DNA into the synthesis of proteins. RNA also stores the genetic information of some viruses.

ruderal: Short-lived but highly fecund plants characteristic of frequently disturbed environments with abundant resources.

run-of-the-river: A hydroelectric development that directly harnesses the flow of a river to drive turbines, without creating a substantial impoundment for water storage.

salinization: The buildup of soluble salts in the soil surface, an important agricultural problem in drier regions.

sanitary landfill: A facility where municipal solid waste is dumped, compacted by heavy machines, and covered with a layer of clean dirt at the end of the day. Some have systems to contain and collect liquid effluent, known as leachate.

science: The systematic and quantitative study of the character and behaviour of the physical and biological world.

scientific creationist: A creationist who attempts to explain some of the discrepancies between his or her beliefs (which are based on a literal interpretation of Genesis) and scientific understanding of the origin and evolution of life. See also creationist.

scientific method: This begins with the identification of a question involving the structure or function of the natural world, usually using inductive logic. The question is interpreted in terms of a theory, and hypotheses are formulated and tested by experiments and observations of nature.

scrubbing: See flue-gas desulphurization.

seascape: A spatial integration of ecological communities over a large marine area.

second law of thermodynamics: A physical principle stating that transformations of energy can occur spontaneously only under conditions in which there is an increase in the entropy (or randomness) of the universe. See also first law of thermodynamics and entropy.

secondary consumer: A carnivore that feeds on primary consumers (or herbivores).

secondary pollutants: Pollutants that are not emitted, but form in the environment by chemical reactions involving emitted chemicals. Compare with primary pollutants.

secondary sewage treatment: Treatment applied to the effluent of primary sewage treatment, usually involving the use of a biological technology to aerobically decompose organic wastes in an engineered environment. The resulting sludge can be used as a soil conditioner, incinerated, or dumped into a landfill. See also primary sewage treatment.

sedimentary rock: Rock formed from precipitated minerals such as calcite, or from lithified particles eroded from other rocks such as sandstone, shale, and conglomerates.

sedimentation: A process by which mass eroded from elsewhere settles to the bottom of rivers, lakes, or an ocean.

seismic sea wave: See tsunami.

selection harvesting: Harvesting of only some trees from a stand, leaving others behind and the forest substantially intact.

sewage treatment: The use of physical filters, chemical treatment, and/or biological treatment to reduce pathogens, organic matter, and nutrients in waste waters containing sewage.

shifting cultivation: An agricultural system in which trees are felled, the woody debris burned, and the land used to grow mixed crops for several years.

significant figures: The number of digits used when reporting data from analyses or calculations.

silvicultural management: The application of practices that increase tree productivity in a managed forest, such as planting seedlings, thinning trees, or applying herbicides to reduce the abundance of weeds.

silviculture: The branch of forestry concerned with the care and tending of trees.

site capability (site quality): The potential of land to sustain the productivity of agricultural crops.

slash-and-burn: An agricultural system that results in a permanent conversion of a forest into crop production, involving cutting and burning the forest followed by continuous use of the land for crops.

slope: The angle of inclination of land, measured in degrees (0° implies a horizontal surface, while 90° is vertical).

SLOSS: An acronym, for single large or several small, in reference to choices in the design of protected areas.

sludge: A solid or semi-solid precipitate that settles from polluted water during treatment; sludge is produced during the treatment of sewage and also in pulp mills and some other industrial facilities. It may be disposed of in a landfill, but if organic, can be used as a beneficial soil amendment.

smog: An event of ground-level air pollution.

snag: A standing dead tree.

social justice: A worldview that calls for equality of consideration for all members of a society, regardless of colour, race, socio-economic class, gender, age, or sexual preference. See also ecological justice.

socio-cultural evolution: See cultural evolution.

socio-economic impact assessment: A process used to identify and evaluate the potential consequences of proposed actions or policies for sociological, economic, and related values. See also environmental impact assessment.

soil: A complex mixture of fragmented rock, organic matter, moisture, gases, and living organisms that covers almost all of Earth's terrestrial landscapes.

soil profile: The vertical stratification of soil on the basis of colour, texture, and chemical qualities.

solar energy: Electromagnetic energy radiated by the sun.

solar system: The sun, its nine orbiting planets, miscellaneous comets, meteors, and other local materials.

solid wastes: Extremely variable municipal wastes that include discarded food, garden discards, newspapers, bottles, cans, construction debris, old cars, and disused furniture.

spaceship Earth: An image of Earth as viewed from space, which illustrates the fact that, except for sunlight, resources needed by humans are present only on that planet.

spaceship world view: This focuses on sustaining only those resources needed by humans and their economy, and it assumes that humans can exert a great degree of control over natural processes and can pilot "spaceship Earth." See also frontier world view and sustainability world view.

special concern: Refers to a species that is not currently threatened but is at risk of becoming so for various reasons.

species: An aggregation of individuals and populations that can potentially interbreed and produce fertile offspring, and is reproductively isolated from other such groups.

speciesism: Discrimination (by humans) against other species purely on the basis that they are not human, especially as manifested by cruelty to or exploitation of animals, or merely by a lack of consideration of their interests.

species richness: The number of species in some area or place.

state-of-the-environment reporting: A governmental, corporate, or NGO function that involves public reporting on environmental conditions.

strategic weapon: Large explosive-yield weapons that are designed to be delivered by a missile or airplane over a distance of thousands of kilometres. Compare with tactical weapon.

stratosphere: The upper atmosphere, extending above the. from 8-17 km to as high as about 50 km. See also troposphere.

stress-tolerator: Long-lived plants adapted to habitats that are marginal in terms of climate, moisture, or nutrient supply, but are infrequently disturbed and therefore stable, such as tundra and desert.

stressor: An environmental factor that constrains the development and productivity of organisms or ecosystems.

succession: A process of community- level recovery following disturbance.

surface flow: Water that moves over the surface of the ground.

surface water: Water that occurs in glaciers, lakes, ponds, rivers, streams, and other surface bodies of water.

sustainability world view: This acknowledges that humans must have access to vital resources, but it asserts that the exploitation of resources should be governed by appropriate ecological, aesthetic, and moral values, and should not deplete the necessary resources. See also frontier world view and spaceship world view.

sustainable development: Refers to progress toward an economic system that uses natural resources in ways that do not deplete their stocks or compromise their availability to future generations.

sustainable economic system (sustainable economy): An economic system that can be maintained over time without any net consumption of natural resources.

swamp: A forested wetland, flooded seasonally or permanently.

symbiosis: An intimate relationship between different species. See also mutualism.

synecology: The study of relationships among species within communities. Compare with autecology.

system: A group or combination of regularly interacting and interdependent elements, which form a collective entity, but one that is more than the sum of its constituents. See also ecosystem.

tactical weapon: Smaller, numerous weapons that are intended for use in a local battlefield, and are delivered by smaller missiles, artillery, aircraft, or torpedoes. Compare with strategic weapon.

taiga: See boreal forest.

tectonic force: Force associated with crustal movements and related geological processes that cause structural deformations of rocks and minerals.

temperate deciduous forest: A forest occurring in relatively moist, temperate climates with short and moderately cold winters and warm summers, and usually composed of a mixture of angiosperm tree species.

temperate grassland: Grass-dominated ecosystems occurring in temperate regions with an annual precipitation of 25–60 cm per year; sufficient to prevent desert from developing but insufficient to support forest.

temperate rainforest: A forest developing in a temperate climate in which winters are mild and precipitation is abundant year-round. Because wildfire is rare, old-growth forests may be common.

temperature inversion: See atmospheric inversion.

teratogen: A chemical or physical agent that induces a developmental abnormality (i.e., a birth defect) in an embryo or fetus.

tertiary sewage treatment: Treatment applied to the effluent of secondary sewage treatment, usually involving a system to remove phosphorus and/or nitrogen from waste waters. See also primary sewage treatment and secondary sewage treatment.

theory: A general term that refers to a set of scientific laws, rules, and explanations supported by a large body of experimental and observational evidence, all leading to robust, internally consistent conclusions.

thermal pollution: An increase in environmental temperature sufficient to result in ecological change.

thermosphere: The layer of the atmosphere extending beyond the mesosphere to 450 km or more above the surface of the Earth. See also mesosphere.

threatened: In Canada, this refers to any indigenous taxa likely to become endangered (in Canada) if factors affecting their vulnerability are not reversed.

tidal energy: Energy that develops in oceanic surface waters because of the gravitational attraction between Earth and the Moon, and can potentially be used to generate electricity.

tilth: The physical structure of soil, closely associated with the concentration of humified organic matter. Tilth is important in water- and nutrient-holding capacity of soil, and is generally beneficial to plant growth.

tolerance: In ecotoxicology, this refers to a genetically based ability of organisms or species to not suffer toxicity when exposed to chemicals or other stressors.

total concentration: The concentrations of metals in soil, sediment, rocks, or water, as determined after dissolving samples in a strongly acidic solution. Compare with available concentration.

total energy production: The use of commercial energy plus traditional fuels in an economy. See also traditional fuels.

total-war economy: An economy that is wholly dedicated to supporting a war effort.

toxic waste: Waste that is poisonous to humans, animals, or plants. See also hazardous waste.

toxicology: The science of the study of poisons, including their chemical nature and their effects on the physiology of organisms. Compare with environmental toxicology and ecotoxicology.

traditional fuels: The non-commercial use of wood, charcoal, animal dung, and other biomass fuels for subsistence purposes, primarily for cooking food and heating homes. See also total energy production and commercial energy production.

transcription: A biochemical process by which the information of double-stranded DNA is encoded on complementary single strands of RNA, which are used to synthesize specific proteins.

translation: A biochemical process occurring on organelles known as ribosomes, in which information encoded in messenger RNA is used to synthesize particular proteins.

transpiration: The evaporation of water from plants. Compare with evapotranspiration.

trophic structure: The organization of productivity in an ecosystem, including the roles of autotrophs, herbivores, carnivores, and detritivores.

troposphere: The lower atmosphere, extending to 8–17 km.

tsunami: A fast-moving, sea-wave caused by an undersea earthquakes, which if large can cause enormous destruction of low-lying coastal places.

tundra: A treeless biome occurring in environments with long, cold winters and short, cool growing seasons.

unexploded ordinance (UXOs): Explosives that remain in place after a conflict has ended.

urban agglomeration: See megacity

urban forest: Urban areas having a substantial density and biomass of trees, although often most are non-native species.

urban planning: An active process of designing better ways of organizing the structure and function of cities, including an orderly siting of land uses and activities.

urbanization: The development of cities and towns on formerly agricultural or natural lands.

utilitarian value: The usefulness of a thing or function to humans.

value added: The increased value of something as a result of manufacturing or some other improvement.

valued ecosystem components (VECs): In environmental impact assessment, these are components of ecosystems perceived to be important to society as economically important resources, as rare or endangered species or communities, or for their cultural or aesthetic significance.

variable: A changeable factor believed to influence a natural phenomenon of interest or that can be manipulated during an experiment.

vascular plant: Relatively complex plants with specialized, tube-like vascular tissues in their stems for conducting water and nutrients.

VECs: See valued ecosystem components.

vector: Species of insects and ticks that transmit pathogens from alternate hosts to people or animals.

vertebrate: Animals with an internal skeleton, and in particular a backbone.

virgin field: In epidemiology, this is a population that is hypersensitive to one or more infectious diseases to which it has not been previously exposed.

volatile organic compounds: Organic compounds that evaporate to the atmosphere at typical environmental temperatures, so they are present in gaseous or vapour forms.

volcano: An opening in Earth's crust from which magmic materials, such as lava, rock fragments, and gases, are ejected into the atmosphere or oceanic waters.

war: A period of organized deadly conflict between human societies, countries, or another defined group.

waste: Any discarded materials. See also hazardous waste and toxic waste.

waste management: The handling of discarded materials using various methods. See also dumping, incineration, recycling, composting, reuse, and waste reduction.

waste prevention: See waste reduction.

waste reduction: Practices intended to reduce the amount of waste that must be disposed of. Also known as waste prevention.

waste-to-energy facility: An incinerator that burns organic waste and uses the heat generated to produce commercial energy.

water cycle: See hydrologic cycle.

watershed: An area of land from which surface water and groundwater flow into a stream, river, or lake.

wave energy: The kinetic energy of oceanic waves, which can be harnessed using specially designed buoys to generate electricity.

weather: The short-term, day-to-day or instantaneous meteorological conditions at a place or region. Compare with climate.

weathering: Physical and chemical processes by which rocks and minerals are broken down by such environmental agents as rain, wind, temperature changes, and biological influences.

weed: An unwanted plant that interferes with some human purpose.

wet deposition: Atmospheric inputs of chemicals with rain and snow. Compare with dry deposition.

wetland: An ecosystem that develops in wet places and is intermediate between aquatic and terrestrial ecosystems. See also bog, fen, marsh, and swamp.

whole-lake experiment: The experimental manipulation of one or more environmental factors in an entire lake.

wind: An air mass moving in Earth's atmosphere.

wind energy: The kinetic energy of moving air masses, which can be tapped and utilized in various ways, including the generation of electricity.

work: In physics, work is defined as the result of a force being applied over a distance.

working hypothesis: A hypothesis being tested in a scientific experiment or another kind of research. See also hypothesis and null hypothesis.

zero population growth (ZPG): When the birth rate plus immigration equal the death rate plus emigration.

zooplankton: Tiny animals that occur in the water column of lakes and oceans