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Introduction to Environmental Science: 2nd Edition

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Introduction to Environmental Science

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Chapter 1: Introduction to Environmental Sciences

Learning Objectives

At the end of this section, students will be able to:

1. Describe, at an introductory level, the basic chemical and biological foundations of life on Earth
2. Define environment, ecosystems, and environmental sciences
3. Give examples of the interdisciplinary nature of environmental science
4. Define sustainability and sustainable development
5. Explain the complex relationship between natural and human systems, pertaining to environmental impact, the precautionary principle, and environmental justifications
6. Understand scientific approach and begin to apply the scientific method

The Chemical and Biological Foundations of Life

Elements in various combinations comprise all matter on Earth, including living things. Some of the most abundant elements in living organisms include carbon, hydrogen, nitrogen, oxygen, sulfur, and phosphorus. These form the nucleic acids, proteins, carbohydrates, and lipids that are the fundamental components of living matter. Biologists must understand these important building blocks and the unique structures of the atoms that make up molecules, allowing for the formation of cells, tissues, organ systems, and entire organisms.

At its most fundamental level, life is made up of matter. **Matter** is any substance that occupies space and has mass. **Elements** are unique forms of matter with specific chemical and physical properties that cannot be broken down into smaller substances by ordinary chemical reactions. There are 118 elements, but only 92 occur naturally. The remaining elements are synthesized in laboratories and are unstable. The five elements common to all living organisms are oxygen (O), carbon (C), hydrogen (H), and nitrogen (N) and phosphorous (P). In the non-living world, elements are found in different proportions, and some elements common to living organisms are relatively rare on the earth as a whole (**Table 1.1**). For example, the atmosphere is rich in nitrogen and oxygen but contains little carbon and hydrogen, while the earth's crust, although it contains oxygen and a small amount of hydrogen, has little nitrogen and carbon. In spite of their differences in abundance, all elements and the chemical reactions between them obey the same chemical and physical laws regardless of whether they are a part of the living or non-living world.

Table 1.1. Approximate percentage of elements in living organisms (from bacteria to humans) compared to the non-living world. Trace represents less than 1%.

	Biosphere	Atmosphere	Lithosphere
Oxygen (O)	65%	21%	46%
Carbon (C)	18%	trace	trace
Hydrogen (H)	10%	trace	trace
Nitrogen (N)	3%	78%	trace
Phosphorus (P)	trace	trace	>30%

The Structure of the Atom

An **atom** is the smallest unit of matter that retains all of the chemical properties of an element. For example, one gold atom has all of the properties of gold in that it is a solid metal at room temperature. A gold coin is simply a very large number of gold atoms molded into the shape of a coin and containing small amounts of other elements known as impurities. Gold atoms cannot be broken down into anything smaller while still retaining the properties of gold. An atom is composed of two regions: the **nucleus**, which is in the center of the atom and contains protons and neutrons, and the outermost region of the atom which holds its electrons in orbit around the nucleus, as illustrated in **Figure 1.1**. Atoms contain protons, electrons, and neutrons, among other subatomic particles. The only exception is hydrogen (H), which is made of one proton and one electron with no neutrons.

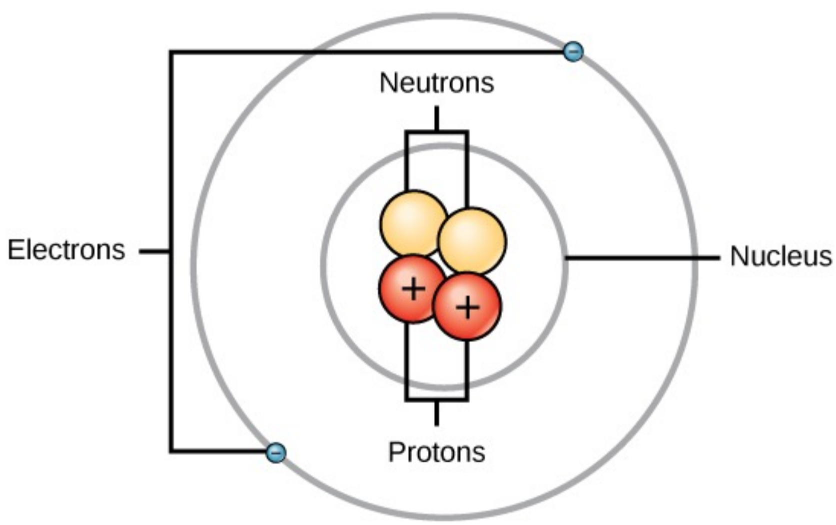


Figure 1.1. Elements, such as helium, depicted here, are made up of atoms. Atoms are made up of protons and neutrons located within the nucleus, with electrons in orbitals surrounding the nucleus.

Protons and neutrons have approximately the same mass, about 1.67×10^{-24} grams. Scientists arbitrarily define this amount of mass as one atomic mass unit (amu) (**Table 1.2**). Although similar in mass, protons and neutrons differ in their electric charge. A **proton** is positively charged whereas a **neutron** is uncharged. Therefore, the number of neutrons in an atom contributes significantly to its mass, but not to its charge.

Table 1.2. Protons, neutrons, and electrons

	Charge	Mass (amu)	Location in atom
Proton	+1	1	Nucleus
Neutron	0	1	Nucleus
Electron	-1	0	Orbitals

Electrons are much smaller in mass than protons, weighing only 9.11×10^{-28} grams, or about 1/1800 of an atomic mass unit. Hence, they do not contribute much to an element's overall atomic mass. Although not significant contributors to mass, electrons do contribute greatly to the atom's charge, as each electron has a negative charge equal to the positive charge of a proton. In uncharged, neutral atoms, the number of electrons orbiting the nucleus is equal to the number of protons inside the nucleus. In these atoms, the positive and negative charges cancel each other out, leading to an atom with no net charge. Accounting for the sizes of protons, neutrons, and electrons, most of the volume of an atom—greater than 99 percent—is, in fact, empty space. With all this empty space, one might ask why so-called solid objects do not just pass through one another. The reason they do not is that the electrons that surround all atoms are negatively charged and negative charges repel each other. When an atom gains or loses an electron, an **ion** is formed. Ions are charged forms of atoms. A positively charged ion, such as sodium (Na^+), has lost one or more electrons. A negatively charged ion, such as chloride (Cl^-), has gained one or more electrons.

Molecules

Molecules are formed when two or more atoms join together through chemical bonds to form a unit of matter. Throughout your study of environmental science, you will encounter many molecules including carbon dioxide gas. Its chemical formula is CO_2, indicating that this molecule is made up of one carbon atom and two oxygen atoms. Some molecules are charged due to the ions they contain. This is the case for the nitrate (NO_3^-), a common source of nitrogen to plants. It contains one nitrogen atom and three oxygen atoms, and has an overall charge of negative one.

Isotopes

Isotopes are different forms of an element that have the same number of protons but a different number of neutrons. Some elements—such as carbon, potassium, and uranium—have naturally occurring isotopes. Carbon-12 contains six protons, six neutrons, and six electrons; therefore, it has a mass number of 12 (six protons and six neutrons). Carbon-14 contains six protons, eight neutrons, and six electrons; its atomic mass is 14 (six protons and eight electrons). These two alternate forms of carbon are isotopes. Some isotopes may emit neutrons, protons, and electrons, and attain a more stable atomic configuration (lower level of potential energy); these are radioactive isotopes, or **radioisotopes**. Radioactive decay describes the energy loss that occurs when an unstable atom's nucleus releases radiation, for example, carbon-14 losing neutrons to eventually become carbon-12.

Carbon

The basic functional unit of life is a cell and all organisms are made up of one or more cells. Cells are made of many complex molecules called macromolecules, such as proteins, nucleic acids (RNA and DNA), carbohydrates, and lipids. The macromolecules are a subset of **organic molecules** that are especially important for life. The fundamental component for all of these macromolecules is carbon. The carbon atom has unique properties that allow it to form covalent bonds with as many as four different atoms, making this versatile element ideal to serve as the basic structural component, or "backbone," of the macromolecules.

Hydrocarbons

Hydrocarbons are organic molecules consisting entirely of carbon and hydrogen, such as methane (CH_4. We often use hydrocarbons in our daily lives as fuels—like the propane in a gas grill or the butane in a lighter. The many covalent bonds between the atoms in hydrocarbons store a great amount of energy, which is released when these molecules are burned (oxidized). Methane, an excellent fuel, is the simplest hydrocarbon molecule, with a central carbon atom bonded to four different hydrogen atoms, as illustrated in **Figure 1.2**.

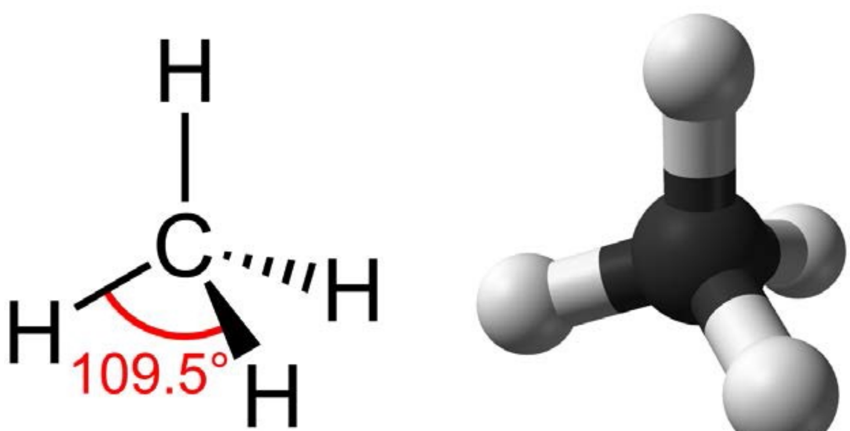


Figure 1.2. Methane (CH_4) has a tetrahedral geometry, with each of the four hydrogen atoms spaced 109.5° apart.

As the backbone of the large molecules of living things, hydrocarbons may exist as linear carbon chains, carbon rings, or combinations of both. This three-dimensional shape or conformation of the large molecules of life (macromolecules) is critical to how they function.

Biological molecules

Life on Earth is primarily made up of four major classes of biological molecules, or biomolecules. These include carbohydrates, lipids, proteins, and nucleic acids.

Most people are familiar with **carbohydrates**, one type of macromolecule, especially when it comes to what we eat. Carbohydrates are, in fact, an essential part of our diet; grains, fruits, and vegetables are all natural sources of carbohydrates. Carbohydrates provide energy to the body, particularly through **glucose**, a simple sugar that is a component of **starch** and an ingredient in many staple foods. Carbohydrates also have other important functions in humans, animals, and plants. Carbohydrates can be represented by the stoichiometric formula $(CH_2O)n$, where n is the number of carbons in the molecule. In other words, the ratio of carbon to hydrogen to oxygen is 1:2:1 in carbohydrate molecules. This formula also explains the origin of the term "carbohydrate": the components are carbon ("carbo") and the components of water (hence, "hydrate"). The chemical formula for glucose is $C_6H_{12}O_6$. In humans, glucose is an important source of energy.

During **cellular respiration**, energy is released from glucose, and that energy is used to help make **adenosine triphosphate** (ATP). Plants synthesize glucose using carbon dioxide and water, and glucose in turn is used for energy requirements for the plant. Excess glucose is often stored as starch that is catabolized (the breakdown of larger molecules by cells) by humans and other animals that feed on plants. Plants are able to synthesize glucose, and the excess glucose, beyond the plant's immediate energy needs, is stored as starch in different plant parts, including roots and seeds. The starch in the seeds provides food for the embryo as it germinates and can also act as a source of food for humans and animals.

Lipids include a diverse group of compounds such as fats, oils, waxes, phospholipids, and steroids that are largely nonpolar in nature. Nonpolar molecules are hydrophobic ("water fearing"), or insoluble in water. These lipids have important roles in energy storage, as well as in the building of cell membranes throughout the body.

Proteins are one of the most abundant organic molecules in living systems and have the most diverse range of functions of all macromolecules. Proteins may be structural, regulatory, contractile, or protective; they may serve in transport, storage, or membranes; or they may be toxins or enzymes. Each cell in a living system may contain thousands of proteins, each with a unique function. Their structures, like their functions, vary greatly.

Enzymes, which are produced by living cells, speed up biochemical reactions (like digestion) and are usually complex proteins. Each enzyme has a specific shape or formation based on its use. The enzyme may help in breakdown, rearrangement, or synthesis reactions.

Proteins have different shapes and molecular weights. Protein shape is critical to its function, and many different types of chemical bonds maintain this shape. Changes in temperature, pH, and exposure to chemicals may cause a protein to **denature**. This is a permanent change in the shape of the protein, leading to loss of function. All proteins are made up of different arrangements of the same 20 types of **amino acids**. These amino acids are the units that make up proteins. Ten of these are considered essential amino acids in humans because the human body cannot produce them and they are obtained from the diet. The sequence and the number of amino acids ultimately determine the protein's shape, size, and function.

Nucleic acids are the most important macromolecules for the continuity of life. They carry the genetic blueprint of a cell and carry instructions for the functioning of the cell. The two main types of nucleic acids are **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**. DNA is the genetic material found in all living organisms, ranging from single-celled bacteria to multicellular mammals. DNA controls all of the cellular activities by turning the genes "on" or "off." The other type of nucleic acid, RNA, is mostly involved in protein synthesis.
DNA has a double-helix structure (**Figure 1.3**).

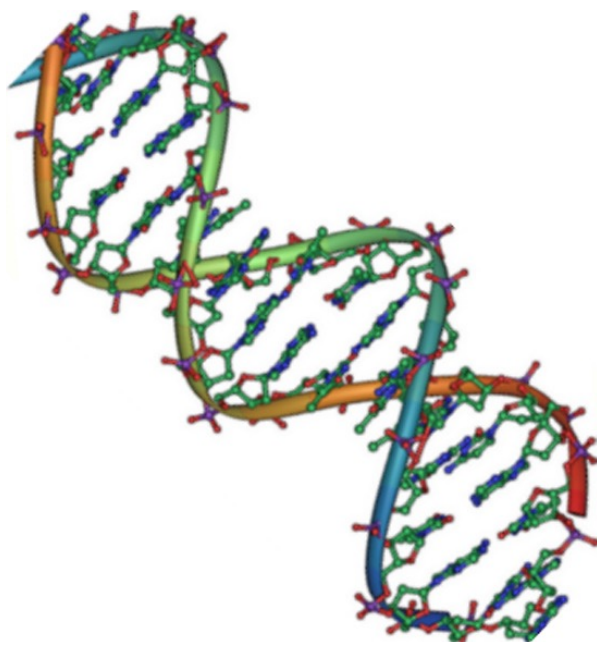


Figure 1.3. Native DNA is an antiparallel double helix. The phosphate backbone (indicated by the curvy lines) is on the outside, and the bases are on the inside. Each base from one strand interacts via hydrogen bonding with a base from the opposing strand. (credit: Jerome Walker/Dennis Myts)

Biological organization

All living things are made of cells; the **cell** itself is the smallest fundamental unit of structure and function in living organisms. In most organisms, these cells contain **organelles**, which provide specific functions for the cell. Living organisms have the following properties: all are highly organized, all require energy for maintenance and growth, and all grow over time and respond to their environment. All organisms adapt to the environment and all ultimately reproduce contributing genes to the next generation. Some organisms consist of a single cell and others are multicellular. **Organisms** are individual living entities. For example, each tree in a forest is an organism.

All the individuals of a species living within a specific area are collectively called a **population**. Populations fluctuate based on a number of factors: seasonal and yearly changes in the environment, natural disasters such as forest fires and volcanic eruptions, and competition for resources between and within species. A **community** is the sum of populations inhabiting a particular area. For instance, all of the trees, insects, and other populations in a forest form the forest's community. The forest itself is an ecosystem.

An **ecosystem** consists of all the living things in a particular area together with the abiotic, non-living parts of that environment such as nitrogen in the soil or rain water. At the highest level of organization, the **biosphere** is the collection of all ecosystems, and it represents the zones of life on earth. It includes land, water, and even the atmosphere to a certain extent.

Life in an ecosystem is often about competition for limited resources, a characteristic of the process of natural selection. **Competition** in communities (all living things within specific habitats) is observed both within species and among different species. The resources for which organisms compete include organic material from living or previously living organisms, sunlight, and mineral nutrients, which provide the energy for living processes and the matter to make up organisms' physical structures. Other critical factors influencing community dynamics are the components of its physical and geographic environment: a habitat's latitude, amount of rainfall, topography (elevation), and available species. These are all important environmental variables that determine which organisms can exist within a particular area. Ecosystems can be small, such as the tidal pools found near the rocky shores of many oceans, or large, such as the Amazon Rainforest in Brazil (**Figure 1.4**).

There are three broad categories of ecosystems based on their general environment: freshwater, ocean water (marine), and terrestrial. Within these broad categories are individual ecosystem types based on the organisms present and the type of environmental habitat. Ocean ecosystems are the most common, comprising 75 percent of the Earth's surface. The shallow ocean ecosystems include extremely biodiverse coral reef ecosystems, and the deep ocean surface is known for its large numbers of plankton and krill (small crustaceans) that support it. These two environments are especially important to aerobic respirators worldwide as the phytoplankton perform 40 percent of all photosynthesis on Earth. Although not as diverse as the other two, deep ocean ecosystems contain a wide variety of marine organisms. Such ecosystems exist even at the bottom of the ocean where light is unable to penetrate through the water.

Freshwater ecosystems are the rarest, occurring on only 1.8 percent of the Earth's surface. Lakes, rivers, streams, and springs comprise these systems; they are quite diverse, and they support a variety of fish, amphibians, reptiles, insects, phytoplankton, fungi, and bacteria.

(a) (b)

Figure 1.4. (a) A tidal pool ecosystem in Matinicus Island, Maine, is a small ecosystem, while (b) the Amazon rainforest in Brazil is a large ecosystem. (credit a: modification of work by Jim Kuhn; credit b: modification of work by Ivan Mlinaric)

Terrestrial ecosystems, also known for their diversity, are grouped into large categories called **biomes**, such as tropical rainforests, savannas, deserts, coniferous forests, deciduous forests, and tundra. Grouping these ecosystems into just a few biome categories obscures the great diversity of the individual ecosystems within them. For example, there is great variation in desert vegetation: the saguaro cacti and other plant life in the Sonoran Desert, in the United States, are relatively abundant compared to the desolate rocky desert of Boa Vista, an island off the coast of Western Africa.

All living things require energy in one form or another. It is important to understand how organisms acquire energy and how that energy is passed from one organism to another through **food webs**. Food webs illustrate how energy flows directionally through ecosystems, including how efficiently organisms acquire it, use it, and how much remains for use by other organisms of the food web. The flow of energy and matter through the ecosystems influences the abundance and distribution of organisms within them.

Ecosystems are complex with many interacting parts. They are routinely exposed to various disturbances: changes in the environment that affect their compositions, such as yearly variations in rainfall and temperature. Many disturbances are a result of natural processes. For example, when lightning causes a forest fire and destroys part of a forest ecosystem, the ground is eventually populated with grasses, followed by bushes and shrubs, and later mature trees: thus, the forest is restored to its former state. This process is so universal that ecologists have given it a name—**succession**. The impact of environmental disturbances caused by human activities is now as significant as the changes wrought by natural processes. Human agricultural practices, air pollution, acid rain, global deforestation, overfishing, oil spills, and illegal dumping on land and into the ocean all have impacts on ecosystems.

We rely on ecosystem services. Earth's natural systems provide **ecosystem services** required for our survival such as: air and water purification, climate regulation, and plant pollination. We have degraded nature's ability to provide these services by depleting resources, destroying habitats, and generating pollution. The benefits people obtain from ecosystems include: nutrient cycling, soil formation, and **primary production**. Another important service of natural ecosystems is provisioning like food production, production of wood, fibers and fuel. Ecosystems are responsible for climate regulation, flood regulation together with disease regulation. Finally ecosystems provide cultural and esthetic services. As humans we benefit from observing natural habitats, recreation in waters and mountains. Nature is a source of inspiration for poets and writers. It is a source of aesthetic, religious and other nonmaterial benefits. Studying ecosystem structure in its original state is the only way we can make **anthropogenic** (man-made) systems like agricultural fields, reservoirs, fracking operations, and dammed rivers work for human benefit with minimal impact on our and other organisms' health.

Environment and environmental science

Viewed from space, Earth (**Figure 1.5**) offers no clues about the diversity of lifeforms that reside there. The first forms of life on Earth are thought to have been microorganisms that existed for billions of years in the ocean before plants and animals appeared. The mammals, birds, and plants so familiar to us are all relatively recent, originating 130 to 200 million years ago. Humans have inhabited this planet for only the last 2.5 million years, and only in the last 200,000 years have humans started looking like we do today. There are around 7.35 billion people today (https://www.census.gov/popclock/).

Figure 1.5 This NASA image is a composite of several satellite-based views of Earth. To make the whole-Earth image, NASA scientists combine observations of different parts of the planet. (credit: NASA/GSFC/NOAA/USGS)

The word **environment** describes living and nonliving surroundings relevant to organisms. It incorporates physical, chemical and biological factors and processes that determine the growth and survival of organisms, populations, and communities. All these components fit within the ecosystem concept as a way to organize all of the factors and processes that make up the environment. The ecosystem includes organisms and their environment within a specific area. Review the previous section for in-depth information regarding the Earth's ecosystems. Today, human activities influence all of the Earth's ecosystems.

Environmental science studies all aspects of the environment in an **interdisciplinary** way. This means that it requires the knowledge of various other subjects including biology, chemistry, physics, statistics, microbiology, biochemistry, geology, economics, law, sociology, etc. It is a relatively new field of study that has evolved from integrated use of many disciplines. **Environmental engineering** is one of the fastest growing and most complex disciplines of engineering. Environmental engineers solve problems and design systems using knowledge of environmental concepts and ecology, thereby providing solutions to various environmental problems. **Environmentalism**, in contrast, is a social movement through which citizens are involved in activism to further the protection of environmental landmarks and natural resources. This is not a field of science, but incorporates some aspects of environmental knowledge to advance conservation and sustainability efforts.

The Process of Science

Environmental science is a science, but what exactly is science? **Science** (from the Latin *scientia*, meaning "knowledge") can be defined as all of the fields of study that attempt to comprehend the nature of the universe and all its parts. The **scientific method** is a method of research with defined steps that include experiments and careful observation. One of the most important aspects of this method is the testing of hypotheses by means of repeatable experiments. A **hypothesis** is a suggested explanation for an event, which can be tested. A **theory** is a tested and confirmed explanation for observations or phenomena that is supported by many repeated experiences and observations.

The scientific method

The scientific process typically starts with an observation (often a problem to be solved) that leads to a question. The scientific method consists of a series of well-defined steps. If a hypothesis is not supported by experimental data, a new hypothesis can be proposed. Let's think about a simple problem that starts with an observation and apply the scientific method to solve the problem. One Monday morning, a student arrives in class and quickly discovers that the classroom is too warm. That is an observation that also describes a problem: the classroom is too warm. The student then asks a question: "Why is the classroom so warm?"

Proposing a Hypothesis

Recall that a hypothesis is a suggested explanation that can be tested. To solve a problem, several hypotheses may be proposed. For example, one hypothesis might be, "The classroom is warm because no one turned on the air conditioning." But there could be other responses to the question, and therefore other hypotheses may be proposed. A second hypothesis might be, "The classroom is warm because there is a power failure, and so the air conditioning doesn't work." Once a hypothesis has been selected, the student can make a prediction. A prediction is similar to a hypothesis but it typically has the format "If . . . then . . . ." For example, the prediction for the first hypothesis might be, "*If* the student turns on the air conditioning, *then* the classroom will no longer be too warm."

Testing a Hypothesis

A valid hypothesis must be testable. It should also be <u>falsifiable</u>, meaning that it can be disproven by experimental results. Importantly, science does not claim to "prove" anything because scientific understandings are always subject to modification with further information. This step — openness to disproving ideas — is what distinguishes sciences from non-sciences. The presence of the supernatural, for instance, is neither testable nor falsifiable.

To test a hypothesis, a researcher will conduct one or more **experiments** designed to eliminate, or disprove, the hypotheses. Each experiment will have one or more variables and one or more controls. A **variable** is any part of the experiment that can vary or change during the experiment. The **independent variable** is the variable that is manipulated throughout the course of the experiment. The **dependent variable**, or response variable is the variable by which we measure change in response to the independent variable. Ideally, all changes that we measure in the dependent variable are because of the manipulations we made to the independent variable. In most experiments, we will maintain one group that has had no experimental change made to it. This is the **control group**. It contains every feature of the **experimental group** except it is not given any manipulation. Therefore, if the results of the experimental group differ from the control group, the difference must be due to the hypothesized manipulation, rather than some outside factor. Look for the variables and controls in the examples that follow.

To test the hypothesis "*The classroom is warm because no one turned on the air conditioning*," the student would find out if the air conditioning is on. If the air conditioning is turned on but does not work, there should be another reason, and this hypothesis should be rejected. To test the second hypothesis, the student could check if the lights in the classroom are functional. If so, there is no power failure and this hypothesis should be rejected. Each hypothesis should be tested by carrying out appropriate experiments. Be aware that rejecting one hypothesis does not determine whether or not the other hypotheses can be accepted; it simply eliminates one hypothesis that is not valid (**Figure 1.7**). Using the scientific method, the hypotheses that are inconsistent with experimental data are rejected.

The scientific method may seem too rigid and structured. It is important to keep in mind that, although scientists often follow this sequence, there is flexibility. Sometimes an experiment leads to conclusions that favor a change in approach; often, an experiment brings entirely new scientific questions to the puzzle. Many times, science does not operate in a linear fashion; instead, scientists continually draw inferences and make generalizations, finding patterns as their research proceeds. Scientific reasoning is more complex than the scientific method alone suggests. Notice, too, that the scientific method can be applied to solving problems that aren't necessarily scientific in nature.

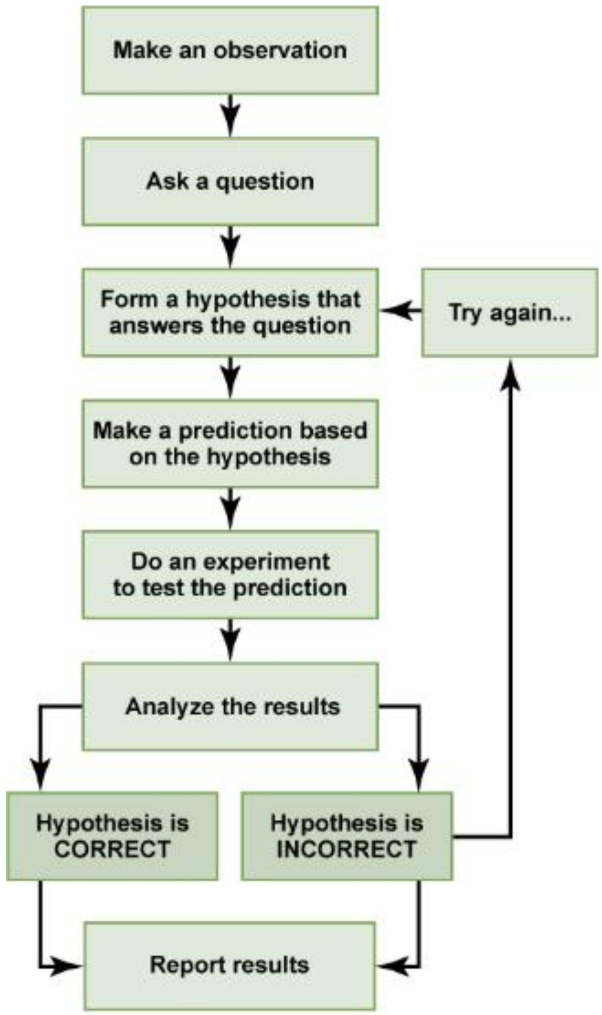


Figure 1.7. The scientific method consists of a series of well-defined steps. If a hypothesis is not supported by experimental data, a new hypothesis can be proposed.

Sustainability and Sustainable Development

In 1983 the United Nations General Assembly passed a resolution that established the Special Commission on the Environmental Perspective to the Year 2000 and Beyond (http://www.un.org/documents/ga/res/38/a38r161.htm). Their charge was:

a. To propose long-term environmental strategies for achieving sustainable development to the year 2000 and beyond;
b. To recommend ways in which concern for the environment may be translated into greater co-operation among developing countries and between countries at different stages of economic and social development and lead to the achievement of common and mutually supportive objectives which take account of the interrelationships between people, resources, environment and development;

c. To consider ways and means by which the international community can deal more effectively with environmental concerns, in light of the other recommendations in its report;
d. To help define shared perceptions of long-term environmental issues and of the appropriate efforts needed to deal successfully with the problems of protecting and enhancing the environment, a long-term agenda for action during the coming decades, and aspirational goals for the world community, taking into account the relevant resolutions of the session of a special character of the Governing Council in 1982.

Although the report did not technically invent the term **sustainability**, it was the first credible and widely disseminated study that used this term in the context of the global impacts of humans on the environment. Its main and often quoted definition refers to **sustainable development** as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs*. The report uses the terms 'sustainable development', 'sustainable', and 'sustainability' interchangeably, emphasizing the connections among social equity, economic productivity, and environmental quality (**Figure 1.6**). This three-pronged approach to sustainability is now commonly referred to as the **triple bottom-line**. Preserving the environment for humans today and in the future is a responsibility of every generation and a long-term global goal. Sustainability and the triple bottom-line (meeting environmental, economic, and social goals simultaneously) require that we limit our environmental impact, while promoting economic well-being and social equity.

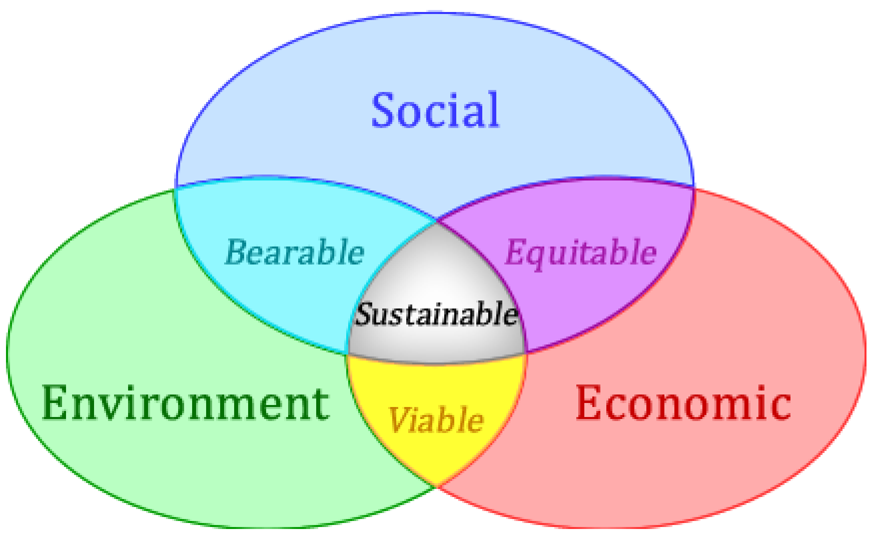


Figure 1.6. A depiction of the sustainability paradigm in terms of its three main components, showing various intersections among them. Source: International Union for the Conservation of Nature.

Examples of sustainable development include sustainable agriculture, which is agriculture that does not deplete soils faster than they form and does not destroy the biodiversity of the area. Sustainable farming and ranching do not reduce the amount of healthy soil, clean water, genetic diversity of crop plants and animals. Maintaining as much ecological **biodiversity** as possible in the agro-ecosystem is essential to long-term crop and livestock production.

The IPAT Equation

As attractive as the concept of sustainability may be as a means of framing our thoughts and goals, its definition is rather broad and difficult to work with when confronted with choices among specific courses of action. One way of measuring progress toward achieving sustainable goals can be with the application of the **IPAT equation**. This equation was designed in an attempt to define the different ways that a variety of factors contribute to the environmental degradation, or impact, of a particular setting. Importantly, IPAT tells us that there are more ways we impact our environment than just through pollution:

$$I = P \times A \times T$$

I represents the impacts on an environment
P is the size of the relevant human population
A is the affluence of the population
T is the technology available to the population

Affluence, or wealth, tells us the level of consumption per person. Wealthy societies consume more goods and services per person. Because of this, their environmental impact is multiplied. Technology, or impact per unit of consumption, interpreted in its broadest sense. This includes any human-created tool, system, or organization designed to enhance efficiency. As societies gain greater access to technology, they are able to do more work with fewer individuals. This equates to a greater impact per person. While this equation is not meant to be mathematically rigorous, it provides a way of organizing information for analysis.

The proportion of people living in cities has greatly increased over the past 50 years. We can use the IPAT equation to estimate the impact of these urban populations. When the impact of technology, which is much easier to access in urban settings, is combined with the impact of population, the impact on the environment is multiplied. In an increasingly urban world, we must focus much of our attention on the environments of cities and on the effects of cities on the rest of the environment. This equation also has large-scale applications in the environmental sciences, and was included in the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (2001) to project future greenhouse gas emissions across the globe.

The precautionary principle

The **precautionary principle** or the precautionary approach is one perspective of environmental risk management. The precautionary principle stakes that “When the health of humans and the environment is at stake, it may not be necessary to wait for scientific certainty to take protective action”. In other words, better to be safe than sorry. Proponents of the precautionary principle also believe that the burden of proof should be on the individual, company or government who is proposing the action, not on the people who will be affected by it. For example, if environmental regulations concerning pesticides were based on the precautionary principle (in the United States, they are not), then any pesticide that could potentially harm the environment or human health would not be used. Overuse of the precautionary principle can have negative consequences as well. If federal regulations concerning medicines for human use were based on the precautionary principle (again, in the United States, they are not), then any medicine that could potentially harm any person would not be used. This would effectively ban nearly all medical trials leading to new medications.

What is the environment worth to you?

The environment, and its benefits to individuals or groups, can be viewed and justified from multiple perspectives. A **utilitarian justification** for environmental conservation means that we should protect the environment because doing so provides a direct economic benefit to people. For example, someone might propose not developing Georgia’s coastal salt marshes because the young of many commercial fishes live in salt marshes and the fishers will collapse without this habitat. An **ecological justification** for environmental conservation means that we should protect the environmental because doing so will protect both species that are beneficial to other as well as other species and an ecological justification for conservation acknowledges the many ecosystem services that we derive from healthy ecosystems. For example, we should protect Georgia’s coastal salt marshes because salt marshes purify water, salt marshes are vital to the survival of many marine fishes and salt marshes protect our coasts from storm surges. An **aesthetic justification** for conservation acknowledges that many people enjoy the outdoors and do not want to live in a world without wilderness. One could also think of this as recreational, inspirational, or spiritual justification for conservation. For example, salt marshes are beautiful places and I always feel relaxed and calm when I am visiting one, therefore we should protect salt marches. And finally a **moral justification** represents the belief that various aspects of the environment have a right to exist and that it is our moral obligation to allow them to continue or help them persist. Someone who was arguing for conservation using a moral justification would say that it is wrong to destroy the coastal salt marshes.

Global perspective

The solution to most environmental problems requires a global perspective. Human population size has now reached a scale where the environmental impacts are global in scale and will require multilateral solutions. You will notice this theme continue as you move through the next seven chapters of this text. As you do so, keep in mind that the set of environmental, regulatory, and economic circumstances common in the United States are not constant throughout the world. Be ready to investigate environmental situations and problems from a diverse set of viewpoints throughout this semester.

Parts of this chapter have been modified from the OpenStax textbooks.

Study questions

1. Why there was a need to study the impact of human population growth on the environment?
2. What does sustainability mean to you?
3. What are the consequences of unsustainable vs. sustainable living? What impacts do these have on quality of life do we want for us and future generations?
4. Think of an environmental problem that requires a global perspective for a solution. How might this problem be examined from a variety of environmental justification perspectives?

Websites for more information and further discussion

Information about the field of environmental science: http://www.environmentalscience.org/
"Process" of science http://undsci.berkeley.edu/

Terms list

Adenosine triphosphate
Aesthetic justification
Amino acid
Anthropogenic
Atom
ATP
Biome
Biosphere
Carbohydrate
Cellular respiration
Community
Competition
Control group
Denature
Deoxyribonucleic acid
Dependent variable
DNA
Ecological justification
Ecosystem
Ecosystem service
Electron
Element
Environment
Environmental engineering
Environmental science
Environmentalism
Experiment
Experimental group
Food web
Glucose
Hydrocarbon
Hypothesis
Independent variable
Interdisciplinary
Ion
IPAT equation
Isotope
Lipid
Matter
Molecule
Moral justification
Neutron
Nucleic acid
Nucleus
Organelle
Organic molecule
Organism
Population
Precautionary principle
Primary production
Protein
Proton
Radioisotope
Ribonucleic acid
RNA
Science
Scientific method
Starch
Succession
Sustainability
Sustainable development
Theory
Tripe bottom-line
Utilitarian justification
Variable

Chapter 2: Population Ecology

A population of elephants at Pinnewala Elephant Orphanage, Sri Lanka. Photo by Paginazero, Wikimedia commons.

A shoal of anchovies in Liguria, Italy. Photo by Alessandro Duci. Wikimedia commons.

Learning Outcomes - At the end of this, chapter students will be able to:

- Define the variables in the exponential and logistic growth equations.
- Use the exponential and logistic equations to predict population growth rate.
- Compare the environmental conditions represented by the exponential growth model vs. the logistic growth model.
- Define carrying capacity and be able to label the carrying capacity on a graph.
- Compare density-dependent and density-independent factors that limit population growth and give examples of each.
- Interpret survivorship curves and give examples of organisms that would fit each type of curve.

Chapter outline

2.1 Population Ecology

Ecology is a sub-discipline of biology that studies the interactions between organisms and their environments. A group of interbreeding individuals (individuals of the same species) living and interacting in a given area at a given time is defined as a **population**. These individuals rely on the same resources and are influenced by the same environmental factors. **Population ecology,** therefore, is the study of how individuals of a particular species interact with their environment and change over time. The study of any population usually begins by determining how many individuals of a particular species exist, and how closely associated they are with each other. Within a particular habitat, a population can be characterized by its **population size** (***N***), defined by the total number of individuals, and its **population density**, the number of individuals of a particular species within a specific area or volume (units are number of individuals/unit area or unit volume). Population *size* and *density* are the two main characteristics used to describe a population. For example, larger populations may be more stable and able to persist better than smaller populations because of the greater amount of genetic variability, and their potential to adapt to the environment or to changes in the environment. On the other hand, a member of a population with low population density (more spread out in the habitat), might have more difficulty finding a mate to reproduce compared to a population of higher density. Other characteristics of a population include **dispersion** – the way individuals are spaced within the area; **age structure** – number of individuals in different age groups and; **sex ratio** – proportion of males to females; and growth – change in population size (increase or decrease) over time.

2.2 Population Growth Models

Populations change over time and space as individuals are born or immigrate (arrive from outside the population) into an area and others die or emigrate (depart from the population to another location). Populations grow and shrink and the age and gender composition also change through time and in response to changing environmental conditions. Some populations, for example trees in a mature forest, are relatively constant over time while others change rapidly. Using idealized models, population ecologists can predict how the size of a particular population will change over time under different conditions.

2.2.1 Exponential Growth

Charles Darwin, in his theory of natural selection, was greatly influenced by the English clergyman Thomas Malthus. Malthus published a book (An Essay on the Principle of Population) in 1798 stating that populations with unlimited natural resources grow very rapidly. According to the Malthus' model, once population size exceeds available resources, population growth decreases dramatically. This accelerating pattern of increasing population size is called **exponential growth,** meaning that the population is increasing by a fixed percentage each year. When plotted (visualized) on a graph showing how the population size increases over time, the result is a J-shaped curve (**Figure 2.1**). Each individual in the population reproduces by a certain amount (***r***) and as the population gets larger, there are more individuals reproducing by that same amount (the fixed percentage). In nature, exponential growth only occurs if there are no external limits.

One example of exponential growth is seen in bacteria. Bacteria are prokaryotes (organisms whose cells lack a nucleus and membrane-bound organelles) that reproduce by fission (each individual cell splits into two new cells). This process takes about an hour for many bacterial species. If 100 bacteria are placed in a large flask with an unlimited supply of nutrients (so the nutrients will not become depleted), after an hour, there is one round of division and each organism divides, resulting in 200 organisms - an increase of 100. In another hour, each of the 200 organisms divides, producing 400 - an increase of 200 organisms. After the third hour, there should be 800 bacteria in the flask - an increase of 400 organisms. After ½ a day and 12 of these cycles, the population would have increased from 100 cells to more than 24,000 cells. When the population size, *N*, is plotted over time, a J-shaped growth curve is produced (**Figure 2.1**). This shows that the number of individuals added during each reproduction generation is accelerating – increasing at a faster rate.

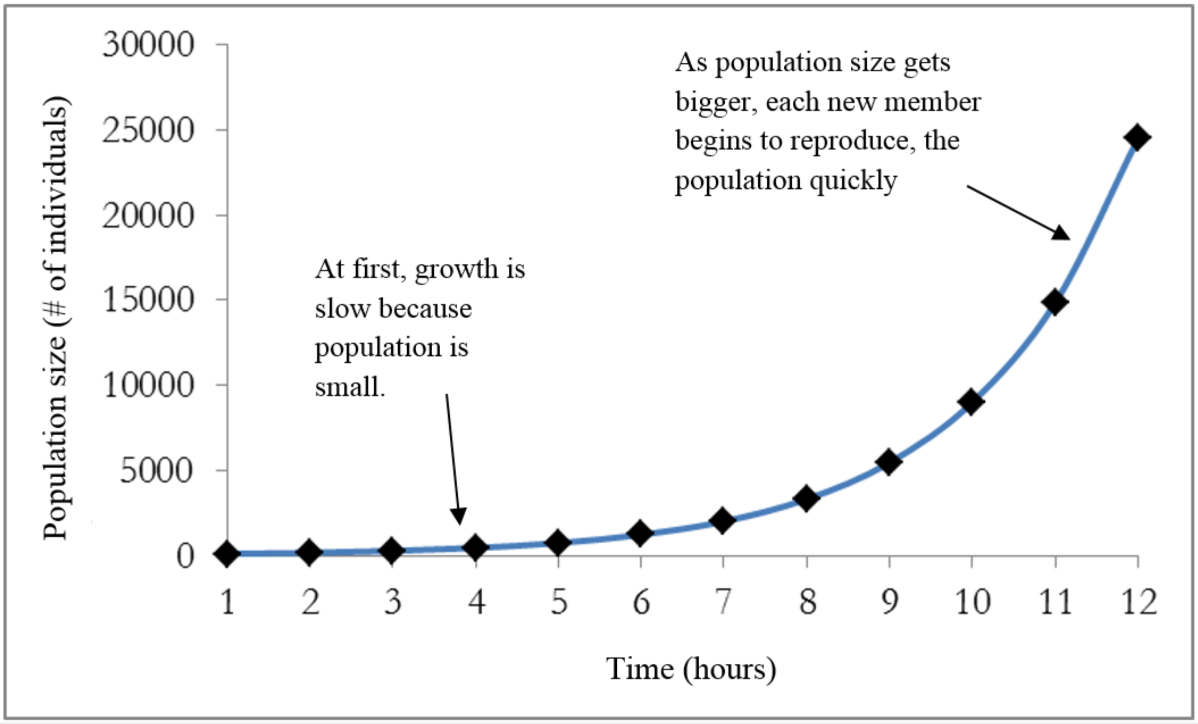


Figure 2.1: The "J" shaped curve of exponential growth for a hypothetical population of bacteria. The population starts out with 100 individuals and after 11 hours there are over 24,000 individuals. As time goes on and the population size increases, the rate of increase also increases (each step up becomes bigger). In this figure "r" is positive.

This type of growth can be represented using a mathematical function known as the **exponential growth model:**

G* = *r* x *N (also expressed as ***dN/dt* = *r* x *N***). In this equation

G (or ***dN/dt***) is the *population growth rate*, it is a measure of the number of individuals added per time interval time.

r is the *per capita rate of increase* (the average contribution of each member in a population to population growth; per capita means "per person").

N is the *population size*, the number of individuals in the population at a particular time.

Per capita rate of increase (r)

In exponential growth, the *population growth rate* (***G***) depends on population size (*N*) and the per capita rate of increase (*r*). In this model *r* does not change (fixed percentage) and change in population growth rate, **G**, is due to change in population size, ***N***. As new individuals are added to the population, each of the new additions contribute to population growth at the same rate (*r*) as the individuals already in the population.

r = (birth rate + immigration rate) – (death rate and emigration rate).

If *r* is positive (> zero), the population is increasing in size; this means that the birth and immigration rates are greater than death and emigration.

If *r* is negative (< zero), the population is decreasing in size; this means that the birth and immigration rates are less than death and emigration rates.

If *r* is zero, then the population growth rate (***G***) is zero and population size is unchanging, a condition known as zero population growth. "***r***" varies depending on the type of organism, for example a population of bacteria would have a much higher "***r***" than an elephant population. In the exponential growth model r is multiplied by the population size, *N*, so population growth rate is largely influenced by *N*. This means that if two populations have the same per capita rate of increase (*r*), the population with a larger *N* will have a larger population growth rate than the one with a smaller *N*.

2.2.2 Logistic Growth

Exponential growth cannot continue forever because resources (food, water, shelter) will become limited. Exponential growth may occur in environments where there are few individuals and plentiful resources, but soon or later, the population gets large enough that individuals run out of vital resources such as food or living space, slowing the growth rate. When resources are limited, populations exhibit **logistic growth.** In logistic growth a population grows nearly exponentially at first when the population is small and resources are plentiful but growth rate slows down as the population size nears limit of the environment and resources begin to be in short supply and finally stabilizes (zero population growth rate) at the maximum population size that can be supported by the environment (**carrying capacity**). This results in a characteristic S-shaped growth curve (**Figure 2.2**). The mathematical function or logistic growth model is represented by the following equation:

$$\boldsymbol{G = r * N * [1 - \frac{N}{K}]}$$

Where,
K is the *carrying capacity* – the maximum population size that a particular environment can sustain ("carry"). Notice that this model is similar to the exponential growth model except for the addition of the carrying capacity.

In the exponential growth model, population growth rate was mainly dependent on *N* so that each new individual added to the population contributed equally to its growth as those individuals previously in the population because per capita rate of increase is fixed. In the logistic growth model, individuals' contribution to population growth rate depends on the amount of resources available (K). As the number of individuals (N) in a population increases, fewer resources are available to each individual. As resources diminish, each individual on average, produces fewer offspring than when resources are plentiful, causing the birth rate of the population to decrease.

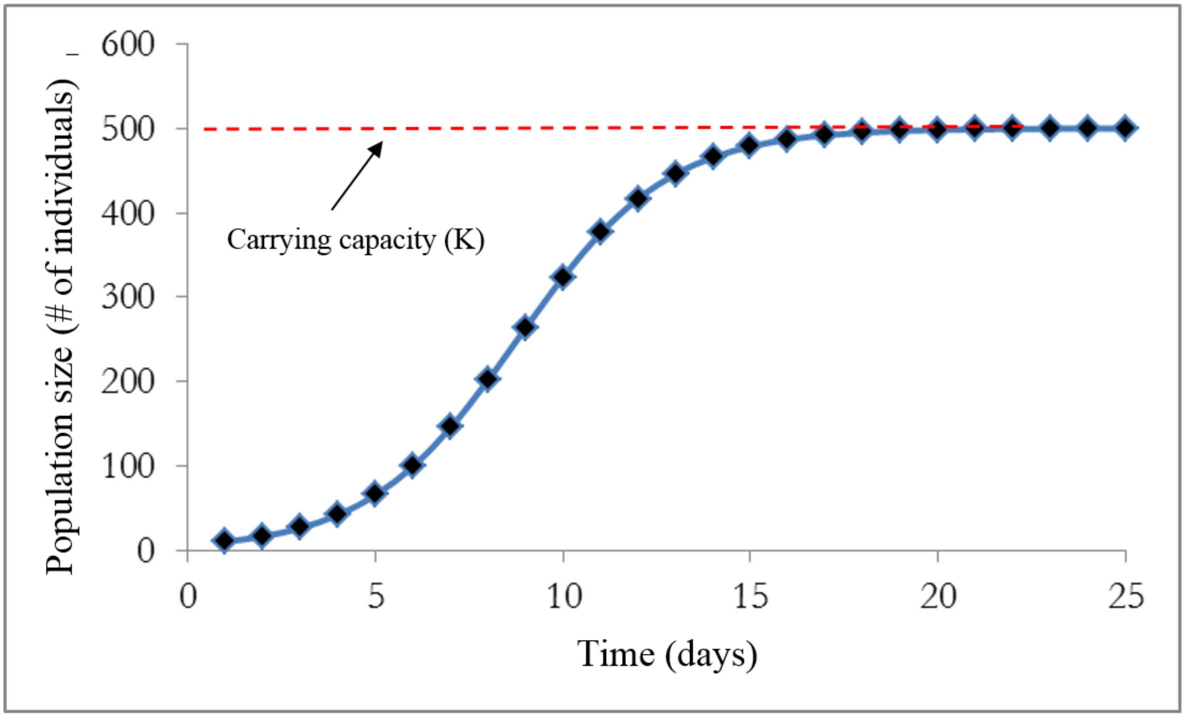
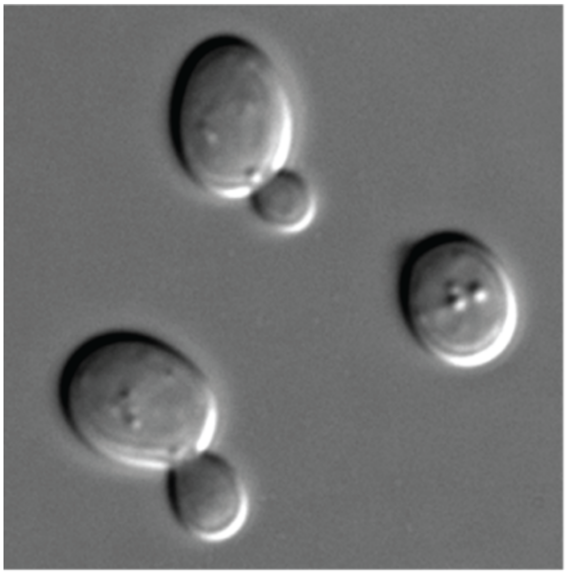


Figure 2.2: Shows logistic growth of a hypothetical bacteria population. The population starts out with 10 individuals and then reaches the carrying capacity of the habitat which is 500 individuals.

Influence of *K* on population growth rate

In the logistic growth model, the exponential growth (***r * N***) is multiplied by fraction or expression that describes the effect that limiting factors (***1 - N/K***) have on an increasing population. Initially when the population is very small compared to the capacity of the environment (*K*), 1 - N/K is a large fraction that nearly equals 1 so population growth rate is close to the exponential growth (r * N). For example, supposing an environment can support a maximum of 100 individuals and N = 2, N is so small that *1 – N/K* (1 – 2/100 = 0.98) will be large, close to 1. As the population increases and population size gets closer to carrying capacity (N nearly equals K), then 1 - N/K is a small fraction that nearly equals zero and when this fraction is multiplied by r * N, population growth rate is slowed down. In the earlier example, if the population grows to 98 individuals, which is close to (but not equal) K, then 1 – N/K (1 – 98/100 = 0.02) will be so small, close to zero. If population size equals the carrying capacity, N/K = 1, so 1 – N/K = 0, population growth rate will be zero (in the above example, 1 – 100/100 = 0). This model, therefore, predicts that *a population's growth rate will be small when the population size is either small or large, and highest when the population is at an intermediate level relative to K*. At small populations, growth rate is limited by the small amount of individuals (*N*) available to reproduce and contribute to population growth rate whereas at large populations, growth rate is limited by the limited amount of resources available to each of the large number of individuals to enable them reproduce successfully. In fact, *maximum population growth rate* ***(G)*** *occurs when N is half of K*.

Yeast is a microscopic fungus, used to make bread and alcoholic beverages, that exhibits the classical S-shaped logistic growth curve when grown in a test tube (**Figure 2.3**). Its growth levels off as the population depletes the nutrients that are necessary for its growth. In the real world, however, there are variations to this idealized curve. For example, a population of harbor seals may exceed the carrying capacity for a short time and then fall below the carrying capacity for a brief time period and as more resources become available, the population grows again (**Figure 2.4**). This fluctuation in population size continues to occur as the population oscillates around its carrying capacity. Still, even with this oscillation, the logistic model is exhibited.



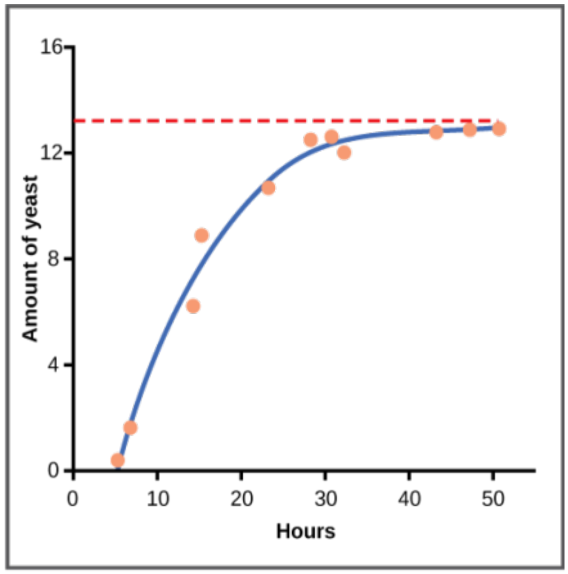


Figure 2.3: Graph showing amount of yeast versus time of growth in hours. The curve rises steeply, and then plateaus at the carrying capacity. Data points tightly follow the curve. The image is a micrograph (microscope image) of yeast cells

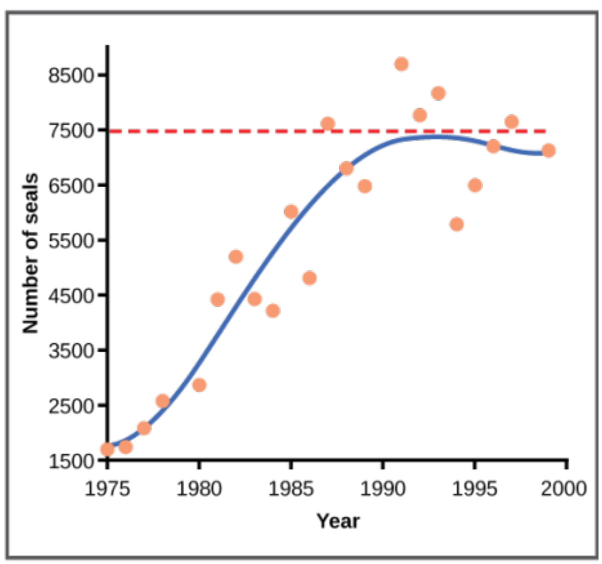


Figure 2.4: Graph showing the number of harbor seals versus time in years. The curve rises steeply then plateaus at the carrying capacity, but this time there is much more scatter in the data. A photo of a harbor seal is shown.

2.3 Factors limiting population growth

Recall previously that we defined density as the number of individuals per unit area. In nature, a population that is introduced to a new environment or is rebounding from a catastrophic decline in numbers may grow exponentially for a while because density is low and resources are not limiting. Eventually, one or more environmental factors will limit its population growth rate as the population size approaches the carrying capacity and density increases. Example: imagine that in an effort to preserve elk, a population of 20 individuals is introduced to a previously unoccupied island that's 200 km^2 in size. The population density of elk on this island is 0.1 elk/km^2 (or 10 km^2 for each individual elk). As this population grows (depending on its per capita rate of increase), the number of individuals increases but the amount of space does not so density increases. Suppose that 10 years later, the elk population has grown to 800 individuals, density = 4 elk/ km^2 (or 0.25 km^2 for each individual). The population growth rate will be limited by various factors in the environment. For example, birth rates may decrease due to limited food or death rate increase due to rapid spread of disease as individuals encounter one another more often. This impact on birth and death rate in turn influences the per capita rate of increase and how the population size changes with changes in the environment. When birth and death rates of a population change as the density of the population changes, the rates are said to be density-dependent and the environmental factors that affect birth and death rates are known as **density-dependent factors**. In other cases, populations are held in check by factors that are not related to the density of the population and are called **density-independent factors** and influence population size regardless of population density. Conservation biologists want to understand both types because this helps them manage populations and prevent extinction or overpopulation.

The density of a population can enhance or diminish the impact of *density-dependent* factors. Most density-dependent factors are *biological* in nature (biotic), and include such things as predation, inter- and intraspecific competition for food and mates, accumulation of waste, and diseases such as those caused by parasites. Usually, higher population density results in higher death rates and lower birth rates. For example, as a population increases in size food becomes scarcer and some individuals will die from starvation meaning that the death rate from starvation increases as population size increases. Also as food becomes scarcer, birth rates decrease due to fewer available resources for the mother meaning that the birth rate decreases as population size increases. For density-dependent factors, there is a feedback loop between population density and the density-dependent factor.

Two examples of density-dependent regulation are shown in **Figure 2.5**. First one is showing results from a study focusing on the giant intestinal roundworm (*Ascaris lumbricoides*), a parasite that infects humans and other mammals. Denser populations of the parasite exhibited lower fecundity (number of eggs per female). One possible explanation for this is that females would be smaller in more dense populations because of limited resources and smaller females produce fewer eggs.

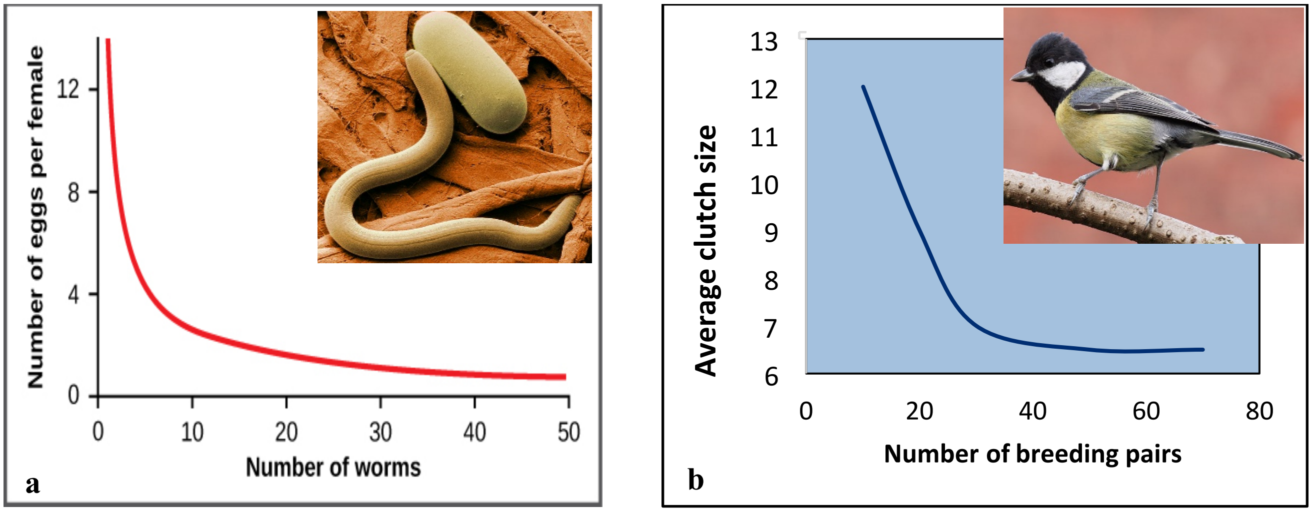


Figure 2.5: (**a**) Graph of number of eggs per female (fecundity), as a function of population size. In this population of roundworms, fecundity (number of eggs) decreases with population density. (**b**) Graph of clutch size (number of eggs per "litter") of the great tits bird as a function of population size (breeding pairs). Again, clutch size decreases as population density increases. (Photo credits: Worm image from Wikimedia commons, public domain image; bird image from Wikimedia commons, photo by Francis C. Franklin / CC-BY-SA-3.0)

Density-independent birth rates and death rates do NOT depend on population size; these factors are independent of, or not influenced by, population density. Many factors influence population size regardless of the population density, including weather extremes, natural disasters (earthquakes, hurricanes, tornadoes, tsunamis, etc.), pollution and other physical/abiotic factors. For example, an individual deer may be killed in a forest fire regardless of how many deer happen to be in the forest. The forest fire is not responding to deer population size. As the weather grows cooler in the winter, many insects die from the cold. The change in weather does not depend on whether there is a population size of 100 mosquitoes or 100,000 mosquitoes, most mosquitoes will die from the cold regardless of the population size and the weather will change irrespective of mosquito population density. Looking at the growth curve of such a population would show something like an exponential growth followed by a rapid decline rather than levelling off (**Figure 2.6**).

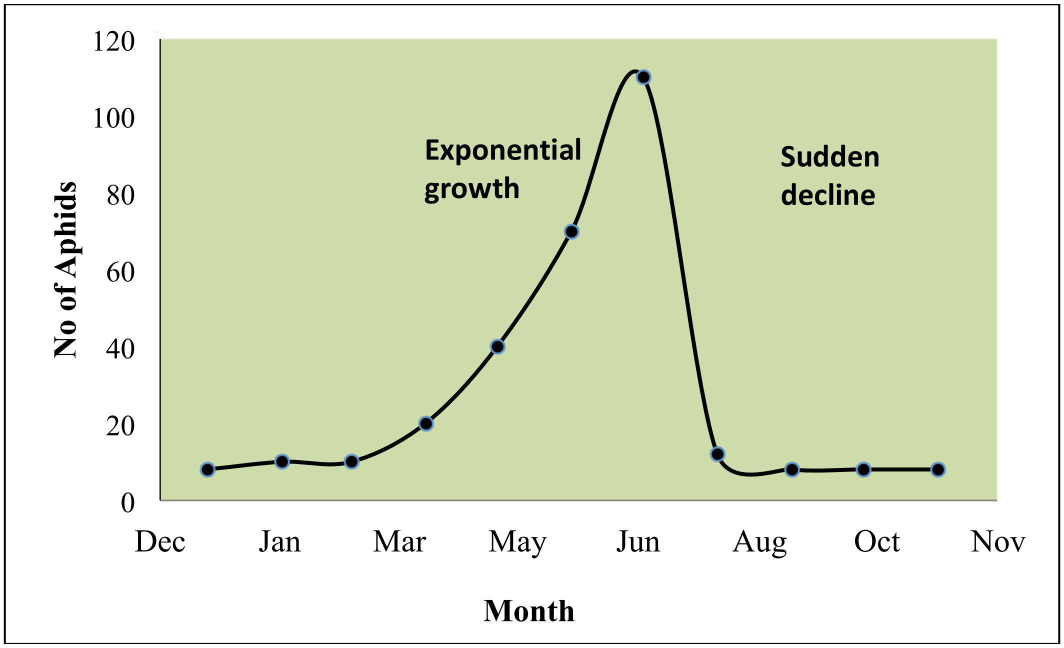


Figure 2.6: Weather change acting as a density-independent factor limiting aphid population growth. This insect undergoes exponential growth in the early spring and then rapidly die off when the weather turns hot and dry in the summer

In real-life situations, density-dependent and independent factors interact. For example, a devastating earthquake occurred in Haiti in 2010. This earthquake was a natural geologic event that caused a high human death toll from this *density-independent event*. Then there were high densities of people in refugee camps and the high density caused disease to spread quickly, representing a *density-dependent* death rate.

Q: Can you think of other *density-dependent* (biological) and *density-independent* (abiotic) population limiting factors?

2.4 Life Tables and Survivorship

Population ecologists use life tables to study species and identify the most vulnerable stages of organisms' lives to develop effective measures for maintaining viable populations. Life tables, like **Table 2.1**, track **survivorship**, the chance of an individual in a given population surviving to various ages. Life tables were invented by the insurance industry to predict how long, on average, a person will live. Biologists use a life table as a quick window into the lives of the individuals of a population, showing how long they are likely to live, when they'll reproduce, and how many offspring they'll produce. Life tables are used to construct **survivorship curves**, which are graphs showing the proportion of individuals of a particular age that are now alive in a population. Survivorship (chance of surviving to a particular age) is plotted on the y-axis as a function of age or time on the x-axis. However, if the percent of maximum lifespan is used on the x-axis instead of actual ages, it is possible to compare survivorship curves for different types of organisms (**Figure 2.7**). All survivorship curves start along the y-axis intercept with all of the individuals in the population (or 100% of the individuals surviving). As the population ages, individuals die and the curves goes down. A survivorship curve never goes up.

Table 2.1: Life Table for the U.S. population in 2011 showing the number who are expected to be alive at the beginning of each age interval based on the death rates in 2011. For example, 95,816 people out of 100,000 are expected to live to age 50 (0.983 chance of survival). The chance of surviving to age 60 is 0.964 but the chance of surviving to age 90 is only 0.570.

Age (years)	Number Living at Start of Age Interval	Number Dying During Interval	Chance of Surviving Interval	Chance of Dying During Interval
0-1	100000	606	0.993942	0.006058
1-5	99394	105	0.998946	0.001054
5-10	99289	60	0.999397	0.000603
10-15	99230	70	0.999291	0.000709
15-20	99159	242	0.997562	0.002438
20-25	98917	425	0.995704	0.004296
25-30	98493	475	0.995176	0.004824
30-35	98017	553	0.994362	0.005638
35-40	97465	681	0.993015	0.006985
40-45	96784	968	0.989994	0.010006
45-50	95816	1535	0.983982	0.016018
50-55	94281	2306	0.975541	0.024459
55-60	91975	3229	0.964895	0.035105
60-65	88746	4378	0.950668	0.049332
65-70	84368	6184	0.926698	0.073302
70-75	87184	8670	0.889101	0.110899
75-80	69513	12021	0.827073	0.172927
80-85	57493	15760	0.725879	0.274121
85-90	41733	17935	0.570241	0.429759
90-95	23798	14701	0.382258	0.617742
95-100	9097	7169	0.211924	0.788076
100 and over	1928	1928	0	1.000000

SOURCE: CDC/NCHS, National Vital Statistics System.

Survivorship curves reveal a huge amount of information about a population, such as whether most offspring die shortly after birth or whether most survive to adulthood and likely to live long lives. They generally fall into one of three typical shapes, Types I, II and III (**Figure 2.7a**). Organisms that exhibit **Type I** survivorship curves have the highest probability of surviving every age interval until old age, then the risk of dying increases dramatically. Humans are an example of a species with a Type I survivorship curve. Others include the giant tortoise and most large mammals such as elephants. These organisms have few natural predators and are, therefore, likely to live long lives. They tend to produce only a few offspring at a time and invest significant time and effort in each offspring, which increases survival.

In the **Type III** survivorship curve most of the deaths occur in the youngest age groups. Juvenile survivorship is very low and many individuals die young but individuals lucky enough to survive the first few age intervals are likely to live a much longer time. Most plants species, insect species, frogs as well as marine species such as oysters and fishes have a Type III survivorship curve. A female frog may lay hundreds of eggs in a pond and these eggs produce hundreds of tadpoles. However, predators eat many of the young tadpoles and competition for food also means that many tadpoles don't survive. But the few tadpoles that do survive and metamorphose into adults then live for a relatively long time (for a frog). The mackerel fish, a female is capable of producing a million eggs and on average only about 2 survive to adulthood. Organisms with this type of survivorship curve tend to produce very large numbers of offspring because most will not survive. They also tend not to provide much parental care, if any.

Type II survivorship is intermediate between the others and suggests that such species have an even chance of dying at any age. Many birds, small mammals such as squirrels, and small reptiles, like lizards, have a Type II survivorship curve. The straight line indicates that the proportion alive in each age interval drops at a steady, regular pace. The likelihood of dying in any age interval is the same.

In reality, most species don't have survivorship curves that are definitively type I, II, or III. They may be anywhere in between. These three, though, represent the extremes and help us make predictions about reproductive rates and parental investment without extensive observations of individual behavior. For example, humans in less industrialized countries tend to have higher mortality rates in all age intervals, particularly in the earliest intervals when compared to individuals in industrialized countries. Looking at the population of the United States in 1900 (**Figure 2.7b**), you can see that mortality was much higher in the earliest intervals and throughout, the population seemed to exhibit a type II survivorship curve, similar to what might be seen in less industrialized countries or amongst the poorest populations.

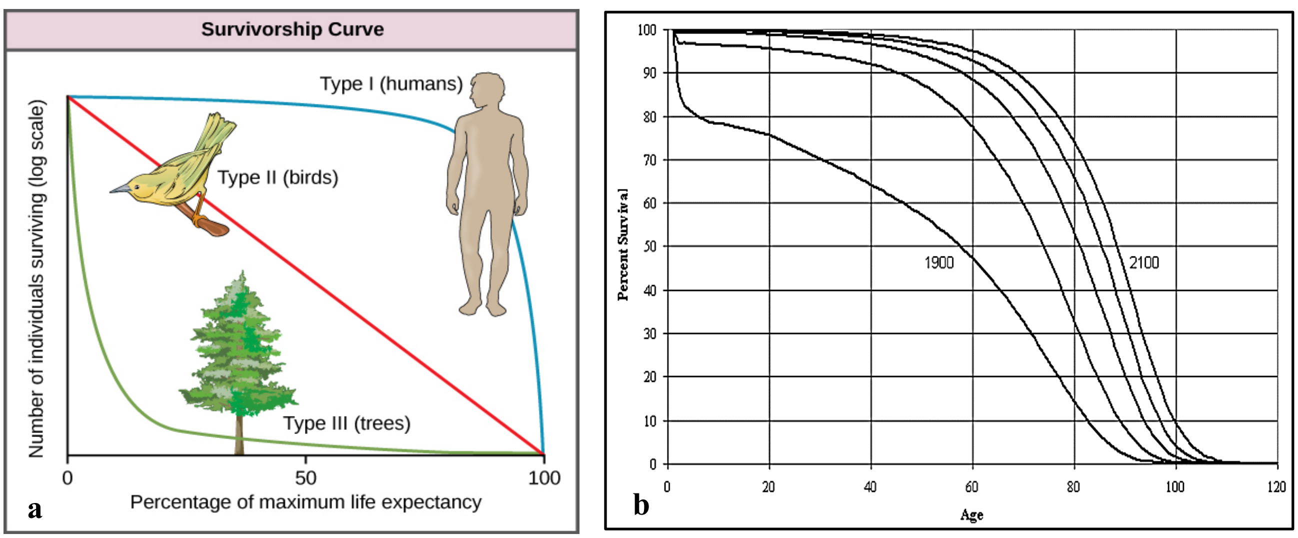


Figure 2.7: (**a**) Survivorship curves show the distribution of individuals in a population according to age. Humans and most large mammals have a Type I survivorship curve because most death occurs in the older years. Birds have a Type II survivorship curve, as death at any age is equally probable. Trees have a Type III survivorship curve because very few survive the younger years, but after a certain age, individuals are much more likely to survive. (**b**) Survivoship curves for the US population for 1900, 1950, 2000, 2050, 2100 *SOURCE: www.ssa.gov*.

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This material has been modified from the OpenStax Biology textbook.

POPULATION ECOLOGY PRACTICE PROBLEMS

1. If a population is experiencing exponential growth, what happens to **N**, ***r*** and **G** over time (increase, decrease or stay the same)?

2. At the beginning of the year, there are 7650 individuals in a population of beavers whose per capita rate of increase for the year is 0.18. What is its population growth rate at the end of the year?

3. A zebrafish population of 1000 individuals lives in an ecosystem that can support a maximum of 2000 zebrafish. The per capita rate of increase for the population is 0.01 for the year. What is the population growth rate?

4. In a scenario where: ***r*** = 0.25; **K** = 18,000;
    a. What is **G** when i) **N** = 4,500; ii) N = 9,000; and iii) **N** = 13,500?
    b. Which **N** level results in the highest population growth rate and why?

5. A chipmunk population is experiencing exponential growth with a population growth rate of 265 individuals/year, and a per capita rate of increase of 0.15. How many chipmunks are currently in this population?

6. Scientists discovered a new species of frog and were able to estimate its population at 755 individuals. At the end of the year, 105 frogs were added to this population. Assuming the population is undergoing exponential growth, what is the per capita rate of increase?

Test your skills (extra challenge)

7. At the beginning of the year, a wildlife area that is 1,000,000 ha in size has a population of 90 Brown bears with a per capita growth rate of 0.02. It's estimated that brown bears **<u>need</u>** a territory of about 10 km^2 per individual (**note**: 1 km^2 = 100 ha). Use this information to answer the following questions.
    a. What is the density of brown bears in this wildlife preserve currently?
    b. What is the *carrying capacity* of the preserve?
    c. What is the population growth rate for this year?

8. A wildlife ranch currently has a population of polar bears whose death rate is 0.05 and birth rate is 0.12 per year. This particular ranch is isolated from other suitable habitats so there's no immigration into or emigration from this population. This population is experiencing logistic growth and currently has 550 bears. If the population growth rate for the year was 36 bears, what is the carrying capacity of the preserve?

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Chapter 3: Human Demography

By the end of this chapter, you will be able to:

- State the current size of the human population.
- Interpret age-structure diagrams.
- Explain what the demographic transition model represents and describe the societal changes that cause the demographic transition.
- Describe what happens to birth rates, death rates, population growth rate, and population size as a country moves through the stages of the demographic transition model.
- Give examples of countries in the different stages of the demographic transition models and match age-structure diagrams with the stages of the demographic transition model.
- Define life expectancy and explain how it changes as a country moves through the demographic transition model.
- Define fertility and explain how it changes as a country moves through the demographic transition model.

Chapter outline

1. The human population
2. Demography
3. Age structure diagrams
4. The demographic transition model
5. Life expectancy
6. Fertility

3.1 The human population.

The human population is growing rapidly. For most of human history, there were fewer than 1 billion people on the planet. During the time of the agricultural revolution, 10,000 B.C., there were only 5-10 million people on Earth - which is basically the population of New York City today. In 1800, when the Industrial Revolution began, there were approximately 1 billion people on Earth (Figure 3.1). We've added 6 billion people to the human population in just a little over 200 years. This demonstrates the capacity of the human population to exhibit exponential growth (Chapter 2).

What is the current human population? Use this World population clock link to determine the current human population: http://math.berkeley.edu/~galen/popclk.html

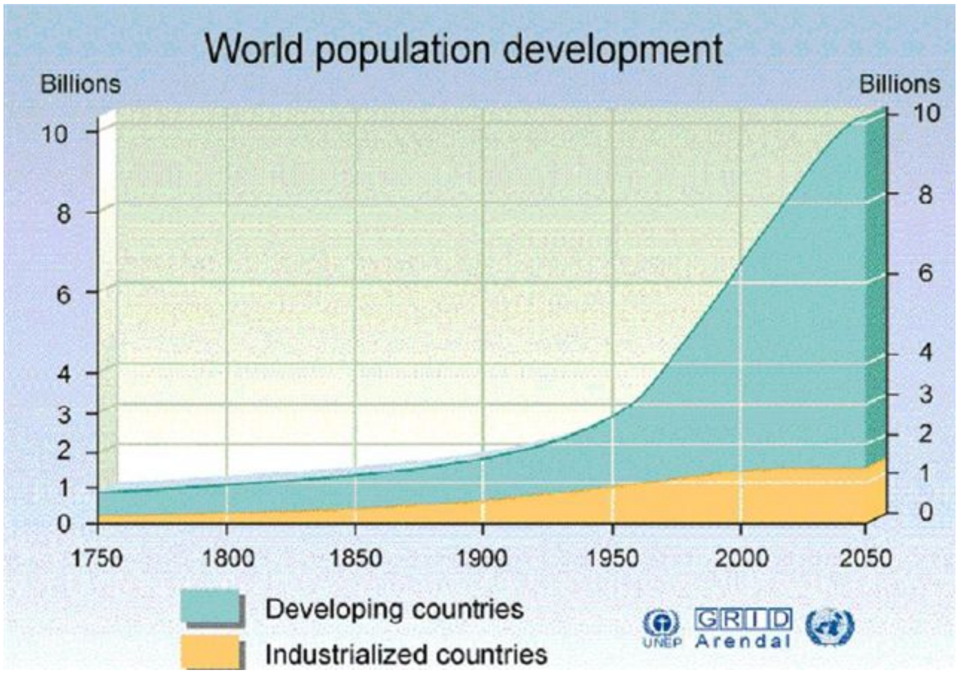


Figure 3.1: Shows the increase in human population size starting in 1750 and predicted out to 2050. The orange area represents the human population in industrialized countries and the blue/green area represents the human population in less-industrialized (developing) countries. The greatest amount of human population growth will be in less-industrialized countries.

3.2 Demography

Demography applies the principles of population ecology (chapter 2) to the human population. Demographers study how human populations grow, shrink, and change in terms of age and gender compositions. Demographers also compare populations in different countries or regions.

3.3 Age structure diagrams

One of the tools that demographers use to understand populations is the **age structure diagram**. This diagram shows the distribution by ages of females and males within a certain population in graphic form. Figure 3.2 shows a diagram for the United States population. In this diagram, the ages are arranged so that age ranges are grouped together, for example: 0 – 4 years, 5 – 9 years, and so on. The population of each group is represented as a bar extending from a central vertical line, with the length of each bar dependent upon the total population for that particular group. The centerline separates the females from the males. The female and male populations for each group are represented by the distance from the centerline, with females on the right and males on the left.

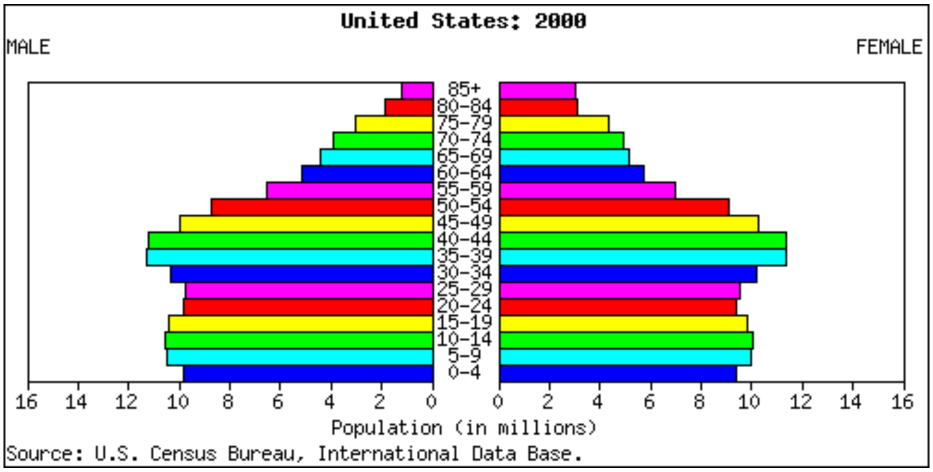


Figure 3.2: Age Structure diagram for the U.S. in 2000

By looking closely at the age structure diagram, one will notice slightly more boys in the younger age groups than girls; however, the ratio tends to reverse in the upper age groups, when females tend to outnumber males. Many countries have a female majority as a result of the longer life expectancy for females.

The following age structure diagrams (Figure 3.3) show the United States in 2005 and 2010. Please note the slightly different x-axes scale on these diagrams compared to the 2000 diagram above (Figure 3.2). You can see the aging group of baby boomers move upward when you compare these 3 age structure diagrams. There are also more elderly (80+) individuals, especially women, in 2005 and 2010.

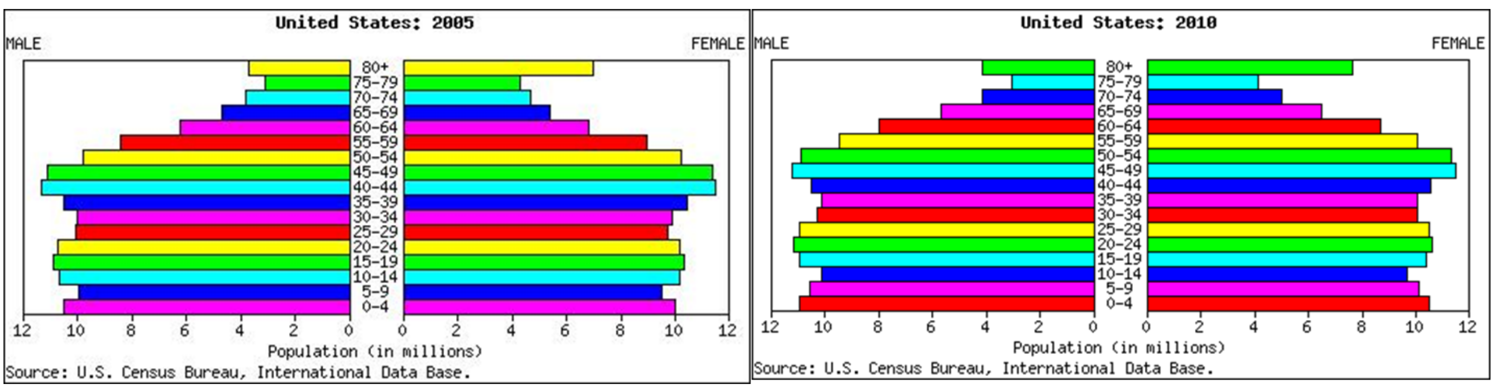


Figure 3.3: Age Structure diagram for the U.S. in 2005 and 2010.

An age-structure diagram provides a snapshot of the current population and can represent information about the past and give potential clues about future problems. When you are interpreting age-structure diagrams, it is important to compare the width of the base to the rest of the population. If the base is very wide compared to the upper parts of the diagram, then this indicates a lot of young people (pre-reproductive) in the population compared to older generations i.e. a high birth rate and a rapidly growing population. If the base is smaller than the upper parts of the diagram, then this indicates few young people in the population compared to older generations (post-reproductive). This population has low birth rates and is shrinking.

3.4 The Demographic Transition Model

The demographic transition model shows the changes in the patterns of birth rates and death rates that typically occur as a country moves through the process of industrialization or development. The demographic transition model was built based on patterns observed in European counties as they were going through industrialization. This model can be applied to other countries, but not all countries or regions fit the model exactly. And the pace or rate at which a country moves through the demographic transition varies among countries.

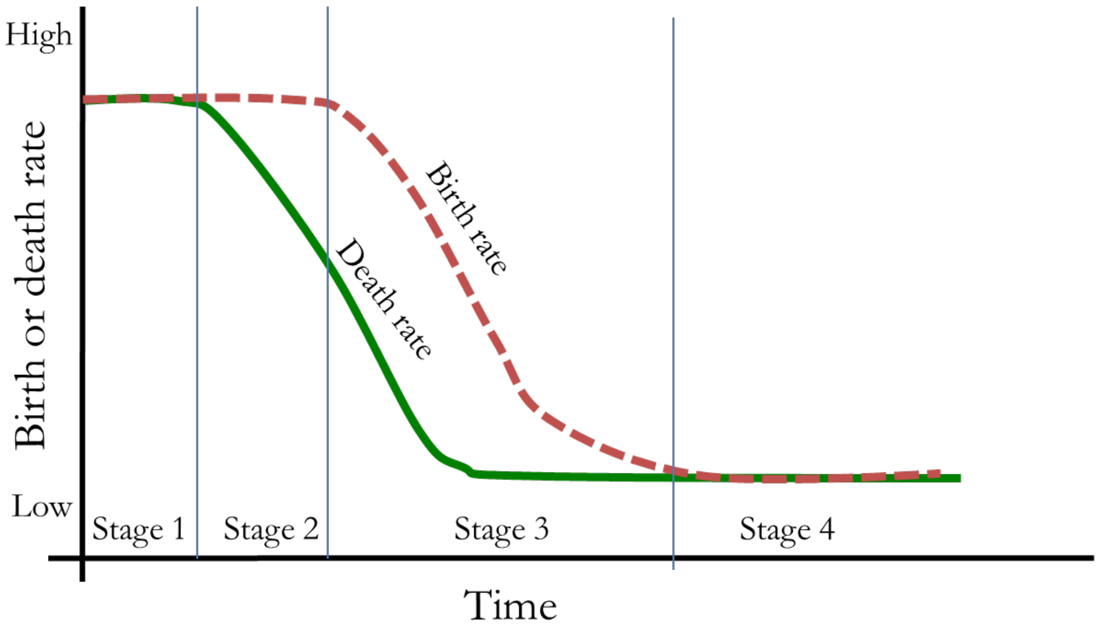


Figure 3.4: The demographic transition model shows how birth rates and death rates change over time as a country becomes more developed. The demographic transition model is typically divided into four stages. The green line represents death rates and the dashed red line represents birth rates.

In the demographic transition model, a country begins in Stage 1, the preindustrial stage. In Stage 1 (Figure 3.4), both birth rates and death rates are high. The high death rates are because of disease and potential food scarcity. A country in Stage 1 of the demographic transition model does not have good health care; there may not be any hospitals or doctors. Children are not vaccinated against common diseases and therefore many children die at a young age. Infant and childhood **mortality rates** (death rates) are very high. A society in Stage 1 is likely based upon agriculture and most people grow their own food. Therefore, droughts or flood can lead to widespread food shortages and death from famine. All of these factors contribute to the high death rate in Stage 1. Partly to compensate for the high death rates, birth rates are also high. High birth rates mean that families are large and each couple, on average, has many children. When death rates are high, having many children means that at least one or two will live to adulthood. In Stage 1, children are an important part of the family workforce and are expected to work growing food and taking care of the family.

As you are examining the stages of the demographic transition model, remember that:

Population Growth Rate = Birth Rate – Death Rate

In Stage 1, birth rates are high, but death rates are high as well. Therefore, population growth rate is low or close to zero (Figure 3.5).

As a country develops, medical advances are made such as access to antibiotics and vaccines. Sanitation improvements, such as proper waste and sewage disposal, and water treatment for clean drinking water also progress. Food production also increases. Together these changes lead to falling death rates which marks the beginning of Stage 2 (Figure 3.4). Death rates continue to fall throughout Stage 2 as conditions improve. This means that people are living longer and childhood morality drops. However, birth rates are still high in Stage 2. There is a time lag between the improving conditions and any subsequent changes in family size, so women are still having many children and now more of these children are living into adulthood. In Stage 2, the birth rate is higher than the death rate, so population growth rate is high. This means that population size increases greatly during Stage 2 of the demographic transition model (Figure 3.5).

A falling birth rate marks the beginning of Stage 3 in the demographic transition model. As a country continues to industrialize, many women join the workforce. Additionally, raising children becomes more expensive and children no longer work on the family farm or make large economic contributions to the family. Individuals may have access to birth control and choose to have fewer children. This leads to a drop in birth rates and smaller family sizes. Death rates also continue to drop during Stage 3 as medicine, sanitation and food security continue to improve. Even though both birth rates and death rates are falling throughout Stage 3, birth rates are higher than death rates. This means that population growth rate is high and that population size continues to increase in Stage 3 of the demographic transition model (Figure 3.5).

Birth rate and death rates drop to low, stable, approximately equal levels in Stage 4. Death rates are low because of medical advances, good sanitation, clean drinking water and food security. Birth rates are low because of access to birth control and many women delay having their first child until they have worked. Childhood mortality is low, life expectancy is high, and family size is approximately two children per couple. With low birth rates and low death rates, population growth rate is approximately zero in Stage 4 (Figure 3.5).

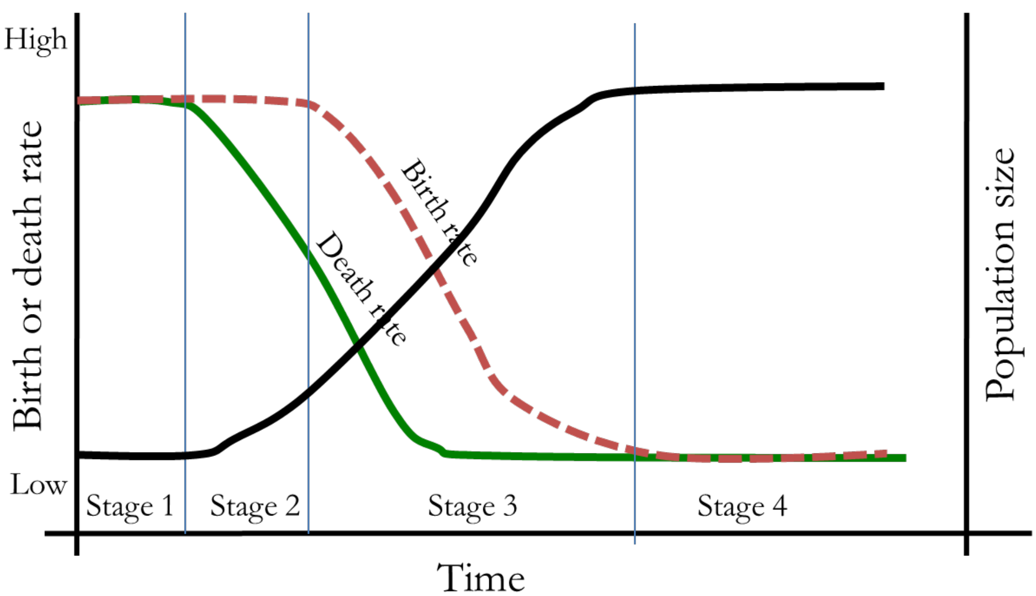


Figure 3.5: This figure repeats the demographic transition model of Figure 3.4, with the changes in population size (y-axes on the far right) shown by the black line. Population size is low and stable in Stage 1, increases

rapidly in Stage 2 and 3 because birth rates are higher than death rates, and then is high and stable again in Stage 4.

3.5 Life expectancy

Life expectancy is the average number of years that a person in a particular population is expected to live. Life expectancy at birth is the number of years a newborn infant would live if mortality rates at the time of its birth did not change. For example, the life expectancy at birth for someone born in 2014 in Japan is 84.46 years while the life expectancy at birth for someone born in the United States in 2014 is 79.56 years (source: https://www.cia.gov). As a country moves through the demographic transition model, life expectancy increases. Overall, life expectancy has increased for most countries and regions over the past 100 years. However, there is still a significant amount of variation in life expectancy in different regions of the world.

Use this World Health Organization interactive map to compare life expectancy among different countries: http://gamapserver.who.int/gho/interactive_charts/mbd/life_expectancy/atlas.html

What other countries have a life expectancy at birth similar to the United States? List two countries that have a higher life expectancy and two countries that have a lower life expectancy than the United States.

3.6 Fertility

Fertility is the actual level of reproduction of a population per individual, based on the number of live births that occur. Total fertility is the average number of children born to each woman, over the woman's lifespan, in a population. Birth rate and fertility are closely linked terms. As a country moves through the demographic transition model, fertility rates decrease. Overall, fertility rates have decreased for most countries and regions over the past 50 years (Figure 3.6). However, there is still a significant amount of variation among different regions of the world.

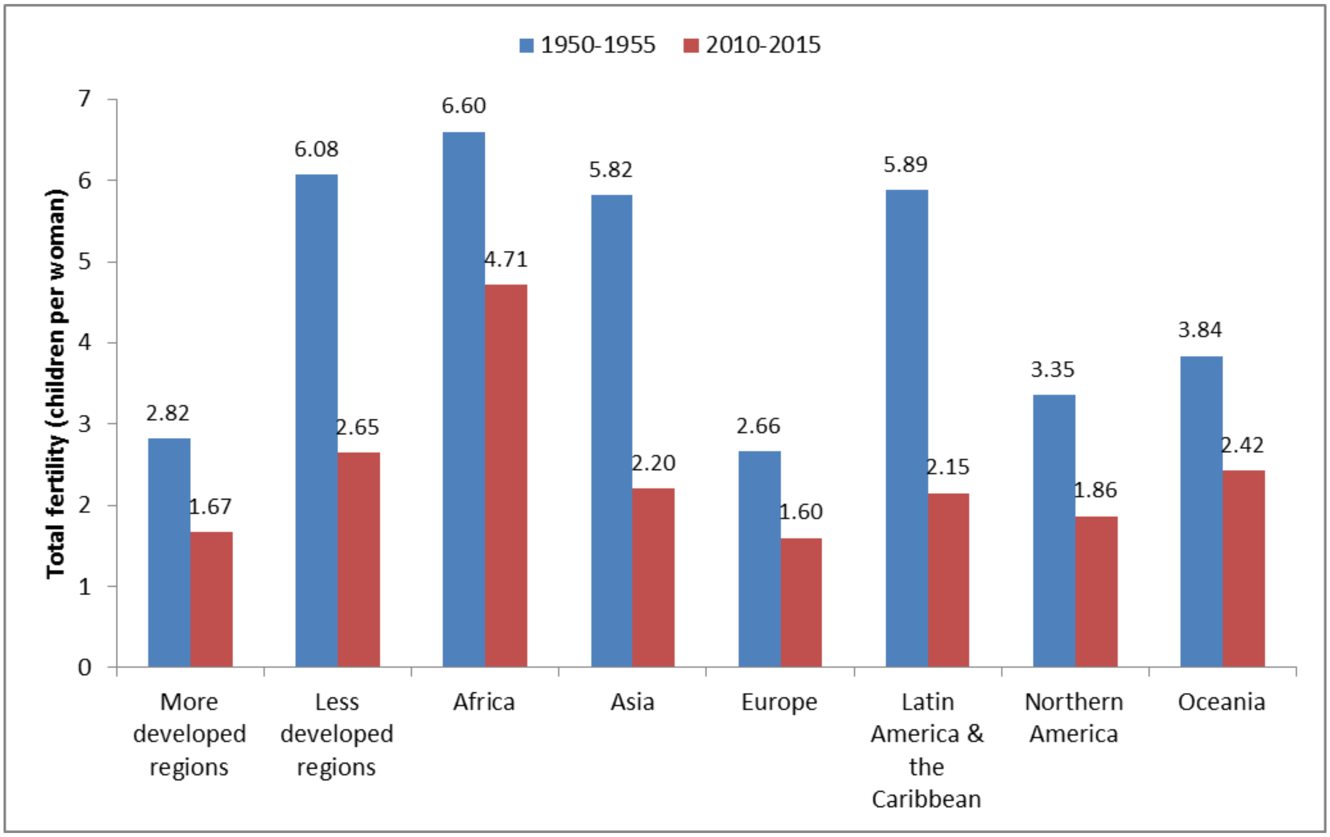


Figure 3.6: Shows the total fertility of different regions of the world. The blue bars are the total fertility estimates from 1950-1955. The red bars are the total fertility estimates from 2010-2015. More developed regions include Europe, Northern America (US and Canada), Australia, New Zealand and Japan. Less developed regions comprise all regions of Africa, Asia (except Japan), Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia. Oceania includes Australia, New Zealand, Melanesia, Micronesia and Polynesia. Data are from the United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects, 2015 Revision. UN http://esa.un.org/unpd/wpp/DVD/

Additional recourses

United Nations Development Programme, Human Development Reports
http://hdr.undp.org/en/content/demography-and-human-development

Carrying capacity of ecosystems and human demography

http://institutmichelserres.ens-lyon.fr/spip.php?article38

Terms list

Age structure diagram

Demography

Demographic transition model

Fertility

Life expectancy

Mortality rate

Population growth rate

Pre-reproductive/post-reproductive age

CHAPTER 4: NON-RENEWABLE ENERGY

Watts Bar Nuclear Power Plant in East Tennessee. Image from Tennessee Valley Authority (Public Domain).

Chapter outline

4.1 What is Energy?
4.2 Fossil Fuels
4.3 Coal
4.4 Oil
4.5 Natural gas
4.6 Fossil fuels and greenhouse gases
4.7 Nuclear energy

Learning Objectives

By the end of this chapter, students will be able to

- List specific examples of non-renewable energy sources
- Explain what makes an energy source non-renewable
- Describe the main types of fossil fuels and how they formed
- Explain the environmental impacts associated with exploration, extraction and use of the different types of fossil fuels
- Explain nuclear energy, how it works, its benefits and risks

4.1 What is Energy?

Energy is the ability of a system to do work. A system has done work if it has exerted a force on another system over some distance. When this happens, energy is transferred from one system to another. At least some of the energy is also transformed from one type to another during this process. One can keep track of how much energy transfers into or out of a system. There are two categories that all energy falls into: kinetic and potential. **Kinetic energy** refers to types of energy associated with motion (Figure 4.1, top). For example, a rock rolling down a hill, the wind blowing through trees, water flowing over a dam, and a cyclist riding a bicycle are just a few examples of kinetic energy. **Potential energy** is energy possessed by an object or system due to its position in space relative to another object or system and forces between the two (Figure 4.1, bottom). Examples include a rock poised at the top of a hill and water stored behind a dam. Some forms of energy are part kinetic and part potential energy. **Chemical energy** describes the *potential* of a chemical substance to undergo a chemical reaction and transform other chemical substances; hence it is a form of potential energy. Examples include energy stored in the food you eat and the gasoline that you put in your car.

Examples of different forms of **kinetic** energy

Examples of different forms of **potential** energy

Figure 4.1: Examples kinetic (top) and potential (bottom) forms of energy. *All images were obtained from Wikimedia commons (public domain).*

Living organisms need energy to perform life-sustaining "work" in order to survive. For nearly all living systems on Earth, the sun is the ultimate source of that energy. Over time, we humans have developed an understanding of energy that has allowed us to harness it for uses well beyond basic survival. The development and evolution of human society is largely attributed to our relationship with energy. The first major advancement in human understanding of energy was the mastery of fire for cooking and heating. Modern civilization is especially dependent on energy and some of its most distinct characteristics such as population growth, environmental impact and climate change are all a consequence of energy use. We use energy to heat and light our homes; power our machinery; fuel our vehicles; produce plastics, pharmaceuticals, and synthetic fibers; and provide the comforts and conveniences to which we have grown accustomed in the industrial age. Societal complexity, affluence, and the gap between poor and rich peoples are all related to our level of energy consumption.

4.2 Fossil Fuels

Fossil fuels is the term given to energy sources with a high **hydrocarbon** content (see Chapter 1 for a review of hydrocarbon molecules) found in the Earth's crust that formed in the geologic past and can be burned to release their energy. They were formed from prehistoric plants and animals that lived hundreds of millions of years ago (100 – 500 million years ago). When these ancient living organisms died they were quickly buried and subjected to immense pressure from overlying earth materials including layers of mud, rock, sand, and sometimes surface water bodies such as oceans and lakes.

During the millions of years that passed, the dead plants and animals slowly decomposed in **anaerobic** (very low to no oxygen) conditions and their chemical energy became concentrated. The organic compounds that once made up tissues of these organisms were chemically changed under high pressures and temperatures. While some fossil fuels may be in the process of formation today, the amount of time required for usable quantities to form is measured in millions of years, so these fuels will never be available for us. Thus for all practical purposes we consider fossil fuels to be finite and **non-renewable.**

4.2.1 Fossil Fuel Types and Formation

There are three main types of fossil fuels – natural gas, oil, and coal – and the specific type formed depends on the combination of organic matter that was present, how long it was buried and what temperature and pressure conditions existed when they were decomposing. **Oil** and **natural gas** were created from organisms that lived in water and were buried under ocean or river sediments. Long after the great prehistoric seas and rivers vanished, heat, pressure, and bacteria combined to compress and transform the organic material under layers of silt or shale rock (Figure 4.2). In most areas, a thick liquid called oil formed first, but in deeper, hot regions underground, the transformation process continued until natural gas was formed. Over time, some of this oil and natural gas began working its way upward through the earth's crust until they ran into rock formations called "**caprocks**" that are dense enough to prevent them from seeping to the surface. It is from under these caprocks that most oil and natural gas is retrieved today.

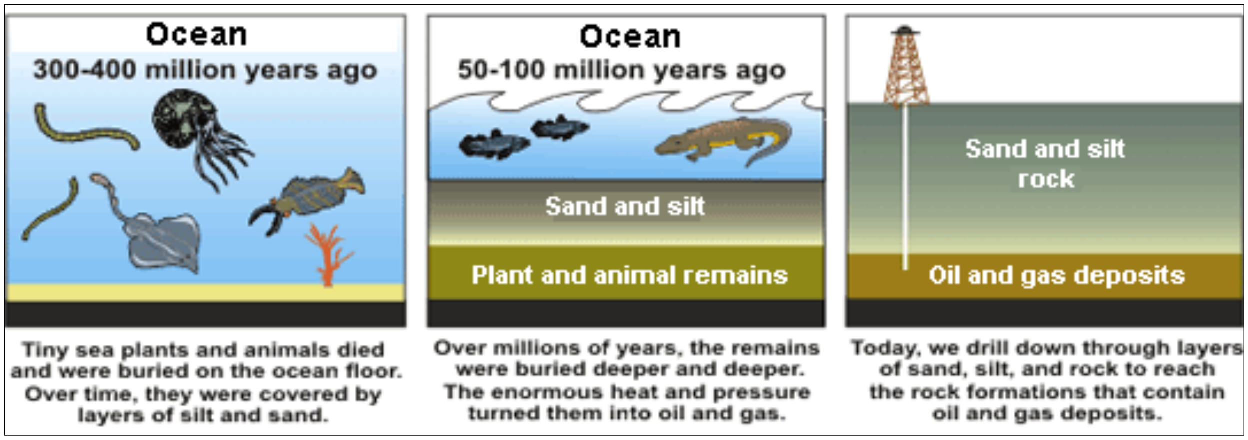


Figure 4.2: Oil and natural gas (petroleum) formation. *Source*: U.S. Energy Information Administration. http://www.eia.gov/energyexplained/index.cfm?page=natural_gas_home

Coal is a fossil fuel that formed from the remains of trees, ferns, and other plants that lived 300 to 400 million years ago (Figure 4.3). In some areas, such as portions of what is now the eastern United States, coal was formed from swamps covered by sea water. The sea water contained a large amount of sulfur, and as the seas dried up, the sulfur was left behind in the coal. Scientists are working on ways to take the sulfur out of coal because when coal burns, the sulfur is released in to the atmosphere as an air pollutant (see Chapter 6). Some coal deposits, however, were formed from freshwater swamps which had very little sulfur in them. These coal deposits, located largely in the western part of the United States, have much less sulfur in them.

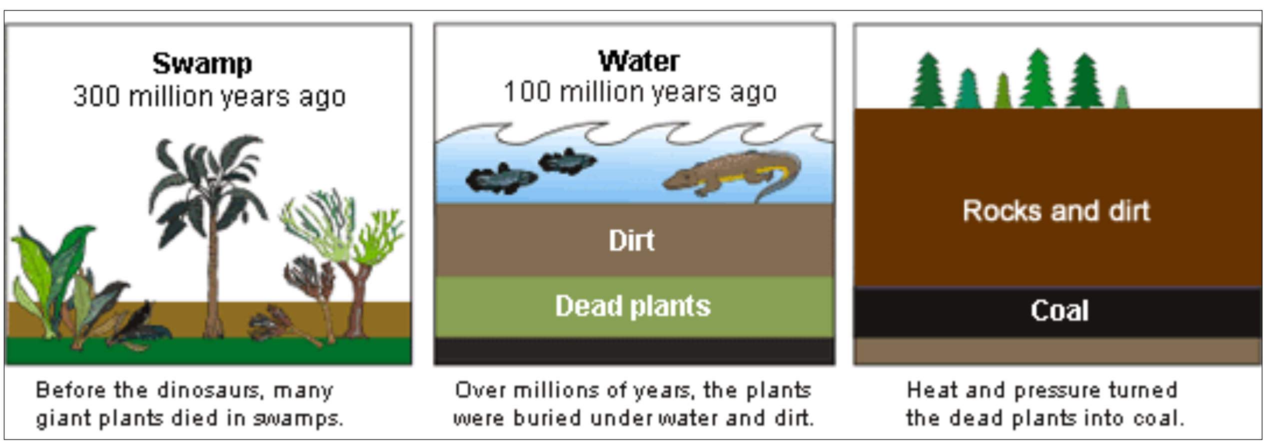


Figure 4.3: The process of coal formation. ***Source:*** U.S. Energy Information Administration.

4.2.2 Consumption

Historically, human prosperity has been directly correlated with energy use. The health and vitality of world societies critically depends on energy, most of which comes from fossil fuels (Figure 4.4). Energy resources, however, are unevenly distributed throughout the world, and so are the consumption rates. Developed regions generally consume far more energy than the developing regions. For example, the United States has only about 5% of the world's population but constitutes over 20% of the world's energy consumption. Additionally, developing countries devote a larger proportion of energy consumption to subsistence activities such as growing and preparing food, and heating homes. Industrialized nations rely more on mechanized equipment and technology and, therefore, a greater proportion of their energy consumption goes to transportation and industry.

Fossil fuels can be utilized without being converted or transformed to another form of energy, this is referred to as **primary energy** consumption. In their primary form, fossil fuels can be used for transportation, heating and cooking, or used to generate electricity. The use of **electricity** is a form of **secondary energy** consumption. Transforming fossil fuel energy into electricity allows for easier transportation over long distances and application to a variety of uses. Additionally, there are four major sectors that consume energy: 1) The *industrial sector* which includes facilities and equipment used for manufacturing, agriculture, mining, and construction; 2) The *transportation sector* includes vehicles that transport people or goods including cars, trucks, buses, motorcycles, trains, aircraft, boats, barges, and ships; 3) The *residential sector* consists of homes and apartments; 4) The *commercial sector* includes offices, malls, stores, schools, hospitals, hotels, warehouses, restaurants, places of worship, and more. Each of these sectors also consumes electricity produced by the electric power sector.

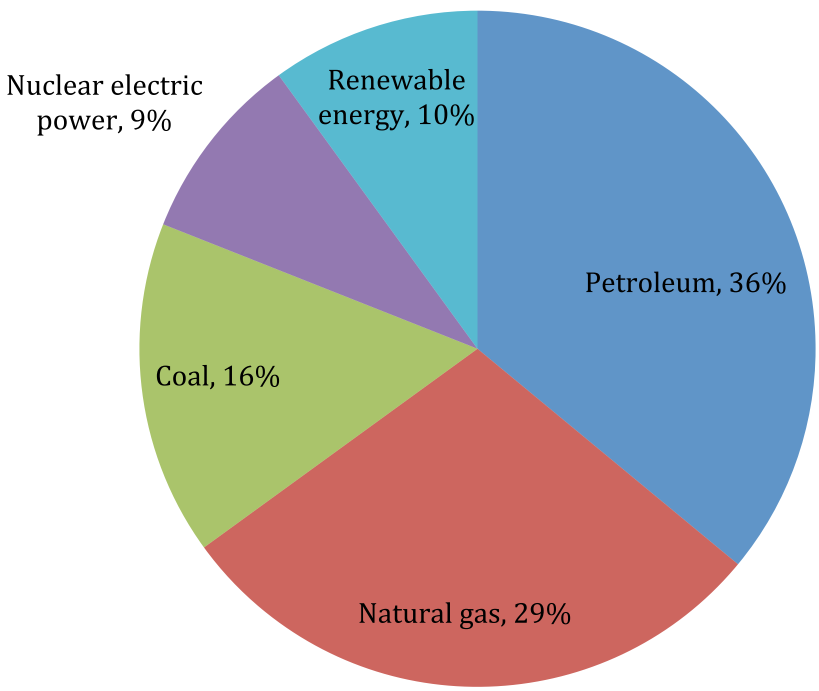


Figure 4.4: U.S. primary energy consumption by source (all sectors), 2015, showing that about 80 % of our energy consumption comes from fossil fuels. Data from U.S. Energy Information Administration, April 2016.

4.3 Coal

Coal is a combustible black or brownish-black sedimentary rock with a high amount of carbon and hydrocarbons. Coal is classified into four main types, or ranks depending on the types and amounts of carbon present and on the amount of heat energy the coal can produce, including anthracite, bituminous, subbituminous, and lignite (highest to lowest ranked, pictured in Figure 4.5). For us to use the potential energy stored in coal, it first must be mined from the ground. This process in itself uses a great deal of resources and has its own environmental impacts. Coal then typically undergoes processing to make it suitable for use in **coal-fire power plants**. Finally, the processed coal is burned in these power plants, and the kinetic energy released from its combustion is harnessed for electricity generation or other purposes. We will investigate each of these steps individually below.

A) Anthracite coal B) Bituminous coal C) Lignite coal

Figure 4.5: Different types of coal. Images obtained from Wikimedia Commons.

4.3.1 Coal Mining and Processing, and Electricity Generation

There are two primary methods of coal mining: **strip mining** and **underground mining**. Strip-, or surface-, mining uses large machines to remove the soil and layers of rock known as **overburden** to expose coal seams. It is typically used when the coal is less than 200 feet underground. **Mountaintop removal** is a form of surface mining where the tops of mountains are blasted with dynamite and removed to access coal seams. After the mining is finished, the disturbed area can be re-covered with topsoil, and the area is replanted. However, the topography of the mountain is permanently altered.

Underground mining, sometimes called deep mining, is used when the coal is several hundred feet below the surface. Some underground mines are thousands of feet deep, and extend for miles. Miners ride elevators down deep mine shafts and travel on small trains in long tunnels to get to the coal. The miners use large machines that dig out the coal.

Once mined, coal may go to a preparation plant located near the mining site where it is cleaned and processed to remove impurities such as rocks and dirt, ash, sulfur, and other unwanted materials. This process increases the amount of energy that can be obtained from a unit of coal, known as its **heating value**.

Finally, the mined and processed coal must be transported. Transportation can be more expensive than mining the coal. Nearly 70% of coal delivered in the United States is transported, for at least part of its trip, by train. Coal can also be transported by barge, ship, or truck. Coal can also be crushed, mixed with water, and sent through a slurry **pipeline**. Sometimes, coal-fired electric power plants are built near coal mines to lower transportation costs.

Once at the power plant, coal is first pulverized into a fine powder then mixed with hot air and blown into a **furnace**, allowing for the most complete combustion and maximum heat possible. Purified water, pumped through pipes inside a **boiler**, is turned into steam by the heat from the combustion of coal. The high pressure of the steam pushing against a series of giant **turbine** blades turns the turbine shaft. The turbine shaft is connected to the shaft of the **generator**, where magnets spin within wire coils to produce electricity. After doing its work in the turbine, the steam is drawn into a **condenser**, a large chamber in the basement of the power plant. In this important step, millions of gallons of cool water from a nearby source (such as a river or lake) are pumped through a network of tubes running through the condenser. The cool water in the tubes converts the steam back into water that can be used over and over again in the plant. The cooling water is returned to its source without any contamination except at a higher temperature than when first extracted from the river or lake. Figure 4.6 below is a schematic diagram showing a typical layout of a coal-fire power plant. You can also watch a short video of a virtual tour of a coal power plant at the URL provided below.

Coal Power Plant
Virtual Tour
Video

https://www.youtube.com/watch?v=2IKECt4Y3RI

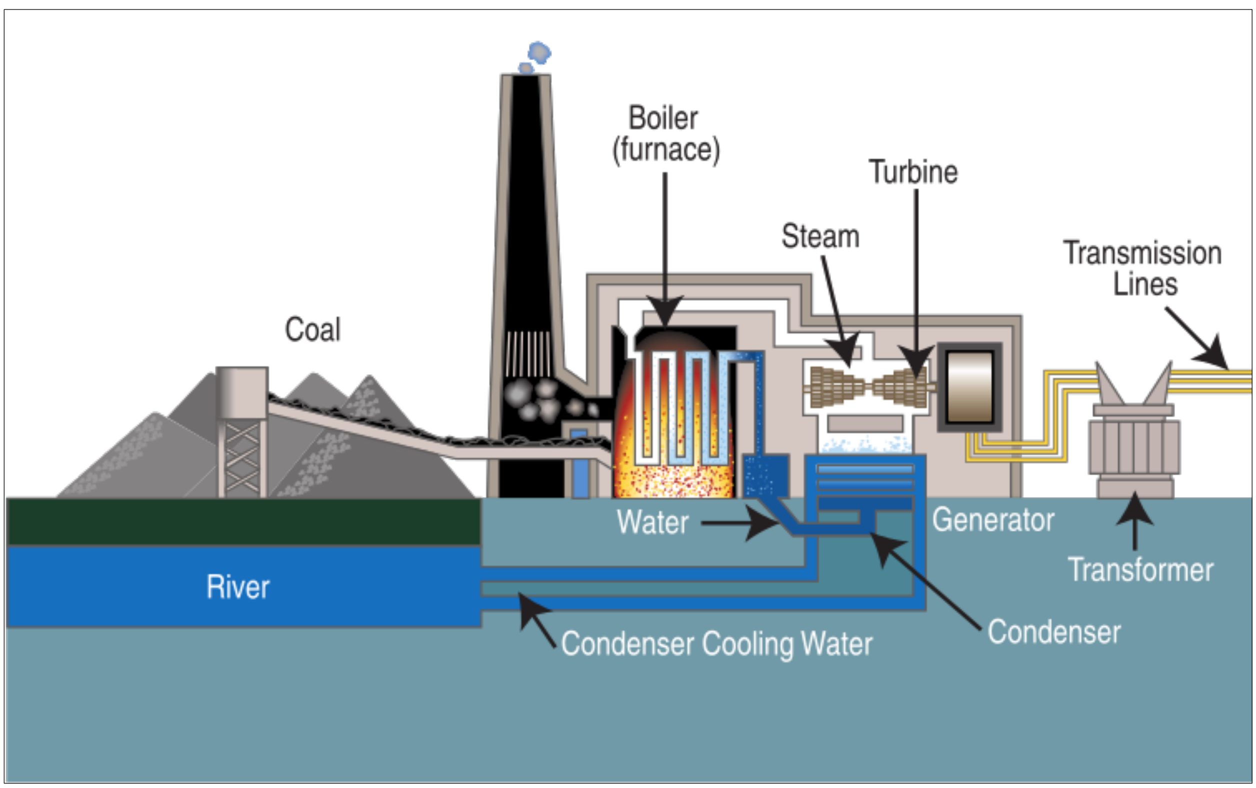


Figure 4.6: Diagram of a typical steam-cycle coal power plant (proceeding from left to right). Image by US Tennessee Valley Authority – Public domain. www.tva.com

4.3.2 Impacts of coal mining and burning

Impacts of coal mining on the environment

A majority of the coal mined in the United States (about 66%) is from surface, or strip mines which leave highly visible impacts at the surface. Strip mining operations generally involve removing soils, rock, and other material to access shallow deposits of coal and therefore leave permanent scars on the landscape. It also involves the destruction of substantial amounts of forests and other ecosystems, destroying natural habitats and threatening biodiversity.

Mountaintop removal, the extreme form of strip mining, has affected large areas of the Appalachian Mountains in West Virginia and Kentucky. The tops of mountains are removed using a combination of explosives and mining equipment and the material is deposited into nearby valleys. This technique not only alters the landscape (Figure 4.7) but affects the health and quality of nearby streams by depositing rocks, dirt, and pollutants that can harm aquatic wildlife. While mountaintop removal mining has existed since the 1970s, its use became more widespread and controversial beginning in the 1990s. U.S. laws require that dust and water runoff from areas affected by coal mining operations be controlled, and that the area be **reclaimed**, and returned to close to its original condition.

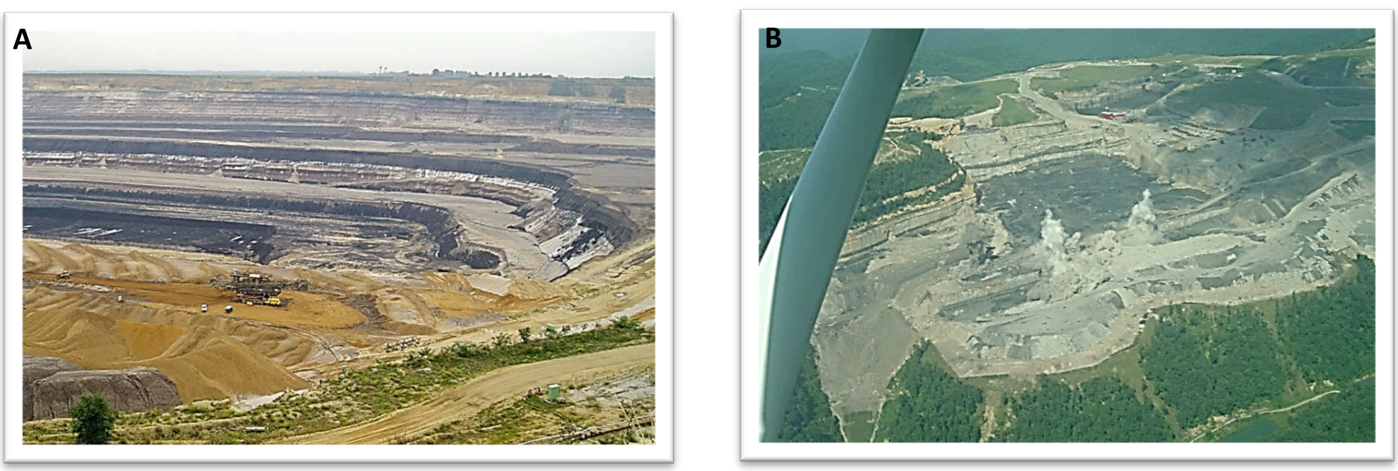


Figure 4.7: A) Strip mine for lignite coal at Garzweiler near Koln, Germany. Image from Wikimedia commons https://commons.wikimedia.org/wiki/File:Garzweiler.strip.mine.jpg B) Mountaintop removal in Eunice WV, photo by Roston, obtained from https://commons.wikimedia.org/wiki/File:Euniceblast3.JPG

One of the largest environmental impacts of underground mining may be the **methane** gas that must be vented out of mines to make the mines a safe place to work. Methane is a **greenhouse gas**, meaning that it enhances the greenhouse effect naturally occurring in our atmosphere, and contributes to global warming and global climate change. Its global warming potential, or relative capacity to produce the greenhouse effect, is higher than that of carbon dioxide (see chapter 7). Other impacts of underground mining include ground collapse above mine tunnels and draining of acidic water from abandoned mines into nearby streams. Acidic water lowers the pH (resulting in increased **acidity**), which is detrimental to aquatic organisms. This **acid mine drainage** is an environmental impact associated with both underground mining and strip mining.

Impacts of coal burning on the environment and human health

In the United States and most of the world, most of the coal consumed is used as a fuel to generate electricity. Burning coal produces emissions such as **sulfur dioxide** (SO_2) and **nitrogen oxides** (NO_x) that are associated with acid rain (more on this in chapter 6). **Carbon dioxide** (CO_2), another emission resulting from burning coal, is a major greenhouse gas that is associated with global warming (see chapter 7).

Ash (including fly ash and bottom ash) is a residue created when coal is burned at power plants. In the past, fly ash was released into the air through the smokestack, where it would contribute to **particulate matter** air pollution (see chapter 6). Laws now require that much of the fly ash now must be be captured by pollution control devices, like scrubbers. In the United States, fly ash is generally stored at coal power plants or placed in landfills. Pollution leaching from ash storage and landfills into groundwater and the rupture of several large impoundments of ash are environmental concerns.

Burning coal produces emissions that also impact human health. Emissions such as sulfur dioxide (SO_2), nitrogen oxides (NO_x) and particulates contribute to respiratory illnesses. Particulates also contribute to a condition among coal miners and other coal workers known as coal workers' pneumoconiosis (CWP) or black lung disease, which results from long exposure to coal dust. Inhaled coal dust progressively builds up in the lungs and is unable to be removed by the body; this leads to inflammation, fibrosis, and in worse cases, tissue death (necrosis).

Coal is the largest source of **mercury** and also a source of other **heavy metals**, many of which have been linked to both neurological and developmental problems in humans and other animals. Mercury concentrations in the air usually are low and of little direct concern. However, when mercury enters water, either directly or through deposition from the air, biological processes transform it into **methylmercury**, a highly toxic chemical that accumulates in fish and the animals (including humans) that eat fish.

4.3.3 Reducing the environmental impacts of coal use

Regulations such as the **Clean Air Act** and the **Clean Water Act** require industries to reduce pollutants released into the air and water. Below are some actions that have been taken to reduce the negative impacts of coal on human and environmental health:

- **Clean coal technology**: Industry has found several ways to reduce sulfur, NO_x, and other impurities from coal before burning.
- Coal consumers have shifted toward greater use of low sulfur coal.
- Power plants use **scrubbers**, to clean SO_2, NO_x, particulate matter, and mercury from the smoke before it leaves their smokestacks. In addition, industry and the U.S. government have cooperated to develop technologies that make coal more energy-efficient so less needs to be burned.
- Research is underway to address emissions of carbon dioxide from coal combustion. **Carbon capture & sequestration** separates CO_2 from emissions sources and recovers it in a

concentrated stream. The CO_2 can then be sequestered, which puts CO_2 into storage, possibly underground, where it will remain permanently (see chapter 7).

- Reuse and recycling can also reduce coal's environmental impact. Land that was previously used for coal mining can be reclaimed and used for airports, landfills, and golf courses. Waste products captured by scrubbers can be used to produce products like cement and synthetic gypsum for wallboard.

4.4 Oil

Petroleum Oil is currently the most widely used fossil fuel and accounts for about one third of global energy consumption. Unlike coal, which is primarily used as a fuel for electricity generation, oil is primarily used as a fuel for **transportation**. Oil is also used to manufacture **plastics** and other synthetic compounds ubiquitous to our everyday life. **Crude** (unprocessed) oil varies greatly in appearance depending on its composition. It is usually black or dark brown (although it may be yellowish, reddish, or even greenish). In the reservoir it is usually found in association with natural gas, which being lighter forms a gas cap over the oil.

Oil is made up of hydrocarbons which are molecules that contain hydrogen and carbon in various lengths and structures, from straight chains to branching chains to rings. Hydrocarbons contain a lot of energy and many of the things derived from crude oil like gasoline, diesel fuel, paraffin wax and so on take advantage of this energy.

4.4.1 Extraction

Oil is mainly obtained by drilling either on land (**onshore**) or in the ocean (**offshore**). Early offshore drilling was generally limited to areas where the water was less than 300 feet deep. Oil and natural gas drilling rigs now operate in water as deep as two miles. Floating platforms are used for drilling in deeper waters. These self-propelled vessels are attached to the ocean floor using large cables and anchors. Wells are drilled from these platforms which are also used to lower production equipment to the ocean floor. Some drilling platforms stand on stilt-like legs that are embedded in the ocean floor. These platforms hold all required drilling equipment as well as housing and storage areas for the work crews.

Offshore oil producers are required to take precautions to prevent pollution, spills, and significant changes to the ocean environment. Offshore rigs are designed to withstand hurricanes. Offshore production is much more expensive than land-based production. When offshore oil wells are no longer productive enough to be economical, they are sealed and abandoned according to applicable regulations.

4.4.2 Processing and Refining

When extracted, crude oil consists of many types of hydrocarbons as well as some unwanted substances such as sulfur, nitrogen, oxygen, dissolved metals, and water all mixed together. Unprocessed crude oil is therefore, not generally useful in industrial applications and must first be separated into different useable products at a **refinery** (Figure 4.8). All refineries perform three basic steps: separation, conversion, and treatment in the processing and refining of crude oil.

Figure 4.8: Tesoro Corporation Oil Refinery in Anacortes, Washington. Photo by Walter Siegmund. https://commons.wikimedia.org/wiki/Oil_refinery#/media/File:Anacortes_Refinery_31904.JPG

During **separation**, the various products (hydrocarbons) are separated in to different components (called *fractions*), by taking advantage of the differences in boiling temperature of the components. This process is called *fractional distillation* and involves heating up the crude, letting it vaporize and then condensing the vapor. The lightest components have the lowest boiling temperature and rise to the top while the heaviest which also have the highest boiling temperature remain at the bottom.

Conversion is the chemical processing in which some of the fractions are transformed in to other products, for example, a refinery can turn diesel fuel into gasoline depending on the demand for gasoline. Conversion can involve breaking larger hydrocarbon chains into smaller ones (cracking), combining smaller chains into larger ones (unification) or rearranging the molecules to created desired products (alteration).

Treatment is done to the fractions to remove impurities such as sulfur, nitrogen and water among others. Refineries also combine the various fractions (processed and unprocessed) into mixtures to make desired products. For example, different mixtures of hydrocarbon chains can create gasolines with different octane ratings, with and without additives, lubricating oils of various weights and grades (e.g., WD-40, 10W-40, 5W-30, etc.), heating oil and many others. The products are stored on-site until they can be delivered to various markets such as gas stations, airports and chemical plants.

A 42 U.S. gallon barrel of crude oil yields about 45 gallons of petroleum products because of refinery processing gain. This increase in volume is similar to what happens to popcorn when it is popped. Gasoline makes up the largest fraction of all petroleum products obtained (Figure 4.9). Other products include diesel fuel and heating oil, jet fuel, petrochemical feedstocks, waxes, lubricating oils, and asphalt.

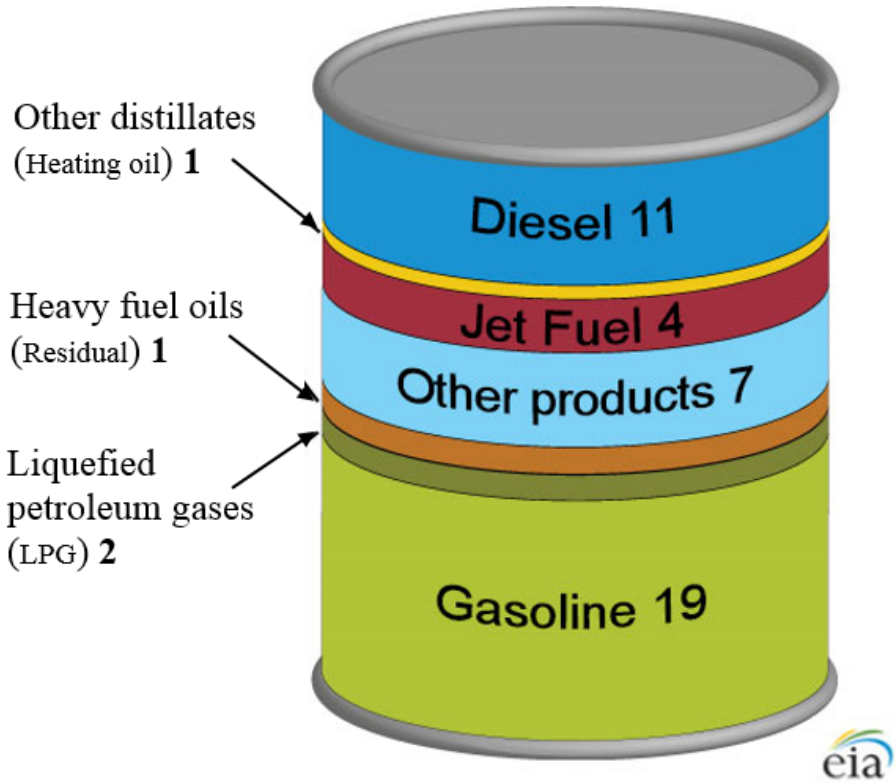


Figure 4.9:Main products (measured in gallons) made from a barrel of crude oil, 2013. ***Source***: U.S. Energy information administration http://www.eia.gov/energyexplained/index.cfm?page=oil_home

4.4.3 Fracking for oil

Hydraulic fracturing, informally referred to as "fracking," is an oil well development process that typically involves injecting water, sand, and chemicals under high pressure into a bedrock formation via the well. This process is intended to create new fractures in the rock as well as increase the size, extent, and connectivity of existing fractures. Hydraulic fracturing is a well-stimulation technique used commonly in low-permeability rocks like tight sandstone, shale, and some coal beds to increase oil flow to a well from petroleum-bearing rock formations (Figure 4.10).

Energy development often requires substantial amounts of water, and hydraulic fracturing is no exception. Water is needed not only for the traditional drilling process, but also for the actual fracturing as well. Water is first mixed with chemicals and fine sands, then pumped at extremely high pressure into the shale rock to fracture it, forming pathways for the oil and gas to reach the well. The water is then recovered, along with the oil and gas.

There are concerns regarding the potential contamination of fresh groundwater resources from oil and gas extraction wells that use hydraulic fracturing; either from the petroleum resource being produced or from the chemicals introduced in the fracturing process. Fracking fluid flowback – the fluid pumped out of the well and separated from oil and gas – not only contains the chemical additives used in the drilling process but also contains heavy metals, radioactive materials, **volatile organic compounds** (VOCs) and hazardous air pollutants such as benzene, toluene, ethylbenzene and xylene. In some cases, this contaminated water is sent to water treatment plants that are not equipped to deal with some of these classes of contamination.

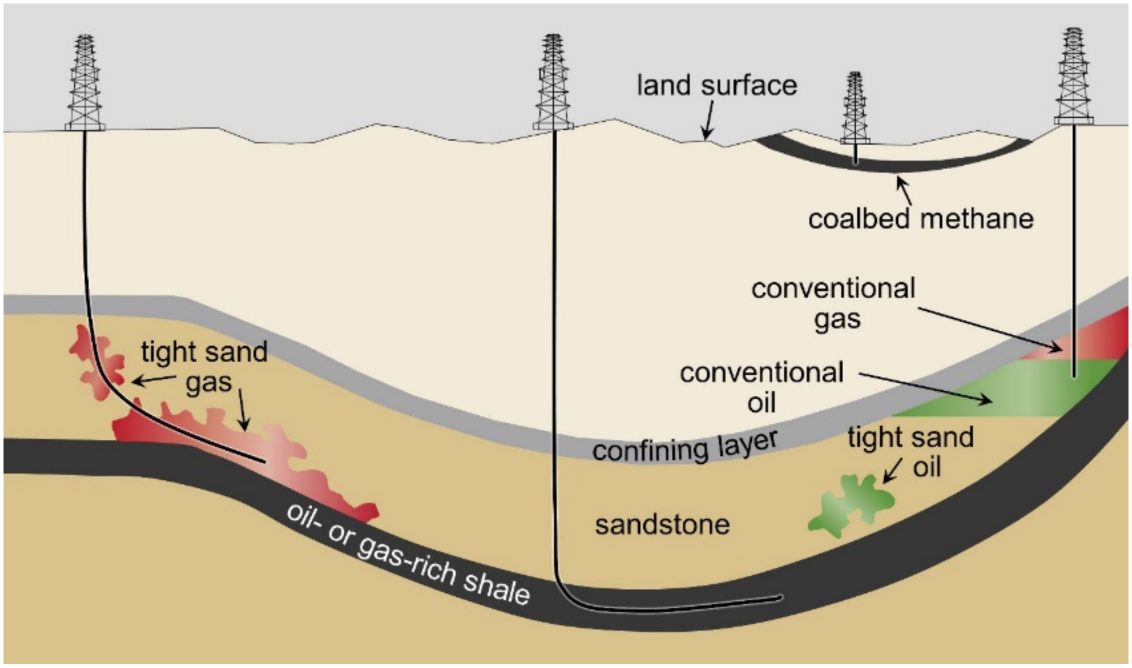


Figure 4.10: Schematic cross-section of general types of oil and gas resources and the orientations of production wells used in hydraulic fracturing. Source: US EPA (Public Domain)

4.4.4 Environmental Impacts of Oil

Burning petroleum oil products releases emission such as **carbon monoxide** (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate material all of which are air pollutants that impact the environment as well as human health (see more on air pollution in Chapter 6). Petroleum also emits carbon dioxide which is a greenhouse gas.

Exploring and drilling for oil may disturb land and ocean habitats. On land, extensive infrastructure such as road networks, transport pipelines and housing for workers are needed to support a full-scale drilling operation. These can pollute soil and water, fragment habitats, and disturb wildlife.

Human-caused **oil spills** in rivers and oceans harm ecosystems. Natural oil seepages do occur and may be a significant source of oil that enters the environment globally, but they are slow, small, and spread out over large areas, and the ecosystem has adapted to them. Spills from tankers or well spills have more catastrophic impacts. The quantity of oil spilled during accidents has ranged from a few hundred tons to several hundred thousand tons but even small spills have been shown to have a great impact on ecosystems.

Oil spills at sea are generally much more damaging than those on land, since they can spread for hundreds of nautical miles in a thin oil slick which can cover beaches with a thin coating of oil. This can kill sea birds, mammals, shellfish and other organisms it coats. Oil spills on land are more readily containable if a makeshift earth dam can be rapidly bulldozed around the spill site before most of the oil escapes, and land animals can avoid the oil more easily. The amount of oil spilled from ships dropped significantly during the 1990s partly because new ships were required to have a double-hull lining to protect against spills.

Leaks also happen when we use petroleum products on land. For example, gasoline sometimes drips onto the ground when people are filling their gas tanks, when motor oil gets thrown away after an oil change, or when fuel escapes from a leaky storage tank. When it rains, the spilled products get washed into the gutter and eventually flow to rivers and into the ocean. Another way that oil sometimes gets into water is when fuel is leaked from motorboats and jet skis.

When a leak in a storage tank or pipeline occurs, petroleum products can also get into the ground, and the ground must be cleaned up. To prevent leaks from underground storage tanks, all buried tanks are supposed to be replaced by tanks with a double lining.

4.5 Natural Gas

Crude oil is frequently found in reservoirs along with natural gas. In the past, natural gas was either burned or allowed to escape into the atmosphere. Now, technology has been developed to capture the natural gas and either reinject it into the well or compress it into **liquid natural gas** (LNG).

Natural gas is predominately composed of methane (CH_4). Some of the gases that are produced along with methane, such as butane and propane (by-products), are separated and cleaned at a gas processing plant. The by-products, once removed, are used in a number of ways. For example, propane can be used for cooking on gas grills. Natural gas withdrawn from a well may contain liquid hydrocarbons and nonhydrocarbon gases. This is called "wet" natural gas. The natural gas is separated from these components near the site of the well or at a processing plant. The gas is then considered "dry" and is sent through pipelines to a local distribution company, and, ultimately, to the consumer.

Most of the natural gas consumed in the United States is produced in the United States. Some is imported from Canada and shipped to the United States in pipelines. A small amount of natural gas is shipped to the United States as LNG. We can also use machines called **digesters** that turn today's organic material (plants, animal wastes, etc.) into natural gas through the process of anaerobic decomposition. This process replaces waiting for millions of years for the gas to form naturally. The natural gas produced by these digesters is not a fossil fuel, but is rather a renewable source of bioenergy (see chapter 5).

4.5.2 Fracking for Gas

Conventional natural gas is found in permeable reservoirs, typically composed of sandstone or limestone, where extraction is relatively straightforward because the gas generally flows freely. Unconventional gas is found in rocks with extremely low permeability, which makes extracting it much more difficult. Such gas is extracted by employing so called “unconventional” techniques such as hydraulic fracturing (fracking), which has been in use since the late 1940s. In recent decades, fracking technology has greatly improved, and its use has been expanded. The process of fracking for gas is very similar to that of fracking for oil, and the environmental impacts are similar also.

4.6 Fossil Fuels and Greenhouse Gases

Fossil fuels are made up mainly of hydrogen and carbon. When burned, the carbon combines with oxygen to create carbon dioxide (CO_2). The amount of CO_2 produced depends on the carbon content of the fuel. For example, for the same amount of energy produced, natural gas produces about half and petroleum produces about three-fourths of the amount of CO_2 produced by coal. Energy-related CO_2 emissions, resulting from the combustion of coal, petroleum, and natural gas, account for about 80% of total U.S. human-caused (anthropogenic) greenhouse gas (GHG) emissions. There are many sources of non-energy CO_2 emissions, but those emissions account for a relatively small share of total GHG emissions. See chapter 7 for a discussion of the results of GHG emissions.

Energy use is largely driven by economic growth and by weather patterns that affect heating and cooling needs. The fuels used in electricity generation also have an impact on the amount of GHG emissions. In the United States, most of the electricity generated comes from coal power plants and consequently, majority of the carbon dioxide emission resulting from electricity generation is from coal combustion (Figure 4.11). Although the industrial sector is the largest consumer of energy (including direct fuel use and purchased electricity), the transportation sector emits more carbon dioxide because of its near complete dependence on petroleum fuels. The residential and commercial sectors have lower emission levels (most of which comes from fossil energy combustion to produce electricity) than the transportation and industry sectors.

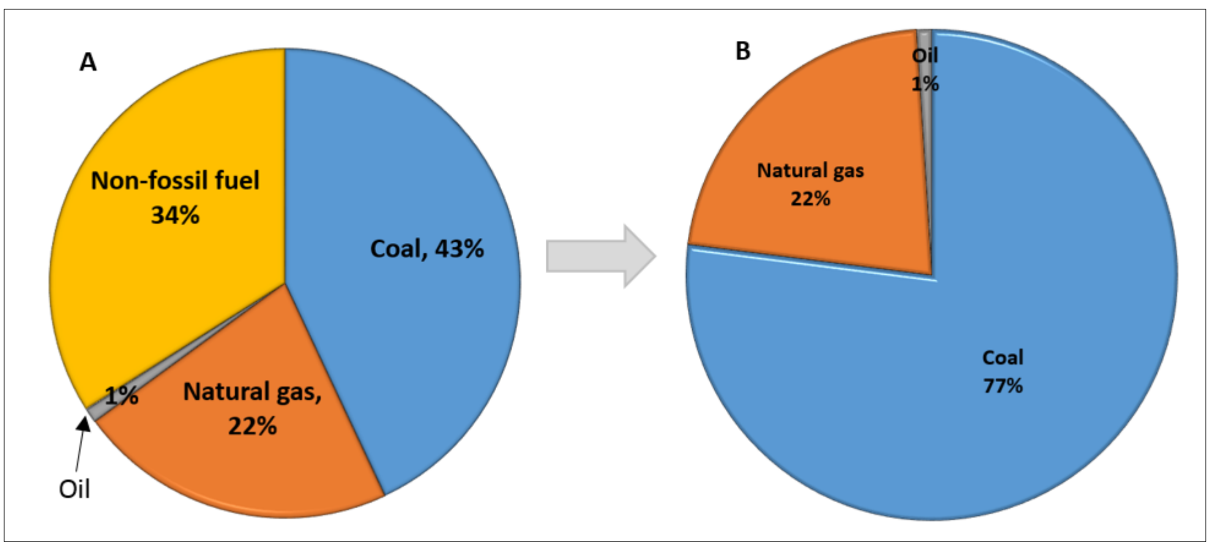


Figure 4.11: A) Major fuel/energy sources for U.S. electricity generation, 2013. B) Resulting carbon dioxide emissions from electricity generation by fuel type, 2013. Based on data from U.S. Energy Information Administration

4.7 Nuclear Energy

Nuclear energy is energy in the **nucleus** (core) of an atom (see chapter 1 for a review of atomic structure). There is enormous energy in the forces that hold protons and neutrons in the nucleus together. Energy is released when those forces are broken. Nuclear energy can be released from atoms by splitting apart the nucleus of an atom to form smaller atoms, a process known as **nuclear fission**. During nuclear fission, a small atomic particle called a **neutron** hits the uranium atom and splits it, releasing a great amount of energy in the form of heat and **radiation**. More neutrons are also released when the uranium atom splits. These neutrons go on to bombard other uranium atoms, and the process repeats itself over and over again. This is called a **chain reaction** (Figure 4.12). Nuclear power plants use the energy from nuclear fission to produce electricity.

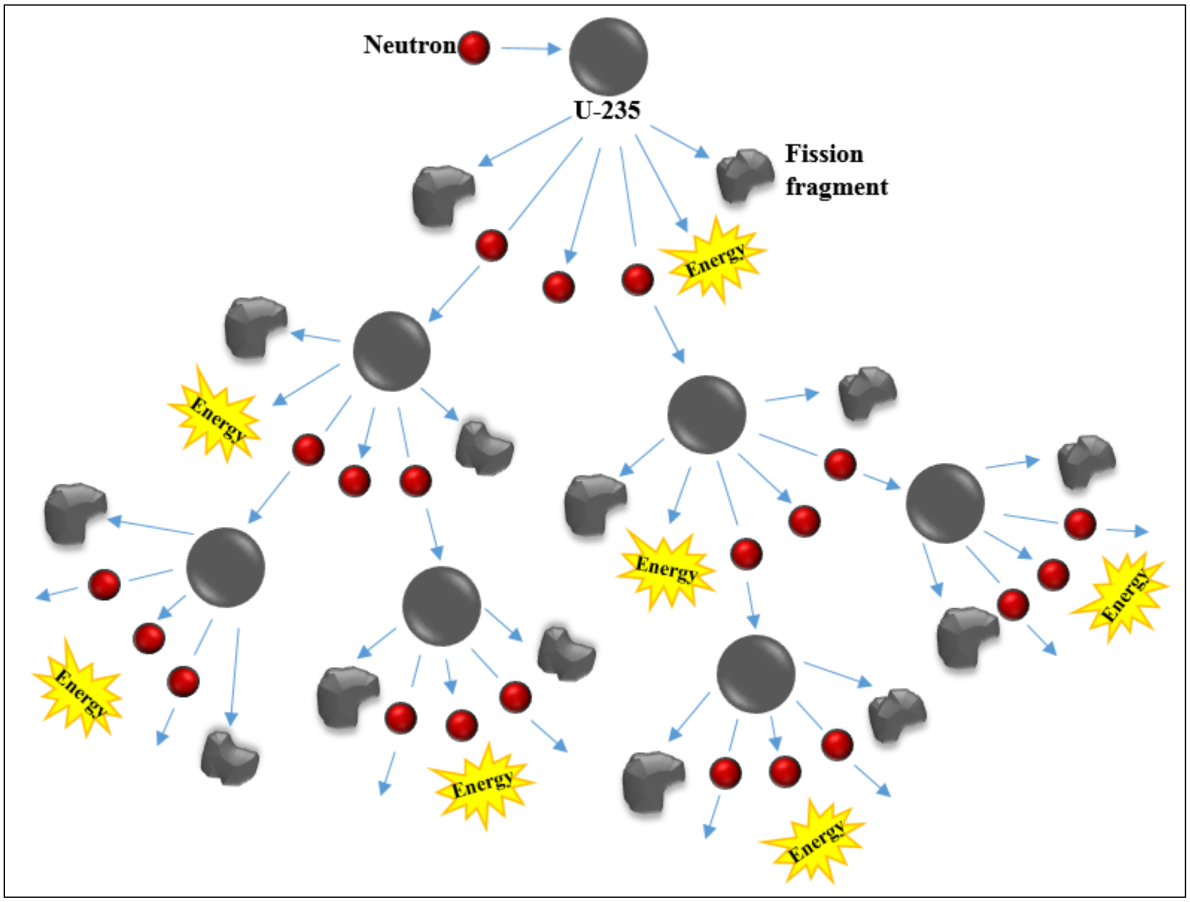


Figure 4.12: Fission chain reaction – begins when a neutron bombards a U-235 atom, splitting it into two fission fragments, along with more neutrons and energy. The neutrons bombard other uranium atoms releasing more energy and more neutrons and the reaction continues.

4.7.1 Nuclear fuel processing

Uranium is a naturally occurring radioactive element that decays into daughter **isotopes** (see chapter 1 for a review of isotopes), releasing radiation energy in the process. There are three naturally occurring isotopes of uranium almost all (99.27 %) of which is uranium-238 (U-238); the remainder consists of U-235 (0.72 %) and U-234 (0.006 %). **U-235** is the preferred nuclear fuel because when its atoms are split (fissioned), they not only emit heat and high energy radiation but also enough neutrons to maintain a chain reaction and provide energy to power a nuclear power plant. Uranium is found in rocks all over the world but is relatively rare and the supply is finite making it a nonrenewable energy source.

Uranium usually occurs in combination with small amounts of other elements and once it is mined, the U-235 must be extracted and processed before it can be used as a fuel in a nuclear power plant to generate electricity. The process begins with **exploration** for uranium and the development of mines to extract the discovered **ore** (*ore* refers to rock that contains minerals of economic importance). Mining is either conventional (underground or open pit) or unconventional, such as in-place solution mining or heap leaching, which use liquid solvents to dissolve and extract the ore. Mined uranium ore (Figure 4.13 A) typically yields one to four pounds of uranium concentrate per ton of uranium ore (0.05% to 0.20%).

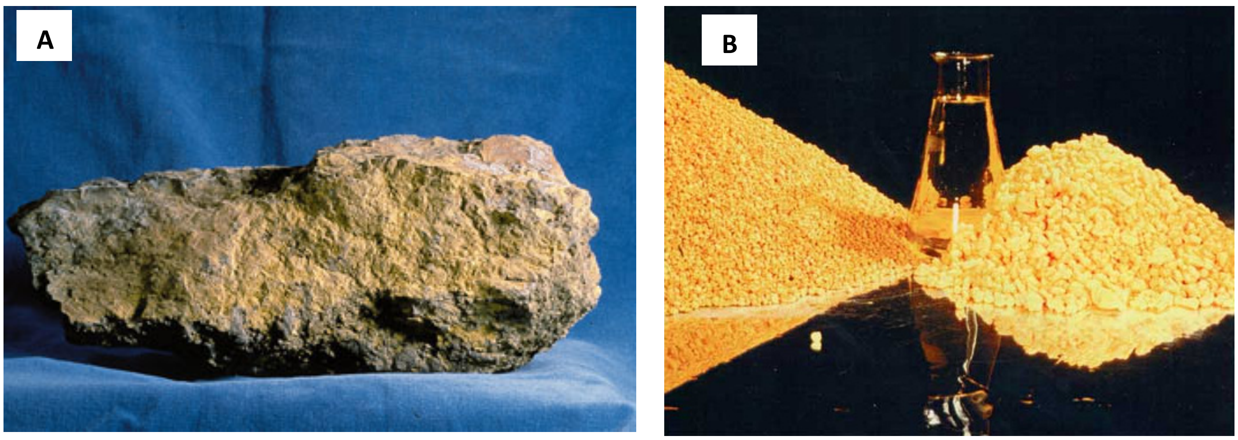


Figure 4.13: A) Uranium ore B) Yellowcake (U_3O_8). Images obtained from United States Geological Survey (A) and United States Department of Energy (B).

Uranium ore from a conventional mine is usually refined into uranium concentrate in a process referred to as **milling**. The ore is crushed and ground into fine powder that is then reacted with chemicals to separate the uranium from other minerals. The concentrated uranium product is typically a bright yellow or orange powder called *yellowcake* (U_3O_8) (Figure 4.13 B), and the waste stream from these operations is called *mill tailings.* Uranium ore in solution is also milled into yellowcake by retrieving the uranium out of the solution and concentrating it.

The yellowcake then undergoes **conversion** into uranium hexafluoride (UF_6) gas. This step enables the atomic segregation of the three naturally occurring uranium isotopes in to individual components. In the UF_6 gas, the original concentrations of uranium isotopes are still unchanged. This gas is then sent to an **enrichment** plant where the isotope separation takes place and the concentration of U-235 is increased to about a 4% to 5% (compared to 0.72 % original concentration). The product, called *enriched* UF_6, is sealed in canisters and allowed to cool and solidify before it is transported to a fuel assembly plant.

The next step in the production of nuclear fuel takes place at fuel **fabrication** facilities. Here, the enriched UF_6 gas is reacted to form a black uranium dioxide (UO_2) powder. The powder is then compressed and formed into the shape of small ceramic *fuel pellets* (Figure 4.14 A). Each ceramic pellet produces roughly the same amount of energy as 150 gallons of oil. The pellets are stacked and sealed into long metal tubes that are about 1 centimeter in diameter to form **fuel rods**. (Figure 4.14 B) fuel rods are then bundled together to make up a *fuel assembly*

(Figure 4.14 C). Depending on the reactor type, there are about 179 to 264 fuel rods in each fuel assembly. A typical reactor core holds 121 to 193 fuel assemblies.

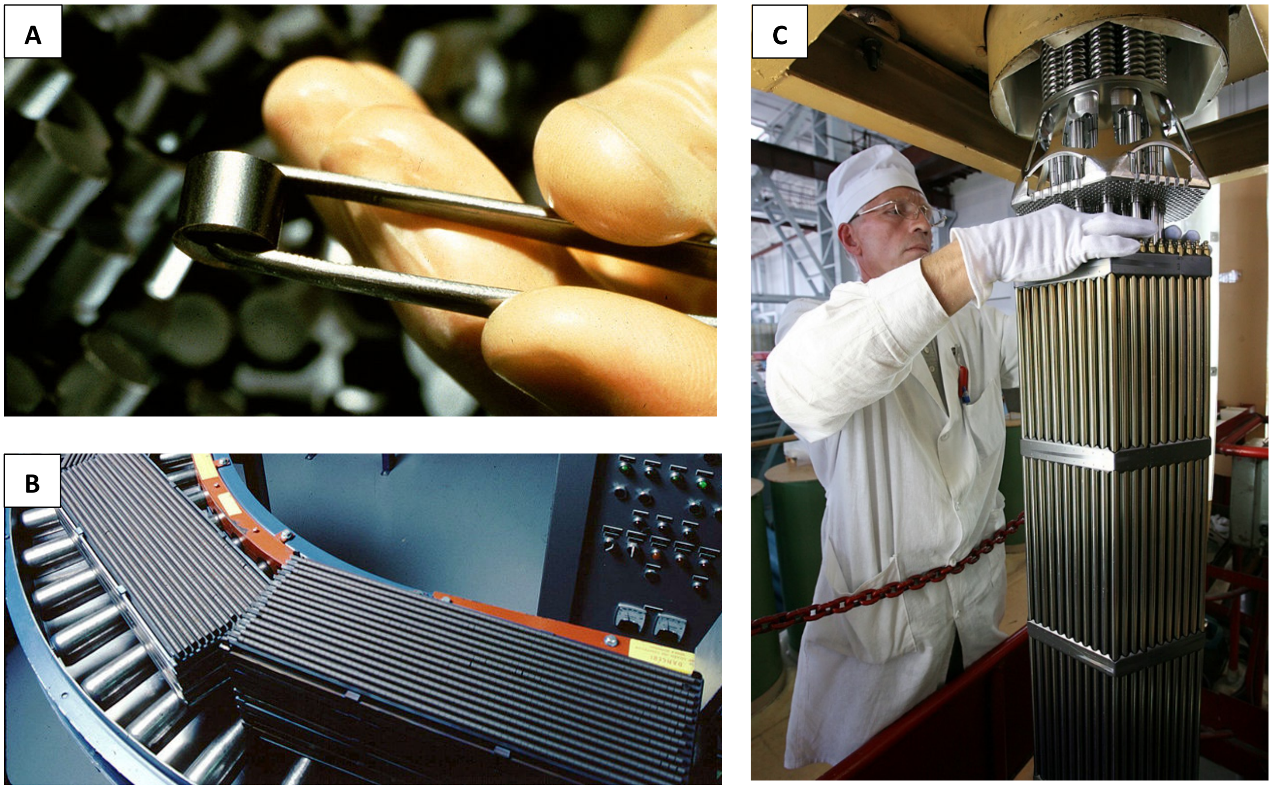


Figure 4.14: Fuel fabrication process. A) Uranium dioxide powder compressed into *fuel pellets*. B) Fuel pellets stacked and sealed in metal tubes forming *fuel rods*. C) Fuel rods are bundled into a *fuel assembly*. Images A and B from NRC (public domain); C from RIA Novosti archive, image #132602 / Ruslan Krivobok / CC-BY-SA 3.0

4.7.2 Nuclear Power Plant

After fabrication, fuel assemblies are transported to nuclear power plants where they are used as a source of energy for generating electricity. They are stored onsite until they are needed by the reactor operators. At this stage, the uranium is only mildly radioactive, and essentially all radiation is contained within the metal tubes. When needed, the fuel is loaded into a reactor core (Figure 4.15). Typically, about one third of the reactor core (40 to 90 fuel assemblies) is changed out every 12 to 24 months.

The most common type of reactors are the **pressurized water reactors** (PWR) (Figure 4.15) in which water is pumped through the *reactor core* and heated by the fission process. The water is kept under high pressure inside the reactor so it does not boil. The heated water from the reactor passes through tubes inside the *steam generator* where the heat is transferred to water flowing around the tubes in the steam generator. The water in the steam generator boils and turns to steam. The steam is piped to the turbines. The force of the expanding steam drives the turbines, which spin a magnet in coil of wire – the generator– to produce electricity.

After passing through the turbines, the steam is converted back to water by circulating it around tubes carrying cooling water in the *condenser*. The condensed steam – now water – is returned to the steam generators to repeat the cycle.

The three water systems (condenser, steam generator, and reactor) are separate from each other and are not permitted to mix. Water in the reactor is radioactive and is contained within the containment structure whereas water in the steam generator and condenser is nonradioactive.

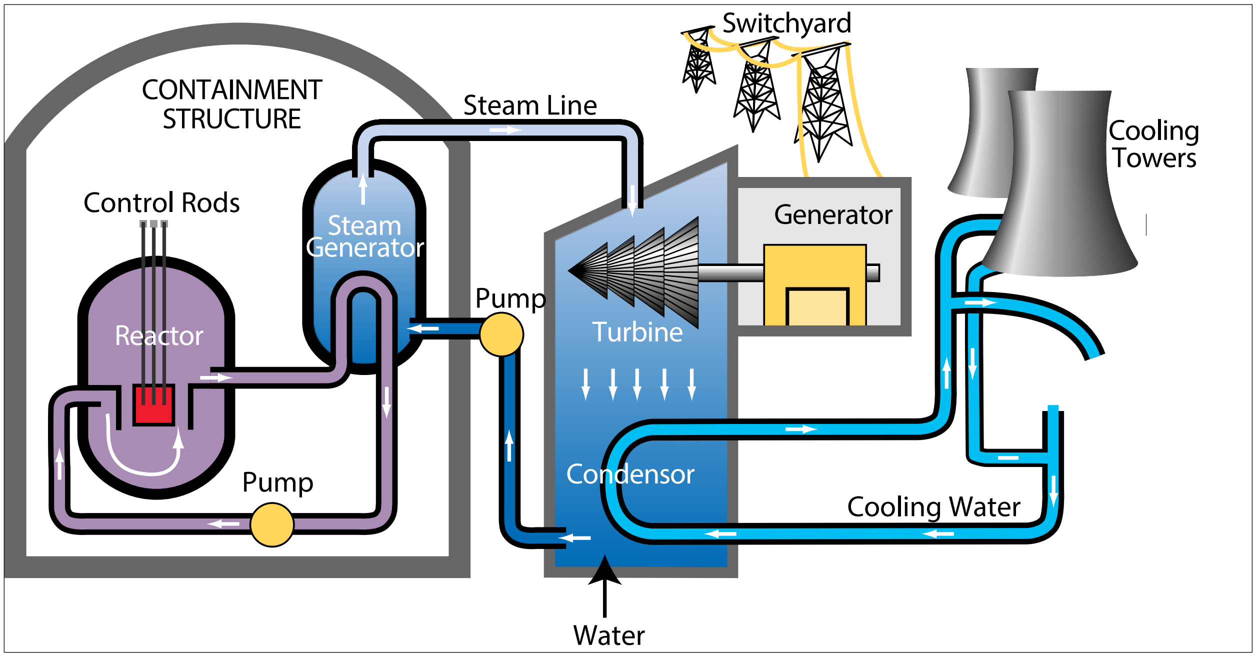


Figure 4.15: A schematic diagram of a pressurized water reactor (PWR), the most common type of nuclear reactor. Diagram from Tennessee Valley Authority (public domain). www.tva.com

4.7.3 Benefits of Nuclear Energy

By using fission, nuclear power plants generate electricity without emitting air pollutants like those emitted by fossil fuel-fired power plants. This means that financial costs related to chronic health problems caused by air pollutants such as particulate material, carbon monoxide, nitrogen oxides and ozone among others are significantly reduced. In addition nuclear reactors do not produce carbon dioxide while operating which means that nuclear energy does not contribute to the global warming problem.

Another benefit of nuclear energy over fossil fuels especially coal is that uranium generates far more power per unit weight or volume. This means that less of it needs to be mined and consequently the damage to the landscapes is less especially when compared to the damage that results from coal mining such as mountaintop removal.

4.7.4 The Drawbacks of Nuclear Energy

The main environmental concern related to nuclear power is the creation of radioactive wastes such as uranium mill tailings, spent (used) reactor fuel, and other radioactive wastes. These materials can remain radioactive and dangerous to human health for thousands of years. Radioactive wastes are classified as low-level and high-level. By volume, most of the waste related to the nuclear power industry has a relatively low-level of radioactivity. Uranium mill tailings contain the radioactive element radium, which decays to produce **radon**, a radioactive gas. Most uranium mill tailings are placed near the processing facility or mill where they come from. Uranium mill tailings are covered with a barrier of material such as clay to prevent radon from escaping into the atmosphere, and they are then covered by a layer of soil, rocks, or other materials to prevent erosion of the sealing barrier.

The other types of low-level radioactive waste are the tools, protective clothing, wiping cloths, and other disposable items that get contaminated with small amounts of radioactive dust or particles at nuclear fuel processing facilities and power plants. These materials are subject to special regulations that govern their handling, storage, and disposal so they will not come in contact with the outside environment.

High-level radioactive waste consists of spent nuclear reactor fuel (i.e., fuel that is no longer useful for producing electricity). The spent reactor fuel is in a solid form consisting of small fuel pellets in long metal tubes called rods. Spent reactor fuel assemblies are initially stored in specially designed pools of water, where the water cools the fuel and acts as a radiation shield. Spent reactor fuel assemblies can also be stored in specially designed dry storage containers. An increasing number of reactor operators now store their older spent fuel in dry storage facilities using special outdoor concrete or steel containers with air cooling. There is currently no permanent disposal facility in the United States for high-level nuclear waste.

When a nuclear reactor stops operating, it must be **decommissioned**. This involves safely removing the reactor and all equipment that has become radioactive from service and reducing radioactivity to a level that permits other uses of the property. The U.S. Nuclear Regulatory Commission has strict rules governing nuclear power plant decommissioning that involve cleanup of radioactively contaminated plant systems and structures, and removal of the radioactive fuel.

A **nuclear meltdown**, or uncontrolled nuclear reaction in a nuclear reactor, can potentially result in widespread contamination of air and water. Some serious nuclear and radiation accidents have occurred worldwide. The most severe accident was the Chernobyl accident of 1986 in the then Soviet Union (now Ukraine) which killed 31 people directly and sickened or caused cancer in thousands more. The Fukushima Daiichi nuclear disaster (2011) in Japan was caused by a 9.0 magnitude earthquake that shut down power supply and a tsunami that flooded the plant's emergency power supply. This resulted in the release of radioactivity although it did not directly result in any deaths at the time of the disaster. Another nuclear accident was the Three Mile Island accident (1979) in Pennsylvania, USA. This accident resulted in a near disastrous core meltdown that was due to a combination of human error and mechanical failure but did not result in any deaths and no cancers or otherwise have been found in follow up studies of this accident. While there are potentially devastating consequences to a nuclear meltdown, the likelihood of one occurring is extremely small. After every meltdown, including the 2011 Fukushima Daiichi disaster, new international regulations were put in place to prevent such an event from occurring again.

The processes for mining and refining uranium ore and making reactor fuel require large amounts of energy. Nuclear power plants have large amounts of metal and concrete, which also require large amounts of energy to manufacture. If fossil fuels are used for mining and refining uranium ore or in constructing the nuclear plant, then the emissions from burning those fuels could be associated with the electricity that nuclear power plants generate.

Sources

Botkin, D. B. and Keller E. A. 2009. 7th Ed. *Environmental Science: Earth as a Living Planet*. John Wiley and Sons, Inc. USA

Cunningham, W. P., and Cunningham, M. A. 2010. 11th Ed. *Environmental Science: a global concern*. McGraw-Hill Companies, USA.

Karr, S., Houtman, A., and Interlandi, J. 2014. *Environmental Science for a Changing world: with extended coverage*. W. H. Freeman and Company, New York.

Withgott J. and Laposata, M. 2012. 4th Ed. *Essential Environment: the science behind the stories*. Pearson Education, Inc. USA.

Nuclear Regulatory Commission www.nrc.gov

Tennessee Valley Authority www.tva.com

U.S. Department of Energy http://www.energy.gov/

U.S Energy Information Administration http://www.eia.gov/

U.S. Environmental Protection Agency www.epa.gov

Terms list

Acid mine drainage
Anaerobic
Ash
Boiler
Caprocks
Carbon capture & sequestration
Carbon dioxide
Carbon monoxide
Chain reaction
Chemical energy
Clean Air Act
Clean coal technology
Clean Water Act
Coal
Coal-fire power plant
Condenser
Conversion
Crude
Decommissioned
Digesters
Electricity
Energy
Enrichment
Exploration
Fabrication
Fossil fuel
Fuel rods
Furnace
Generator
Greenhouse gas
Heating value
Heavy metals
Hydraulic fracturing
Hydrocarbon
Isotope
Kinetic energy
Liquid natural gas
Mercury
Methane
Methylmercury
Milling
Mountaintop removal
Natural gas
Neutron
Nitrogen oxides
Non-renewable
Nuclear fission
Nuclear meltdown
Nucleus
Offshore
Oil
Oil spill
Onshore
Ore
Overburden
Particulate matter
Petroleum
Pipeline
Plastic
Potential energy
Pressurized water reactors
Primary energy
Radiation
Radon
Reclaimed
Refinery
Scrubber
Secondary energy

Separation
Strip mining
Sulfur dioxide
Transporation
Treatment
Turbine
U-235
Underground mining
Uranium
Volatile organic
compounds

Chapter 5: Alternative energy

Learning outcomes - by the end of this chapter, students should be able to.

1. Describe arguments for alternative energy
2. Explain the following aspects of solar energy:
    a. How passive solar energy works and provide examples of its use.
    b. How solar panels (photovoltaic cells) work.
    c. The limitations and environmental costs associated with solar energy.
3. Explain the following aspects of biofuels / biomass energy:
    a. Describe what is meant by the term "carbon neutral" and explain how biomass energy can and cannot be carbon neutral.
    b. Describe current achievements in biofuels and potential of this area for growth.
4. Describe wind energy and explain the advantages and disadvantages.
5. Describe geothermal energy and explain the advantages and disadvantages
6. Describe hydroelectric energy, advantages and disadvantages

Chapter Outline

5.1 INTRODUCTION

Energy sources that are more or less continuously made available in a time frame useful to people are called **renewable energy**. Renewable energy sources are often considered alternative sources because, in general, most industrialized countries do not rely on them as their main energy source. Instead, they tend to rely on the conventional energy sources such as fossil fuels or nuclear power that are non-renewable. Because of the energy crisis in the United States during the 1970s, dwindling supplies of fossil fuels and hazards associated with nuclear power, use of renewable energy sources such as solar energy, hydroelectric, wind, biomass, and geothermal has grown. Renewable energy comes from the sun (considered an "unlimited" supply) or other sources that can theoretically be renewed at least as quickly as they are consumed. If used at a sustainable rate, these sources will be available for consumption for thousands of years or longer. Renewable alternatives derive from wind, water, solar or biomass (**Figure 5.1**). Note that wind, water and biomass energy sources are indirect sources of solar energy. One limitation currently associated with most forms of renewable energy is that the energy is not concentrated and not easily portable.

Figure 5.1 A variety of voltage sources (clockwise from top left): the Brazos Wind Farm in Fluvanna, Texas (credit: Leaflet, Wikimedia Commons); the Krasnoyarsk Dam in Russia (credit: Alex Polezhaev); a solar farm (credit: U.S. Department of Energy); and a group of nickel metal hydride batteries (credit: Tiaa Monto). The voltage output of each depends on its construction and load, and equals emf only if there is no load.

Energy is an important ingredient in all phases of society. We live in a very interdependent world, and access to adequate and reliable energy resources is crucial for economic growth and for maintaining the quality of our lives. However, current levels of energy consumption and production are not sustainable because of the heavy reliance on non-renewable energy sources. The principal energy resources used in the world are shown in **Figure 5.2**. The fuel mix has changed over the years but now is dominated by oil, although natural gas and solar contributions are increasing. About 80 % of our energy comes from nonrenewable fossil fuels and nuclear. The link between global warming and fossil fuel use, with its production of carbon dioxide through combustion, has made, in the eyes of many scientists, a shift to non-fossil fuels of utmost importance – but it will not be easy. About 40 % of the world's energy comes from oil, and much of that goes to transportation uses.

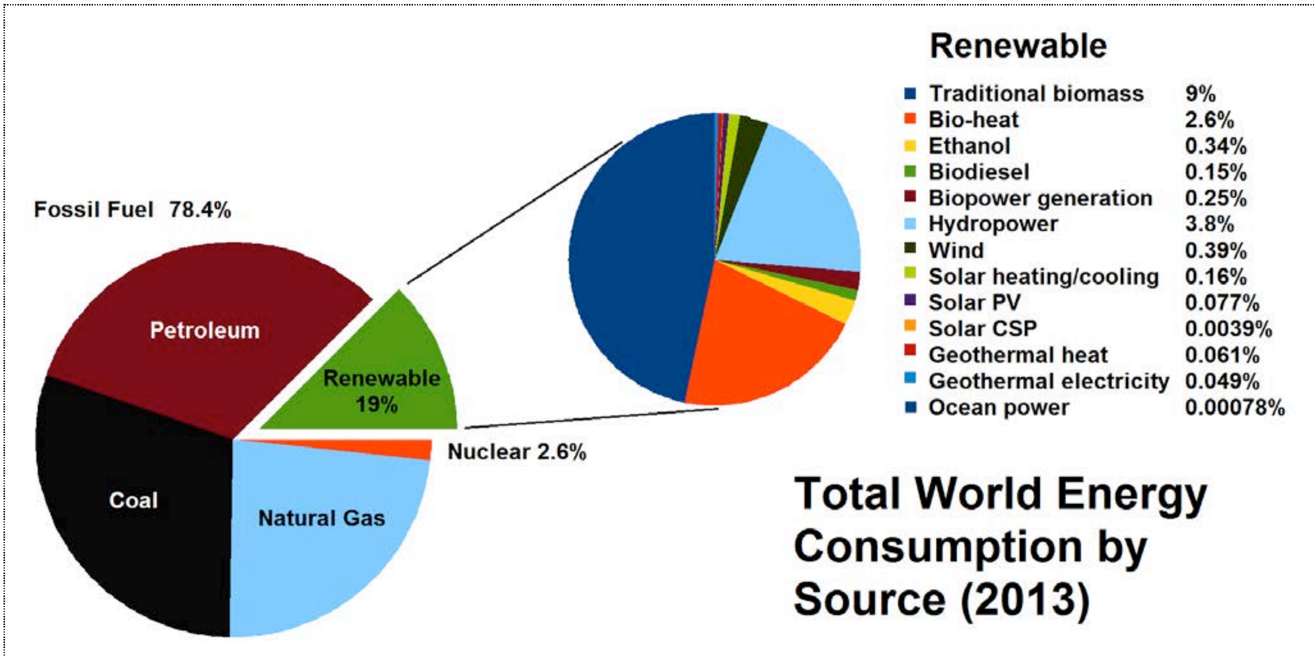


Figure 5.2. World energy consumption by source, 2013, in percent. Notice that when all forms of biomass energy are combined, biomass makes up the largest proportion of renewable energy used worldwide. Source: Wikimedia commons - By Delphi234 - Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=33567170

5.1.1 The World's Growing Energy Needs

World energy consumption continues to rise especially in countries like China where the economy is improving. Global demand for energy has tripled in the past 50 years and might triple again in the next 30 years (**Figure 5.3**). While much of this growth will come from the rapidly booming economies of China and India, many of the industrialized countries, especially those in Europe, are hoping to meet their energy needs by expanding the use of renewable sources. Although presently only a small percentage, renewable energy is growing very fast, especially wind energy. For example, Germany plans to meet 20% of its electricity and 10% of its overall energy needs with renewable resources by the year 2020. Energy is a key constraint in the rapid economic growth of China and India. In 2003, China surpassed Japan as the world's second largest consumer of oil. However, over 1/3 of this oil is imported. Unlike most Western countries, coal dominates the commercial energy resources of China, accounting for 2/3 of its energy consumption. In 2009 China surpassed the United States as the largest emitter of CO_2. In India, the main energy resources are biomass (wood and dung) and coal. Half of India's oil is imported. About 70% of India's electricity is generated by highly polluting coal. Yet there are sizeable strides being made in renewable energy. India has a rapidly growing wind energy base, and it has the largest solar cooking program in the world. While non-renewable sources dominate, some countries get a sizeable percentage of their electricity from renewable resources. For example, about 67% of New Zealand's electricity demand is met by hydroelectric. Renewable resources, primarily hydroelectric, generate only 10% of the U.S. electricity.

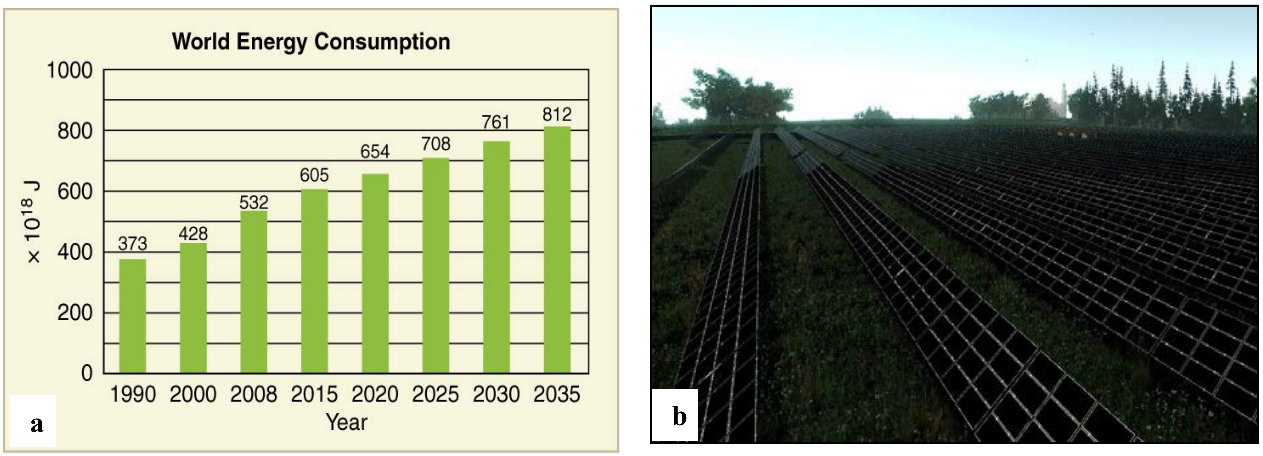


Figure 5.3: (**a**) Past and projected world energy use (source: Based on data from U.S. Energy Information Administration, 2011). (**b**) Solar cell arrays at a power plant in Steindorf, Germany (credit: Michael Betke, Flickr).

5.1.2 Why Use Renewable Energy Sources?

Majority of renewable energy sources including solar, wind, water, and biomass can be directly or indirectly attributed to the sun. The fact that the sun will continue burning for another 4-5 billion years makes it inexhaustible as an energy source for human civilization. With appropriate technology, renewable energy sources allow for local, decentralized control over power. Homes, businesses, and isolated communities can use sources such as solar to produce electricity without being near a power plant or being connected to a grid. This eliminates problems such as spills associated with extraction and transportation of fossil fuels that is needed in order to supply these fossil fuels to those areas that are lacking. Most renewable energy sources do not pollute the air with greenhouse gas emissions and other air pollutants associated with fossil fuels. This is especially important in combating climate change.

5.2 SOLAR ENERGY

Solar energy is the ultimate energy source driving life on earth and many human activities. Though only one billionth of the energy that leaves the sun (**Figure 5.4**) actually reaches the earth's surface, this is more than enough to meet the world's energy requirement. In fact, all other sources of energy, renewable and non-renewable, are actually stored forms of solar energy. The process of directly converting solar energy to heat or electricity is considered a renewable energy source. Solar energy represents an essentially unlimited supply of energy as the sun will long outlast human civilization on earth. The difficulties lie in harnessing the energy. Solar energy has been used for centuries to heat homes and water, and modern technology (photovoltaic cells) has provided a way to produce electricity from sunlight. There are two basic forms of solar energy collectors are passive and active.

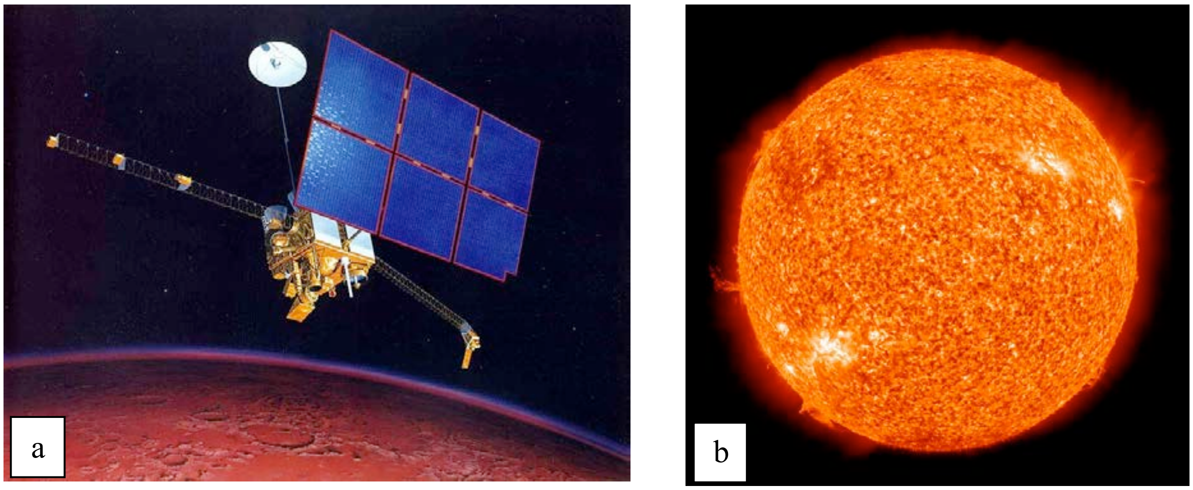


Figure 5.4. a) Mars Observer in Mars Orbit showing the solar panel. (Picture: Wikimedia Commons http://www.jpl.nasa.gov/images/spacecraft/marsobserver/craft1-browse.jpg,). b) The Sun photographed at 304 angstroms by the Atmospheric Imaging Assembly (AIA 304) of NASA's Solar Dynamics Observatory (SDO). This is a false-color image of the Sun observed in the extreme ultraviolet region of the spectrum. http://sdo.gsfc.nasa.gov/assets/img/browse/2010/08/19/20100819_003221_4096_0304.jpg, NASA/SDO (AIA)

5.2.1 Passive and Active Solar Energy

Passive solar energy uses heating and cooling strategies that have been used historically such as natural ventilation, solar heat gain, solar shading and efficient insulation. Passive solar space heating happens when the sun shines through the windows of a building and warms the interior (**Figure 5.5**). Building designs that optimize passive solar heating usually have south-facing windows that allow the sun to shine on solar heat-absorbing walls or floors during the winter. The solar energy heats the building by natural radiation and convection and the heat is trapped, absorbed and stored by materials with high thermal mass (usually bricks or concrete) inside the house. The heat is released at night when needed to warm up the building as it loses heat to the cooler outdoors. Window overhangs or shades block the sun from entering the windows during the summer to keep the building cool.

Active solar energy systems require the input of some energy to pump a heat-absorbing fluid medium through a *collector* to store and distribute the energy. Fans or pumps circulate air or heat-absorbing liquids through collectors and then transfer the heated fluid directly to a room or to a heat storage system. The solar collectors are either concentrating or non-concentrating. In the **non-concentrating collectors**, the surface area that intercepts the solar radiation is the same as the area absorbing the radiation. *Flat-plate collectors* are the most common type of non-concentrating collectors and are used when temperatures lower than 200°F are sufficient. The collectors absorb and transfer heat to a fluid (water or air) which is then circulated to provide heating to a building. In **concentrating collectors** the surface area intercepting the solar radiation is greater, sometimes hundreds of times greater, than the absorber area. The collector focuses or concentrates solar energy onto an absorber. The collector usually moves so that it maintains a high degree of concentration on the absorber.

Figure 5.5. Passive solar building near Crestone, Colorado (image from Wiki Commons)

Photovoltaic (PV) Cells

Solar photovoltaic (PV) devices, or solar cells, change sunlight directly into electricity. PV uses semiconducting materials such as silicon to produce electricity from sunlight: when light hits the cells, the material produces free electrons that migrate across the cell, creating an electric current. Small PV cells can power calculators, watches, and other small electronic devices. Arrangements of many solar cells in PV panels and arrangements of multiple PV panels in PV arrays can produce electricity for an entire house (**Figure 5.6a**). Some PV power plants have large arrays that cover many acres to produce electricity for thousands of homes.

Hundreds of thousands of houses and buildings around the world have PV systems on their roofs. Many multi-megawatt PV power plants have also been built. Covering 4% of the world's desert areas with photovoltaics could supply the equivalent of all of the world's electricity. The Gobi Desert alone could supply almost all of the world's total electricity demand.

Solar Thermal Power Plants

Solar thermal power plants, like the one in **Figure 5.6b** use concentrating solar collector systems to collect and concentrate sunlight to produce the high temperature heat needed to generate electricity. All solar thermal power systems have solar energy collectors with two main components: *reflectors* (mirrors) that capture and focus sunlight onto a *receiver*. In most types of systems, a heat-transfer fluid is heated and circulated in the receiver and used to produce steam. The steam is converted into mechanical energy in a turbine, which powers a generator to produce electricity. Solar thermal power systems have tracking systems that keep sunlight focused onto the receiver throughout the day as the sun changes position in the sky.

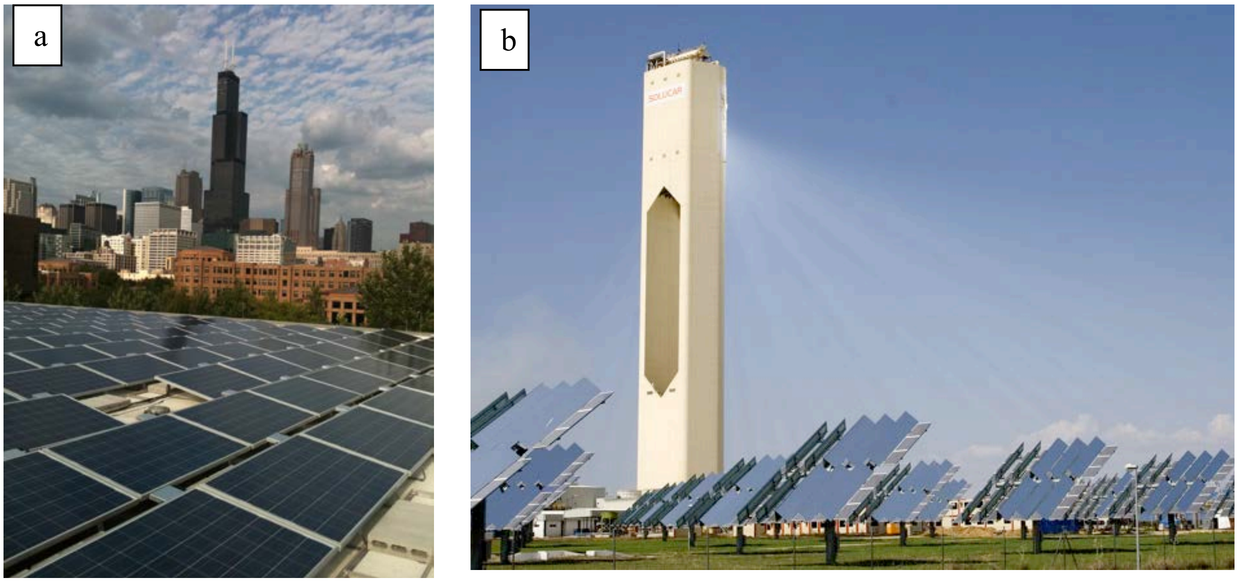


Figure 5.6: a) Rooftop Solar Installations on Douglas Hall at the University of Illinois at Chicago has no effect on land resources, while producing electricity with zero emissions. Source: Office of Sustainability. **b**) Solucar PS10 solar power tower in Andalusia, Spain, is a solar thermal power plant that generates electricity commercially. (Photo by Afloresm Solucar PS10 CC BY 2.0)

5.2.3 Environmental Impacts of solar energy

Solar power has minimal impact on the environment, depending on where it is placed. In 2009, one percent of the renewable energy generated in the United States was from solar power (1646 MW) out of the eight percent of the total electricity generation that was from renewable sources. The manufacturing of photovoltaic (PV) cells generates some hazardous waste from the chemicals and solvents used in processing. Often solar arrays are placed on roofs of buildings or over parking lots or integrated into construction in other ways. However, large systems may be placed on land and particularly in deserts where those fragile ecosystems could be damaged if care is not taken. Some solar thermal systems use potentially hazardous fluids (to transfer heat) that require proper handling and disposal. Concentrated solar systems may need to be cleaned regularly with water, which is also needed for cooling the turbine-generator. Using water from underground wells may affect the ecosystem in some arid locations.

5.3 BIOMASS ENERGY

Biomass energy is from the energy stored in materials of biological origin such as plants and animals. Biomass energy is the oldest energy source used by humans. Until the Industrial Revolution prompted a shift to fossil fuels in the mid-18th century, biomass energy was the world's dominant fuel source. It includes *direct combustion* of solid biomass to provide energy for heating, cooking, and even generating electricity. The most common source for direct combustion is wood, but energy can also be generated by burning animal manure (dung), herbaceous plant material (non-wood), peat (partially decomposed plant and animal tissues), or converted biomass such as charcoal (wood that has been partially burned to produce a coal-like substance). Biomass can also be converted into a *liquid biofuels* used to power vehicles such as ethanol from corn, sugarcane residue and soybeans or even used cooking oil for biodiesel. Biomass energy can also be in *gaseous* form such as methane. Currently, about 12 percent of the world's energy comes from biomass (**Figure 5.2**). Biomass is most frequently used as a fuel source in many developing nations, but with the decline of fossil fuel availability and the increase in fossil fuel prices, biomass is increasingly being used as a fuel source even in developed nations.

5.3.1 Direct combustion of solid biomass

Using wood and charcoal made from wood, for heating and cooking can replace fossil fuels and may result in lower CO_2 emissions. If wood is harvested from forests or woodlots that have to be thinned or from urban trees that fall down or needed be cut down anyway, then using it for biomass does not impact those ecosystems. However, wood smoke contains harmful pollutants like carbon monoxide and particulate matter. For home heating, it is most efficient and least polluting when using a modern wood stove or replace insert that are designed to release small amounts of particulates. However, in places where wood and charcoal are major cooking and heating fuels such as in industrializing countries, the wood may be harvested faster than trees can grow resulting in deforestation.

Biomass is also being used on a larger scale, where small power plants are powered by biomass such as woodchips (**Figure 5.7**). For instance, Central State Hospital, Milledgeville, GA has a woodchip burning plant that was the most advanced system available for its time and operating today. Colgate University in Hamilton, New York, has had a wood-burning boiler since the mid-1980's that processes about 20,000 tons of locally and sustainably harvested wood chips, the equivalent of 1.17 million gallons (4.43 million liters) of fuel oil, avoiding 13,757 tons of emissions, and saving the university over $1.8 million in heating costs. The University's steam-generating wood-burning facility now satisfies more than 75 percent of the campus's heat and domestic hot water needs. For more information about this, click here Colgate University.

Figure 5.7. A biomass (woodchip) power plant in Germany. Image from Wikimedia Public Domain.

Waste products of various industries and processes such as lumber mill sawdust, paper mill sludge, yard waste, oat hulls from an oatmeal processing plant, woody debris from logging, organic waste from feedlots, and residue from crops can also be used for energy. Waste to energy processes are gaining renewed interest as they can solve two problems at once: 1) disposal of waste as landfill capacity decreases; and 2) production of energy from a renewable resource. In the United States, several plants have been constructed to burn urban biomass waste and use the energy to generate electricity. Many of the environmental impacts are similar to those of a coal plant like air pollution, ash generation, etc. Since the fuel source is less standardized than coal and hazardous materials may be present in municipal solid waste (MSW), or garbage, incinerators and waste-to-energy power plants need to clean the stack gases of harmful materials. The U.S. EPA regulates these plants very strictly and requires anti-pollution devices to be installed. If not contained, waste is distributed in many ecosystems. The ash from these plants may contain high concentrations of various metals that were present in the original waste. If ash is clean enough it can be recycled as a MSW landfill cover or to build roads, cement block and artificial reefs. Also, while incinerating at high temperature many of the toxic chemicals may break down into less harmful compounds.

5.3.2 Gaseous Biomass

Organic material can be converted to methane, the main component of natural gas, by anaerobic decomposition or fermentation, a process that utilizes anaerobic bacteria. Methane is a relatively clean fuel that burns efficiently. It can be generated from any kind of organic waste such as municipal sewage and garbage, livestock manure, kitchen, and garden scraps. In fact, municipal landfills are active sites of methane production contributing annually to methane in the atmosphere and to global warming. This gas can and is currently being captured by numerous landfills around the United States that burn it to generate electricity at power plants or supply it to homes for heating. The electricity may replace electricity produced by burning fossil fuels and result in a net reduction in CO_2 emissions. Burning methane produced from manure provides more heat than burning the dung itself, and the sludge left over from bacterial digestion is a rich fertilizer, containing healthy bacteria as well as most of the nutrients originally in the dung. The main environmental impacts are from the construction of the plant itself. Burning methane releases CO_2 and although CO_2 is a greenhouse gas, its global warming potential is much lower than that of methane (see chapter 7). Also, since this methane if from organic waste resulting from ongoing photosynthetic processes, it is considered carbon-neutral, unlike CO_2 from fossil fuels.

5.3.3 Liquid Biofuels

Biofuels are transportation fuels produced from plant sources and used to power vehicles. The most common ones are ethanol and biodiesel. **Ethanol**, also known as ethyl alcohol or grain alcohol, is produced by fermenting crops such as corn, sugarcane, and other crops and then mixed with conventional gasoline. As an additive, ethanol lowers reliance on conventional oil and increases the combustion efficiency of gasoline, reducing pollutant emissions. In Brazil, which has a sizeable ethanol industry based on sugarcane, all gasoline sold contains 25 percent alcohol, and over 70 percent of the cars sold each year can run on either ethanol or gasoline. Ethanol-gasoline mixtures burn cleaner than pure gasoline but are more volatile and thus have higher "evaporative emissions" from fuel tanks and dispensing equipment. These emissions contribute to the formation of harmful, ground level ozone and smog. Gasoline requires extra processing to reduce evaporative emissions before it is blended with ethanol.

Biodiesel which is essentially vegetable oil, can also be derived from a wide range of plant sources, including rapeseed, sunflowers, and soybeans, and can be used in most conventional diesel engines. Biodiesel can also be made from used vegetable oil and has been produced on a very local basis. Because it burns more cleanly than its petroleum-based counterpart, biodiesel can reduce pollution from heavy-duty vehicles such as trucks and buses. Compared to petroleum diesel, biodiesel combustion produces less sulfur oxides, particulate matter, carbon monoxide, and unburned and other hydrocarbons, but more nitrogen oxide.

Calculating the net energy or CO_2 generated or reduced in the process of producing the biofuel is crucial to determining its environmental impact. Biofuels may be derived from parts of plants not used for food (cellulosic biomass) thus reducing that impact. Cellulosic ethanol feedstock includes native prairie grasses, fast growing trees, sawdust, and even waste paper. Also, in some parts of the world, large areas of natural vegetation and forests have been cut down to grow sugarcane for ethanol and soybeans and palm-oil trees to make biodiesel. This is not sustainable land use.

Biomass energy may be considered to be **carbon-neutral** because the plants that are used to make them (such as corn and sugarcane for ethanol, or soy beans and palm oil trees for biodiesel) take up CO_2 from the atmosphere through photosynthesis as they grow and may offset the CO_2 produced when burned. If the biomass is not burned for energy generation, the carbon contained in the biomass would still be returned to the atmosphere as CO_2 when the organisms die and decompose to complete the cycle. Burning biomass, therefore, does not result in new additional CO_2 in the atmosphere but rather returns carbon that came from the atmosphere and used to produce the biomass in the first place. On the other hand, burning fossil fuels introduces new carbon into the atmosphere that was previously stored deep in the Earth's crust and would have stayed there if we (humans) did not extract it.

5.3.4 Environmental Impacts of Biomass Energy

A major challenge of biomass is determining if it is really a more sustainable option. The energy content of some biomass energy sources may not be as high as fossil fuels so more must be burned to generate the same energy. It often takes energy to make energy and biomass is one example where the processing to make it may not be offset by the energy it produces. If traditional monoculture crops like corn or soybeans are used, they require major quantities of fossil fuel to manufacture fertilizer, run farm machines, and ship the fuel to markets, so these biofuels do not always offer significant net energy savings over gasoline and diesel fuel. In such instances, biofuels may not be carbon-neutral because the process of producing the biofuels results in more CO_2 added to the atmosphere than that removed by the growing crops. Even if the environmental impact is net positive, for example if renewable energy sources are used to make the biofuels, the economic and social effects of growing plants for fuels need to be considered. The land, fertilizers, water, and energy used to grow biofuel crops could be used to grow food crops instead. The competition of land for fuel vs. food can increase the price of food, which has a negative effect on society. It could also decrease the food supply and increase malnutrition and starvation globally.

Trees that are cut for firewood are frequently not replanted. In order to be used sustainably, one tree must be planted for every one cut down. If too much biomass is taken it can reduce forest and grassland contributions to ecosystem services. Forests and grasslands help take

CO_2 out of the atmosphere through photosynthesis and the loss of photosynthetic activity results in increased amounts of CO_2 in the atmosphere and contribute to global warming since CO_2 is a greenhouse gas. Burning biomass directly (wood, manure, etc.) produces high particulate material pollution (see chapter 6 on Air Pollution), produces CO_2 and deprives the soil of nutrients it normally would have received from the decomposition of the organic matter. Each type of biomass energy source, therefore, must be evaluated for its full life-cycle impact in order to determine if it is really advancing sustainability and reducing environmental impacts.

5.4 WIND POWER

Wind is a renewable energy source that uses the power of moving air to generate electricity. Wind turbines use blades to collect the wind's kinetic energy. Wind flows over the blades creating lift (similar to the effect on airplane wings), which causes the blades to turn. The blades are connected to a drive shaft that turns an electric generator, which produces electricity (**Figure 5.8**). Wind turbines are becoming a more prominent sight across the United States, even in regions that are considered to have less wind potential. Wind turbines (often called windmills) do not release emissions that pollute the air or water (with rare exceptions), and they do not require water for cooling. The U.S. wind industry had 40,181 MW of wind power capacity installed at the end of 2010, with 5,116 MW installed in 2010 alone, providing more than 20 % of installed wind power around the globe. According to the American Wind Energy Association, over 35 % of all new electrical generating capacity in the United States since 2006 was due to wind, surpassed only by natural gas.

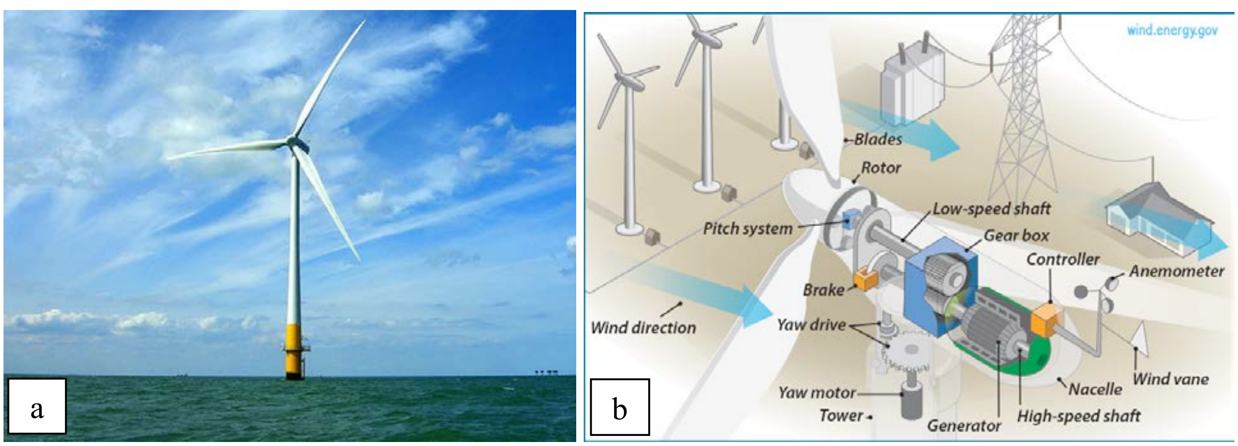


Figure 5.8. a) This wind turbine in the Thames Estuary in the UK is an example of induction at work, (credit: Phault, Flickr). Wind pushes the blades of the turbine, spinning a shaft attached to magnets, see image **b** for parts. The magnets spin around a conductive coil, inducing an electric current in the coil, and eventually feeding the electrical grid. Follow this link for an Animation.

Most windmills generate about 1kW of electricity, which is only practical for decentralized power generation. California has about 17,000 windmills with a capacity of about 1,400 MW. This is about 80% of all windmills in the U.S. In West Europe windmill generators are quite common. Since a wind turbine (**Figure 5.8**) has a small physical footprint relative to the amount of electricity it produces, many wind farms are located on crop, pasture, forest land, or coastal areas. They contribute to economic sustainability by providing extra income to farmers and ranchers, allowing them to stay in business and keep their property from being developed for other uses. For example, energy can be produced by installing wind turbines in the Appalachian Mountains of the United States instead of engaging in mountain top removal for coal mining.

5.4.1 Environmental Impacts of Wind Energy

Off shore wind turbines on lakes or the ocean may have smaller environmental impacts than turbines on land. Wind turbines do have a few environmental challenges. There are aesthetic concerns to some people when they see them on the landscape. A few wind turbines have caught on fire, and some have leaked lubricating fluids, though this is relatively rare. Some people do not like the sound that wind turbine blades make.

Turbines have been found to cause bird and bat deaths particularly if they are located along their migratory path. This is of particular concern if these are threatened or endangered species. There are ways to mitigate that impact and it is currently being researched.

There are some small impacts from the construction of wind projects or farms, such as the construction of service roads, the production of the turbines themselves, and the concrete for the foundations. However, overall life cycle analysis has found that turbines make much more energy than the amount used to make and install them.

5.5 GEOTHERMAL ENERGY

Geothermal energy uses heat from the Earth's internal geologic processes in order to produce electricity or provide heating. The subsurface temperature of the Earth provides an endless energy resource. One source of geothermal energy is steam. Groundwater percolates down through cracks in the subsurface rocks until it reaches rocks heated by underlying magma, and the heat converts the water to steam. Sometimes this steam makes its way back to the surface in the form of a geyser or hot spring. Wells can be dug to tap the steam reservoir and bring it to the surface, to drive generating turbines and produce electricity (**Figure 5.9 a**). Hot water can be circulated to heat buildings. Regions near tectonic plate boundaries have the best potential for geothermal activity.

A geothermal system requires heat, permeability, and water. The heat from the Earth's core continuously flows outward. Sometimes the heat, as magma, reaches the surface as lava, but it usually remains below the Earth's crust, heating nearby rock and water — sometimes to levels as hot as 700°F. When water is heated by the earth's heat, hot water or steam can be trapped in permeable and porous rocks under a layer of impermeable rock and a geothermal reservoir can form. Geothermal energy can be used for electricity production, for commercial, industrial, and residential direct heating purposes, and for efficient home heating and cooling through geothermal heat pumps.

To develop electricity from geothermal resources, wells are drilled into a geothermal reservoir. The wells bring the geothermal water to the surface, where its heat energy is converted into electricity at a geothermal power plant (**Figure 5.9 b**). Geothermal power plants do not burn fuel to generate electricity so their emission levels are very low.

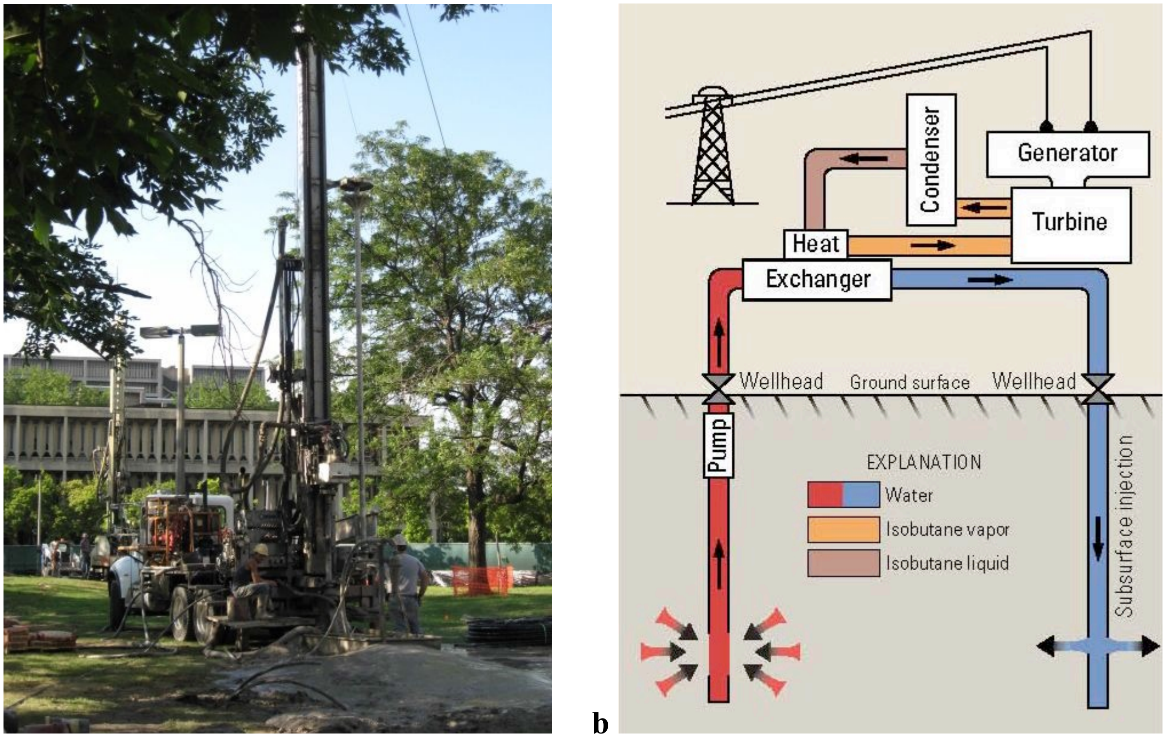


Figure 5.9. **a**) Installing a Geothermal Pipe System Drilling to install geothermal ground source pipe system. Source: Office of Sustainability. **b**) Electricity generation at a moderate-temperature hydrothermal system. The geothermal water is used to boil a second fluid (isobutane in this example) whose vapor then drives a turbine generator. The wastewater is injected back into the subsurface. Source: USGS.

5.5.1 Environmental Impacts of Geothermal Energy

The environmental impact of geothermal energy depends on how it is being used. Direct use and heating applications have almost no negative impact on the environment. Geothermally heated water can release dissolved gases, including carbon dioxide, methane, ammonia and hydrogen sulfide, although these are usually in very small quantities when compared to those released from fossil fuel plants. In addition, geothermal plants use scrubber systems to clean the air of hydrogen sulfide that is naturally found in the steam and hot water. They emit 97 % less acid rain-causing sulfur compounds than are emitted by fossil fuel plants.

Even though geothermal energy is renewable, not every plant built to capture this energy will be able to operate indefinitely because the energy relies on groundwater recharge. If the heated water is used faster than the recharge rate of groundwater, the plant will eventually run out of water. The Geysers in California started experiencing this and operators responded by injecting municipal wastewater into the ground to replenish the supply. Also, patterns of geothermal activity in the Earth's crust naturally shift over time and an area that produces hot groundwater now may not always so do. The water of many hot springs is laced with salts and minerals that corrode equipment, shorten the lifetime of plants and increase maintenance costs.

Electrical power is restricted to regions where energy can be tapped from naturally heated groundwater but most areas of the world are not rich in naturally heated groundwater. Engineers are trying to overcome this by drilling deeply into dry rock, fracture the rock and pump in cold water which becomes heated and drawn up through an outlet well and used to generate power. However, this approach is said to trigger minor earthquakes.

5.6 HYDROELECTRIC POWER (HYDROPOWER)

This is the second largest source of renewable energy used, next to biomass energy. Majority of hydropower currently comes from dams built across a river to block the flow of river water. The water stored behind the dam contains potential energy (see chapter 4) and when released, the potential energy is converted to kinetic energy as the water rushes down. This energy is used to turn blades of turbines and causing a generator to generate electricity. Electricity generated in the powerhouse of a dam is transmitted to the electric grid by transmission lines while the water flows into the riverbed below the dam and continues down river. An alternative approach considered less disruptive involves diverting a portion of the river's water through a pipe or channel and passed through a powerhouse to generate electricity and returned to the river. Another approach involves pumping water from a lower reservoir to a higher reservoir and then allowed to flow downhill through a turbine, generating electricity. This approach, however, requires energy input to pump the water.

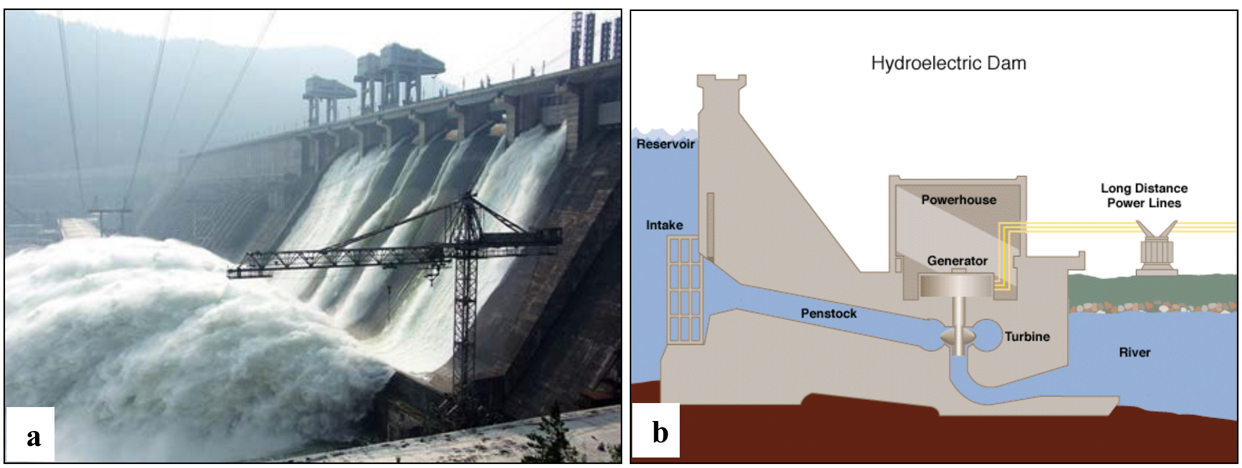


Figure 5.10. a) Hydroelectric facility (credit: Denis Belevich, Wikimedia Commons); **b)** An illustration showing how water is funneled through a portion of the dam to rotate turbines and generate electricity. (Image from Wikimedia, public domain).

Figure 5.11 shows the Hoover Power Plant located on the Colorado River. In the U.S., hydroelectric plants account for about 10% of total production and account for about 35 % of the United States' renewable energy consumption. In 2003 capacity was at 96,000 MW and it was estimated that 30,000 MW capacity is undeveloped. Energy produced can be calculated and modeled as shown in **Figure 5.12**.

Figure 5.11. a) A view of the Hoover dam from above (credit Adam Kliczek). **b)** Hydroelectric generators at the Hoover dam (credit: Jon Sullivan).

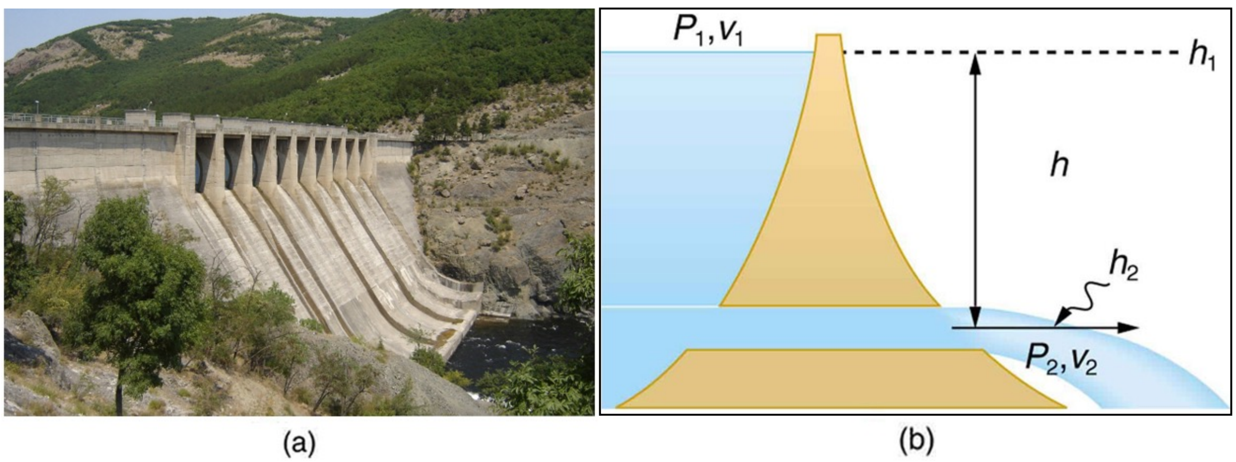


Figure 5.12. (a) Water gushes from the base of the Studen Kladenetz dam in Bulgaria. (credit: Kiril Kapustin; http://www.ImagesFromBulgaria.com) (b) In the absence of significant resistance, water flows from the reservoir with the same speed it would have if it fell the distance *h* without friction.

5.6.1 Environmental Impacts of Hydroelectric Power

Hydropower (hydro-electric) is considered a clean and renewable source of energy since it does not directly produce emissions of air pollutants and the source of power is regenerated. However, hydropower dams, reservoirs, and the operation of generators can have serious environmental impacts. A dam that is used to create a reservoir or to divert water to a run-of-river hydropower plant can obstruct migration of fish to their upstream spawning areas in areas where salmon must travel upstream to spawn, such as along the Columbia River in Washington and Oregon. Hydro turbines kill and injure some of the fish that pass through the turbine although there are ways to reduce that effect. This problem can be partially alleviated by using 'fish ladders' that help the salmon get up the dams.

A reservoir and operation of the dam can affect the natural water habitat due to changes in water temperatures, chemistry, flow characteristics, and silt loads, all of which can lead to significant changes in the ecology and physical characteristics of the river upstream and downstream. Construction of reservoirs may cause natural areas, farms, and archeological sites to be covered and force populations to relocate and result in the loss of scenic rivers

Carbon dioxide and methane may also form in reservoirs where water is more stagnant and be emitted to the atmosphere. The exact amount of greenhouse gases produced from hydropower plant reservoirs is uncertain. If the reservoirs are located in tropical and temperate regions, including the United States, those emissions may be equal to or greater than the greenhouse effect of the carbon dioxide emissions from an equivalent amount of electricity generated with fossil fuels (EIA, 2011 p. 333).

5.6.2 Potential of Tidal Power

Tidal power involves placing turbines in zones of the ocean with significant tides and currents, and using the power of flowing water to turn the blades of a turbine to generate electricity. Ocean power systems are still being researched and currently still experimental. For example, the Bay of Fundy, which has a 15 m tide, a dam constructed across the estuary would let water enter on the incoming tide, then release the water through turbines at low tide. The energy potential is great http://www.ialtenergy.com/tidal-power-news.html , and so is the environmental cost. Tapping tidal energy resources involves building major dams on inlets and estuaries that are prized for other purposes, so few tidal energy facilities have been developed. Harnessing waves and currents on a significant scale will involve designing turbine structures that are large, inexpensive, and can operate for long periods under the physical stresses and corrosive forces of ocean environments. Though proposed, a tidal power plant has not been constructed at Fundy. There is a 240,000 kW tidal plant at La Rance, France.

5.7 OTHER ALTERNATIVE RENEWABLE ENERGY SOURCES

5.7.1 Hydrogen

Hydrogen gas may be an important clean fuel of the future. Hydrogen is considered an energy carrier, like electricity and batteries, it carries energy that can be converted for use later. Hydrogen gas does not tend to exist freely but rather hydrogen atoms bind to other atoms and molecules becoming incorporated in everything from water to organic compounds. Therefore, to obtain hydrogen gas for fuel, energy is needed to force these substances to release their hydrogen atoms. One such procedure is known as **electrolysis** in which an electric current is passed through water to decompose the water molecule into oxygen and hydrogen **(Figure 5.13)**. Hydrogen can also be produced from hydrocarbons such as natural gas and coal, fermentation of plant waste material, and using algae.

The nation of Iceland is attempting to become the first hydrogen based energy economy using its abundant geothermal energy resources. Some energy experts believe that combining hydrogen fuel and electricity could serve as a basis for a clean, safe, and energy efficient energy system. Electricity generated from intermittent renewable sources such as wind and solar can be used to produce hydrogen fuel for fuel cells that would then generate electricity to power vehicles, computers, heat homes and many other uses. An energy system based on hydrogen would alleviate dependence on foreign fuels and help fight climate change. Hydrogen is the most abundant element in the universe and we will never run out of it.

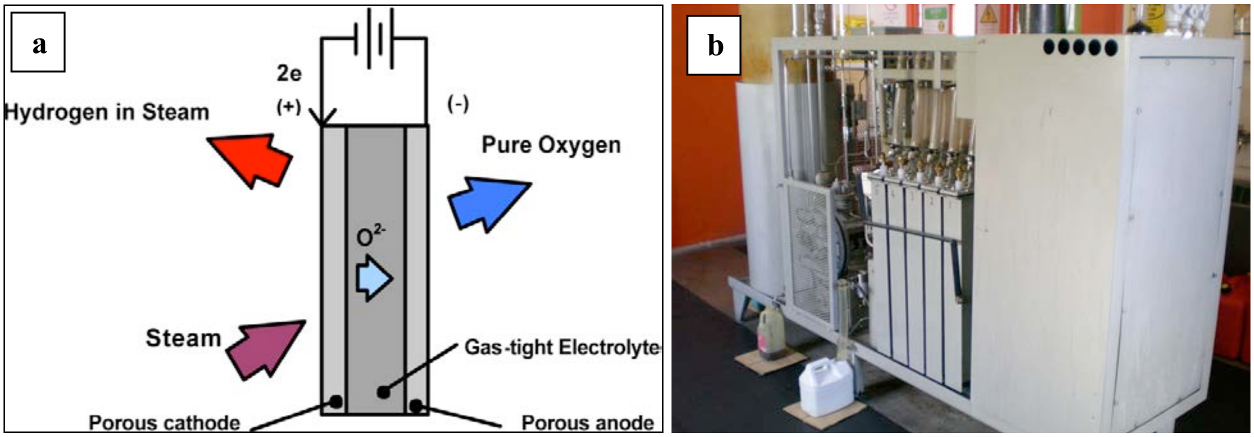


Figure 5.13 a) An electric current passed through water resulting in the separation of hydrogen atoms from oxygen to produce the hydrogen fuel. **b**) An electrolyser used in the production of hydrogen by CambridgeBayWeather. After production the hydrogen is used to inflate weather balloons to which a radiosonde is attached. The oxygen produced is vented to the outside.

Fuel Cells

Fuel cells are highly efficient power plants that produce electricity using hydrogen fuel in a chemical reaction that is a reverse of the electrolysis process that produced the hydrogen fuel (**Figure 5.14**). Energy is released by an exothermic electrochemical reaction that combines hydrogen and oxygen ions through an electrolyte material to generate electricity and heat. Experimental fuel cells that can power automobiles have been developed (**Figure 5.14**).

Figure 5.14: The electrochemical processes showing how hydrogen fuel is combined with oxygen generating heat energy along with water as a waste product. Some vehicles that use the fuel cell include buses (photo is a hydrogen fuel bus on Tower Bridge London, photo by Sludge G.), cars (The Toyota Fine N car based on fuel cell technology, photo by Chris 73, CC BY-SA 3.0) and motorcycles (Suzuki Burgman Fuel Cell cutaway model shown here, Photo by Mario CC BY-SA 3.0).

Challenges of Hydrogen

Currently, the infrastructure for using hydrogen fuel is lacking and converting a nation such as the United States to hydrogen would require massive and costly development of facilities to produce, store, transport, and provide the fuel. The environmental impact of hydrogen production itself depends on the source of material used to supply the hydrogen. For example, biomass and fossil fuel sources result in carbon-based emissions. Some research suggests that leakage of hydrogen from its production, transport, and use could potentially deplete stratospheric ozone. Research into this is still ongoing.

5.7.2 Electric cars

Electric cars are vehicles that solely depend on electricity to work. They are charged using fossil fuel energy sources (**Figure 5.15 a**), but they are very efficient. Although it might seem like science fiction the electric car is already here, and has been here for the last hundred years. The main problem with the electric car is that it cannot go very far before it needs to be recharged, something that takes between three to six hours. Different models have been explored (**Figure 5.15 b**), but for now most cars are equipped as a hybrid with a back up reservoir using fossil fuel.

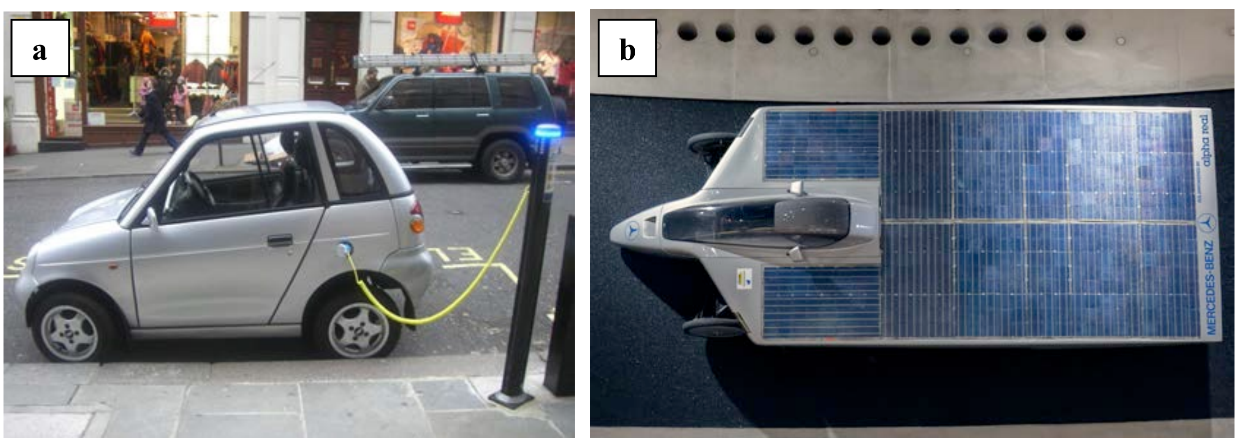


Figure 5.15. a) This REVAi, an electric car, gets recharged on a street in London. (credit: Frank Hebbert). **b**) 1985 Mercedes-Benz/Alpha Real "Tour de Sol" Solarmobile; built for the 1985 Tour de Sol Centennial Rally, solar car race from Lake Constance to Lake Geneva.

5.8 POLICY AND CONSERVATION

As we finish this chapter on energy and work, it is relevant to draw some distinctions between two sometimes misunderstood terms in the area of energy use. As has been mentioned elsewhere, the "*law of the conservation of energy*" is a very useful principle in analyzing physical processes. It is a statement that cannot be proven from basic principles, but is a very good bookkeeping device, and no exceptions have ever been found. It states that the total amount of energy in an isolated system will always remain constant. Related to this principle, but remarkably different from it, is the important philosophy of energy *conservation*. Conservation has to do with seeking to decrease the amount of energy used by an individual or a group through (1) reduced consumption (e.g., turning down thermostats, driving fewer kilometers) and/or (2) increasing conversion efficiencies in the performance of a particular task—such as developing and using more efficient room heaters, cars that have greater miles-per-gallon ratings, energy efficient compact fluorescent lights, energy efficient appliances, etc. Since energy in an isolated system is not destroyed or created, one might wonder why we need to be concerned about our energy resources, since energy is a conserved quantity. The problem is that the final result of most energy transformations is waste heat transfer to the environment and conversion to energy forms no longer useful for doing work. To state it in another way, the potential for energy to produce useful work has been "degraded" in the energy transformation.

A rational energy policy should encourage research by private industry and should provide funding for basic research, ensure fair access to alternative energy sources, encourage the internalization of external cost of fossil fuel energy, and promote the dissemination of information about the costs and benefits of alternative energy sources.

Questions:

1. Describe three major environmental challenges for fossil fuels in general or one in particular.
2. Rate the following electricity sources for their contribution to climate change from most to least: biomass, coal, solar, wind, nuclear, natural gas, oil, geothermal, hydroelectric, MSW. Is there any compelling reason not to use any of the carbon neutral (no net carbon emissions) sources?
3. Describe the environmental and social concerns associated with biofuels.

In class activities: Design a sustainable city of the future

Websites for more information and further discussion

News: algae car: http://inhabitat.com/first-algae-powered-car-attempts-to-cross-us-on-25-gallons/

For a video presentation on the different ways to use geothermal energy, visit http://geothermal.marin.org/video/vid_pt5.html

Are Electric Vehicles Better for the Environment than Gas-Powered Ones? http://www.technologyreview.com/view/517146/are-electric-vehicles-better-for-the-environment-than-gas-powered-ones/

See excel file with terminology introduced in this chapter.

Chapter 6: Air pollution

Emissions from this power plant in New Mexico contained excessive amounts of sulfur dioxide. Image from National Parks Service (Public Domain).

Learning Objectives:

By the end of this chapter, students will be able to

- Describe the composition and structure of the atmosphere.
- Explain the importance of the ozone layer, its depletion, and specific steps taken to address it.
- Distinguish between indoor and outdoor air pollution and how these compare among industrialized and less industrialized countries
- Identify natural and anthropogenic sources of air pollution
- Explain the effects of air pollution on human and ecosystem health
- Explain how the Clean Air Act legislation works and describe its outcomes

Chapter Outline

6.1 Composition and Structure of the Atmosphere

Atmosphere refers to the layer of gases that surrounds Earth and is held in place by Earth's gravitational attraction (gravity). The mix of gases in the atmosphere forms a complex system organized into layers that together support life on Earth. Although there are numerous gases, as shown in Table 6.1, the top four gases make up 99.998 % of the volume of *clean dry air* (unpolluted air that does not contain water vapor). Of this dry composition of the atmosphere **nitrogen**, by far, is the most common (78%). Nitrogen dilutes oxygen and prevents rapid or instantaneous burning at the Earth's surface, as oxygen gas is a necessary reactant of the combustion process. Nitrogen is also needed and used by living things to make proteins, though as nitrogen gas, N_2, it is unavailable to most living things. **Oxygen** is used by all living things to make molecules that are essential for life. It is also essential for aerobic respiration as well as combustion or burning. **Argon** is a non-reactive gas and we use it in light bulbs, in double-pane windows, and to preserve priceless documents such as the original Declaration of Independence and the Constitution. **Carbon dioxide** is an essential gas used by plants and other organisms to make sugar (food) through photosynthesis. This process is essential for other life as well because during photosynthesis, water molecules are split apart and their oxygen is released back to the atmosphere. Carbon dioxide also acts as a blanket that prevents the escape of heat into outer space (see more on this in Chapter 7). The atmosphere is rarely, if ever, completely dry. **Water vapor** (water in a 'gas' state) is usually present up to about 4% of the total volume depending on location. In the Earth's desert regions (30° N/S) when dry winds are blowing, the water vapor contribution to the composition of the atmosphere will be near zero.

Table 6.1: Average composition of clean dry air in the lower atmosphere

Gas	Symbol	Content	
Nitrogen	N_2	78.08%	99.998%
Oxygen	O_2	20.95%	
Argon	Ar	0.93%	
Carbon dioxide	CO_2	0.03%	
Neon	Ne	18.20 parts per million	
Helium	He	5.20 parts per million	
Krypton	Kr	1.10 parts per million	
Sulfur dioxide	SO_2	1.00 parts per million	
Methane	CH_4	2.00 parts per million	
Hydrogen	H_2	0.50 parts per million	
Nitrous oxide	N_2O	0.50 parts per million	
Xenon	Xe	0.09 parts per million	
Ozone	O_3	0.07 parts per million	
Nitrogen dioxide	NO_2	0.02 parts per million	
Iodine	I_2	0.01 parts per million	
Carbon monoxide	CO	Trace	
Ammonia	NH_3	Trace	

Source: National Weather Service http://www.srh.noaa.gov/jetstream/atmos/atmos_intro.htm

Earth's atmosphere is divided into four distinct layers based on thermal characteristics (temperature changes), chemical composition, movement, and density (Figure 6.1). The **troposphere** is the lowest layer extending from the surface up to roughly 18 km above the surface depending on location (varies from as low as 6 km to as high as 20 km). There is continuous flow and swirling of air constantly through convection currents redistributing heat and moisture around the globe. This results in the short-lived and local patterns of temperature and moisture that we call **weather**. Because gravity holds most air molecules close to the Earth's surface, the troposphere is the densest of all layers, containing about 75% of the total mass of the atmosphere. The density of the gases in this layer decrease with height so the air becomes thinner. In response, the temperature in the troposphere also decreases with height. As one climbs higher, the temperature drops from an average around 17°C (62°F) at sea level to about -51°C (-60°F) at the **tropopause,** a sharp boundary at the top of the troposphere that limits mixing between the troposphere and the upper layers.

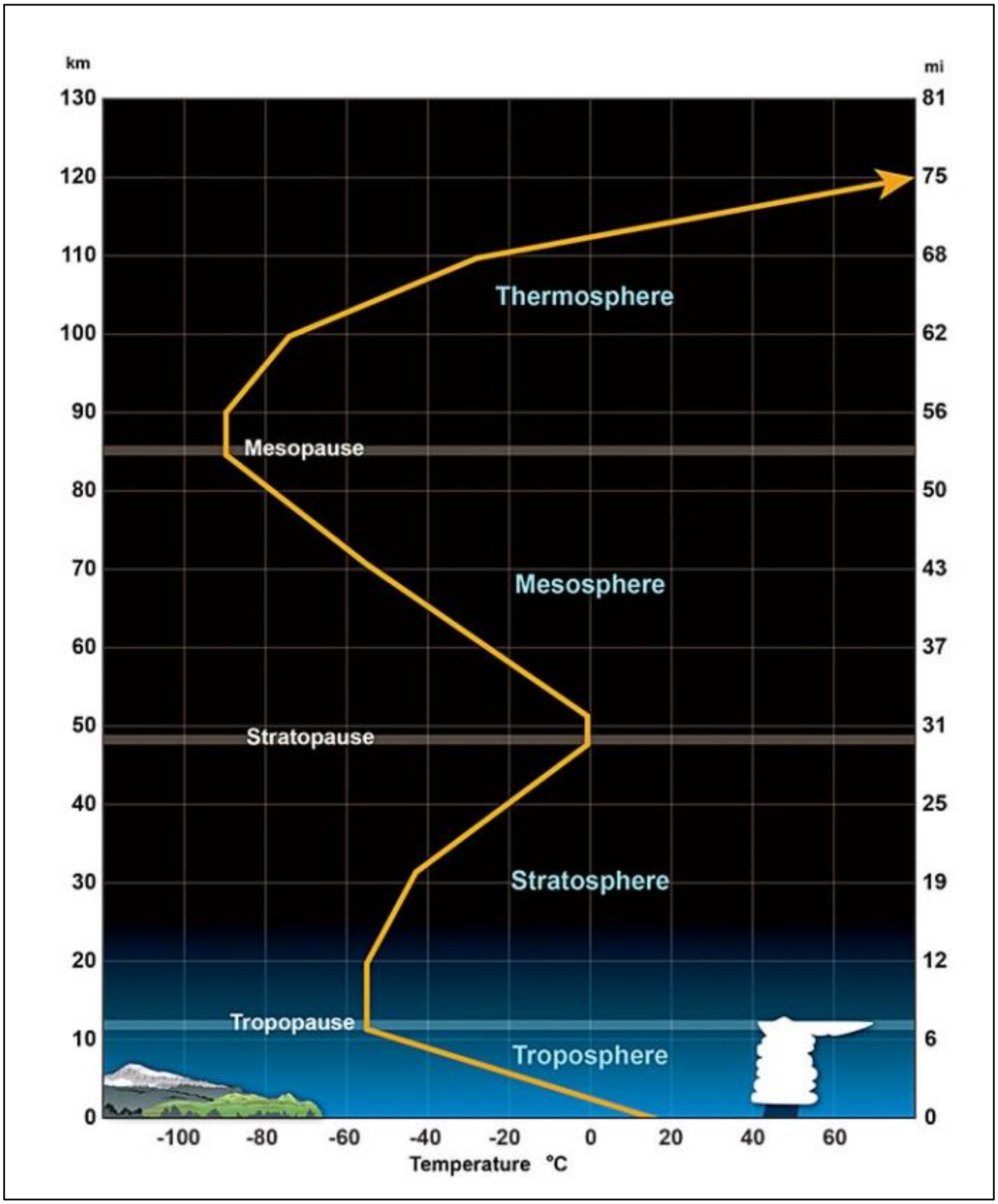


Figure 6.1: An average temperature profile through the lower layers of the atmosphere. Height (in miles and kilometers) is indicated along each side. **Source:** National Weather Service
http://www.srh.noaa.gov/jetstream/atmos/atmprofile.htm

The **stratosphere** is the layer that extends from the tropopause up to about 50 km to 53 km above the Earth's surface depending on location. The proportions of most gases in this layer is similar to that of the troposphere with two main exceptions: 1) there is almost no water vapor in the stratosphere and 2) the stratosphere has nearly 1,000 times more ozone (O_3) than the troposphere. With only about 19% of the total mass of the atmosphere, the density of the stratosphere is significantly lower than the troposphere. However, temperature in this region increases with height as a result of heat that is produced during the formation of ozone (more on ozone in section 6.2). This heat is responsible for temperature increases from an average -51 °C (-60°F) at tropopause to a maximum of about -15°C (5°F) at the top of the stratosphere. This increase in temperature with height means warmer air is located above cooler air. This prevents "convection" as there is no upward vertical movement of the gases. The consequence of this little to no mixing of gases in the stratosphere makes it relatively calm but also means that once substances such as pollutants enter this zone, they can remain suspended for many years. The top of the stratosphere is bound by a boundary known as the **stratopause**.

Above the stratosphere is the **mesosphere** which extends to about 85 km above the Earth's surface. The mesosphere has no ozone molecules and the other gases such as oxygen and nitrogen continue to become less dense with height. As a result, not much ultraviolet and x-ray radiation from the sun is absorbed by molecules in this layer so temperature decreases with altitude. Both the stratosphere and the mesosphere are considered the middle atmosphere.

Between about 85 km and 600 km lies the **thermosphere**. This layer is known as the upper atmosphere. Unlike the mesosphere, the gases in this layer readily absorb incoming high energy ultraviolet and x-ray radiation from the sun. Because of this absorption, the temperature in the thermosphere increases with height and can reach as high as 2,000°C (3,600°F) near the top depending on solar activity. However, despite the high temperature, this layer of the atmosphere would still feel very cold to our skin due to the very thin atmosphere. The high temperature indicates the amount of energy absorbed by molecules but with so few in this layer, the total number of molecules is not enough to heat our skin. There's no sharp boundary that marks the end of the atmosphere. Pressure and density simply continue to decrease with distance until they become indistinguishable from the near-vacuum of outer space.

6.2 Ozone

Ozone (O_3) is a molecule in which three atoms of oxygen are bonded together. The oxygen gas in the air we breathe has two oxygen atoms bonded together (O_2). Ozone is relatively unstable and releases its third oxygen atom readily so it oxidizes and burns things more readily than oxygen gas. This characteristic makes ozone in the troposphere (ground-level ozone) an air pollutant (see section 6.3) but in the stratosphere, ozone is essential for protecting life on Earth. Ozone in the stratosphere is formed when an oxygen molecule (O_2) is broken apart into two separate oxygen atoms (O) by high-energy ultra violet (UV) solar radiation. Each of the resulting oxygen atoms (O) in turn reacts with an oxygen molecule (O_2) creating ozone (O_3) (Figure 6.2). Once produced, ozone can absorb UV radiation breaking the molecule to regenerate an oxygen molecule and a single oxygen atom. So, while ozone is continually being replenished, it is also continually being destroyed. If the rate of ozone creation is equal to the rate of destruction, the total amount will remain the same. Because there is so much oxygen in our atmosphere, this "ozone-oxygen cycle" is continuously absorbing UV radiation.

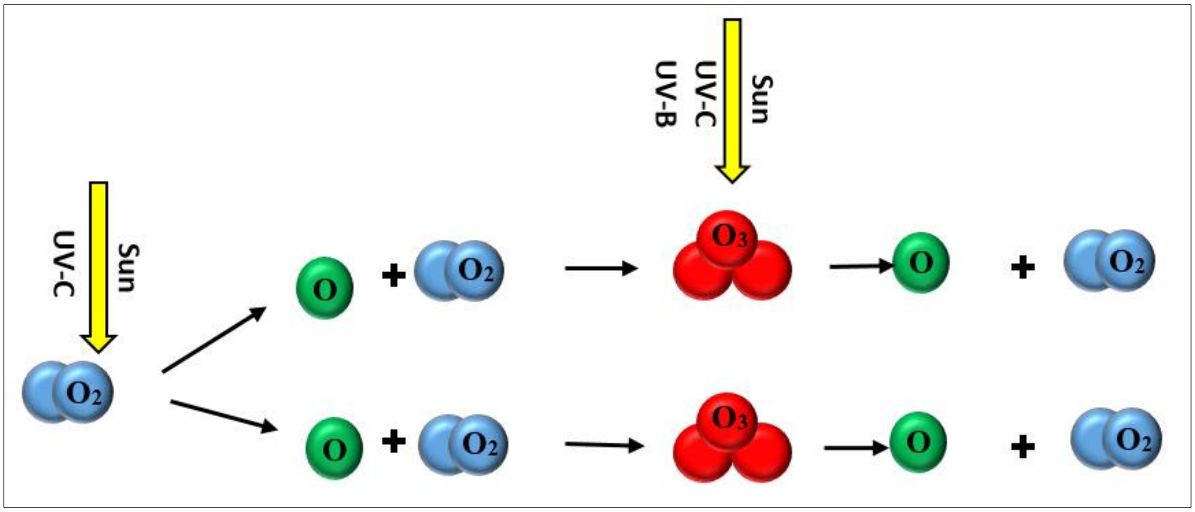


Figure 6.2: The "ozone-oxygen cycle" showing the natural formation and breaking of ozone (O_3) in the stratosphere

6.2.1 The Ozone Layer

Ozone makes up a very small proportion of the gases in our atmosphere and most of it is concentrated in a portion of the stratosphere roughly 17 – 30 km above the surface. This region, called the **ozone layer**, acts as a protective shield that protects life on the surface of the Earth by absorbing most of the harmful portions of the high-energy UV radiation coming from the sun. UV is subdivided into three types namely UV-A, UV-B, and UV-C (Figure 6.3). Of these three types, UV-A is the least energetic and least harmful but can cause some damage to living cells, resulting in sunburns and skin damage. UV-A is also not absorbed by ozone in the stratosphere and is therefore transmitted through the atmosphere to the surface of the Earth. UV-C is the most harmful and most energetic of all UV, but is strongly absorbed in both the thermosphere and the stratosphere and does not make it to the Earth's surface. UV-C is the one responsible for the splitting of oxygen molecules in the stratosphere that leads to the formation of ozone. When ozone absorbs UV it regenerates oxygen atoms and releases heat which warms the upper part of the stratosphere. Since UV-C does not make it to the Earth's surface, the most harmful form of UV radiation that reaches the surface is UV-B. However, the amount of UV-B that reaches Earth's surface is significantly reduced because most of it is absorbed by ozone in the stratosphere. Ozone is the only known gas that absorbs UV-B.

Natural conditions in the stratosphere sustain a dynamic balance between the creation and destruction of ozone which helps to ensure the continued existence of the ozone layer. Any disruption of this balance that results in a higher rate of ozone destruction than ozone creation would result in depletion of ozone. Ozone depletion, consequently, leads to significant increase in the amount of harmful UV-B radiation that reaches the Earth's surface and this what we are talking about when we discuss the **ozone problem**.

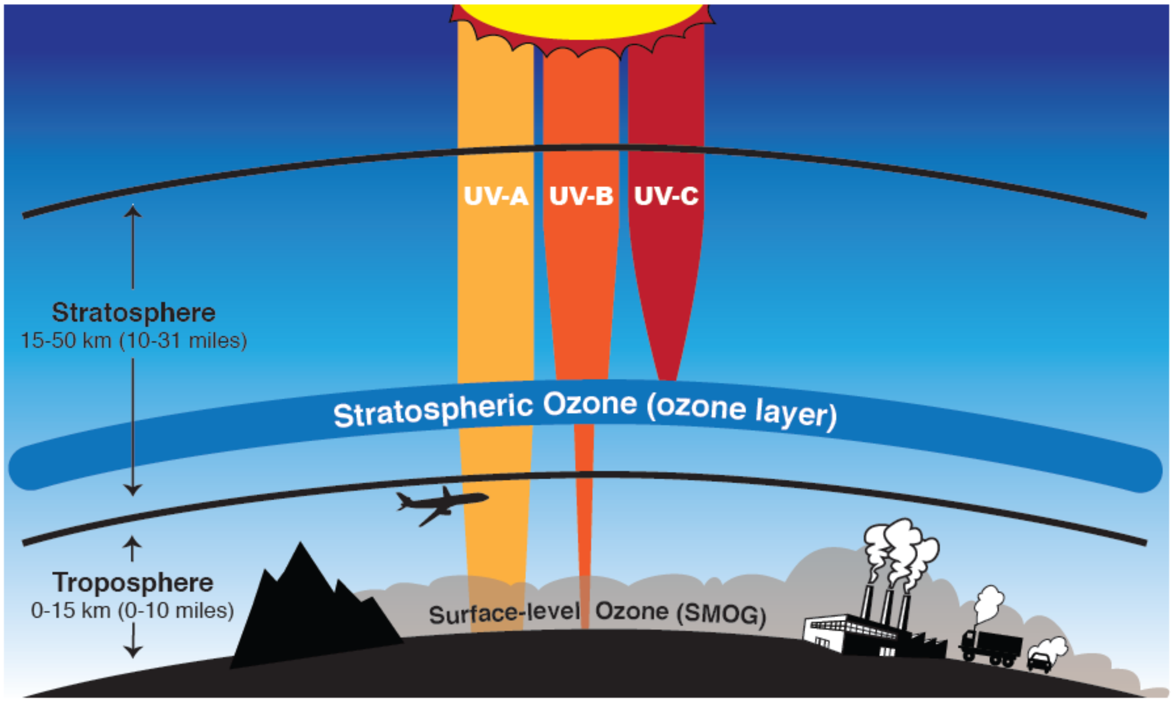


Figure 6.3: Ozone is "good" in the stratosphere because it absorbs most ultraviolet radiation. Ozone is "bad" in the troposphere because it is harmful to breathe and is the primary component of smog in summer. ***Source****:* www.nasa.gov

6.2.2 The Ozone Hole

The **Ozone Hole** is not really a "hole" but rather an area where the thickness of the ozone layer is greatly reduced. This hole is a result of ozone depletion that occurs every year during the Antarctic spring (Figure 6.4) and was first reported to the public by the British Antarctic Survey in 1985. The thickness of the ozone layer above the Antarctic continued to decline while the geographic area covered by the ozone hole continued to increase, reaching its lowest concentration (thickness) in 1994 and largest geographic area in 2000. Recent data shows that ozone concentration globally and in the Arctic and Antarctic is no longer declining.

During the long winter months of darkness over the Antarctic, atmospheric temperatures drop, creating unique conditions for chemical reactions that are not found anywhere else in the atmosphere. During this time, the Antarctic air mass is isolated from the rest of the atmosphere and circulates around the pole in what is known as the *polar vortex*. This isolation allows temperatures to drop low enough to create ice crystals at high altitudes. Ozone, nitric acid, sulfuric acid and other chlorine containing molecules are absorbed on the surfaces of these ice particles. When the sun rises over the Antarctic in the southern spring (October), light rapidly releases free chlorine atoms into the stratosphere. The chlorine atoms react with ozone breaking it down to molecular oxygen and an oxygen atom. The polar vortex keeps the ozone-depleted air inside the vortex from mixing with the undepleted air outside the vortex, hence the formation of an ozone hole.

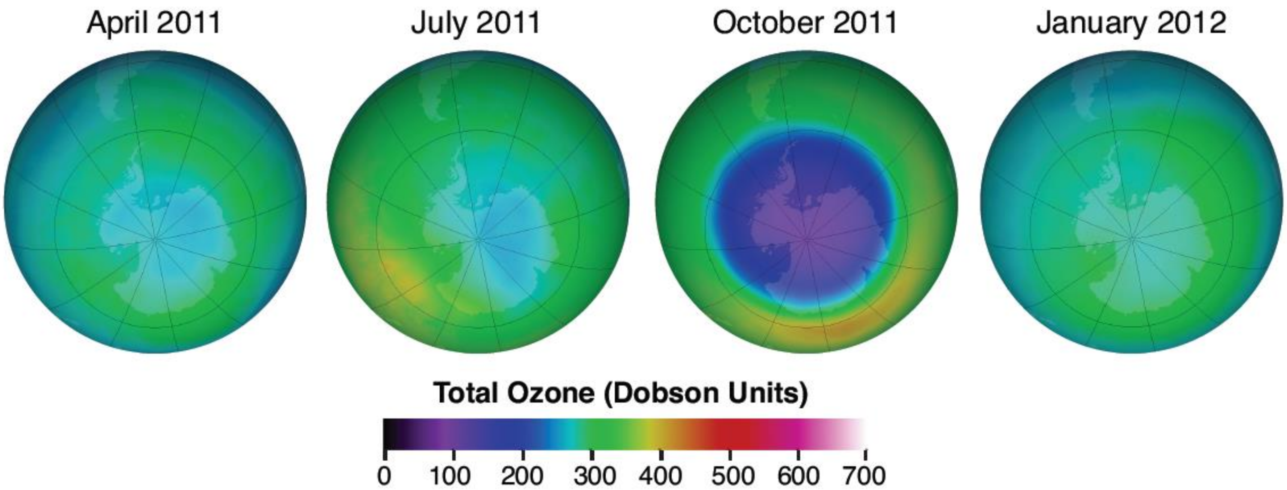


Figure 6.4: Ozone concentrations over the Antarctic region for four months representing the four seasons. Ozone concentration drops significantly during the Antarctic spring (October). ***Source:*** www.nasa.gov

6.2.3 Ozone Depletion

Global ozone concentrations change periodically with regular natural cycles such as changing seasons, winds, and long time scale sun variations. Concentrations of ozone in the atmosphere are measured in parts per billion (ppb). Scientists have been measuring ozone since the 1920's using ground-based instruments that look skyward. Satellite measurements of concentrations of atmospheric ozone began in 1970 and continue today.

Ozone depletion occurs when the rate at which ozone is broken down is greater than the rate of its creation, interfering with the dynamic balance between creation and destruction that maintains the ozone layer. When this happens, the amount of harmful UV-B radiation that reaches the Earth's surface increases. Ozone depletion was first identified over the Antarctic. Scientists suggested that reactions involving man-made chlorine-containing compounds were responsible for depleting ozone in the stratosphere. This hypothesis was based mostly on the physical and chemical properties of these compounds and knowledge about atmospheric conditions.

Chlorofluorocarbons (CFCs) are man-made compounds made up of chlorine, fluorine and carbon. These compounds were commonly used as propellants in everyday products such as shaving cream, hair spray, deodorants, paints and insecticides and as coolants in refrigerators and air conditioners. CFCs are extremely stable molecules and do not react with other chemicals in the lower atmosphere, part of the reason why they were considered a safe choice. Their stability means that they tend to remain in the atmosphere for a very long time. With the constant movement of air in the lower atmosphere, CFCs eventually make their way into the stratosphere. Exposure to ultraviolet radiation in the stratosphere breaks them apart, releasing chlorine atoms. Free chlorine (Cl) atoms then react with ozone molecules, taking one oxygen atom to form chlorine monoxide (ClO) and leaving an oxygen molecule (O_2) (Figure 6.5). The ClO reacts with other atoms freeing up the Cl making it available to react with another ozone molecule, repeating the cycle over and over resulting in ozone depletion.

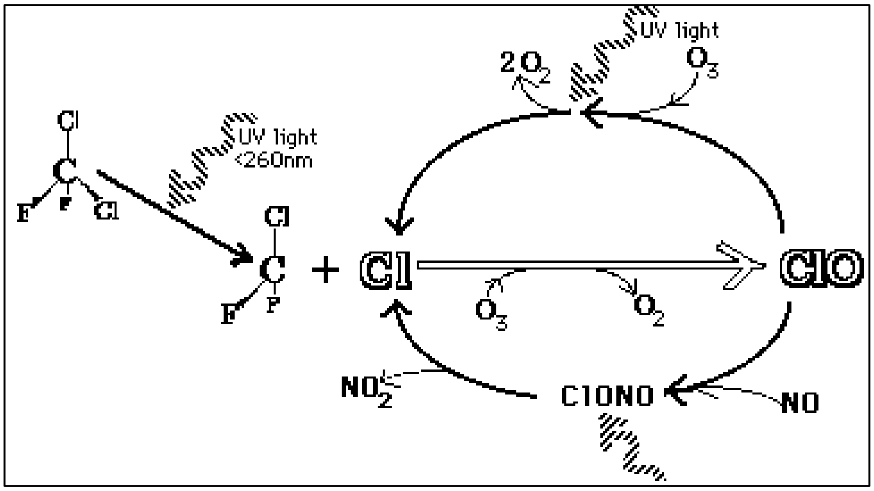


Figure 6.5: Ozone destruction. UV radiation frees a chlorine (Cl) atom from a CFC molecule, this atom reacts with ozone and produces an oxygen gas molecule and chlorine monoxide (ClO). ClO reacts with another oxygen atom, it frees up the Cl atom which then proceeds to destroy another ozone molecule.
Source: Wiki commons https://commons.wikimedia.org/wiki/Category:Ozone#/media/File:Chlorine_catalysis.GIF

If each chlorine atom released from a CFC molecule destroyed only one ozone molecule, CFCs would pose very little threat to the ozone layer. However, when a chlorine monoxide molecule encounters a free atom of oxygen, the oxygen atom breaks up the chlorine monoxide, stealing the oxygen atom and releasing the chlorine atom back into the stratosphere to destroy another ozone molecule. These two reactions happen over and over again, so that a single atom of chlorine, acting as a catalyst, destroys many molecules (about 100,000) of ozone. The consequence of stratospheric ozone depletion is increased levels of UV-B radiation reaching the Earth's surface, posing a threat to human health and the environment. Figure 6.6 shows a lower than average amount of stratospheric ozone over North America in 1997 when it was abnormally cold compared to 1984, which was warmer than average, showing that ozone depletion does not exclusively affect just the South Pole (Antarctic).

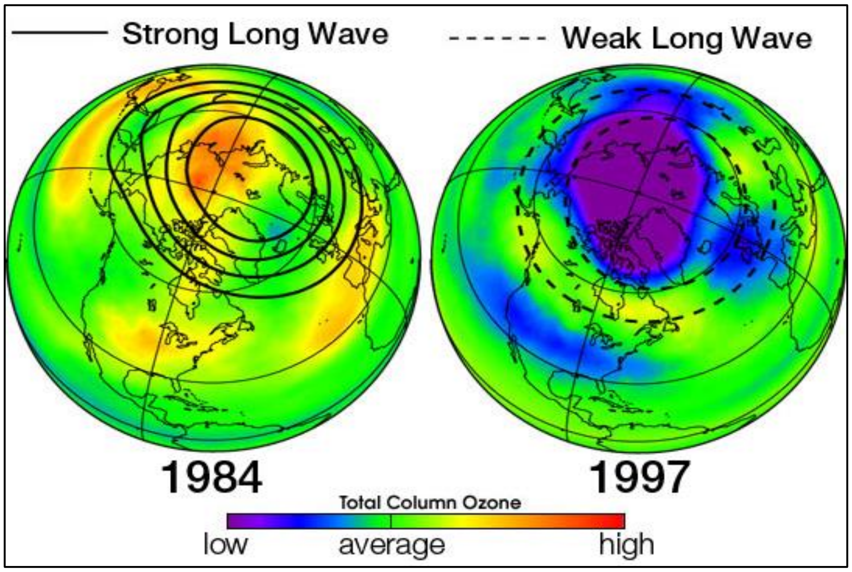


Figure 6.6: Seasonal ozone depletion over North America was lower in 1984 and greater in 1997.
Source: NASA http://earthobservatory.nasa.gov/IOTD/view.php?id=1771

6.2.4 The Montreal Protocol

International policy efforts to restrict production of ozone depleting CFCs culminated in the 1987 treaty known as the **Montreal Protocol** in which signing nations agreed to cut CFC production in half by 1998. At least five follow-up agreements since then helped to deepen the cuts, advanced timetables for compliance, and addressed additional ozone-depleting substances such as halons, methyl chloroform, carbon tetrachloride, and hydrochlorofluorocarbons (HCFCs). Most countries around the world have phased out production of the substances covered by the agreements and industry has been able to shift to safer alternative chemicals. As a result, there's evidence that the Antarctic ozone hole has stopped growing worse, although recovery is not expected anytime soon. Phasing out CFCs and HCFCs is also beneficial in protecting the earth's climate, as these substances are also very damaging greenhouse gases.

As part of the United States' commitment to implementing the Montreal Protocol, the U.S. Congress amended the Clean Air Act (section 6.7), adding provisions for protection of the ozone layer. Most importantly, the amended Act required the gradual end to the production of chemicals that deplete the ozone layer. The Clean Air Act amendments passed by Congress requires the Environmental Protection Agency (EPA) to develop and implement regulations for the responsible management of ozone-depleting substances in the United States. Under the Clean Air Act, EPA has created several regulatory programs to address numerous issues, including:

- ending the production of ozone-depleting substances,
- ensuring that refrigerants and halon fire extinguishing agents are recycled properly,
- identifying safe and effective alternatives to ozone-depleting substances,
- banning the release of ozone-depleting refrigerants during the service, maintenance, and disposal of air conditioners and other refrigeration equipment,
- requiring that manufacturers label products either containing or made with the most harmful ozone depleting substances.

6.3 Outdoor Air Pollution

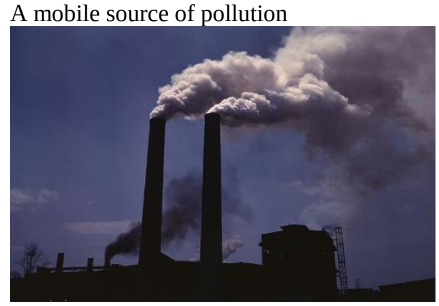
Air pollution refers to the introduction, into the atmosphere, of substances that have harmful effects on humans, other living organisms, and the environment either as solid particles, liquid droplets or gases. Air pollution can result from natural processes such as dust storms, forest fires, and volcanic eruptions, or from human activities such as biomass burning, vehicular emissions, mining, agriculture, and industrial processes. Improved technology and government policies have helped reduce most types of outdoor air pollution in many industrialized countries including the United States, in recent decades. However, outdoor air quality is still a problem in less industrialized nations, especially in megacities of rapidly industrializing nations such as China and India.

Outdoor pollutants can come from **stationary** (**point**) sources or **mobile** (**nonpoint**) sources (Figure 6.7). Stationary sources have a fixed location, for example power plant smokestacks, burning, construction sites, farmlands and surface mines among others. Mobile sources of air pollutants move from place to place while emitting pollutants. Examples of mobile sources include vehicles, aircrafts, ships, and trains.

Volcanic eruption, a natural source

Aircraft, a mobile source

A mobile source of pollution



Smokestack, a stationary source

Figure 6.7: Images showing various sources of air pollution, including natural and anthropogenic, stationary and mobile. **Source**: All images obtained from Wiki Commons https://commons.wikimedia.org/wiki/Air_pollution

Pollutants are categorized into two major types based on how they originated namely primary and secondary pollutants. **Primary pollutants** are those released directly from the source into the air in a harmful form. The primary pollutants that account for nearly all air pollution problems are carbon monoxide (58%), volatile organic compounds (VOCs, 11%), nitrogen oxides (15%), sulfur dioxides (13%), and particulate material (3%). **Secondary pollutants** are produced through reactions between primary pollutants and normal atmospheric compounds. For example, ground-level ozone forms over urban areas through reactions, powered by sunlight, between primary pollutants (oxides of nitrogen) and other atmospheric gases such as VOCs.

6.3.1 Criteria pollutants

Under the Clean Air Act (see section 6.7.1), the Environmental Protection Agency (EPA) establishes air quality standards to protect public health and the environment. EPA has set national air quality standards for six common air pollutants namely: 1) carbon monoxide; 2) ground-level ozone; 3) nitrogen dioxide; 4) Sulfur dioxide; 5) lead; and 6) particulate matter (also known as particle pollution). Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats. EPA calls these pollutants "criteria" air pollutants because it regulates them by developing human health-based and/or environmentally-based criteria (science-based guidelines) for setting permissible levels. The set of limits based on human health is called primary standards. Another set of limits intended to prevent environmental and property damage is called secondary standards.

1. **Carbon Monoxide (CO):** is a colorless, odorless gas emitted from combustion processes, specifically, the incomplete combustion of fuel. Nationally and, particularly in urban areas, the majority of CO emissions to ambient air come from mobile sources. CO can cause harmful health effects by reducing oxygen delivery to the body's organs (like the heart and brain) and tissues. At extremely high levels, CO can cause death.

2. **Ground-level ozone (O_3):** is a colorless gas with a slightly sweet odor that is not emitted directly into the air, but is created by the interaction of sunlight, heat, oxides of nitrogen (NO_x) and volatile organic compounds (VOCs). Ozone is likely to reach unhealthy levels on hot sunny days in urban environments. Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of NO_x and VOCs.

3. **Nitrogen dioxide (NO_2)**: is one of a group of highly reactive gasses known as "oxides of nitrogen," or "nitrogen oxides (NO_x)." Other nitrogen oxides include nitrous acid and nitric acid. NO_2 is a yellowish-brown to reddish-brown foul-smelling gas that is a major contributor to smog and acid rain. Nitrogen oxides result when atmospheric nitrogen and oxygen react at the high temperatures created by combustion engines. Most emissions in the U.S. result from combustion in vehicle engines, electrical utility, and industrial combustion.

4. **Sulfur dioxide (SO_2)**: Sulfur dioxide is one of a group of highly reactive gasses known as "oxides of sulfur." The largest sources of SO_2 emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO_2 emissions include industrial processes such as extracting metals from their ores, and the burning of high sulfur containing fuels by locomotives, large ships, and non-road equipment.

5. **Lead (Pb)**: is a metal found naturally in the environment as well as in manufactured products. The major sources of lead emissions have historically been from fuels in motor vehicles (such as cars and trucks) and industrial sources. As a result of EPA's regulatory efforts to remove lead from gasoline, emissions of lead from the transportation sector dramatically declined by 95 percent between 1980 and 1999, and levels of lead in the air decreased by 94 percent during that time period. The major sources of lead emissions today are ore and metal processing and piston-engine aircraft operating on leaded aviation gasoline. Today, the highest levels of lead in air are usually found near lead smelters.

6. **Particulate material** (PM), sometimes known simply as "**particulates**" refers to solid particles and liquid droplets suspended in the air we breathe. Particulate pollution is made up of a variety of components, including acids (nitrates and sulfates), organic chemicals, metals, soil or dust particles, and allergens (pollen and mold spores). The size of the particles in directly linked to their potential for causing health problems. Particles that are 10 micrometers in diameter or smaller generally pass through the throat and nose and enter the lungs. EPA groups these into two types: "**inhalable coarse particles**," with diameters larger than 2.5 micrometers and smaller than 10 micrometers and "**fine particles**," with diameters that are 2.5 micrometers and smaller. How small is 2.5 micrometers? Think about a single hair from your head. The average human hair is about 70 micrometers in diameter – making it 30 times larger than the largest fine particle (Figure 6.8). Our respiratory systems are equipped to filter larger particles out of the air once it is inhaled. However, the lungs are vulnerable to both coarse particles (PM_{10}), and fine particles ($PM_{2.5}$). These can slip past the respiratory system's natural defenses and get deep into the lungs and some may even get into the bloodstream. Coarse particles come from road dust while fine particles come from combustion processes.

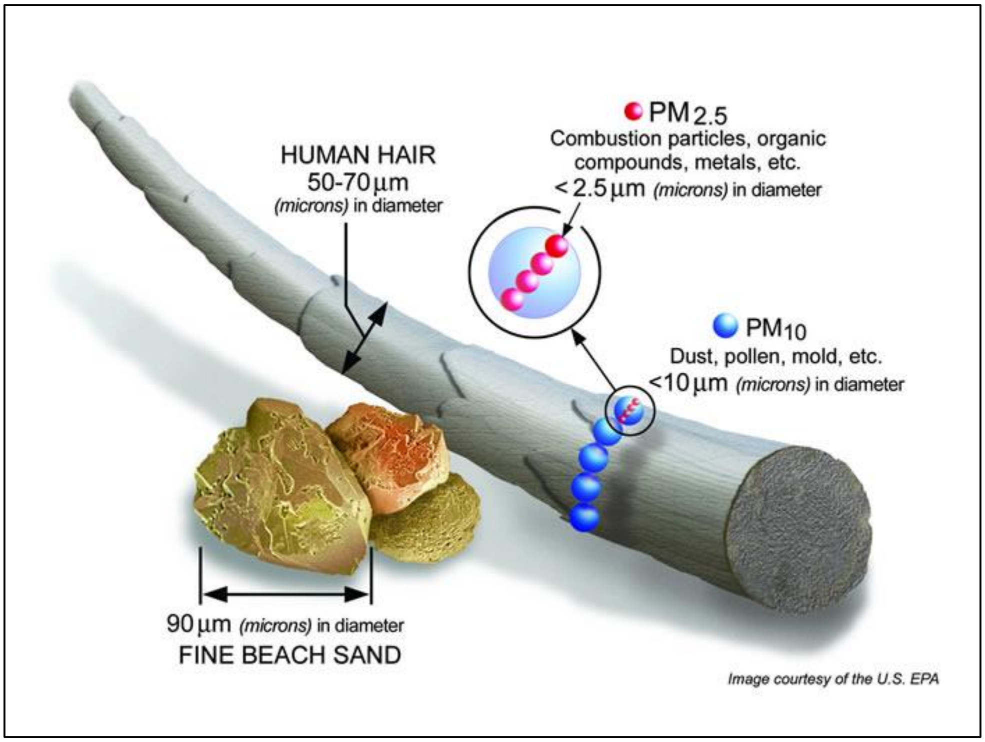


Figure 6.8: Graphic showing size comparison of particulate material (PM_{10} and $PM_{2.5}$) compared to fine beach sand and human hair. **Source**: US EPA http://www.epa.gov/air/particlepollution/basic.html

6.3.2 Volatile Organic Compounds

Volatile organic compounds (VOCs) are carbon-containing chemicals emitted as gases from natural and human-made sources. Natural sources of VOCs include plants, the largest source, and bacteria in the guts of termites and ruminant animals. These compounds are generally oxidized to carbon monoxide and carbon dioxide in the atmosphere. VOCs are of great concern because they are precursors for the formation of ozone, a secondary air pollutant.

A large number of synthetic organic chemicals such as benzene, toluene, formaldehyde, vinyl chloride, chloroform, and phenols are widely used as ingredients in countless household products. Paints, paint strippers, varnishes, many cleaning, disinfecting, cosmetic, degreasing, and hobby products all contain VOCs. Fuels are also made up of organic chemicals. All of these products can release organic compounds while you are using them, and, to some degree, when they are stored. The "new car smell" characteristic of new cars is from a complex mix of dozens of VOC. Also, concentrations of many VOCs are consistently higher indoors (up to ten times higher) than outdoors. They are often held responsible for sick building syndrome, an illness resulting from indoor pollution in which the specific cause is not identified

6.3.3 Smog

Smog is a mixture of air pollutants (sulfur dioxide, nitrogen oxides, ozone, and particulates) that often form over urban areas as a result of fossil fuel combustion. The term was coined from the terms "smoke" and "fog" referring to a brownish haze that pollutes the air, greatly reducing visibility and making it difficult for some people to breathe (Figure 6.9 and 6.10). There are two main types of smog: industrial and photochemical smog. **Industrial smog** is produced primarily by the burning of fossil fuels which produces carbon dioxide (from complete combustion), carbon monoxides (from partial combustion), sulfur, and mercury. The sulfur reacts with other chemicals in the atmosphere producing several sulfur compounds including sulfur dioxide. These compounds along with particulate material make up industrial smog.   **Photochemical smog** is formed when sunlight drives chemical reactions between primary pollutants from automobiles and normal atmospheric compounds. The product is a mix of over 100 different chemicals with the most abundant being ground-level ozone.

Figure 6.9: Smog over Almaty city, Kazakhstan. Photo by Igors Jefimovs. **Source:** Wikicommons https://commons.wikimedia.org/wiki/Category:Smog#/media/File:Smog_over_Almaty.jpg

Figure 6.10: Smog over Santiago in Chile. **Source**: German Wikipedia https://commons.wikimedia.org/wiki/Category:Smog#/media/File:Santiago30std.jpg

6.3.4 Toxic pollutants

Toxic air pollutants, also known as hazardous air pollutants, are those pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects. Examples of toxic air pollutants include benzene, which is found in gasoline; perchloroethylene, which is emitted from some dry cleaning facilities; methylene chloride, which is used as a solvent and paint stripper by a number of industries; and others such as dioxin, asbestos, toluene, and metals such as cadmium, mercury, chromium, and lead compounds.

Most air toxics originate from human-made sources, including mobile sources (e.g., cars, trucks, buses) and stationary sources (e.g., factories, refineries, power plants), as well as indoor sources (e.g., some building materials and cleaning solvents). Some air toxics are also released from natural sources such as volcanic eruptions and forest fires. Exposure to air toxics is mainly through breathing but some toxic air pollutants such as mercury can deposit onto soils or surface waters, where they are taken up by plants and ingested by animals and are eventually magnified up through the food chain. Like humans, animals may experience health problems if exposed to sufficiently high quantities of air toxics over time.

6.4 Indoor Air Pollution

In both developed and developing nations, indoor air pollution poses a greater health risk than outdoor air pollution. According to the World Health Organization (WHO) and other agencies such as the Environmental Protection Agency (EPA), indoor air generally contains higher concentrations of toxic pollutants than outdoor air. Additionally, people generally spend more time indoors than outdoors, hence, the health effects from indoor air pollution in workplaces, schools, and homes are far greater than outdoor. Indoor pollution sources that release gases or particles into the air are the primary cause of indoor air quality problems in homes. Inadequate ventilation can increase indoor pollutant levels by not bringing in enough outdoor air to dilute emissions from indoor sources and by not carrying indoor air pollutants out of the home.

Outdoor air enters and leaves a building by infiltration, natural ventilation, and mechanical ventilation. In infiltration, outdoor air flows into the house through openings, joints, and cracks in walls, floors, and ceilings, and around windows and doors. In natural ventilation, air moves through opened windows and doors. Air movement associated with infiltration and natural ventilation is caused by air temperature differences between indoors and outdoors and by wind. Finally, there are a number of mechanical ventilation devices, from outdoor-vented fans that intermittently remove air from a single room, such as bathrooms and kitchen, to air handling systems that use fans and duct work to continuously remove indoor air and distribute filtered and conditioned outdoor air to strategic points throughout the house. The rate at which outdoor air replaces indoor air is described as the air exchange rate. When there is little infiltration, natural ventilation, or mechanical ventilation, the air exchange rate is low and pollutant levels can increase. High temperature and humidity levels can also increase concentrations of some pollutants.

There are many sources of indoor air pollution in any home (Figure 6.11). These include combustion sources such as oil, gas, kerosene, coal, wood, and tobacco products; building materials and furnishings as diverse as deteriorated, asbestos-containing insulation, wet or damp carpet, and cabinetry or furniture made of certain pressed wood products; products for household cleaning and maintenance, personal care, or hobbies; central heating and cooling systems and humidification devices. Pollutants causing indoor air pollution can also originate from outside sources such as radon, pesticides, and outdoor air pollution. Radon is a naturally occurring radioactive gas produced from the decay of uranium in rock. If a building/home is constructed in an area with uranium containing rock, the gas can seep through the foundations and accumulate in basements. Exposure to radon can cause lung cancer.

The relative importance of any single source depends on how much of a given pollutant it emits and how hazardous those emissions are. In some cases, factors such as how old the source is and whether it is properly maintained are significant. For example, an improperly adjusted gas stove can emit significantly more carbon monoxide than one that is properly adjusted. Some sources, such as building materials, furnishings, and household products like air fresheners, release pollutants more or less continuously. Other sources, related to activities carried out in the home, release pollutants intermittently. These include smoking, the use of unvented or malfunctioning stoves, furnaces, or space heaters, the use of solvents in cleaning and hobby activities, the use of paint strippers in redecorating activities, and the use of cleaning products and pesticides in house-keeping. High pollutant concentrations can remain in the air for long periods after some of these activities.

Risks from indoor air pollution differ between less industrialized and industrialized nations. Indoor pollution has a greater impact in less industrialized nations where many people use cheaper sources of fuel such as wood, charcoal, and crop waste among others for cooking and heating, often with little or no ventilation. The most significant indoor pollutant, therefore, is soot and carbon monoxide. In industrialized nations, the primary indoor air health risks are cigarette smoke and radon.

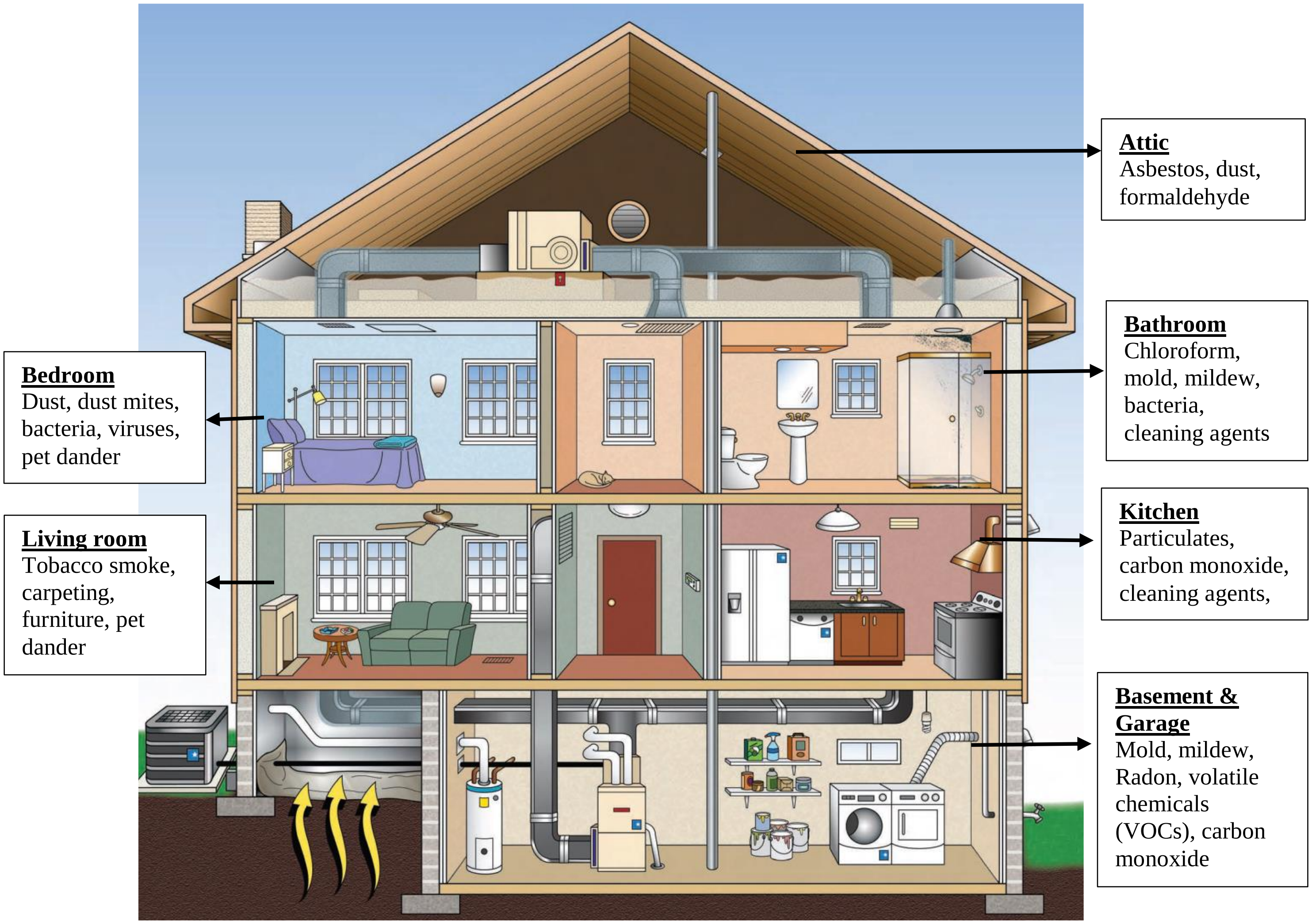


Figure 6.11: Sources of indoor air pollution. **Image source**: EPA
http://www.epa.gov/iaq/pdfs/careforyourair.pdf

6.5 Effects of Air Pollution on Human Health

The World Health Organization (WHO) and other international agencies recognize air pollution as a major threat to human health. Numerous scientific studies have linked air pollution to a variety of health problems (Table 6.2) including: aggravation of respiratory and cardiovascular diseases; decreased lung function; increased frequency and severity of respiratory symptoms such as difficulty breathing and coughing; increased susceptibility to respiratory infections; effects on the nervous system, including the brain, such as IQ loss and impacts on learning, memory, and behavior; cancer; and premature death. Immediate effects of air pollution may show up after a single exposure or repeated exposures. Other health effects may show up either years after exposure has occurred or only after long or repeated periods of exposure.

Immediate effects of air pollution include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue. Such immediate effects are usually short-term and treatable. Sometimes the treatment is simply eliminating the person's exposure to the source of the pollution, if it can be identified. Symptoms of some diseases, including asthma, hypersensitivity pneumonitis, and humidifier fever , may also show up soon after exposure to some indoor air pollutants.

Table 6.2: Sources and health effects of criteria pollutants

Pollutant	Sources	Health Effects
Ground-level Ozone (O_3)	Secondary pollutant typically formed by chemical reaction of volatile organic compounds (VOCs) and NO_x in the presence of sunlight.	Decreases lung function and causes respiratory symptoms, such as coughing and shortness of breath; aggravates asthma and other lung diseases leading to increased medication use, hospital admissions, emergency department (ED) visits, and premature mortality.
Particulate Matter (PM)	Emitted or formed through chemical reactions; fuel combustion (e.g., burning coal, wood, diesel); industrial processes; agriculture (plowing, field burning); and unpaved roads.	Short-term exposures can aggravate heart or lung diseases leading to respiratory symptoms, increased medication use, hospital admissions, ED visits, and premature mortality; long-term exposures can lead to the development of heart or lung disease and premature mortality.
Lead	Smelters (metal refineries) and other metal industries; combustion of leaded gasoline in piston engine aircraft; waste incinerators; and battery manufacturing.	Damages the developing nervous system, resulting in IQ loss and impacts on learning, memory, and behavior in children. Cardiovascular and renal effects in adults and early effects related to anemia.
Oxides of Nitrogen (NO_x)	Fuel combustion (e.g., electric utilities, industrial boilers, and vehicles) and wood burning.	Aggravate lung diseases leading to respiratory symptoms, hospital admissions, and ED visits; increased susceptibility to respiratory infection.
Carbon Monoxide (CO)	Fuel combustion (especially vehicles), industrial processes, fires, waste combustion, and residential wood burning.	Reduces the amount of oxygen reaching the body's organs and tissues; aggravates heart disease, resulting in chest pain and other symptoms leading to hospital admissions and ED visits.
Sulfur Dioxide (SO_2)	Fuel combustion (especially high-sulfur coal); electric utilities and industrial processes; and natural sources such as volcanoes.	Aggravates asthma and increased respiratory symptoms. Contributes to particle formation with associated health effects.

Source: www.epa.gov

The likelihood of immediate reactions to air pollutants depends on several factors. Age and preexisting medical conditions are two important influences. Some sensitive individuals appear to be at greater risk for air pollution-related health effects, for example, those with pre-existing heart and lung diseases (e.g., heart failure/ischemic heart disease, asthma, emphysema, and chronic bronchitis), diabetics, older adults, and children. In other cases, whether a person reacts to a pollutant depends on individual sensitivity, which varies tremendously from person to person. Some people can become sensitized to biological pollutants after repeated exposures, and it appears that some people can become sensitized to chemical pollutants as well.

6.6 Acid Rain

Pure rainfall is slightly acidic, pH 5.6, because water reacts with atmospheric carbon dioxide to produce weak carbonic acid. When higher than normal amounts of nitric and sulfuric acid occur in the atmosphere, the result is precipitation with a pH below 5.6 which is referred to as **acid rain**. Acid rain includes both wet deposition (rainfall, snow, fog) and dry deposition (particulates). Acid rain formation result from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) resulting from fossil fuel combustion. In the United States, roughly $^2/_3$ of all SO_2 and ¼ of all NO_x come from electric power generation that relies on burning fossil fuels, like coal. Acid rain occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds (Figure 6.12). The result is a mild solution of sulfuric acid and nitric acid. When sulfur dioxide and nitrogen oxides are released from power plants and other sources, prevailing winds blow these compounds across state and national borders, sometimes over hundreds of miles. Regions of greatest acidification tend to be downwind from heavily industrialized source areas of pollution.

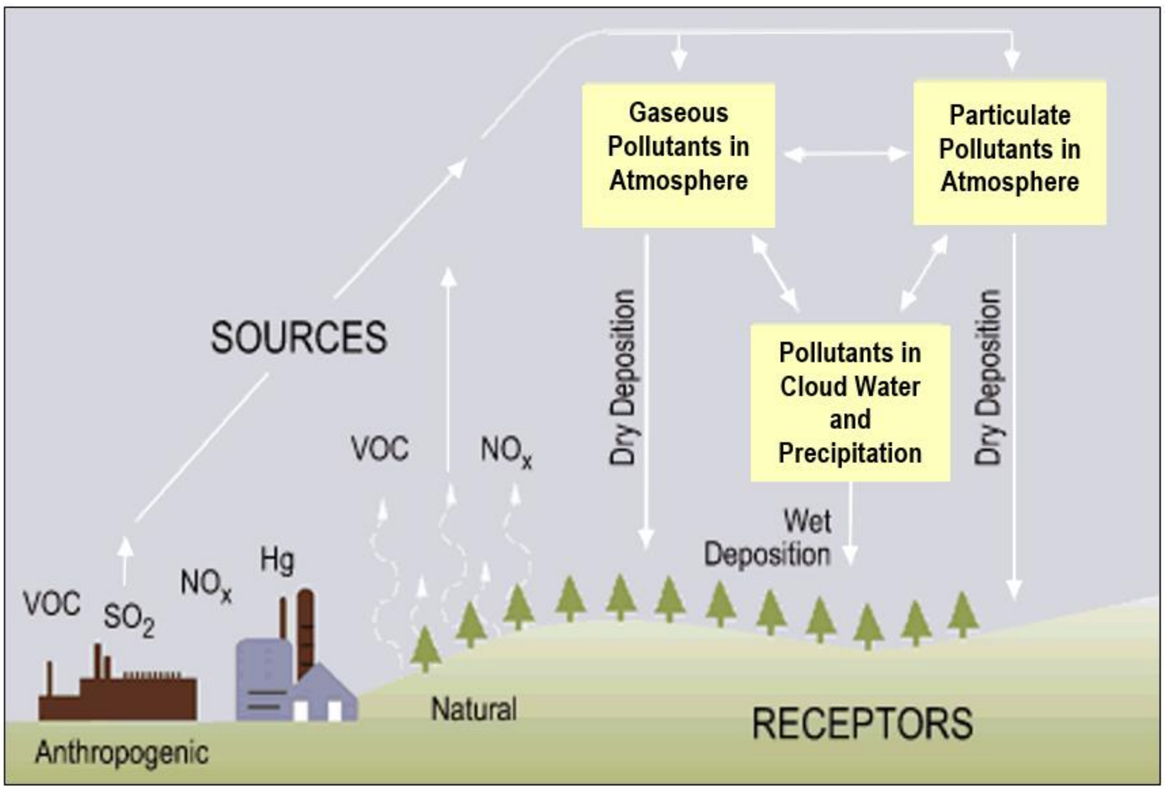


Figure 6.12: Formation of acid rain from both natural and anthropogenic pollutants
Source: US EPA http://www.epa.gov/acidrain/images/origins.gif

Acid rain is a serious environmental problem that is particularly damaging to lakes, streams, and forests and the plants and animals that live in these ecosystems, as well as to infrastructure. Some of the impacts include:

- Leaching of soil nutrients such as calcium, magnesium, and potassium out of the topsoil, altering soil chemistry and harming plants and soil organisms.
- Acid rain causes the release of substances that are toxic to trees and other plants, such as aluminum, into the soil. Scientists hypothesize that this combination of loss of soil nutrients and increase of

toxic aluminum may be one way that acid rain harms trees (Figure 6.13). Such substances also wash away in the runoff and are carried into streams, rivers, and lakes.

- Damage to automotive paints and other coatings. The reported damage typically occurs on horizontal surfaces and appears as irregularly shaped, permanently etched areas.
- Acidic particles contribute to the corrosion of metals (such as bronze) and the deterioration of paint and stone (such as marble and limestone). These effects significantly reduce the societal value of buildings, bridges, cultural objects (such as statues, monuments, and tombstones) (Figure 6.14).
- Sulfates and nitrates that form in the atmosphere contribute to visibility impairment, meaning we cannot see as far or as clearly through the air. Sulfate particles account for 50 to 70 percent of the visibility reduction in the eastern part of the U.S., affecting our enjoyment of national parks, such as the Shenandoah and the Great Smoky Mountains

Figure 6.13: Effects of acid rain on trees, Jizera Mountains, Czech Republic. Image from Wikimedia commons, Public Domain. https://commons.wikimedia.org/wiki/Category:Acid_rain#/media/File:Acid_rain_woods1.JPG

Figure 6.14: Effects of acid rain on a monument in Greenwood cemetery, Brooklyn New York. Photo by James P. Fischer. https://commons.wikimedia.org/wiki/Category:Acid_rain#/media/File:Charlotte_Canda_Memorial_(Angel).jpg

6.7 Air Pollution Legislation

In 1930, 63 people died and 1000 were sickened in Belgium when a phenomenon referred to as temperature inversion caused pollutants to be trapped near the surface, leading to a sudden spike in atmospheric sulfur levels. In October 1948, a thick cloud of air pollution formed above the industrial town of Donora, Pennsylvania. The cloud which lingered for five days, killed 20 people and caused sickness in 6,000 of the town's 14,000 people. In 1952, the infamous London fog in which acid aerosols trapped in the lower atmosphere killed 4000 people. Events like these alerted us to the dangers that air pollution poses to public health.

6.7.1 Clean Air Act

In the United States, several federal and state laws were passed, including the original Clean Air Act of 1963, which established funding for the study and cleanup of air pollution. But there was no comprehensive federal response to address air pollution until Congress passed a much stronger **Clean Air Act in 1970**. That same year Congress created the Environmental Protection Agency (EPA) and gave it the primary role in carrying out the law. Since 1970, EPA has been responsible for a variety of Clean Air Act programs to reduce air pollution nationwide. The Clean Air Act is a federal law covering the entire country. However, states, tribes and local governments do a lot of the work to meet the Act's requirements. For example, representatives from these agencies work with companies to reduce air pollution. They also review and approve permit applications for industries or chemical processes.

6.7.2 EPA's Role

EPA's mission is basic health and environmental protection from air pollution for all Americans. To achieve this mission, EPA implements a variety of programs under the Clean Air Act that focus on:

- reducing outdoor, or ambient, concentrations of air pollutants that cause smog, haze, acid rain, and other problems;
- reducing emissions of toxic air pollutants that are known to, or are suspected of, causing cancer or other serious health effects; and
- phasing out production and use of chemicals that destroy stratospheric ozone.

Under the Clean Air Act, EPA sets limits on certain air pollutants, including setting limits on how much can be in the air anywhere in the United States. The Clean Air Act also gives EPA the authority to limit emissions of air pollutants coming from sources like chemical plants, utilities, and steel mills. Individual states or tribes may have stronger air pollution laws, but they may not have weaker pollution limits than those set by EPA. EPA must approve state, tribal, and local agency plans for reducing air pollution. If a plan does not meet the necessary requirements, EPA can issue sanctions against the state and, if necessary, take over enforcing the Clean Air Act in that area. EPA assists state, tribal, and local agencies by providing research, expert studies, engineering designs, and funding to support clean air progress. Since 1970, Congress and the EPA have provided several billion dollars to the states, local agencies, and tribal nations to accomplish this.

6.7.3 State and Local Governments' Role

It makes sense for state and local air pollution agencies to take the lead in carrying out the Clean Air Act. They are able to develop solutions for pollution problems that require special understanding of local industries, geography, housing, and travel patterns, as well as other factors. State, local, and tribal governments also monitor air quality, inspect facilities under their jurisdictions and enforce Clean Air Act regulations. States have to develop State Implementation Plans (SIPs) that outline how each state will control air pollution under the Clean Air Act. A SIP is a collection of the regulations, programs and policies that a state will use to clean up polluted areas. The states must involve the public and industries through hearings and opportunities to comment on the development of each state plan.

6.7.4 Outcomes of the Clean Air Act

For more than forty years, the Clean Air Act has cut pollution as the U.S. economy has grown. The combined emissions of the six criteria pollutants has continued to decrease while population, gross domestic product, energy consumption, and vehicle miles travelled have all continued to increase (Figure 6.14). The following is a summary of some of the accomplishments of the Clean Air Act:

- Clean Air Act programs have lowered levels of the six criteria pollutants - particulates, ozone, lead, carbon monoxide, nitrogen dioxide and sulfur dioxide - as well as numerous toxic pollutants.

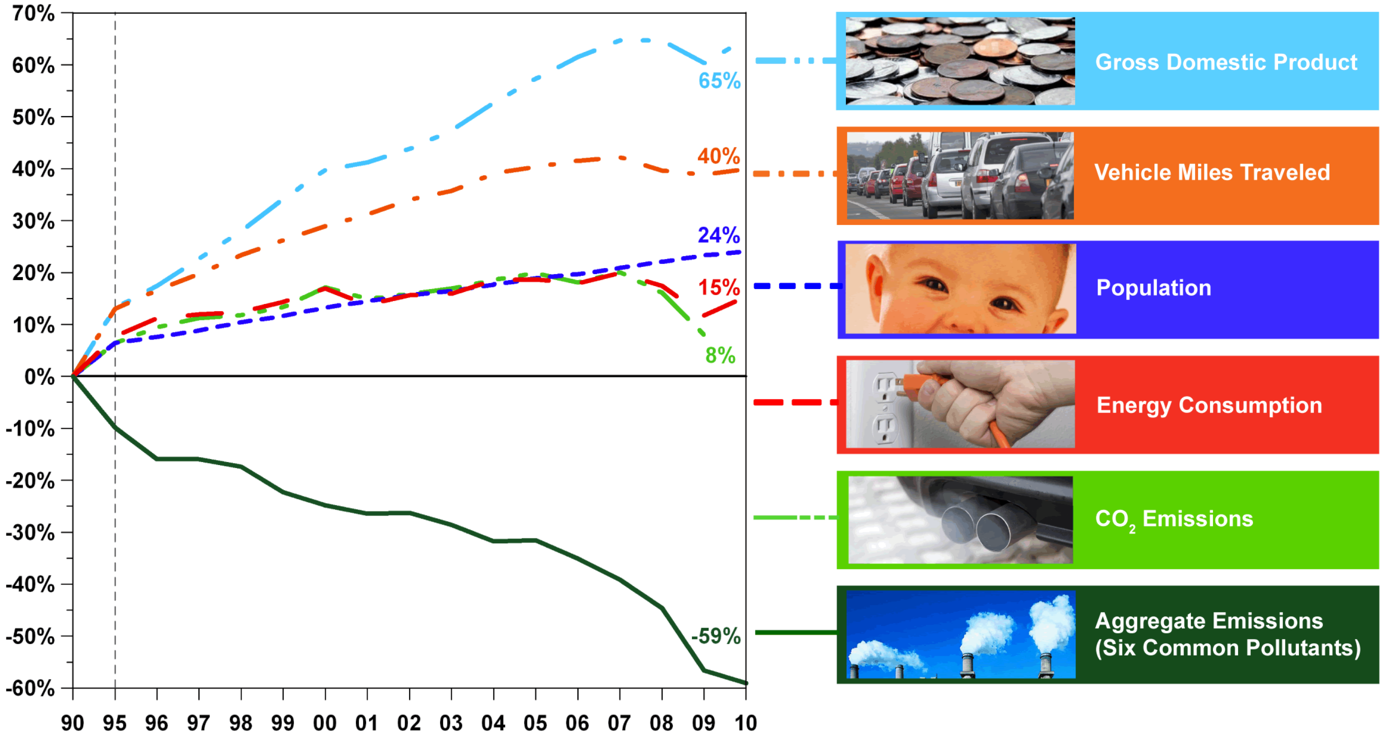


Figure 6.14: Showing a decrease in the combined emissions for the six criterial pollutants in the past two decades. Meanwhile, population, energy consumption, vehicle miles travelled, and gross domestic product have all increased. **Source**: US EPA

- From 1970 to 2012, aggregate national emissions of the six common pollutants alone dropped an average of 72 percent while gross domestic product grew by 219 percent (Figure 6.14). This progress reflects efforts by state, local and tribal governments; EPA; private sector companies; environmental groups and others.
- The emissions reductions have led to dramatic improvements in the quality of the air that we breathe.
- These air quality improvements have enabled many areas of the country to meet national air quality standards set to protect public health and the environment. For example, all of the 41 areas that had unhealthy levels of carbon monoxide in 1991 now have levels that meet the health-based national air quality standard. A key reason is that the motor vehicle fleet is much cleaner because of Clean Air Act emissions standards for new motor vehicles.
- Airborne lead pollution, a widespread health concern before EPA phased out lead in motor vehicle gasoline under Clean Air Act authority, now meets national air quality standards in most areas of the country.

Sources

Botkin, D. B. and Keller E. A. 2009. 7th Ed. *Environmental Science: Earth as a Living Planet*. John Wiley and Sons, Inc. USA

Cunningham, W. P., and Cunningham, M. A. 2010. 11th Ed. *Environmental Science: a global concern*. McGraw-Hill Companies, USA.

Karr, S., Houtman, A., and Interlandi, J. 2014. *Environmental Science for a Changing world: with extended coverage*. W. H. Freeman and Company, New York.

Withgott J. and Laposata, M. 2012. 4th Ed. *Essential Environment: the science behind the stories*. Pearson Education, Inc. USA.

Hewitt, P. G., Lyons, S. A., Suchocki, J. A., & Yeh, J. 2012 2nd Ed. *Conceptual Integrated Science*. Addison-Wesley, San Francisco.

Websites

Wikimedia Commons https://commons.wikimedia.org/wiki/ Source of various photos and images

Environmental Protection Agency http://www.epa.gov/

National Aeronautics and Space Administration (NASA) http://www.nasa.gov/

National Weather Service http://www.srh.noaa.gov/jetstream/atmos/layers.htm

Chapter 7: Climate Change

The Carbon Cycle

Carbon, just like all other elements, cycles through the environment and is constantly in the process of changing forms and locations. In this section, as in many other pieces of scientific literature, we will periodically refer to carbon by its chemical symbol, C. There is no new carbon in the world, rather, all carbon is continuously recycled from one form to another. All plants, animals (including humans!), fungi, bacteria, and archaea are made of mostly carbon-based molecules such as lipids, carbohydrates, proteins, and nucleic acids. Carbon is also prevalent in soils, rocks and sediments, water bodies (dissolved), and the atmosphere. These locations where carbon resides are known as pools or **reservoirs**, and the processes that move carbon from one location to another are called **fluxes**. Figure 7.1 shows a simplified version of the global carbon cycle.

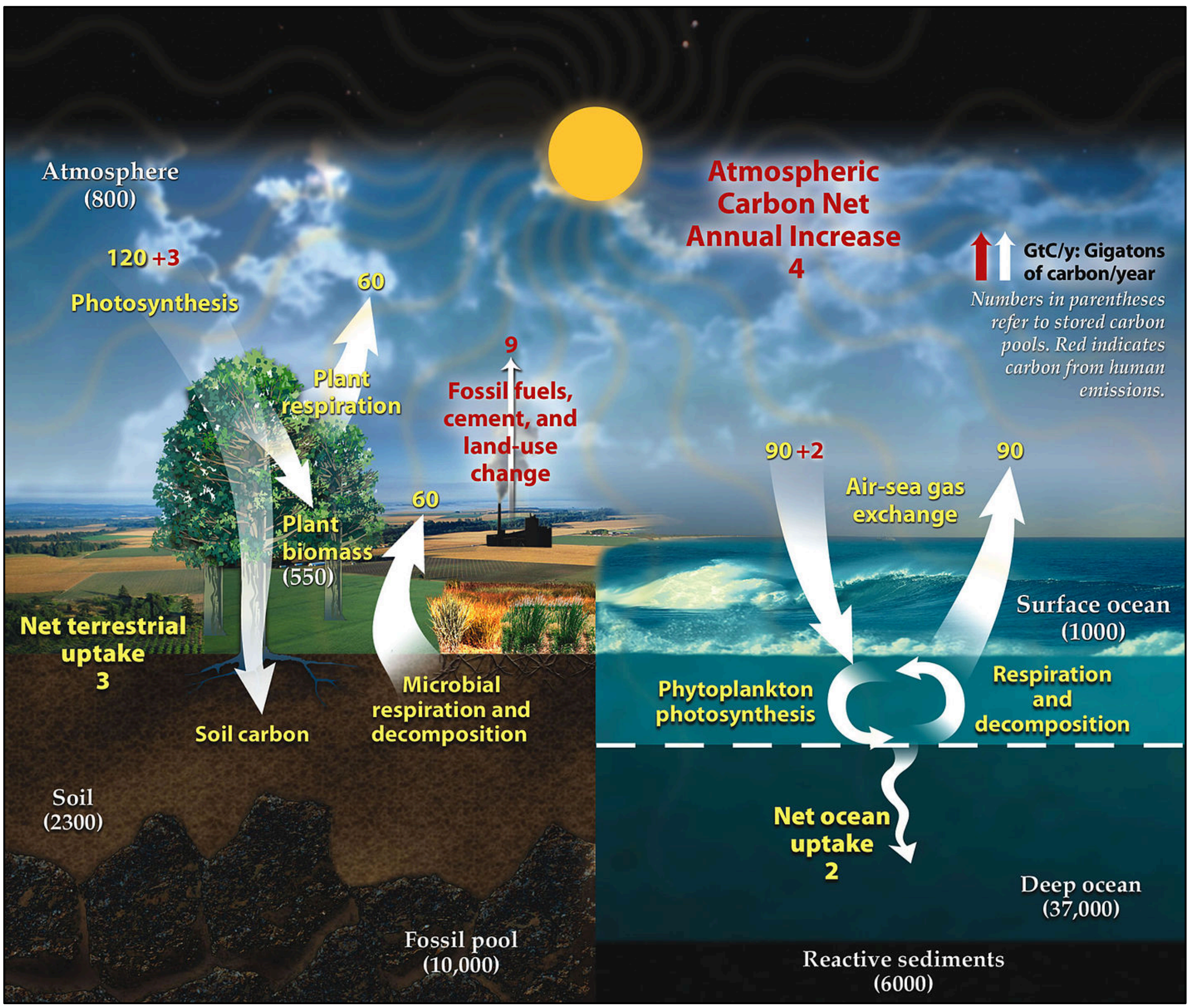


Figure 7.1: A simplified carbon cycle. Diagram adapted from U.S. DOE, Biological and Environmental Research Information System.

Some reservoirs hold on to carbon for only a short time. **Aerobic** (oxygen-using) organisms convert carbohydrates created by other organisms into **carbon dioxide** (CO_2) almost instantaneously, which they exhale into the atmosphere. When considering the flux of respiration, living organisms are the **source** of carbon, and the atmosphere is the **sink**. The carbon stays in the reservoir of living organisms for a relatively short time, depending on their life span, from hours and days to years and decades. In contrast, the **residence time** of carbon in the fossil pool is dramatically different. Fossil fuels form over a course of 300-400 million years, forming from ancient plants and animals that decomposed slowly under very specific, **anaerobic** (without oxygen) conditions in wetland environments. Their bodies were gradually transformed by the heat and pressure of the Earth's crust into the fossil fuels that we mine today to provide petroleum oil, natural gas, and coal (see more on this in chapter 4).

Reservoirs and fluxes of importance

The two largest reservoirs of carbon on Earth are the oceans, which cover the majority of Earth's surface, and the **lithosphere** (the mineral fraction of Earth: soils, rocks, and sediments). Each of these reservoirs holds more carbon than all of the other reservoirs combined. Much of the carbon stored in these reservoirs, especially deep in the lithosphere or in deep ocean environments, has an extremely long residence time, and does not actively participate in rapid fluxes. The notable exceptions here, of course, are fossil fuels, which are mined by humans and converted into gaseous forms of carbon through combustion.

Biomass, which is biological material derived from living, or recently living organisms, is a much smaller reservoir of carbon. The amount of carbon stored in all of the terrestrial vegetation (550 Gt C) (Gt = gigatonne = 10^9 metric tons = 10^{15} g) is just a fraction of that stored in the oceans (38,000 Gt C) and lithosphere (18,000 Gt C). All of the carbon that is currently stored in all of the vegetation on Earth got there through the process of **photosynthesis**. Plants and other photosynthetic organisms are called **primary producers**, because they "fix" atmospheric CO_2 into organic carbon, such as sugar, a form that is usable by animals and other organisms that need to consume their carbon molecules.

Photosynthetic organisms, such as plants, algae, and cyanobacteria, bring in CO_2 from the atmosphere and, using energy from the sun, convert CO_2 and water into glucose molecules (organic carbon). The products of photosynthesis are oxygen and glucose (Equation 7.1). These glucose molecules are simple sugars that **autotrophs** ("self-feeders") can "burn" for energy, or transform into other usable carbon molecules through the process of cellular respiration (described in the next paragraph), or to build plant biomass. Photosynthesis takes place in organelles called **chloroplasts**, shown in Figure 7.2. Photosynthesis accounts for 123 Gt of C per year that is removed from the atmosphere and stored in plant biomass. Such a massive amount of photosynthesis occurs on Earth that no other single flux moves as much carbon in the same timeframe.

$$6CO_2 + 6H_2O + \text{solar energy} \rightarrow C_6H_{12}O_6 + 6O_2 \qquad \textbf{Eq. 7.1}$$

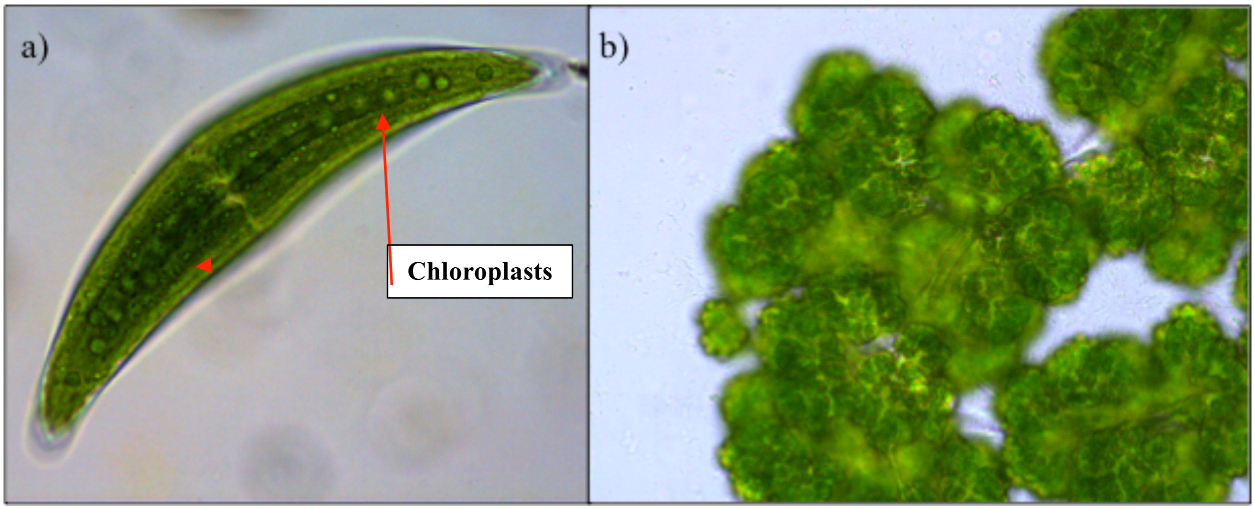


Figure 7.2: Chloroplasts visible in freshwater algae. Chloroplasts are green in color due to the chlorophyll *a* they contain, and are the site of photosynthesis. Chlorophyll *a* is the green pigment that allows plants, algae, and cyanobacteria to absorb the energy they need for photosynthesis from sunlight. a) *Closterium moniliferum* Ralfs, (Chlorophyta) green coccoid algae; b) *Botryococcus braunii* Kützing, (Chlorophyta) green coccoid algae with discoid chloroplasts. Image credit: K. Manoylov, Lake Sinclair, GA

Biomass in the carbon cycle, including plants and animals, is the reservoir of carbon that we are most likely most familiar with, and also the reservoir that is most readily available to us. We all participate in the flux of **consumption** of carbon when we eat food. All of our food is simply plant and/or animal biomass. Our body takes the carbon molecules contained in this biomass, and uses them, along with the oxygen we breathe in, for **cellular respiration** to create the adenosine triphosphate (ATP) we need for energy. The products of cellular respiration include the CO_2 we exhale, water, and energy that is stored in ATP (Equation 7.2). Our bodies also builds additional biomass out of the carbon molecules in this food, allowing us to create new cells for growth or replenishment. This is the only way we, and all other **heterotrophs** ("other-eaters"), can bring in the carbon we need to build and maintain our bodies. Remember, you are what you eat!

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy} \qquad \textbf{Eq. 7.2}$$

Cellular respiration is an important flux in the carbon cycle, and one that contributes carbon to the atmosphere. Remember that animals and other heterotrophs complete cellular respiration using the carbon molecules that they bring in through their food. Plants and other photosynthetic autotrophs complete cellular respiration using the carbon molecules they formed from CO_2 through photosynthesis. Any carbon molecules that are left over after the organism has acquired sufficient energy through cellular respiration make up the biomass of the plant. As plants and animals die and decompose, their bodies are consumed by decomposer organisms such as fungi and bacteria. Through the flux of **decomposition**, some decaying biomass is converted into atmospheric carbon by the decomposers, while most of the biomass is buried into the soil, contributing to soil carbon. In oxygen-rich environments, decomposers rapidly consume dead and decaying biomass using the same process of aerobic cellular respiration described above. In oxygen-deficient environments, decomposers complete other metabolic pathways, and very slowly consume the organic matter. Some of the gases produced from anaerobic decomposition include **methane** (CH_4), **nitrous oxide** (N_2O), and the foul-smelling hydrogen sulfide (H_2S).

The biomass reservoir of the carbon cycle is also important to us as a source of energy. Through the flux of **combustion**, we convert the **potential energy** held in biomass into heat energy that we can use, and release carbon dioxide in the process. If you have ever burned logs on a campfire, or even burned food on the stove, you have completed this flux of biomass combustion. Of course, this happens naturally as well, the best example being natural forest fires caused by lightning strikes. The chemical reaction for combustion is identical to the chemical reaction for cellular respiration. The difference is that in cellular respiration, energy is released in a controlled fashion, and captured in ATP molecules. In combustion, all of this energy is released rapidly in the form of light and heat.

As all of the fluxes we've discussed so far involve the atmosphere, we have not yet discussed the flux that connects the atmosphere to the oceans. Carbon can enter the oceans through two primary fluxes: first through photosynthesis by algae or cyanobacteria (also called phytoplankton in Figure 7.1), and second through the chemical reaction of **ocean-atmosphere exchange**. The ocean, as with all surface water bodies, always contains some dissolved CO_2. This CO_2 is in **equilibrium** with the CO_2 in the air. Some atmospheric CO_2 is constantly dissolving into the ocean, while some dissolved CO_2 is constantly diffusing into the atmosphere. Under normal conditions, these two fluxes will be happening at equal rates. As you can see in Figure 7.1, however, this is no longer the case. In the section *Human impacts on the carbon cycle*, we will discuss why this is the case.

Activity: Better understanding the carbon cycle

To further review the carbon cycle, and better understand the human impacts on it, use this interactive graphic from Woods Hole laboratories: http://www.whoi.edu/feature/carboncycle/. As you will see, the information described in this text is only a small portion of the total carbon cycle on Earth. Finally, complete Table 7.1 as a way to review the sink/source relationship within this cycle. See if you can correctly identify the source and sink of carbon for each of these important fluxes in the carbon cycle.

Table 7.1. Practice understanding the sink/source relationship with cycles

Carbon flux	Carbon source	Carbon sink
Cellular respiration	Carbohydrates in living organisms	CO_2 in the atmosphere
Photosynthesis		
Consumption		
Combustion		
Decomposition		
Ocean/atmosphere exchange		
Fossil fuel formation		

Human impacts on the carbon cycle

Humans, just like all other living organisms, have impacted the global carbon cycle since the dawn of our species. However, the magnitude of our impacts has changed dramatically throughout history. The **Industrial Revolution**, which occurred around the turn of the 19th century, began to make major changes in the use of resources around the world. Beginning in Britain, industrialization eventually affected the whole world. The development of coal-fueled steam power, and later transportation following the discovery of large oil deposits, had enormous influence on the economic and social structure of the world. As the world accelerated in the production and transportation of manufactured goods, the production and consumption of fossil fuels grew. As economic growth continued to increase, so did the production of carbon dioxide through fossil fuel combustion. See Figure 7.4 later in this text.

Some of the human impacts on the carbon cycle have been quantified for you in Figure 7.1. Changes to fluxes in the carbon cycle that humans are responsible for include: increased contribution of CO_2 and other **greenhouse gases** to the atmosphere through the combustion of fossil fuels and biomass; increased contribution of CO_2 to the atmosphere due to land-use changes; increased CO_2 dissolving into the ocean through ocean-atmosphere exchange; and increased terrestrial photosynthesis. The first two impacts, both contributing excess CO_2 to the atmosphere at a rate of 4 Gt of carbon per year have, by far, the largest impact on our planet. For this reason, this is the change that we will most often focus on throughout this section. The excess CO_2 in the atmosphere is responsible for the increased CO_2 dissolving into the ocean, which we will discuss later in this section. This is also, in part, responsible for the increased terrestrial photosynthesis that can be observed, as additional CO_2 is available to plants for photosynthesis. However, intensive agricultural and forestry practices also contribute to the change in this flux.

One characteristic example of a human impact on the carbon cycle is illustrated in Figure 7.3. Throughout most of our recent human history, people have been physically altering the landscape around them in order to have more control over their surroundings and increase their odds of survival. One way that people have done this is through agriculture. In order for most forms of agriculture to be successful, native vegetation is eliminated or minimized. Resources from this native vegetation, such as wood, may be used for combustion to provide heat, sanitation, or fuel for cooking. Combustion may also be used as an efficient way to clear the land and make way for crops or grazing lands for livestock. Often, settlements are formed around these newly fashioned agricultural fields, and the land is used in a similar fashion for many years in the future.

Let's identify the ways in which humans are impacting the carbon cycle in this scenario of agricultural establishment. You should be able to identify from the above paragraph that the flux of combustion will release CO_2 previously held in vegetation into the atmosphere. In addition, remember that the land that used to house native vegetation is now home to agricultural lands. In most controlled agricultural environments, there is less total vegetative biomass than there would be under natural conditions. This decreased biomass leads to lower total photosynthesis rates, thereby decreasing the amount of CO_2 that is removed from the atmosphere and turned into plant biomass. Also, open soil on the fields between crops, during the winter months, or as a result of overgrazing allows for the air to penetrate deep into the soil structure. This provides the environment necessary for enhanced aerobic respiration by soil microorganisms. This decreases soil carbon, which can lead to erosion and soil degradation, and also releases additional CO_2 to the atmosphere.

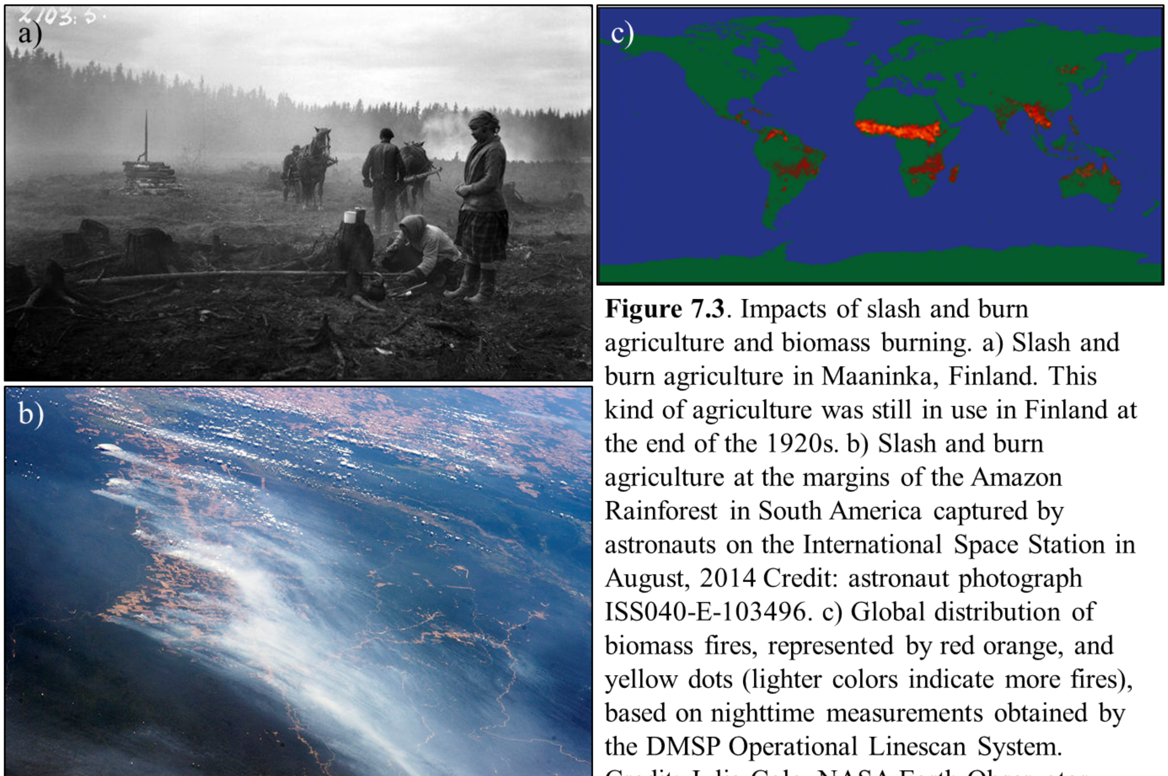


Figure 7.3. Impacts of slash and burn agriculture and biomass burning. a) Slash and burn agriculture in Maaninka, Finland. This kind of agriculture was still in use in Finland at the end of the 1920s. b) Slash and burn agriculture at the margins of the Amazon Rainforest in South America captured by astronauts on the International Space Station in August, 2014 Credit: astronaut photograph ISS040-E-103496. c) Global distribution of biomass fires, represented by red orange, and yellow dots (lighter colors indicate more fires), based on nighttime measurements obtained by the DMSP Operational Linescan System. Credit: Julia Cole, NASA Earth Observatory

As you learned in Chapter 5, biomass is an important form of energy to human civilization. Prior to the Industrial Revolution, this was essentially the only form of fuel to which most people on Earth had access. In many **less-industrialized countries**, combustion of biomass such as wood or animal dung is still the primary energy source that many citizens, particularly in rural areas, depend on for domestic use (heating, sanitation, and cooking) as it is inexpensive, relatively efficient, and readily available. Figure 7.3c shows the global distribution of biomass fires in the world. While the burning of biomass for domestic use contributes to some of these fires, it is the so-called **slash-and-burn agriculture** that makes up a larger contribution. Take a minute to compare the areas highlighted in Figure 7.3c to the countries of the world that are currently experiencing rapid population growth (Chapter 3). If you need a refresher, use the CIA World Factbook website to view current global population growth values by country: https://www.cia.gov/library/publications/the-world-factbook/rankorder/2002rank.html.

While biomass burning still has a significant impact on the global carbon cycle, human impacts on fluxes such as fossil fuel extraction and combustion continue to grow. For a review of the impacts of non-renewable energy sources such as fossil fuels, see Chapter 4. Burning of any fossil fuel (coal, natural gas, crude oil) moves carbon from a previously-sequestered state deep within the Earth's crust into carbon dioxide in the atmosphere. As countries become more industrialized, their reliance on and combustion of fossil fuels tends to increase. Look at the graph in Figure 7.4, which compares CO_2 emissions from fossil fuels of regions across the globe.

How has the use and distribution of fossil fuels changed throughout the past 250 years?

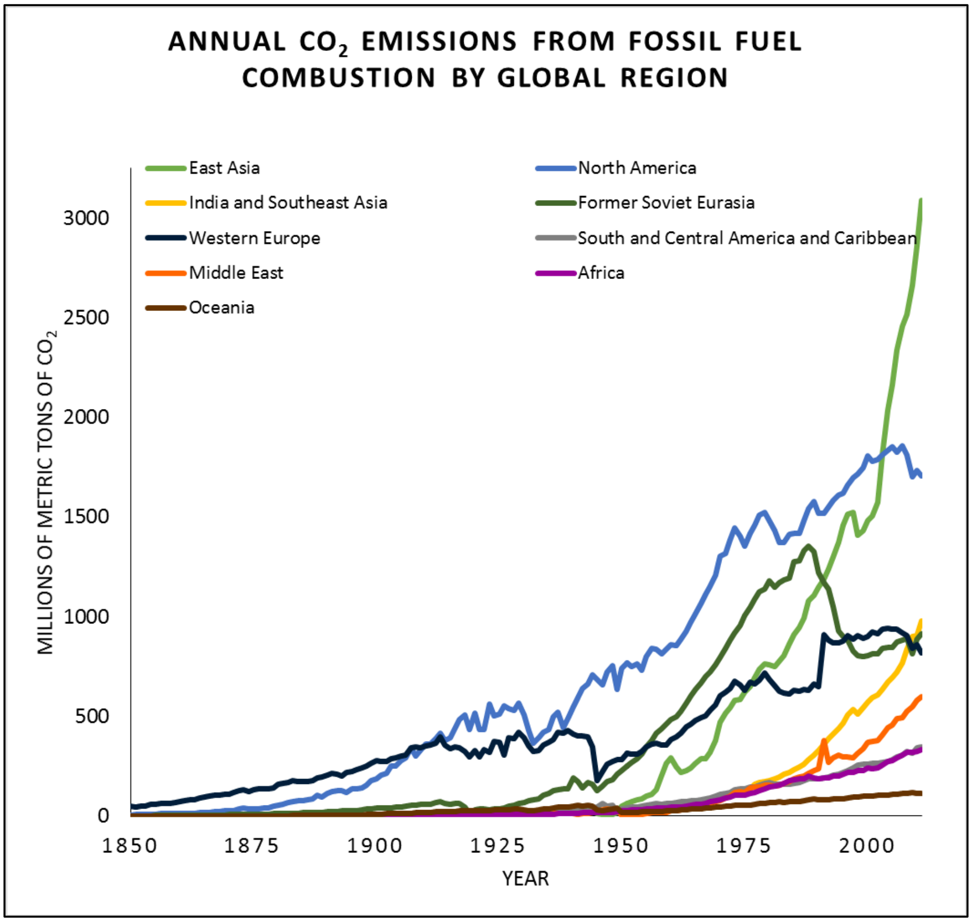


Figure 7.4. Total annual CO_2 emissions from fossil fuel combustion 1850-2011 by global region. Data from the Carbon Dioxide Information Analysis Center (CDIAC) http://cdiac.esd.ornl.gov/

The data shown in Figure 7.4 reveals much about the regions of the world it depicts. The effects of historic events such as the Great Depression of 1929-1939, World Wars, the fall of the Soviet Union in 1991, and the Kuwait oil fires of 1991 can be seen. Furthermore, between 1850 and 2011, different regions have gone in and out of the lead position as top producer of CO_2 from fossil fuel emissions. Population is one reason why fossil fuel use has changed throughout time. This is particularly apparent when comparing the data for Western Europe to that of India and Southeast Asia.

As countries industrialize, their relationship with agriculture also changes. **More-industrialized countries** rely very little on slash-and-burn agriculture. Their agricultural practices, however, are no less impactful on the environment. The growing population (Chapter 3) in many countries has required agriculture to become industrialized in order to meet demand. As a person living in the United States, **industrialized agriculture** probably produces the vast majority of the food you eat, including grains, fruits and vegetables, dairy and eggs, meats, and even fish. Industrialized agriculture can refer to a variety of practices, but has several main components: the use of motorized machinery; the use of chemicals such as fertilizers, pesticides, hormones, and/or antibiotics; and the intense and efficient production of one product across a large area of land.

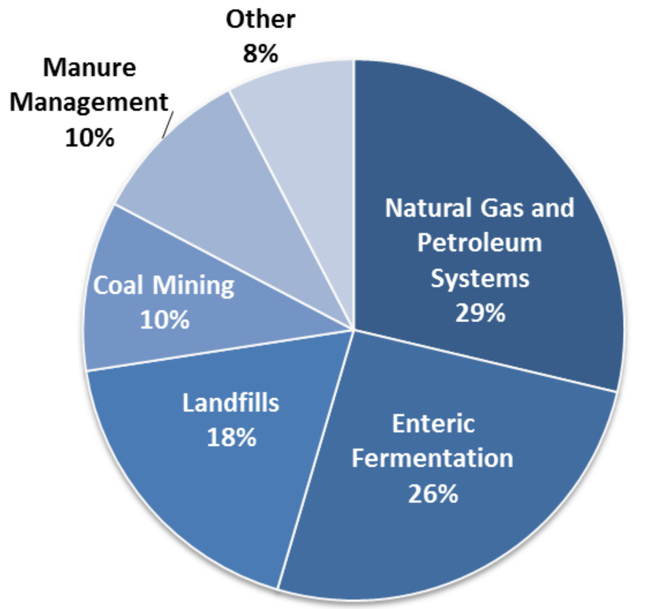


Figure 7.5. US methane emissions by source. 36% of the US methane production comes from agriculture: enteric fermentation (production of methane by anaerobic bacteria within the ruminant gut) and manure management. All emissions estimates from the Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2013. US EPA.

One example of the impacts of industrialized agriculture is the production of methane (CH_4), a potent greenhouse gas. You will learn more about methane later in this section. As you saw earlier, methane is a common product of anaerobic metabolisms. The gut of **ruminant animals** (such as sheep, cattle, and goats) has evolved to allow the animals to digest the very tough carbon molecules, such as cellulose, in grass. They do this through symbiosis, or cooperation, with anaerobic bacteria who live in the gut tract. These anaerobic bacteria produce methane and other gases as a result of their metabolism when they break down molecules like cellulose. This is sometimes called enteric fermentation. The methane gas is excreted from the animal, and this contributes significantly to total methane emissions (Figure 7.5). A similar type of bacteria live in the fecal matter, or manure, of livestock. As the manure is handled or stored for future use, methane is also released to the environment.

The methane excretions of one cow or a few sheep would be miniscule and insignificant. If you were a small farmer with only enough livestock to feed your family, your contribution to total methane emissions would be close to zero. However, the demand for animal protein from meat, dairy, and eggs is very large in the United States. As of January 2015, the United States had a total cattle inventory of 89.9 million animals, and in 2014, 25.5 billion pounds of beef was consumed in the United States (statistics: National Cattlemen's Beef Association). The impacts of enteric fermentation and manure management for almost 90 million animals are very significant, as seen in Figure 7.5. In both cases, carbon that was previously stored in biomass (cattle feed) is moved into the atmosphere, this time in the form of CH_4. This is another example of how humans have impacted the carbon cycle.

Previously in this chapter, you identified other ways the carbon cycle is impacted by human agriculture. Through industrialized agriculture, we must also account for the fossil fuels that are used. In order to deliver agricultural products to consumers, fossil fuels are used numerous times: deliveries of fertilizer, feed, and/or seed to farms; farm machinery; delivery of products to processers; food processing; delivery of foods to super markets; etc.

As animal products, especially meat, are expensive, the demand is typically greater in more-industrialized countries than it is in less-industrialized countries. This makes industrialized agriculture, and especially industrialized animal agriculture, one of the major contributors to greenhouse gas emissions in more-industrialized countries.

Knowledge check – answer these questions on your own to further explore the impacts of biomass and fossil fuel burning on the global carbon cycle.

1. Why is there a correlation between population growth rate and global distribution of biomass fires?
2. Do you think this correlation is more likely due to personal biomass fires for activities such as cooking, or due to slash-and-burn agriculture? Why?
3. Given any other knowledge you might have about the areas highlighted in in Figure 7.3c, what other environmental impacts may be occurring here besides carbon cycle alterations?
4. Compare the production of CO_2 emissions from fossil fuel combustion across world regions in 1900, 1950, and 2011 in Figure 7.4. What has accounted for these differences?
5. Has the total worldwide production of CO_2 from fossil fuels increased evenly relative to human population growth during the time period displayed in Figure 7.4? Why or why not?
6. What are the differences in contributions of greenhouse gas emissions from more-industrialized countries and less-industrialized countries? What are the similarities?

Resources

Carbon Dioxide Information Analysis Center http://cdiac.esd.ornl.gov/

NOAA Earth System Research Laboratory: Carbon Cycle Science
http://www.esrl.noaa.gov/research/themes/carbon/

Sass, Ronald. *Q2: What are the Causes of Global Climate Change?* OpenStax CNX. Sep 22, 2009 http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3

USDA Climate Change and Agriculture in the United States: Effects and Adaptation http://www.usda.gov/oce/climate_change/effects_2012/effects_agriculture.htm

US EPA Overview of Greenhouse Gases: Methane http://epa.gov/climatechange/ghgemissions/gases/ch4.html

Woods Hole Oceanographic Institution: Carbon Around the Earth http://www.whoi.edu/feature/carboncycle/

Terms list

Aerobic

Anaerobic

Autotroph

Biomass

Carbon

Carbon dioxide

Cellular respiration

Chloroplast

Combustion

Consumption

Decomposition

Equilibrium

Flux

Greenhouse gas

Heterotroph

Industrial Revolution

Industrialized agriculture

Less-industrialized country

Lithosphere

Methane

More-industrialized country

Nitrous oxide

Ocean-atmosphere exchange

Photosynthesis

Potential energy

Primary producer

Reservoir

Residence time

Ruminant animal

Sink

Slash-and-burn agriculture

Source

The Science of Climate Change

What is causing global climate change?

Scientists have identified the source of our current global climate change as being the increased human-caused emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), since the industrial revolution. Greenhouse gases are defined as large (at least three atoms) gas molecules that participate in the **greenhouse effect**. While you already know about the "big three" greenhouse gases (CO_2, CH_4, and N_2O), it's important to realize that **water vapor** (H_2O) is also a greenhouse gas. While humans have little direct impact on water vapor concentrations in the atmosphere, is it still an essential component of the natural greenhouse effect that occurs in our atmosphere.

The Earth receives energy from the sun and in turn radiates energy back into space. When these two energies are equal, a stable temperature of the Earth is achieved. This temperature can be calculated from basic physics and is equal to about 18°C (0°F). This **thermal equilibrium temperature** is obviously much colder than that of the surface of the Earth. The actual average value of the Earth's surface temperature is about 15°C (59°F). The difference between these temperatures is due primarily to the natural greenhouse gas concentrations in the atmosphere, causing the greenhouse effect. If the Earth had no naturally occurring atmospheric greenhouse gases, the temperature at the surface of the Earth would equal the thermal equilibrium temperature. The influence of these greenhouse gases, mainly water and some CO_2, moderates the Earth's climate and makes life possible (Figure 7.6).

As **solar radiation** reaches the Earth's atmosphere, there are a variety of possibilities for its fate. Some solar radiation is reflected by the Earth and its atmosphere, and does not contribute to warming. Some passes through the atmosphere and reaches the surface of the Earth. When this solar radiation is absorbed by objects on Earth's surface, it is re-emitted as infrared radiation (heat) that escapes to space. However, some of this heat is intercepted in the atmosphere by greenhouse gases. These gases absorb and re-emit the radiation in all directions. This creates a warming impact on the Earth's surface Radiation can be bounced around from one greenhouse gas molecule to another, becoming trapped, and increasing its warming potential. For this reason, an increased greenhouse gas concentration causes an increase in the overall warming potential of the Earth's atmosphere.

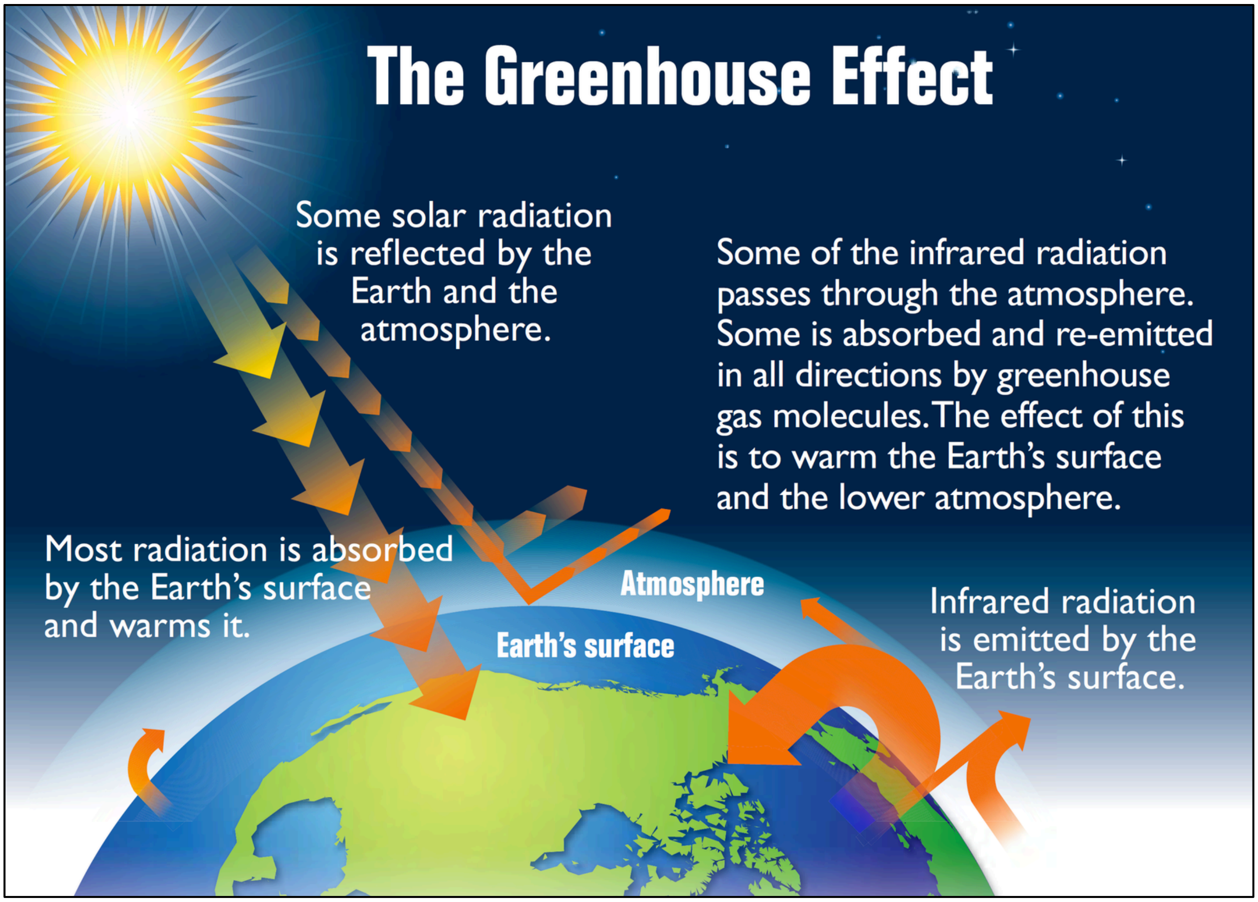


Figure 7.6. This diagram shows the Earth's greenhouse effect. The Earth absorbs some of the energy it receives from the sun and radiates the rest back toward space. However, certain gases in the atmosphere, called greenhouse gases, absorb some of the energy radiated from the Earth and trap it in the atmosphere. These gases essentially act as a blanket, making the Earth's surface warmer than it otherwise would be. While this greenhouse effect occurs naturally, making life as we know it possible, human activities in the past century have substantially increased the amount of greenhouse gases in the atmosphere, causing the atmosphere to trap more heat and leading to changes in the Earth's temperature. Credit: US EPA

On a geological time scale, the climate has changed many times in the past, even before the presence of humans. These changes occurred naturally because man had not yet evolved. A well-known example of past climate change is the occurrence of **ice ages**. Ice ages have occurred repeatedly throughout Earth's history, the most severe ice age of which scientists have reliable data occurred around 650,000 years ago. During this time, solid, glacial ice covered much of Canada, the northern United States, and northern Europe; the level of the ocean decreased 120 m, and the global average temperature decreased by 5°C. A geologic history of ice events is preserved in the ice sheets covering Antarctica and Greenland. This history has been uncovered over the past decades by scientists who have cored deeply into the ice and deciphered the temperature and atmospheric composition records stored in the ice. This process of obtaining **ice cores** is shown in Figure 7.7. The temperature at which the ice originally formed can be obtained from an interpretation of the measured ratio of the **stable isotopes** (see Chapter 1 supplement for a description of isotopes) of oxygen in the molecules of water forming the ice. The atmospheric gas composition is taken from air bubbles trapped in the ice at the time of formation. From these data, scientists have gathered a set of reliable data that track atmospheric temperature and gas concentrations that dates back 800,000 years. These data helped scientists come to the conclusion that the Earth's temperature and greenhouse gas concentrations are directly correlated to one another (Figure 7.8). During the ice age 650,000 years ago, the Earth was experiencing depressed temperature and atmospheric CO_2 concentrations below 200 **parts per million** (ppm). We can also see from these data, that CO_2 concentrations can be naturally elevated to as high as 300 ppm, correlating with increased temperatures.

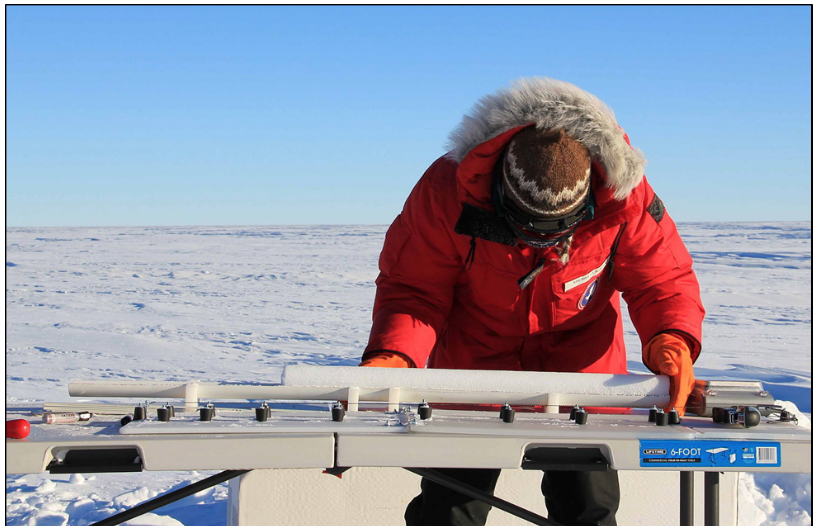


Figure 7.7. On Dec. 8, 2010, Michelle Koutnik, of the University of Copenhagen's Center for Ice and Climate, prepared a core of Antarctic ice to be wrapped and put into core tubes for transport back to labs at Brigham Young University in Utah. But first, Koutnik measured the core's length, diameter and weight. The traverse was the first of two field campaigns to study snow accumulation on the West Antarctic Ice Sheet and tie the information back to larger-scale data collected from satellites. Credit: NASA/Lora Koenig.

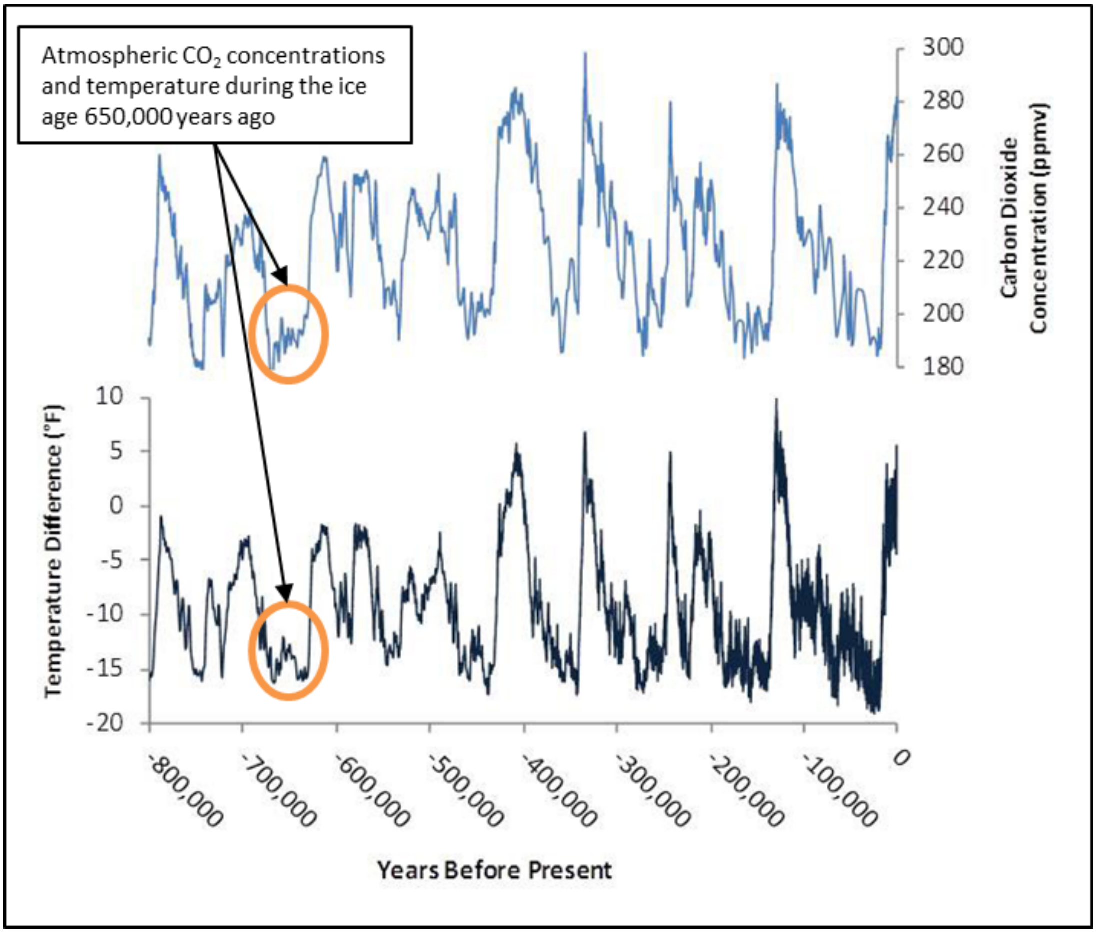


Figure 7.8. Estimates of the Earth's changing CO_2 concentration (top) and Antarctic temperature (bottom), based on analysis of ice core data extending back 800,000 years. Until the past century, natural factors caused atmospheric CO_2 concentrations to vary within a range of about 180 to 300 ppm. Warmer periods coincide with periods of relatively high CO_2 concentrations. NOTE: The past century's temperature changes and rapid CO_2 rise (to 400 ppm in 2015) are not shown here. Source: Based on data appearing in NRC (2010).

The 100,000 year major cycle of the ice ages and some variations within the cycles agree very well with predicted periodic relationships between the Earth's orbit around the sun, generally referred to as the **Milankovitch cycles**. Milankovitch cycles describe the very slight "wobbles" that occur in the Earth's tilt and path as it moves around the sun. The Earth is always slightly tilted on its axis with respect to the sun. The angle of this tilt, however, changes periodically, varying from about 22° to about 25°. A less severe tilt will cause milder summers and winters close to the poles, preventing full summer ice melt in the northern- and southernmost regions, and allowing for a buildup of ice from year to year.

The path through which the Earth travels on its journey around the sun also changes from a more circular to a more elongated shape. Again, a round orbit will cause milder summers and winters close to the poles. These are very long term changes, and the results of the Milankovitch cycles can be observed in the changes in temperature and atmospheric CO_2 concentration shown in Figure 7.8. The climate change event that scientists are currently documenting is occurring much more rapidly than could be explained by Milankovitch cycles. Therefore, scientists agree that the cause of our currently changing climate is due to human impacts and not natural forces.

Greenhouse gases

We will be covering the four major categories of greenhouse gases that have been impacted by humans the most. See Table 7.2 for a numeric comparison of these greenhouse gases.

- Carbon dioxide, CO_2
- Methane, CH_4
- Nitrous oxide, N_2O
- Synthetic **fluorinated gases**, including **hydrofluorocarbons** (HFCs), **perfluorocarbons** (PFCs), and **sulfur hexafluoride** (SF_6)

Carbon dioxide (CO_2) is the greenhouse gas responsible for most of the human-caused climate change in our atmosphere. It has the highest concentration in the atmosphere of any of the greenhouse gases that we'll discuss here. Remember that CO_2 is a direct product of both combustion and cellular respiration, causing it to be produced in great quantities both naturally and anthropogenically. Any time biomass or fossil fuels are burned, CO_2 is released. Major anthropogenic sources include: electricity production from coal-fired and natural gas power plants, transportation, and industry (Chapter 4). To get an idea of how CO_2 concentration has changed over time, watch this video compiled by the National Oceanic and Atmospheric Administration (NOAA): http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html. This video contains atmospheric CO_2 concentrations measured directly, dating back to 1958, as well as atmospheric CO_2 concentrations measured indirectly from ice core data, dating back to 800,000 BCE. By 1990, a quantity of over seven billion tons of carbon (equivalent to 26 billion tons of

carbon dioxide when the weight of the oxygen atoms are also considered) was being emitted into the atmosphere every year, much of it from industrialized nations. Similar to the action of the naturally existing greenhouse gases, any additional greenhouse gases leads to an increase in the surface temperature of the Earth.

While CO_2 is produced by aerobic cellular respiration, gases such as CH_4 and N_2O are often the products of anaerobic metabolisms. Agriculture is a major contributor to CH_4 emissions, as you saw in section 7.1. In addition to anaerobic bacteria, methane is also a significant component of natural gas, and is commonly emitted through the mining and use of natural gas and petroleum, in addition to coal mining. For a review of how fossil fuels are mined, see Chapter 4. Finally, **landfills** contribute significantly to CH_4 emissions, as the waste put into the landfill largely undergoes anaerobic decomposition as it is buried under many layers of trash and soil. Natural sources of CH_4 include swamps and wetlands, and volcanoes.

The vast majority of N_2O production by humans comes from agricultural land management. While some N_2O is naturally emitted to the atmosphere from soil as part of the nitrogen cycle, human changes in land management, largely due to agricultural practices, have greatly increased N_2O emissions. Some N_2O is also emitted from transportation and industry.

Due to their relatively high concentrations in the atmosphere compared to synthetic gases, CO_2, CH_4, and N_2O, are responsible for most of the human-caused global climate change over the past century. Figure 7.9 shows the increases in all three gases following the industrial revolution. Ice core data (Figure 7.8) shows us that the atmospheric CO_2 concentration never exceeded 300 ppm before the industrial revolution. As of early 2015, the current atmospheric CO_2 concentration is 400 ppm. Comparing Figure 7.9 to Figure 7.8, above, what is likely to happen to global temperature following this unprecedented rise in greenhouse gas levels?

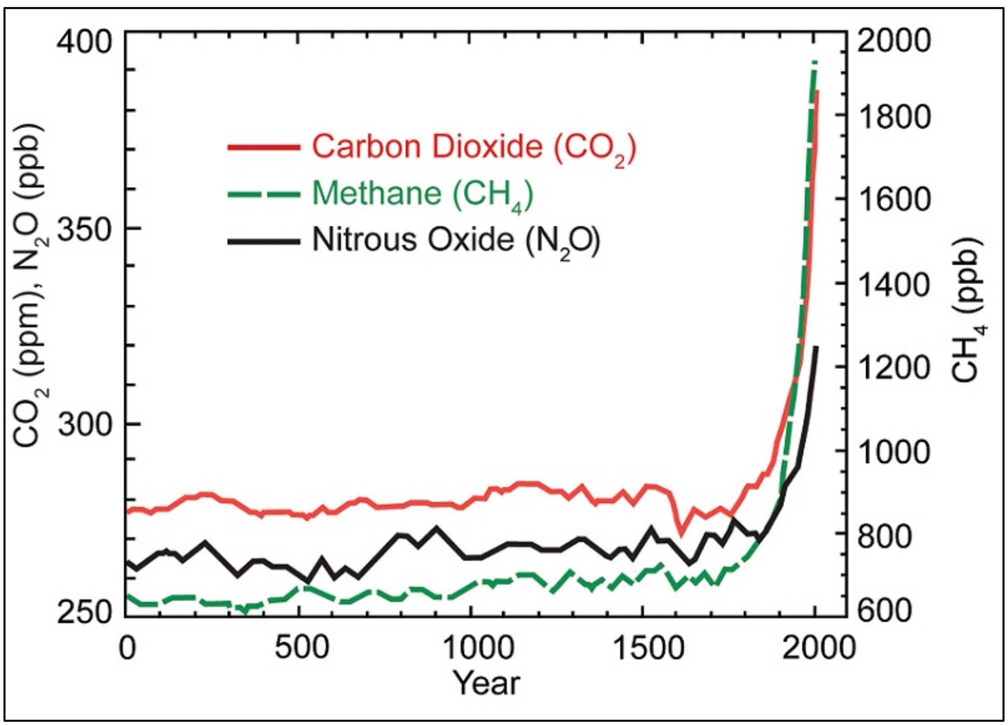


Figure 7.9. Increase in greenhouse gas concentrations in the atmosphere over the last 2,000 years. Increases in concentrations of these gases since 1750 are due to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion molecules of air. Source: USGCRP (2009)

One class of greenhouse gas chemicals that has no natural sources is the fluorinated gases. These include HFCs, PFCs, and SF_6, among others. Because these are synthetic chemicals that are only created by humans, these gases were essentially non-existent before the industrial revolution. These synthetic gases are used for a wide variety of applications, from refrigerants to semiconductor manufacturing, and propellants to fire retardants. They tend to have a long lifetime in the atmosphere, as seen in Table 7.2. Some of these chemicals, as well as the older **chlorofluorocarbons** (CFCs), have been phased out by international environmental legislation under the Montreal Protocol (see Chapter 6). Due to their long lifespan, many of these now-banned CFCs remain in the atmosphere. Newer chemical replacements, such as HFCs, provide many of the same industrial applications, but unfortunately have their own environmental consequences.

Just as greenhouse gases differ in their sources and their residence time in the atmosphere, they also differ in their ability to produce the greenhouse effect. This is measured by the **global warming potential**, or GWP, of each greenhouse gas. The GWP of a greenhouse gas is based on its ability to absorb and scatter energy, as well as its lifetime in the atmosphere. Since CO_2 is the most prevalent greenhouse gas, all other greenhouse gases are measured relative to it. As the reference point, CO_2 always has a GWP of 1. Note the very high GWP values of the synthetic fluorinated gases in Table 7.2. This is largely due to their very long residence time in the atmosphere. Also note the higher GWP values for CH_4 and N_2O compared to CO_2. How does this impact the comparison of the environmental effects of agricultural practices in less-industrialized and more-industrialized countries that we completed in section 7.1?

Table 7.2. Comparison of common greenhouse gases in the atmosphere. Data from US EPA. For more information: http://epa.gov/climatechange/ghgemissions/gases.html

Greenhouse gas	Chemical formula or abbreviation	Lifetime in atmosphere	Global warming potential (100-year)
Carbon dioxide	CO_2	Variable	1
Methane	CH_4	12 years	28-36
Nitrous oxide	N_2O	114 years	298
Hydrofluorocarbons	Abbreviation: HFCs	1-270 years	12-14,800
Perfluorocarbons	Abbreviation: PFCs	2,600-50,000 years	7,390
Sulfur hexafluoride	SF_6	3,200 years	22,800

Other climate influencers

In addition to greenhouse gases, other manmade changes may be forcing climate change. Increases in near surface ozone from internal combustion engines, aerosols such as carbon black, mineral dust and aviation-induced exhaust are acting to raise the surface temperature. This primarily occurs due to a decrease in the **albedo** of light-colored surfaces by the darker-colored carbon black, soot, dust, or particulate matter. As you know, it is more comfortable to wear a white shirt on a hot summer day than a black shirt. Why is this? Because the lighter-colored material bounces more solar radiation back toward space than the darker-colored material does, allowing it to stay cooler. The darker-colored material absorbs more solar radiation, increasing its temperature. Just as the white shirt has a higher albedo than the black shirt, light-colored objects in nature (such as snow) have a higher albedo than dark-colored objects (such as soot or dust). As humans increase the amount of carbon black, soot, dust, and particulates in the atmosphere, we decrease the albedo of light-colored surfaces, causing them to absorb more solar radiation and become warmer than they would without human influence. An example of this can be seen in the snow on Figure 7.10.

Figure 7.10. A photograph of the extreme dust deposition from the deserts of the Colorado Plateau onto the Colorado Rockies snowpack in 2009. Taken from the high point of the Senator Beck Basin in the San Juan Mountains, it captures the extent of the impact of darkening in which the snow albedo dropped to about 30%, more than doubling the absorption of sunlight. Credit: S. McKenzie Skiles, Snow Optics Laboratory, NASA/JPL

Tools scientists use to study climate change

Scientists must gather together all data that is available to them in order to make meaningful conclusions and predictions regarding climate change. When they bring these data together, the prediction they make is in the form of a scientific **model**. A model is a projection of what might happen in the future based on knowledge of current and past events. The models that are published to predict climate change must pass a rigorous scientific peer-review process, and often require the combination of findings of hundreds of experiments. These large-scale models are typically beyond the capacity of a standard desktop computer, and must be run by large super-computers housed at research universities or government laboratories. For more information on how scientists build and test models, follow the link below and click on the slideshow animation, paying special attention to the sections "Model Overview" and "Testing Models." http://www.epa.gov/climatechange/science/future.html

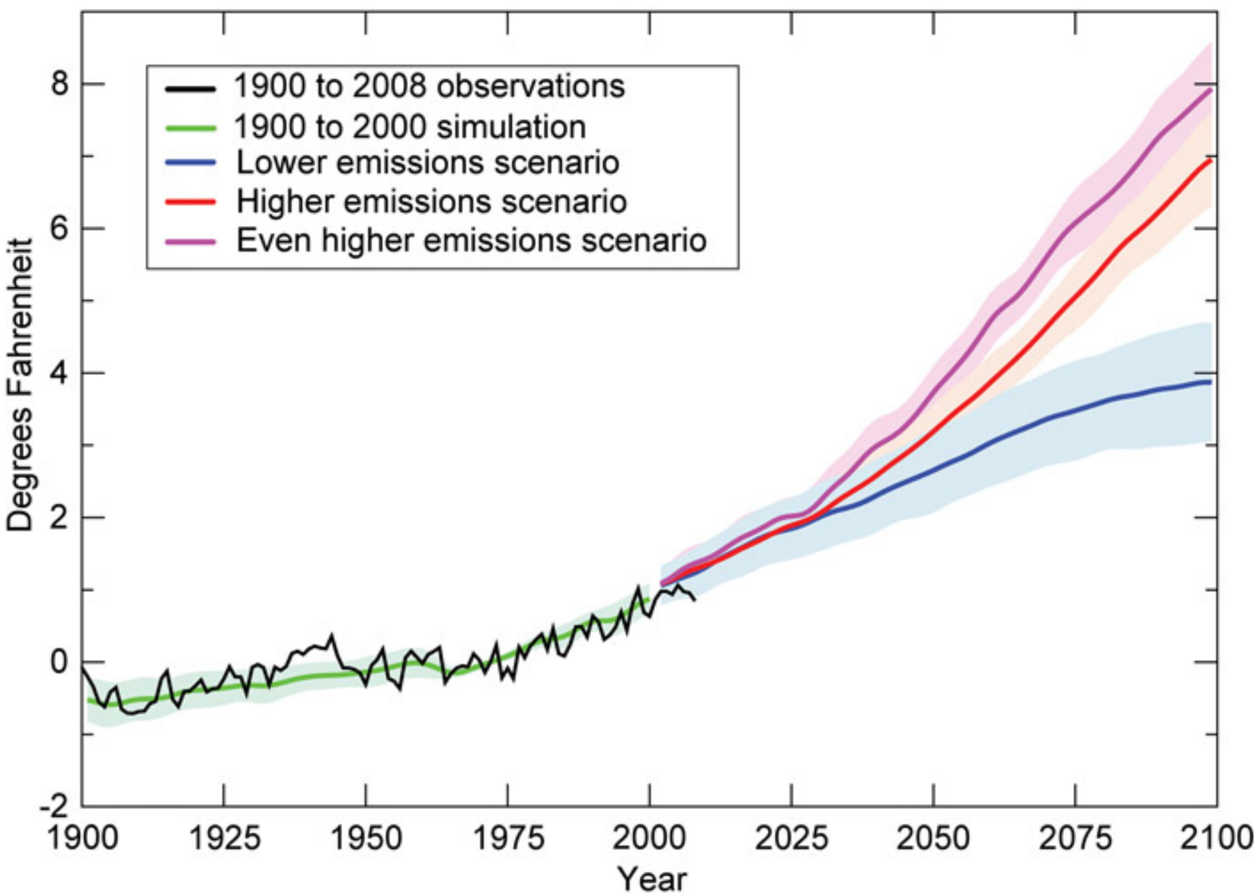


Figure 7.11. Observed and projected changes in global average temperature under three no-policy emissions scenarios. The shaded areas show the likely ranges while the lines show the central projections from a set of climate models. A wider range of model types shows outcomes from 2 to 11.5°F. Changes are relative to the 1960-1979 average. Source: USGCRP 2009

Figure 7.11 is one example of a scientific model of the impacts of climate change. Within this figure, we see the directly-measured observations of global average temperature (black line). We also see models of four different scenarios: 1900 to 2000 simulation using actual greenhouse emissions (green line), and 2000 to 2100 simulation using very high (purple line), high (red line), and low (blue line) greenhouse gas emissions scenarios.

Why did scientists make a model of the data from 1900 to 2000 in Figure 7.11 when they could just look up the data in published literature? This is an important component of model testing. In order to ensure accuracy of the model, you should not only be able to predict future events, but past events as well. Scientists use this as a way to "calibrate" their model. Since this model reliably predicts past events, chances are good that it will reliably predict future events as well.

Another example of a climate model is shown in Figure 7.12, this time comparing climate projections with and without the influences of humans on greenhouse gas emissions. This large model is a combination of the work of many different models, in order to achieve the most accurate outcome.

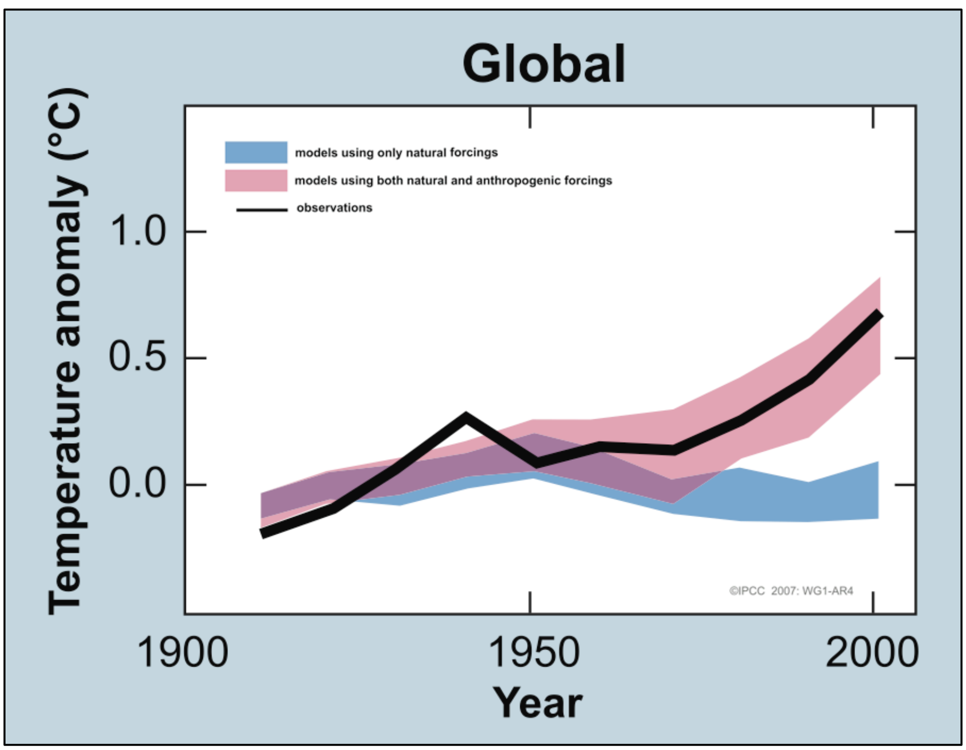


Figure 7.12. Comparison between observed average global temperatures and corresponding modeled temperatures with and without anthropogenic climate forces (IPCC, Working group 1, 2007).

In Figure 7.12, the decadal averages of observations are shown for the period 1906 to 2005 (black line). All temperatures are plotted relative to zero being defined as the corresponding average for the period from 1901 to 1950. The blue shaded band shows the 5% to 95% **confidence interval** for 19 simulations from 5 climate models using only the natural forcing effects due to solar activity and volcanoes. The red shaded band shows the 5% to 95% confidence interval for 58 different simulations from 14 climate models using both natural and anthropogenic forces. These different simulations and the different models are used by different scientific groups and represent different treatments of the Earth's systems. It is thus quite encouraging that model calculations are in major agreement with the assumption that global temperature change from 1900 to 2000 is due to both natural and anthropogenic effects, with anthropogenic effects being the major causes in its recent dramatic increase.

You will see more examples of climate models as you make your way into the final section of the climate change chapter: consequences of climate change.

Resources

NASA Global Climate Change: Vital Signs of the Planet http://climate.nasa.gov/

NOAA Paleoclimatology: Astronomical Theory of Climate Change http://www.ncdc.noaa.gov/paleo/milankovitch.html

Sass, Ronald. *Q2: What are the Causes of Global Climate Change?* OpenStax CNX. Sep 22, 2009 http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3

University of San Diego Virtual Museum: Climate Change http://earthguide.ucsd.edu/virtualmuseum/climatechange2/01_1.shtml

US EPA: Future Climate Change http://www.epa.gov/climatechange/science/future.html

US EPA: Overview of Greenhouse Gases http://epa.gov/climatechange/ghgemissions/gases.html

Terms list

Albedo

Chlorofluorocarbon

Confidence interval

Fluorinated gases

Global warming potential

Greenhouse effect

Hydrofluorocarbon

Ice age

Ice core

Landfill

Milankovitch cycles

Model

Parts per million

Perfluorocarbon

Solar radiation

Stable isotopes

Sulfur hexafluoride

Thermal equilibrium temperature

Water vapor

Consequences of Climate Change

As part of your assigned reading for this section, read the article “The Coming Storm” by Don Belt published in *National Geographic*:
http://ngm.nationalgeographic.com/print/2011/05/bangladesh/belt-text

In this section, we will discuss the effects of climate change, both those that have already been observed, as well as future predictions based on scientific climate models (see section 7.2 for a discussion of scientific models). Here, the differences between the terms **global warming** and **climate change** become apparent. Global warming refers to the increase in the average temperature of the Earth’s atmosphere due to elevated greenhouse gas concentrations, heightening the greenhouse effect. We have already observed this increase occurring, as you saw in Figure 7.12 from section 7.2. We have also seen, and expect to continue to see, other changes occurring in the **climate** of the Earth. Furthermore, changes have been observed, and we expect to continue to observe, changes in other chemical, physical, and biological aspects of the Earth’s environment. We will only discuss some of the consequences of climate change in this section, including changes in temperature, precipitation, ocean level, and ocean acidity. There are many more changes that have been seen, and are projected to continue in the future. These include: changes in the amount and distribution of ice and snow, changes in seasonality, ecosystem shift, and habitat changes of plant and animal populations, in addition to others. For more information about these consequence of climate change, visit this site:
http://www.epa.gov/climatechange/science/indicators/index.html.

Temperature and precipitation

Temperature and **precipitation** are the two most direct impacts on the Earth’s climate due to climate change. By now, you should already understand why an increase in greenhouse gas levels in the atmosphere causes an increase in temperature. But why does it also impact precipitation patterns? As you already know, water vapor is an important component of the Earth’s atmosphere (see Chapter 6). As the air in the troposphere warms and cools, the amount of water vapor that it holds changes dramatically. Here in Georgia, we have very hot and humid summers. The high summer humidity in this region is possible due to the increased capability warm air has to hold water vapor. Simply put, warmer air can hold more water than cooler air. As air cools, its ability to hold water vapor decreases, and any excess water will leave the air as liquid water. A great example of this is the formation of dew on surfaces overnight. During the day, the temperature is warmer than it is at night, and the air has a relatively high holding capacity for water vapor. When the sun sets, the air cools, decreasing its capacity to hold water vapor. That extra water must go somewhere, and it does that by accumulating on surfaces. Similarly, when warm and cool air fronts collide, the chances for rain and thunderstorms increase. Furthermore, an increase in temperature enhances evaporation occurring at the Earth’s surface. This increased evaporation leads to greater concentrations of water vapor in the atmosphere which can lead to increased precipitation.

The change in temperature that we have already seen in the Earth's average atmospheric temperature is relatively small (about 0.6 °C, according to Figure 7.12 from section 7.2). However, as with many of the aspects of climate change, the potential for greater changes increases dramatically as time progresses in the future. This can be seen in Figure 7.13, which displays a model of the predicted temperature increase. Notice that these changes occur relatively rapidly, and are not uniform across the globe. What might be some of the reasons for this?

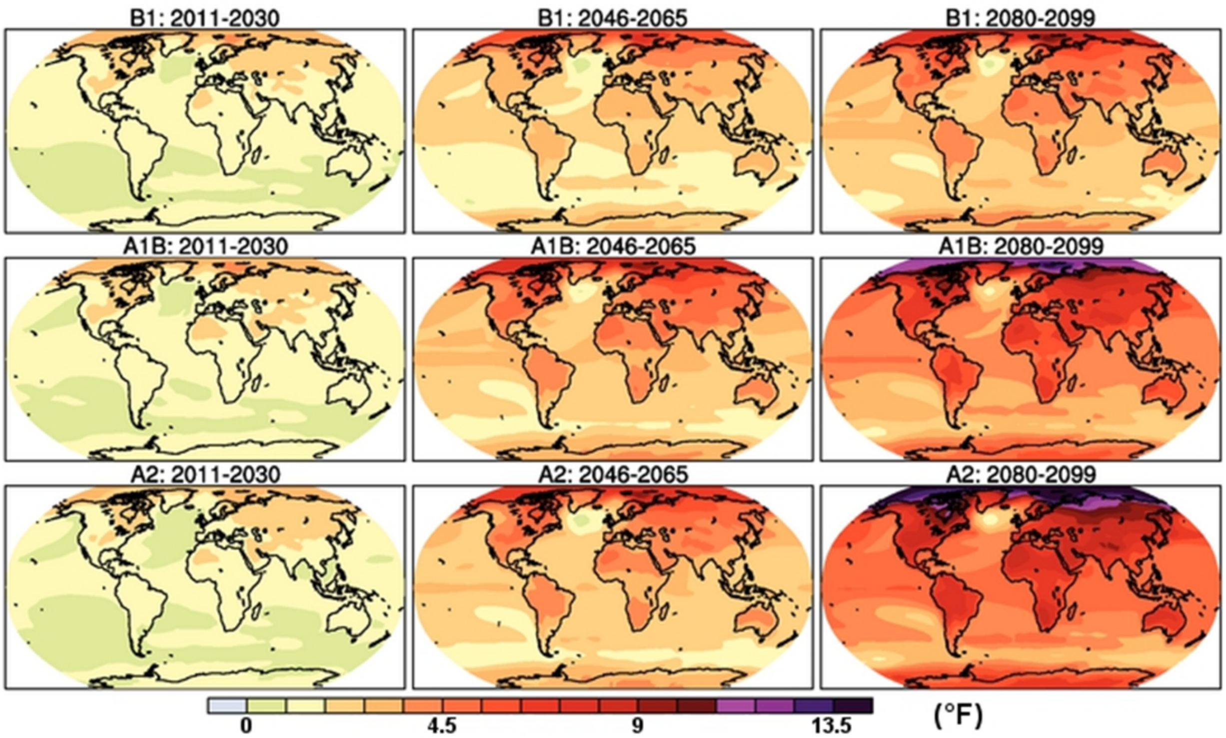


Figure 7.13. Projected changes in global average temperatures under three emissions scenarios (rows) for three different time periods (columns). Changes in temperatures are relative to 1961-1990 averages. The scenarios come from the IPCC Special Report on Emissions Scenarios: B1 is a low emissions scenario, A1B is a medium-high emissions scenario, and A2 is a high emissions scenario. Source: IPCC Working Group I: The Physical Science Basis, 2007.

Changes in precipitation occur due to a variety of factors, including changes in atmospheric water vapor content due to changing temperature, as discussed above. Also at play is the heightened **evaporation** rate of water on Earth's surface under warmer temperatures. More evaporation leads to more precipitation. Finally, shifts in wind patterns impact the distribution of precipitation events. As you can see in Figure 7.14, there are some areas of the globe that are expected to have an increase in precipitation, while others are expected to have a dramatic decrease. Some major population centers projected to have a moderate to severe precipitation increase include (population estimates of the metropolitan area given in parentheses): New York, United States (20.1 million); Bogotá, Colombia (12.1 m.); and Manila, Philippines (11.9 m.). What sort of challenges might these cities face in the future as they deal with this change in their climate?

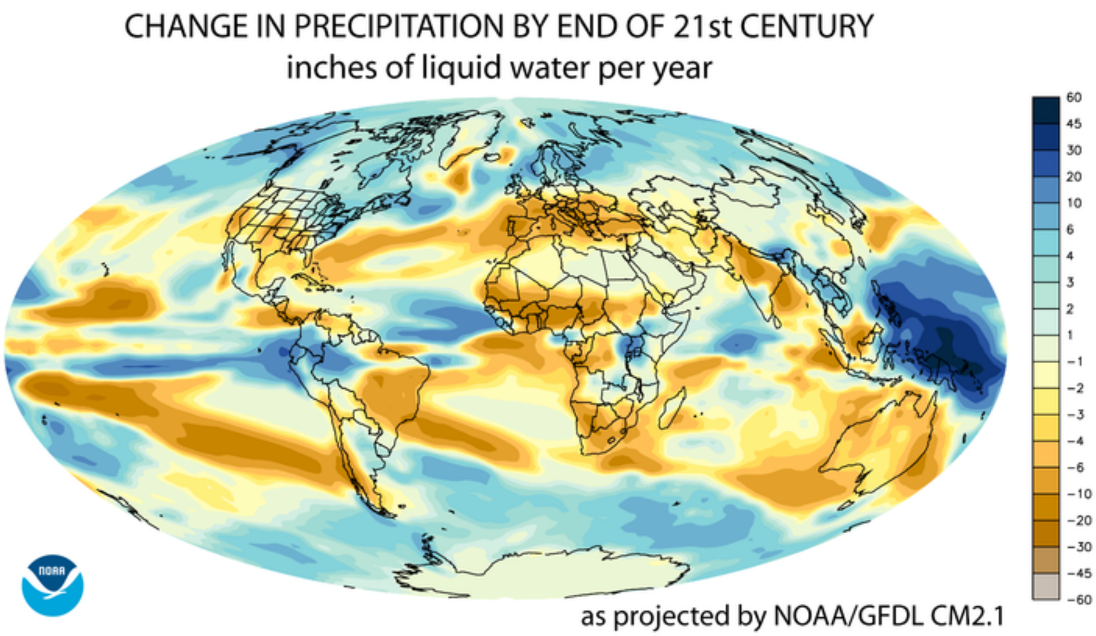


Figure 7.14. Change in annual average precipitation projected by the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) by the GFDL CM2.1 model for the 21st century based on the A1B emissions scenario (see Figure 7.13). The plotted precipitation differences were computed as the difference between the 2081 to 2100 20-year averages minus the 1951 to 2000 50-year average. Blue areas project increases in precipitation; brown areas project decreases.

In contrast, many more major metropolitan areas are projected to have a moderate to severe precipitation decrease (droughts) by the end of the 21st century. These include Delhi, India (21.8 m.); Lagos, Nigeria (21 m.); São Paulo, Brazil (20.9 m.); Kolkata, India (14.6 m.); Istanbul, Turkey (14.4 m.); Los Angeles, United States (13.3 m.); Rio de Janeiro, Brazil (12 m.); Paris, France (12 m.); and Lahore, Pakistan (11.3 m.). The largest challenge that these areas are likely to face is a dwindling water supply for drinking and agriculture. See Chapter 8 for more detail on challenges faced by societies to supply clean, reliable water to their populations and farms.

Additional challenges may be felt by all areas of the world with regard to changes in the seasonality or timing of precipitation, as well the form in which precipitation falls (e.g., mist or downpour; rain, ice, or snow). All of these factors affect the availability of soil water for plants, the flow of rivers and streams, and the overall accessibility of water worldwide. Furthermore, scientists predict an increase in the number and severity of storms as climate change progresses. For a full discussion of the potential impacts of this, see the assigned article.

Sea level rise

While we know that water continuously cycles around the world (see Chapter 8 for information on the water cycle), and that the overall quantity of water on Earth will not change due to global climate change, the distribution of this water is changing. In particular, oceans are increasing in volume while land ice stores (such as **glaciers**) are decreasing. This contributes to an increase in sea level worldwide (Figure 7.15).

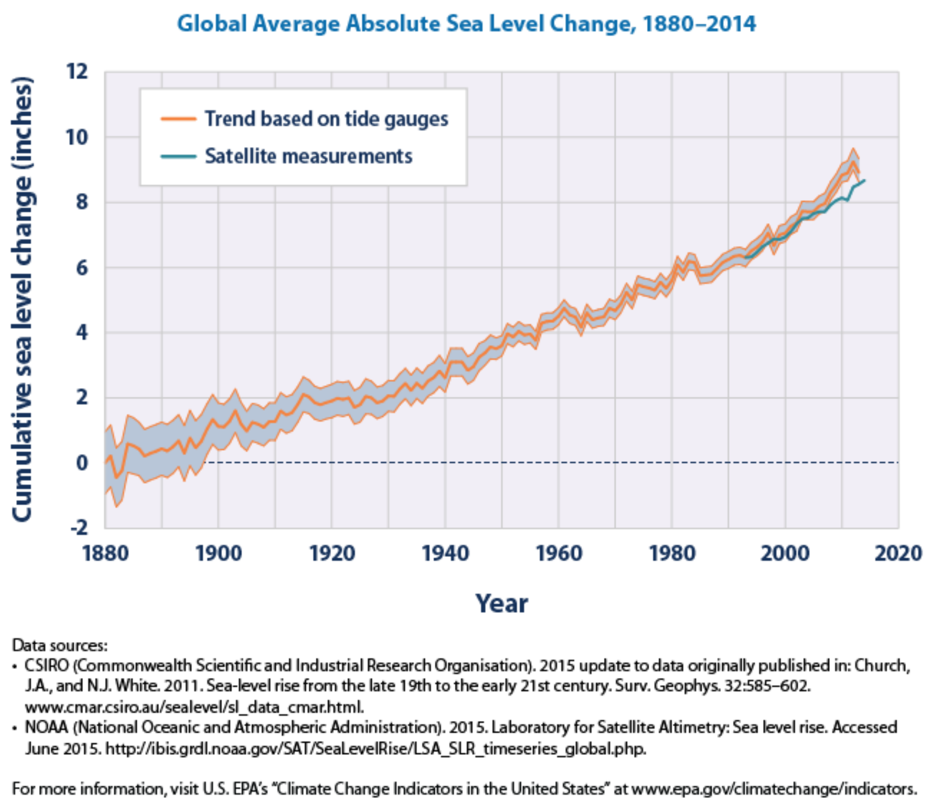


Figure 7.15. This graph shows average absolute cumulative changes in sea level for the world's oceans since 1880, based on a combination of tide gauge measurements and recent satellite measurements. The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used.

From the data in Figure 7.15, we see that sea level has increased at an average of 0.06 inches (0.15 cm) per year over the time period shown above. Most of this rise, however, has occurred within the most recent decades. The rate of increase has gone up to between 0.11 to 0.14 inches

(0.28 to 0.36 cm) per year since 1993. There are two forces causing sea level to rise, both caused by climate change. First, the increased global temperature has caused increased ice melting in many regions of the globe. Melting **land ice** (such as the glacier shown in figure 7.16) contributes to sea level rise because water that used to be stored in ice sitting on top of land becomes running water which reaches the ocean through **runoff**. We also observe **sea ice** melting (see http://www.epa.gov/climatechange/science/indicators/index.html for data and figures). Sea ice, such as the ice that covers the arctic regions of the Northern Hemisphere, has no land underneath it. When it melts, the water stays in the same locations, and the overall sea level does not change.

Photographs of McCall Glacier, Alaska, 1958 and 2003

Sources:
- Post, A. 1958. McCall Glacier. Glacier photograph collection. Boulder, Colorado: National Snow and Ice Data Center/World Data Center for Glaciology. http://nsidc.org/data/g00472.html.
- Nolan, M. 2003. McCall Glacier. Glacier photograph collection. Boulder, Colorado: National Snow and Ice Data Center/World Data Center for Glaciology. http://nsidc.org/data/g00472.html.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climatechange/indicators.

The second factor that influences sea level rise is a phenomenon called **thermal expansion**. Due to the physical properties of water, as water warms, its density decreases. A less dense substance will have fewer molecules in a given area than a more dense substance (see Chapter 1 supplemental material). This means that as the overall temperature of the oceans increases due to global climate change, the same amount of water molecules will now occupy a slightly larger volume. This may not seem significant, but considering the 1.3 billion trillion liters (264 billion gallons) of water in the ocean, even a small change in density can have large effects on sea level as a whole.

Scientists have already documented sea level rise in some areas of the world, including one familiar to most of us: the Southeastern United States. Figure 7.17 depicts the measured land area lost due to increasing sea level since 1996. Note that the Southeast (defined here as the

Atlantic coast of North Carolina south to Florida) is particularly susceptible to land area loss due to the gently sloping nature of our coastline. Moving northward into the Mid-Atlantic States (defined here as Virginia north to Long Island, New York), coastal habitats tend to have a steeper geography, which protects against some losses.

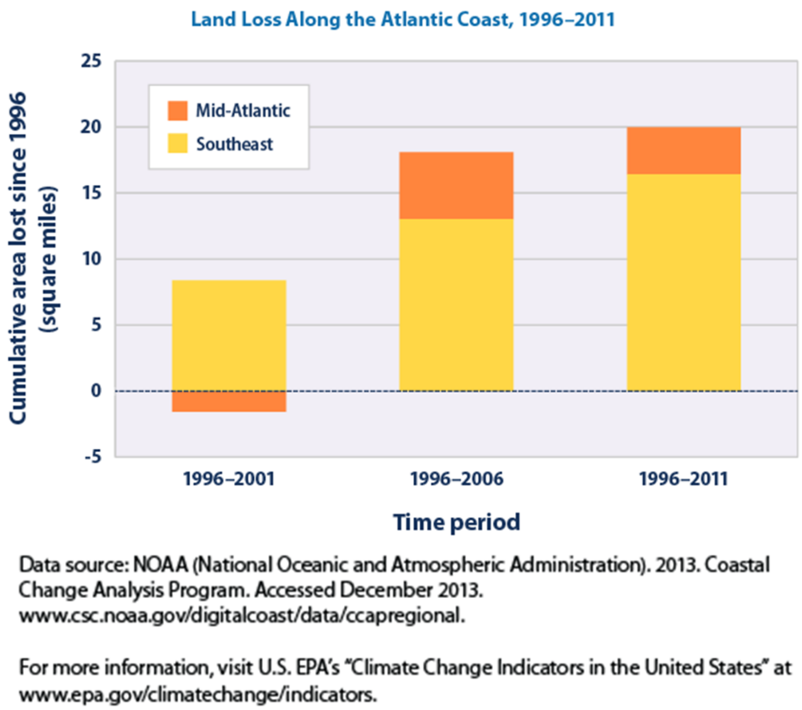


Figure 7.17. This graph shows the net amount of land converted to open water along the Atlantic coast during three time periods: 1996–2001, 1996–2006, and 1996–2011. The results are divided into two regions: the Southeast and the Mid-Atlantic. Negative numbers show where land loss is outpaced by the accumulation of new land.

While the ecological effects of sea level rise remain in the United States, we don't project any catastrophic loss of life, property, or livelihood for some time. This is, in part, due to large investments that we have made in infrastructure to protect our cities and farmlands. This is not the case in many areas of the world. For a discussion of the impacts of sea level rise on less-industrialized nations of Bangladesh, Maldives, Kiribati, and Fiji, review the required article reading.

Ocean acidification

Dissolved CO_2 is essential for many organisms, including shell-building animals and other organisms that form a hard coating on their exterior (e.g., shellfish, corals, Haptophyte algae). This hard coating is built out of **aragonite**, a mineral form of the molecule **calcium carbonate**,

$CaCO_3$. These organisms rely on the formation of **carbonate** ions (see Chapter 1 supplemental material for information on ions), CO_3^{2-}, from dissolved CO_2, through a natural, chemical reaction that occurs. This takes place through a chain-reaction equation, where **bicarbonate** (HCO_3^-) is formed as an intermediate, and **hydrogen ions** (H^+) are generated (equations 7.3 and 7.4).

$$CO_2 + H_2O \leftrightarrow H^+ + HCO_3^- \qquad \textbf{Eq. 7.3}$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \qquad \textbf{Eq. 7.4}$$

To have a better visualization of this process, follow along with the interactive graphic at: http://www.whoi.edu/home/oceanus_images/ries/calcification.html.

As you can see, both equations 7.3 and 7.4 each produce one H^+. This is significant to water chemistry because an increase in H^+ concentration means a decrease in the **pH** of the water. You can see in Figure 7.18 that a lower pH means that the liquid is more **acidic**. As shown in the interactive graphic, an increase in CO_2 in the atmosphere causes additional CO_2 to be dissolved in the ocean. This means that more CO_2 in the atmosphere leads to more acidic ocean environments.

Unfortunately for shell-building animals, the buildup of H^+ in the more acidic ocean environment blocks the absorption of calcium and CO_3^{2-}, and makes the formation of aragonite more difficult. An aragonite deficit is already being documented in many of the world's oceans, as shown in Figure 7.19.

The increasing acidity of the world's oceans is resulting in habitat changes across the globe. This is only expected to worsen as atmospheric CO_2 levels continue to increase. Many organisms, including the corals that are the foundation species of the beautiful coral reefs, are very sensitive to changes in ocean pH. Scientists have documented cases of ecosystem destruction through **coral bleaching**, caused by the effects of climate change including ocean acidification and increased temperature. For

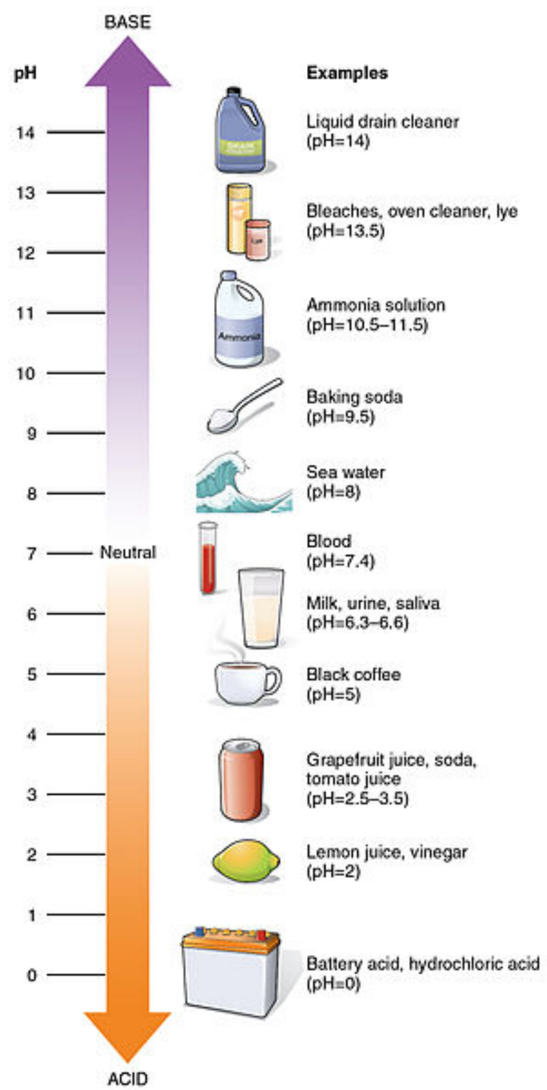


Figure 7.18. The pH scale and relative acidity. Illustration from Anatomy & Physiology, Connexions Web site. http://cnx.org/content/col11496/1.6/, Jun 19, 2013.

more information, visit the NOAA Coral Reef Conservation Program website: http://coralreef.noaa.gov/threats/climate/.

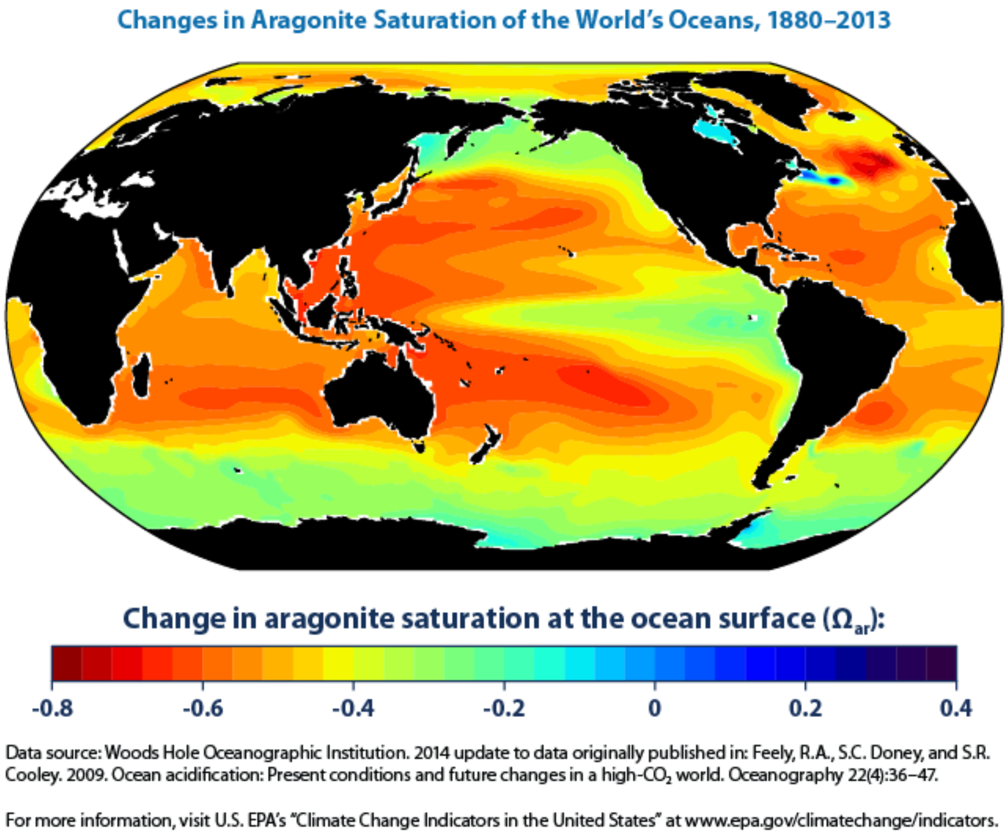


Figure 7.19. This map shows changes in the aragonite saturation level of ocean surface waters between the 1880s and the most recent decade (2004–2013). Aragonite is a form of calcium carbonate that many marine animals use to build their skeletons and shells. A negative change represents a decrease in saturation.

Looking Forward: Climate Solutions

While the situation surrounding global climate change is in serious need of our attention, it is important to realize that many scientists, leaders, and concerned citizens are making solutions to climate change part of their life's work. The two solutions to the problems caused by climate change are **mitigation** and **adaptation**, and we will likely need a combination of both in order to prosper in the future.

Adaptation strategies

We know that climate change is already occurring, as we can see and feel the effects of it. For this reason, it is essential to also adapt to our changing environment. This means that we must change our behaviors in response to the changing environment around us. Some adaptation strategies are discussed in the required article reading.

Adaption strategies will vary greatly by region, depending on the largest specific impacts in that area. For example, in the city of Delhi, India, a dramatic decrease in rainfall is projected over the next century (Figure 7.14). This city will likely need to implement policies and practices relating to conservation of water, for example: rainwater harvesting, water re-use, and increased irrigation efficiency. Rain-limited cities near oceans, such as Los Angeles, California may choose to use **desalination** to provide drinking water to their citizens. Desalination involves taking the salt out of seawater to make it potable (Chapter 8).

Cities with low elevations near oceans may need to implement adaptation strategies to rising sea levels, from seawalls and levees to relocation of citizens. One adaptations strategy gaining use is the creation or conservation of **wetlands**, which provide natural protection against storm surges and flooding.

Mitigation strategies

In general, a strategy to mitigate climate change is one that reduces the amount of greenhouse gases in the atmosphere or prevents additional emissions. Mitigations strategies attempt to "fix" the problems caused by climate change. Governmental regulations regarding fuel efficiency of vehicles is one example of an institutionalized mitigation strategy already in place in the United States and in many other countries around the world. Unlike some other countries, there are no **carbon taxes** or charges on burning fossil fuels in the United States. This is another governmental mitigation strategy that has been shown to be effective in many countries including India, Japan, France, Costa Rica, Canada, and the United Kingdom.

In addition to government measures and incentives, technology can also be harnessed to mitigate climate change. One strategy for this is the use of **carbon capture and sequestration** (CCS). Through CCS, 80-90% of the CO_2 that would have been emitted to the atmosphere from sources such as a coal-fired power plant is instead captured and then stored deep beneath the Earth's surface. The CO_2 is often injected and sequestered hundreds of miles underground into porous rock formations sealed below an impermeable layer, where it is stored permanently (Figure 7.20).

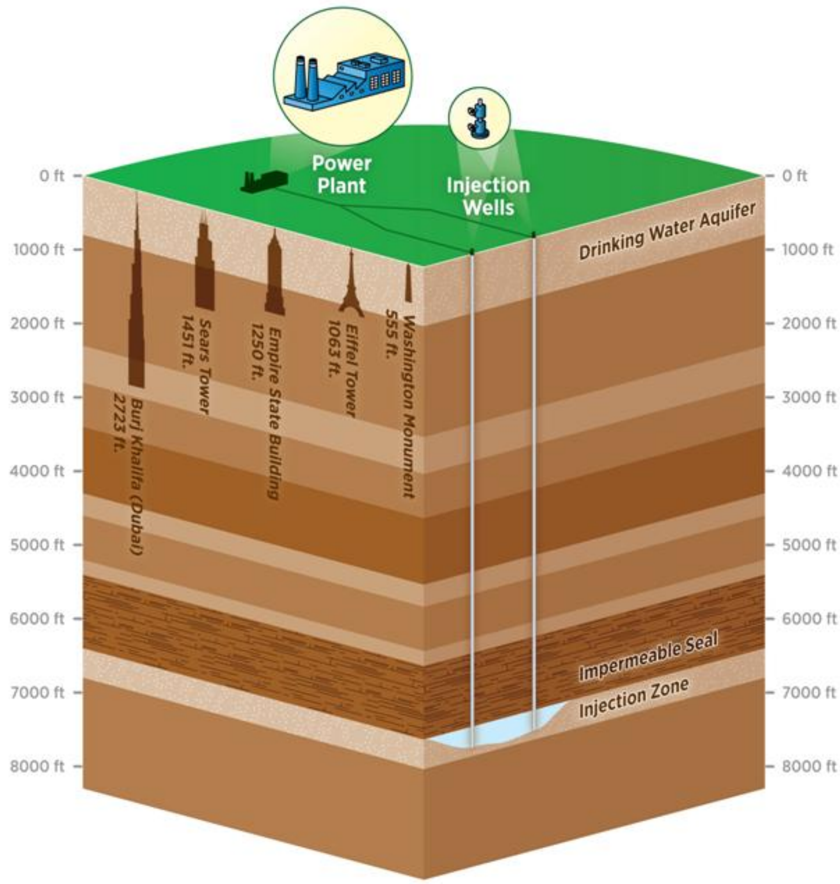


Figure 7.20. Carbon capture and sequestration schematic with landmarks shown to scale for depth reference. Source: US EPA.

Scientists are also looking into the use of soils and vegetation for carbon storage potential. Proper management of soil and forest ecosystems has been shown to create additional carbon sinks for atmospheric carbon, reducing the overall atmospheric CO_2 burden. Increasing soil carbon further benefits communities by providing better-quality soil for agriculture and cultivation.

Technologies related to alternative energy sources (Chapter 5) mitigate climate change by providing people with energy not derived from the combustion of fossil fuels. Finally, simple activities such as energy conservation, choosing to walk or bike instead of driving, and disposing of waste properly are activities that, when done by large numbers of people, actively mitigate climate change by preventing carbon emissions.

Take a moment to identify ways that you personally can be involved in the mitigation of or adaptation to climate change. What changes can you make in your own life to prevent excess carbon emissions? Similar to your ecological footprint, which you should have already calculated in lab, you can also calculate your **carbon footprint**. Use the EPA's carbon footprint calculator to do so, and investigate the Reduce Your Emissions section to find ways to decrease your carbon footprint.

Resources

Belt, Don. "The Coming Storm." *National Geographic Magazine*, May 2011. http://ngm.nationalgeographic.com/print/2011/05/bangladesh/belt-text

IPCC Fourth Assessment Report: Climate Change 2007 Synthesis Report. 4. Adaptation and mitigation options https://www.ipcc.ch/publications_and_data/ar4/syr/en/spms4.html

NOAA Coral Reef Conservation Program: Climate Change http://coralreef.noaa.gov/threats/climate/

NOAA Geophysical Fluid Dynamics Laboratory: Will the wet get wetter and the dry drier? http://www.gfdl.noaa.gov/will-the-wet-get-wetter-and-the-dry-drier

Ontl, Todd and Lisa Schulte (2012) Soil Carbon Storage. Nature Education Knowledge 3(10):35 http://www.nature.com/scitable/knowledge/library/soil-carbon-storage-84223790

US EPA Carbon Dioxide Capture and Sequestration http://www.epa.gov/climatechange/ccs/

US EPA Carbon Footprint Calculator http://www3.epa.gov/carbon-footprint-calculator/

US EPA Climate Change Indicators in the United States http://www.epa.gov/climatechange/science/indicators/index.html

Terms list

Acidity

Adaptation

Aragonite

Bicarbonate

Calcium carbonate

Carbon capture and sequestration

Carbon footprint

Carbon tax

Carbonate

Climate

Climate change

Coral bleaching

Desalination

Evaporation

Glacier

Global warming

Hydrogen ions

Land ice

Mitigation

pH

Precipitation

Runoff

Sea ice

Thermal expansion

Wetland

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CHAPTER 8: WATER

Learning Objectives

As a result of this unit:

- Students will be able to draw multiple interacting water molecules and identify the bonds and atoms
- Students will explain how the molecular structure of the water molecule contributes to the unique properties of water.
- Students will demonstrate an understanding of how much water is available on Earth and how it is distributed
- Students will be able to compare regional and national responses to water issues.
- Students will be able to explain water-related problems (for example water scarcity, water-borne diseases, water pollution, flooding) from different regions of the world
- Students will be able to explain how human modifications of natural water systems can be both beneficial and destructive
- Students will be able to describe solutions to water-related problems
- Students will be able to read and interpret graphs and charts about water
- Students will demonstrate knowledge of some of the major regulations related to water in the USA
- Students will gain a rudimentary understanding of groundwater flow, management and protection

CHAPTER 8: WATER

This chapter has been adapted from OpenStax (Biology and Concepts in Biology texts), USGS Water Resources, the EPA and The Encyclopedia of Earth

"Whiskey is for drinking. Water is for fighting"

Introduction

Why do scientists spend time looking for water on other planets? Why is water so important? It is because water is essential for life as we know it. Water is one of the more abundant molecules and the one most critical to life on Earth. Approximately 60–70 percent of the human body is made up of water. Without it, life as we know it simply would not exist. The quotation above, which has been attributed to Mark Twain, suggested (by the quote above) that water was extremely important. In recent years, we have seen a rise in conflicts and dispute about water. Fortunately, most of the conflicts have ended up in the courts instead of the battlefields. This chapter is devoted to this precious resource that sustains our planet and its living things.

Chapter outline:

1. Properties of water
    a. hydrogen bonding
    b. Physical state of water
    c. Heat capacity
    d. Heat of Vaporization
    e. Universal Solvent
    f. Cohesion and Adhesion

2. Global Water Distribution and Use
3. The Hydrologic Cycle
4. Components of the Hydrologic Cycle
    a. Atmosphere and precipitation
    b. Rivers and Streams
    c. Lakes, Ponds and reservoirs
    d. Wetlands
    e. Oceans
    f. Groundwater
5. Water Scarcity and Shortage
6. Water Pollution and Quality
    a. Types of water pollution
    b. Sources of water pollution
7. Water Management
    a. Water pollution control
    b. Watershed Management
    c. Regulations

Water

Water is an important commodity for life on Earth and is something we all need in our daily activities. It is referred to by many people as the "essence of life", "blue gold" and "more precious than oil". What makes water so important is its unique and special properties. These special properties of water include water's high heat capacity and heat of vaporization, its ability to dissolve numerous polar molecules, its cohesive and adhesive properties, and its dissociation into ions that leads to the generation of pH. Understanding these characteristics helps us understand and appreciate its importance in maintaining life on Earth. Before we discuss these properties, we will review the molecular structure of water, which gives rise to these special properties.

Properties of Water

A water molecule is composed of one oxygen and two hydrogen atoms that are joined together by **polar covalent** bonds. Covalent mean that the atoms share electrons, instead of completely giving up electrons to one another. **Polar** means that the electrons are not shared equally. These polar covalent bonds (**Figure 8.1**), along with the molecular shape, cause the water molecule to have a slightly positive charge on the hydrogen end and a slightly negative charge on the oxygen side. Water's charges are generated because oxygen is more electronegative than hydrogen, making it more likely that a shared electron would be found near the oxygen nucleus than the hydrogen nucleus, thus generating the partial negative charge near the oxygen. This gives water molecules their properties of attraction.

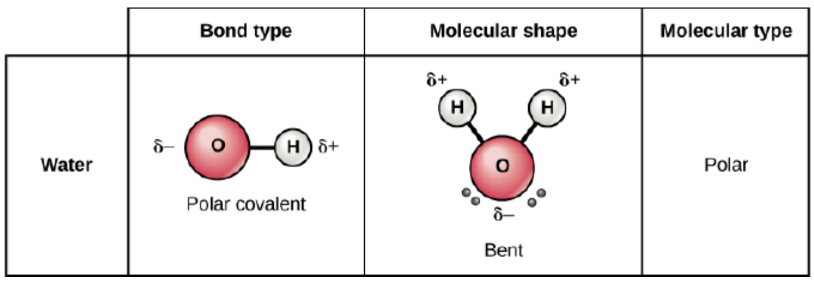

Figure 8.1: Polarity of the water molecule due to the uneven distribution of electrons in its covalent bond. C (From OpenStax Concepts of Biology text)

Hydrogen Bonds

Due to water's polarity, each water molecule attracts other water molecules as oppositely charged ends of the molecules attract each other. When this happens, a weak interaction occurs between the *positive* hydrogen end from one molecule and the *negative* oxygen end of another molecule. This interaction is called a **hydrogen bond**. This hydrogen bonding contributes to the following water's unique properties.

1. Water is the universal solvent
2. Exists in nature as a solid, liquid, and gas
3. The density of ice is less than liquid water
4. Water has a high surface tension
5. Water has a high heat capacity
6. Water exists as a liquid at room temperature

It is important to note here that even we are only focusing on water in this text book, hydrogen bonding also occurs in other substances that have polar molecules**.**

Physical State of Water on Earth

Water on Earth can naturally exist as either solid, liquid or gas depending on the prevailing temperature and pressure conditions. The formation of hydrogen bonds (described above) is an important quality of liquid water that is crucial to life as we know it on Earth. As water molecules make hydrogen bonds with each other, liquid water takes on some unique physical and chemical characteristics when compared to other liquids. In liquid water, hydrogen bonds are constantly being formed and broken as the water molecules slide past each other. The energy of the moving water molecules (kinetic energy) is responsible for breaking the bonds. When heat is added to water (increasing temperature), the kinetic energy of the molecules goes up and more bonds are broken. As more heat is added to boiling water, the higher kinetic energy of the water molecules causes the hydrogen bonds to break completely and allow them to escape into the air as water vapor. On the other hand, when the temperature of water is reduced and water freezes, the water molecules form a crystalline structure maintained by hydrogen bonding (since there isn't enough energy to break the hydrogen bonds). The crystalline structure, ice, has a more open structure than the liquid form of water. The open structure of ice (Figure 8.2) makes ice less dense than liquid water, a phenomenon not seen in the solidification of other liquids.

The lower density of ice, illustrated in Figure 8.2, causes it to float at the surface of liquid water, such as an iceberg in the ocean or ice cubes in a glass of ice water. In lakes and ponds, ice will form on the surface of water creating an insulating barrier that protects animals and plant life that live in the water from freezing. Without this layer of insulating ice, plants and animals living in the water would freeze in the solid block of ice and not survive. The ice crystals that form upon freezing would rupture the delicate membranes essential for the function of living cells, irreversibly damaging them.

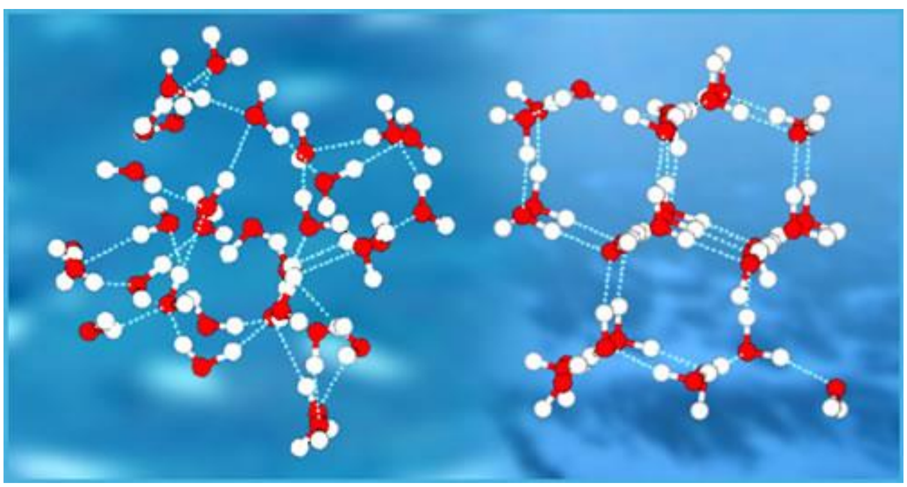

Figure 8.2: Hydrogen bonding makes ice less dense than liquid water. The lattice structure water is more condensed (left structure) than that of ice (right structure). The lattice structure of ice makes it less dense than freely flowing molecules of liquid water, enabling ice to float on liquid water. (Image credit: Lynn Yarris, http://www2.lbl.gov/Science-Articles/Archive/sabl/2005/February/water-solid.html)

High Heat Capacity

Water has the highest **specific heat capacity** of any liquid. Water's high heat capacity is a property caused by hydrogen bonding among the water molecules. **Specific heat** is defined as the amount of heat one gram of a substance must absorb or lose to change its temperature by one degree Celsius. For water, this amount is one **calorie**. It takes water a long time to heat up and a long time to cool down. In fact, the specific heat capacity of water is about five times more than that of sand. This explains why land cools faster than the sea. Due to its high heat capacity, warm blooded animals use water to disperse heat more evenly and maintain temperature in their bodies: it acts in a similar manner to a car's cooling system, transporting heat from warm places to cool places, causing the body to maintain a more even temperature.

Heat of Vaporization

Water also has a high **heat of vaporization**, the amount of energy required to change one gram of a liquid substance to a gas. A considerable amount of heat energy (586 calories) is required to accomplish this change in water. This process occurs on the surface of water. As liquid water heats up, hydrogen bonding makes it difficult to separate the liquid water molecules from each other, which is required for it to enter the gas phase (steam). Thus, water acts as a heat sink and requires much more heat to boil than liquids such as ethanol, whose hydrogen bonds are weaker. Eventually, as water reaches its boiling point of 100° Celsius (212° Fahrenheit), the heat can break the hydrogen bonds between the water molecules, and the kinetic energy between the water molecules allows them to escape from the liquid as a gas. Even when below its boiling point, water's individual molecules acquire enough energy from other water molecules such that some surface water molecules can escape and vaporize: this process is known as **evaporation**.

Since hydrogen bonds need to be broken for water to evaporate means that a substantial amount of energy is used in the evaporation process. As the water evaporates, energy is taken up by the process, cooling the environment where the evaporation is taking place. In many living organisms, including in humans, the evaporation of sweat, which is 90 percent water, allows the organism to cool so that homeostasis of body temperature can be maintained.

Water is a Solvent

Since water is a polar molecule with slightly positive and slightly negative charges, ions and polar molecules can readily dissolve in it. Water is, therefore, referred to as a **solvent**, because it is capable of dissolving more substances (polar substances) than any other liquid. The charges associated with these molecules will form hydrogen bonds with water, surrounding the particle with water molecules. This is very important as it enables water to dissolve various chemicals and distribute them within living organisms, including taking toxic substances out of living things, and in the environment.

Water's Cohesive and Adhesive Properties

Have you ever filled a glass of water to the very top and then slowly added a few more drops? Before it overflows, the water forms a dome-like shape above the rim of the glass (Figure 8.3)

Figure 8.3. Water in a glass form a dome shape above the glass due to cohesive forces of attraction among water molecules. Photo Credit: Sam Mutiti

This water can stay above the glass because of its **cohesive** properties. In cohesion, water molecules are attracted to each other (because of hydrogen bonding), keeping the molecules together at the liquid-gas (water-air) interface, although there is no more room in the glass. Cohesion allows for the development of **surface tension**, the capacity of a substance to resist rupture when placed under tension or stress. This is also why water forms droplets when placed on a dry surface rather than being flattened out by gravity (**Figure 8.4**)

Figure 8.4. Beading up of water due strong cohesive forces between water molecules (Water USGS, right hand photo credit: J Schmidt; National Park Service).

When a steel needle is placed carefully on water it does not sink even though steel is denser (heavier) than the water. Cohesion and surface tension keep the hydrogen bonds of water molecules intact and support the item floating on the top. It is even possible for an insect to “float” on water if it sits gently without breaking the surface tension, as shown in **Figure 8.5**.

Figure 8.5 The weights of the needle and water strider are pulling the surface downward; at the same time, the surface tension is pulling it up, suspending them on the surface of the water and keeping them from sinking. (Credit: Cory Zanker (left) and Tim Vickers (right)

Another important property of water is **adhesion**, or the attraction between water molecules and other molecules. This attraction is sometimes stronger than water's cohesive forces, especially when water is exposed to charged surfaces such as on the inside of thin glass tubes known as capillary tubes. Adhesion is observed when water "climbs" up the tube placed in a glass of water: notice that the water appears to be higher on the sides of the tube than in the middle. This is because the water molecules are attracted to the charged glass walls of the capillary tube more than they are to each other and, therefore, adhere to it. This type of adhesion is called **capillary action**, and is illustrated in **Figure 8.6**. This process is also involved in the movement of water and nutrients from the soil around the root systems to other parts of plants above the ground.

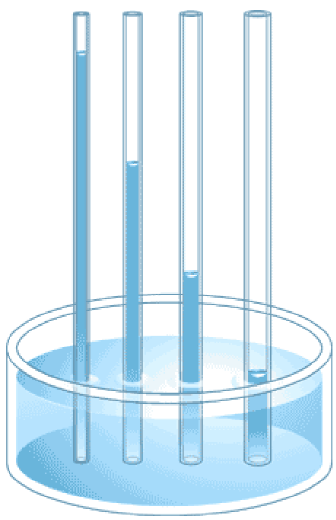

Figure 8.6: Capillary action in a glass tube is caused by the adhesive forces exerted by the internal surface of the glass exceeding the cohesive forces between the water molecules themselves. (Credit: http://moodle.clsd.k12.pa.us/district_videos/Biology/iText/products/0-13-115540-7/ch23/ch23_s5_1.html)

Global Water Distribution and Use

Most of the water on the planet is in oceans and unavailable for human consumption due to its high salinity (**Figure 8.7**).

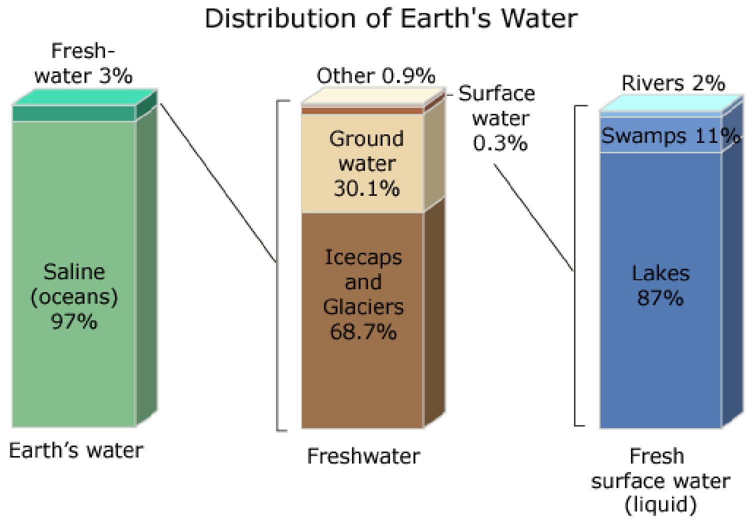

Figure 8.7: Graphical representation of available water:
http://water.usgs.gov/edu/earthwherewater.html

Of all the water in the world, only about 0.64% is fresh water that is available for consumption (the other fresh water is locked up in ice). Of this available fresh water, 98.4% is found as groundwater below the surface of the Earth and only 1.4% is surface water in rivers and lakes.

The largest percentage of water withdrawn in the US goes to thermoelectric cooling (**Figure 8.8**). In some countries, such as Egypt, irrigation accounts for over 70% of water withdrawn. Irrigation is water that is applied by a water system to sustain plant growth. Irrigation also includes water that is used for frost protection, application of chemicals, weed control, field preparation, crop cooling, harvesting, dust suppression, and leaching salts from the root zone.

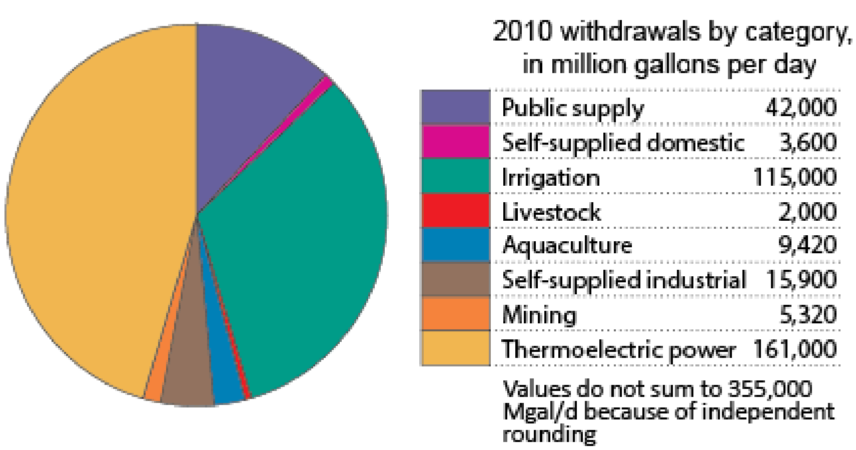

Figure 8.8: Estimated 2010 water withdrawals. Irrigation and thermoelectric power usages account for most water withdrawals. http://water.usgs.gov/watuse/images/category-pages/2010/total-category-pie-2010.png
More water use terminology can be found at: http://water.usgs.gov/watuse/wuglossary.html

The Hydrologic Cycle

The major water reservoirs on Earth are oceans, glaciers, groundwater, rivers, and lakes. Water spends different amounts of time in the various reservoirs. The main factors that control the amount of time water stays in a reservoir are the amount of water in the reservoir and how fast water moves in and out. The hydrologic cycle (water cycle) represents a continuous global cycling of water from one reservoir to another **8.9**.

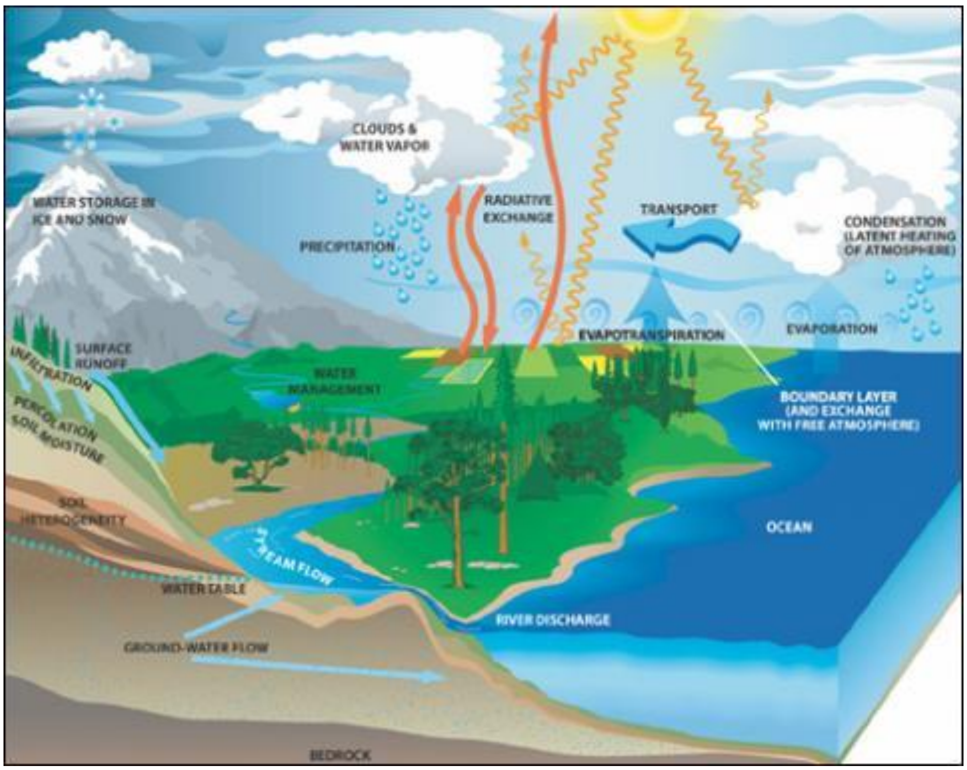

Figure 8.9: The water cycle at the global scale showing water moving through all the major reservoirs, including the ocean reservoir (source https://science.nasa.gov/earth-science/oceanography/ocean-earth-system/ocean-water-cycle).

To gain a deeper appreciation of the water cycle, let us follow a water molecule through the water cycle. Starting in the ocean (an arbitrary starting point) the water molecule can become part of the water that is converted into vapor and enter the atmosphere. Heat energy from the sun, which drives the water cycle, heats water in the oceans and cause evaporation. Evaporation is the process by which water changes from a liquid to a gas or vapor. Evaporation is the primary pathway that water takes from the liquid state back into the water cycle as atmospheric water vapor. Nearly 90% of moisture in the atmosphere comes from evaporation, with the remaining 10% coming from transpiration. **Transpiration** is the process by which moisture is carried through plants from roots to small pores (**stoma**) on the underside of leaves, where it changes to vapor and is released to the atmosphere. Transpiration is essentially evaporation of water from plant leaves. Rising air currents take the vapor up into the atmosphere, along with water from **evapotranspiration,** which is a combination of water transpired from plants and that evaporated from the soil. The vapor rises into the air where cooler temperatures cause it to condense into clouds. **Condensation** is the process by which water vapor is converted from gaseous state back into liquid state. Clouds might eventually grow bigger and moist enough to release the water molecule in the form of **precipitation**. Precipitation is water falling from the clouds in the atmosphere in form of ice (snow, sleet, hail) or liquid (e.g. rain, drizzle). Precipitation that falls as snow can accumulate as ice caps and glaciers.

Did you know that the largest glacier on Earth is the Severny Island ice cap in the Russian Arctic?

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Precipitation that falls as liquid usually ends up as **surface flow** and **stream flow**. **Surface runoff** is precipitation which travels over the soil surface to the nearest stream channel. **Stream flow** is the movement of water in a natural channel, such as a river. Most precipitation falls directly onto the ocean and returns the water molecule back to restart the journey. This is also true for surface runoff, most of the water eventually returns to the ocean via stream flow. This also returns the water molecule back the ocean to start the journey again.

A portion of the water that falls as precipitation can enter lakes where it can evaporate back into the atmosphere, condense, and fall back as precipitation again. Water in the lake can also be taken up by plants and transpired back into the atmosphere. Some of the water that falls as precipitation can infiltrate into the ground and become part of groundwater. **Infiltration** is the process by which water enters the subsurface by gravitation pull. Some of the water infiltrates into the ground and replenishes **aquifers** (saturated subsurface rock), which store huge amounts of freshwater for long periods of time. Some infiltration stays close to the land surface and can seep back into surface-water bodies (and the ocean) as **groundwater discharge**, and some groundwater finds openings in the land surface and emerges as freshwater **springs.** Plant roots absorb yet more groundwater to end up as evapotranspiration from the leaves. Over time, though, all this water keeps moving and most of it ends up in the ocean.

Components of the Hydrologic Cycle

Most precipitation falls in the form of rain but there are other forms such as snow, hail, and sleet. Once it runs sufficiently, surface water runoff is generated when the ground is saturated or impervious. **Surface water** is a major component of the hydrological cycle and one that we interact with very regularly. It includes lakes, wetlands, stormwater **runoff** (overland flow), ponds, potholes, rivers and streams.

Streams and Rivers

A river forms from water moving from a higher altitude to lower altitude, under the force of gravity. When rain falls on the land, it either evaporates, seeps into the ground or becomes runoff (water running on the surface). When water runs on the land surface it usually converges as it moves towards lower elevation. The converging runoff can concentrate into single channels of conveyance called creeks, stream, or rivers. Usually these start as small rill and rivulets that would join up downhill into larger streams and creeks which can also join up downstream to form even bigger rivers. The streams and rivers that join up to form a larger river are called **tributaries, Figure 8.10**. The land area drained by a river and all its tributaries is called a **watershed** or catchment or river basin

The area adjacent to a river that floods frequently is a called a floodplain. **Floodplains** are areas that rivers use to temporarily store excess water during storm events and frequently contain very fertile soils. This has historically encouraged humans to move into floodplains and use them for agriculture, resulting in a reduction in the capacity of the floodplain to act as temporally storage for excess water during storm events, causing increased damaging flooding downstream. Properly functioning floodplains reduce the negative impacts of floods (by reducing severity of flood), and they assist in filtering stormwater and protecting the water quality of rivers. They also act as areas of recharge for groundwater.

A

B

C

Figure 8.10: River systems. (A) A river with a small tributary (B) A meandering river with a mature floodplain (C) A satellite image of river system with multiple tributaries (Source USGS)

The US has numerous rivers that run throughout the nation's landscape. It is estimated that the US has over 200, 000 rivers with the Mississippi River being the largest by volume despite it only being the second longest. The Missouri River is the longest river in US. Most states have at least one important river. In Georgia, the main rivers are the Flint, Ochlockonee, Suwannee, Saint Marys, Satilla, Ogeechee, Altamaha, Oconee, Savannah, Chattahoochee, Tallapoosa, Coosa, Ocmulgee and the Tennessee rivers (**Figure 8.11**).

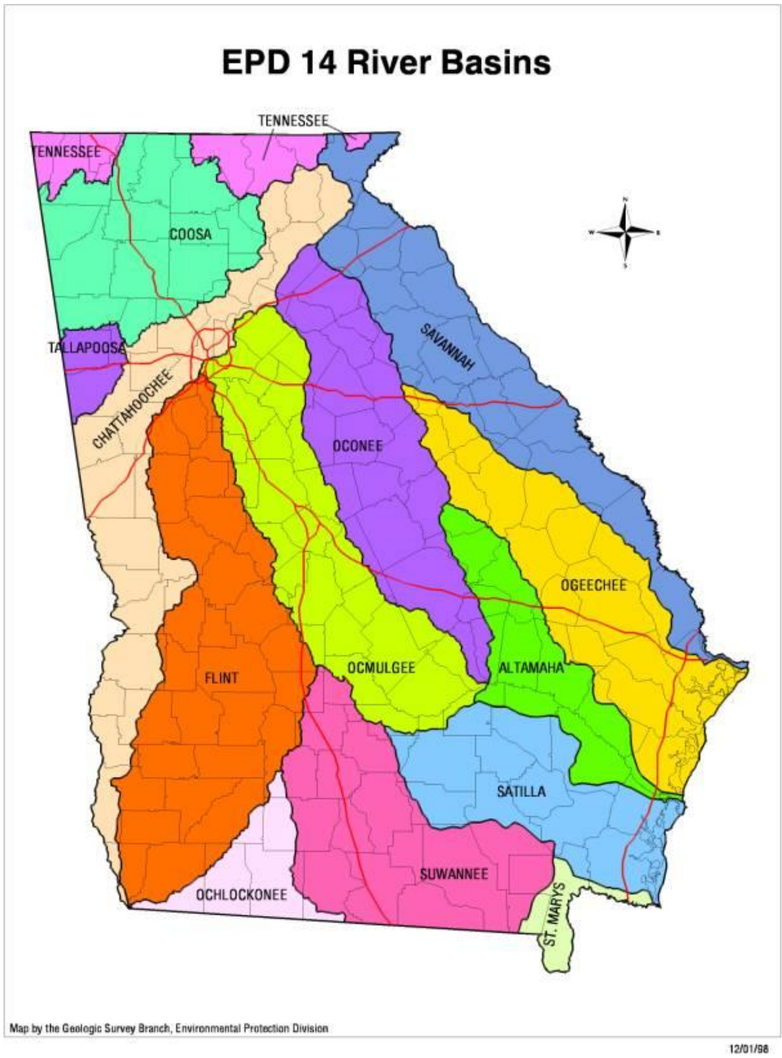


Figure 8.11: Major watershed of Georgia representing the main rivers in the state. (Source Georgia Environmental Protection Division: georgiaadoptastream.com)

These rivers are very important for supplying water to the cities and populations of the states. The rivers also contain important biological communities and provide opportunities for recreation such as swimming, fishing, and white water rafting. Rivers are so important and largely control settlement patterns all over the world. Major cities, communities, factories, industries, and power stations are located along rivers. It is, therefore, very important to protect the quality and integrity of rivers all over the world.

Unfortunately, most of the rivers in the world are too polluted to support certain human activities, especially swimming, fishing, and drinking. Close to half of the rivers in the US have been deemed too polluted to support swimming and fishing. A lot of the rivers have also been channelized, dredged, or impounded by dams which have ruined their ability to support a lot of human and biological activities. It is estimated that over 600, 000 river miles have been dammed in the US. Benefits of dams to humans include providing a source of water (reservoirs and farms ponds), recreation waters and reducing local flooding. On the other side, dams can also have negative impacts on people and the environment. They can lead to increased severe flooding downstream of the dam, especially during high rain events.

The impoundments can trap stream sediments resulting in reduced sediment supply downstream as well as increased deposition behind the dam. This shift in sediments flow can disrupt and damage aquatic habitats and can increase downstream stream erosion due to lack of sediment supply. The impoundments can also prevent certain aquatic organisms from migrating either upstream or downstream, therefore reducing their range and abilities to survive environmental changes as well cutting them off from spawning areas. Construction of dams can also result in displacement of the local people and loss of traditional lands and cultural history. Reservoirs and ponds usually form behind these impoundments.

Lakes, Reservoirs and ponds: If water flows to a place that is surrounded by higher land on all sides, a lake will form (**Figure 8.12**). A lake, pond or reservoir is a body of standing water on the land surface. When people build dams to stop rivers from flowing, the lakes that form are called reservoirs. It is estimated that over 300 million water bodies in the world are lakes, reservoirs, and ponds. Most of the Earth's lakes (about 60%) are found in Canada. Even though lakes and rivers contain less than 1% of the Earths water, the US gets over two thirds (70%) of its water (for drinking, industry, irrigation, and hydroelectric power generation) from lakes and reservoirs. Lakes are also the cornerstone of the US's freshwater fishing industry and are the backbone of the nation's state tourism industries and inland water recreational activities. (http://water.epa.gov/type/lakes/)

Figure 8.12: Lake Sinclair in Baldwin and Putnam counties (Photo Credits: GCSU Hydrology Research lab)

Wetland: A **wetland** is an area which is home to standing water for notable parts of the year, has saturated soils for a large part of the year and has plants that require large amounts of water to survive. Wetlands include swamps, marshes, and bogs. Wetlands are identified using three characteristics: soils (water-saturated soils are present), hydrology (shallow water table) and vegetation (wetland plants that are adapted to areas that are saturated with water for long periods of time). Wetlands are very important areas of biological diversity and productivity. These are also important areas where geochemical and biological cycles/ processes are consistently taking place. For instance, wetlands are considered as areas of significant carbon sequestration (storage), which impacts global climate change. They also act as filters for storm-water runoff before it enters rivers and lakes.

Oceans

As you have probably already guessed, oceans are an important component of the hydrologic cycle because they store majority of all water on Earth (about 95%). Most of the major rivers drain into them. The five oceans covering the surface of the Earth are the Atlantic, Indian, Pacific, Arctic and the Southern Ocean (**Figure 8.13**).

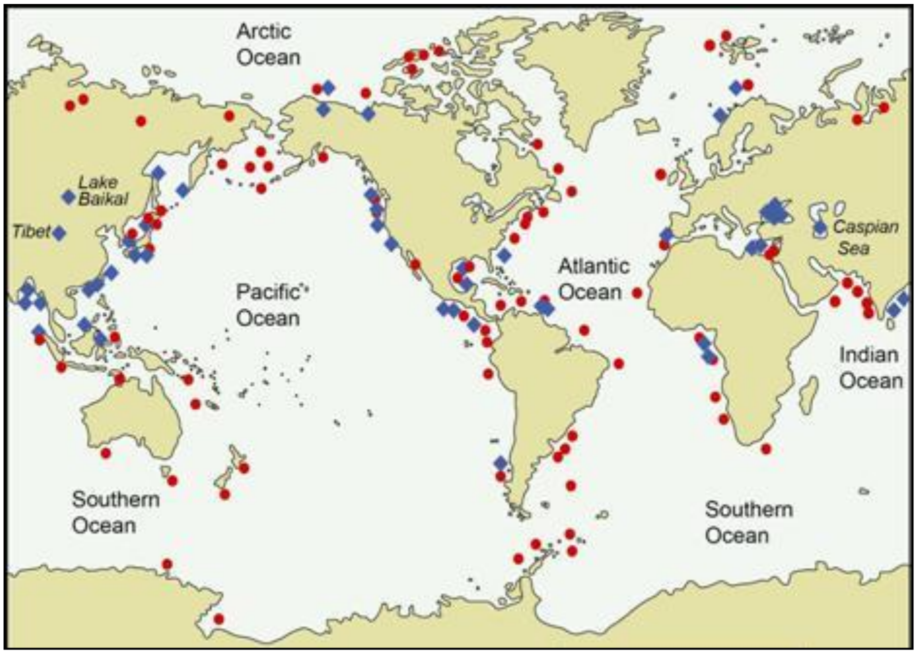


Figure 8.13: The five oceans found on planet Earth. The Pacific Ocean is the largest. Source: https://woodshole.er.usgs.gov/project-pages/hydrates/primer.html

Approximately 90 % of the water that is evaporated into the hydrologic cycle comes from the ocean. Oceans are an important and large part of the hydrologic cycle, with lots biological diversity and many landforms. *Did you know that the average depth of the oceans is about 3.6 km with a maximum depth that can exceed 10 kilometers in areas known as ocean trenches?* The ocean is also home to many forms of life uniquely adapted to survive in this habitat. Unfortunately, humans have degraded the oceans and their life through pollution, overfishing, carbon dioxide acidification and resource exploitation. **Figure 8.14** shows a couple of examples of human impacts on the ocean environment.

From NOAA Libraries

Figure 8.14: Trash washed up on the beach (A) and seal tangles up and being struggled by plastic trash in the ocean (B).

Also watch the video from the Habitable Planet: Oceans Video vhttp://www.learner.org/courses/envsci/unit/text.php?unit=3&secNum=1

Groundwater

Storage and Flow

Almost 99% of the available fresh water is found below the surface as groundwater. Groundwater is not created by some mysterious processes below ground, but is part of the recycled water in the hydrologic cycle. When precipitation falls, some of the water runs off on the surface while some infiltrates into the ground. Groundwater is replenished when water moves from the surface, through unsaturated rocks or sediment (**unsaturated**), all the way down the saturated parts (**saturated zone**) in a process called infiltration and becomes groundwater (**Figure 8.15**). The top of the saturated portion is called the **water table**, which is the boundary between saturated and unsaturated zone.

Groundwater is found in **aquifers**, which are bodies of rock or sediment that store (and yield) large amounts of usable water in their pores. Aquifer productivity is controlled by **porosity** and **permeability**. **Porosity** is the percentage of open space in a rock or sediment body. **Permeability** is the ability of subsurface material to transmit fluids. Groundwater is found in the saturated zone of a rock body where all pores are filled with water. An important concept is that surface water always moves from higher elevation to lower elevation while groundwater always moves from higher energy (hydraulic head) to lower energy.

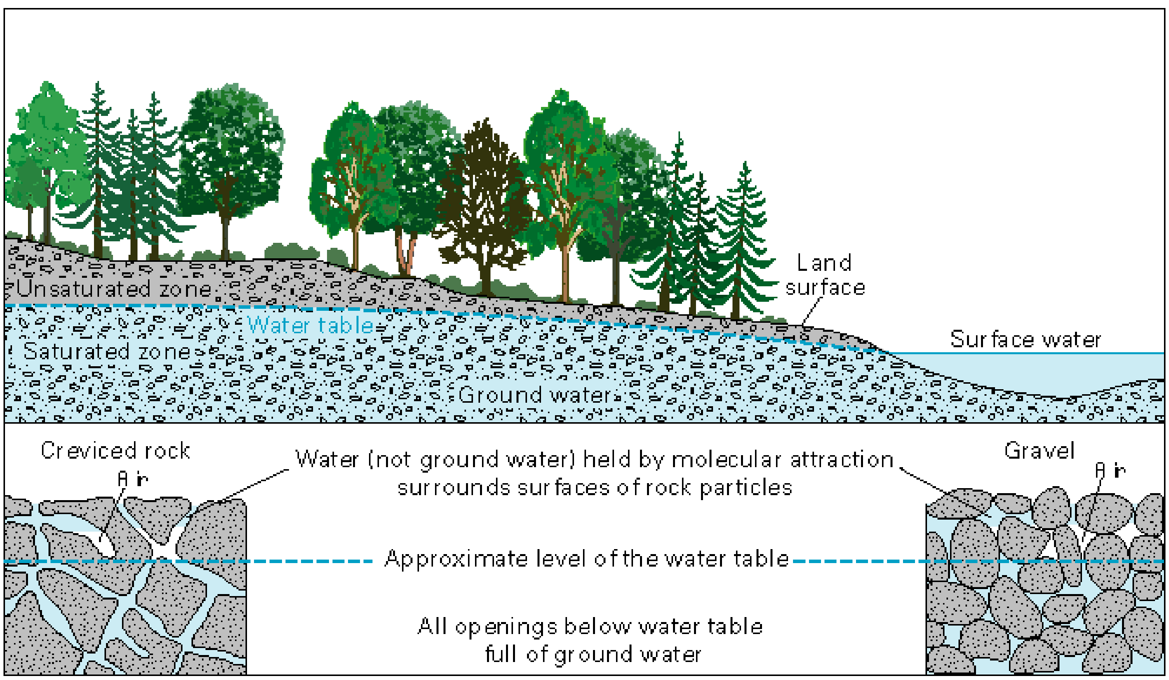
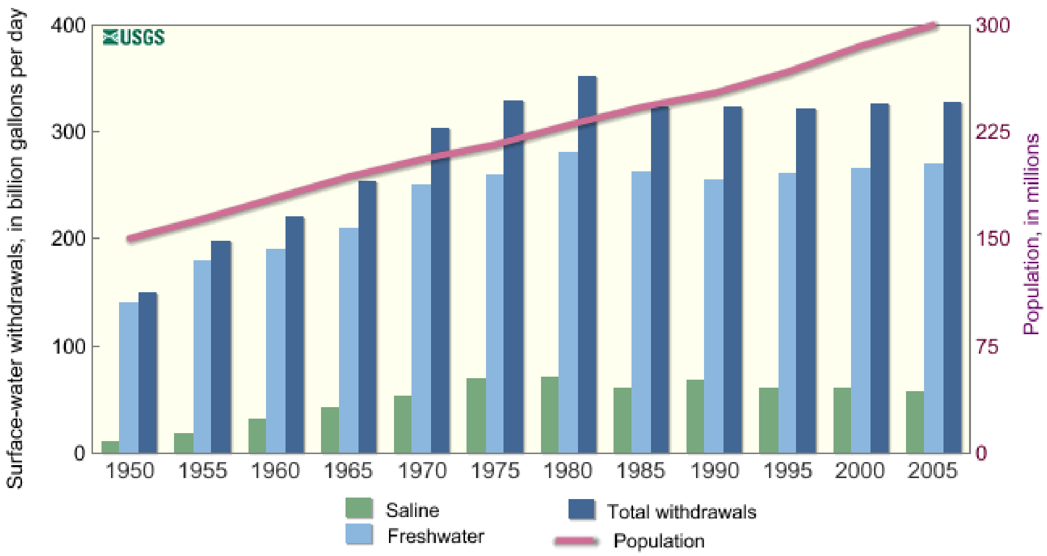


Figure 8.15: Model of groundwater system showing the different components of an unconfined groundwater system: http://water.usgs.gov/edu/earthgwaquifer.html

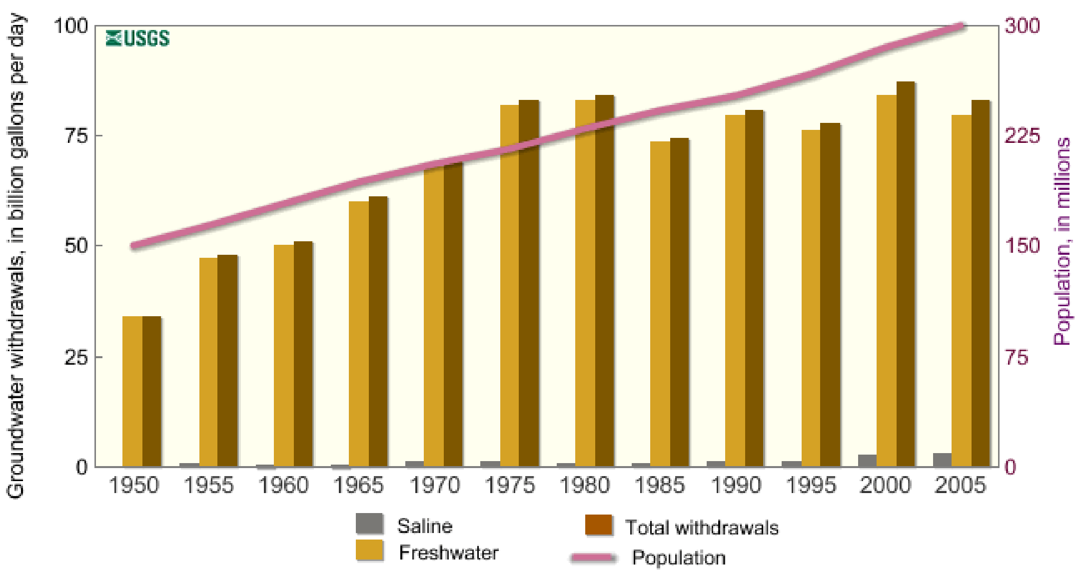
Groundwater will continue to flow until it emerges as a spring, or discharges into surface water bodies on the land or in the ocean. To utilize groundwater, we drill holes (wells) into the ground and pump the water out.

Water Scarcity and Shortage

Water has been identified as one of the major environmental crisis facing the world today. More than one billion people in the world lack access to clean drinking water. The demand for water has grown at a very fast pace in response to the rate of global population growth. **Figures 8.16, and 8.17** illustrate this change in water use over time. It is predicted that over the next two decades, the average supply of water per person will drop by a third.



A)



B)

Figure 8.16: Trends in fresh and saline water withdrawals in response to population growth (A) surface water withdrawals (B) Groundwater withdrawal trends: http://water.usgs.gov/edu/wugw.html

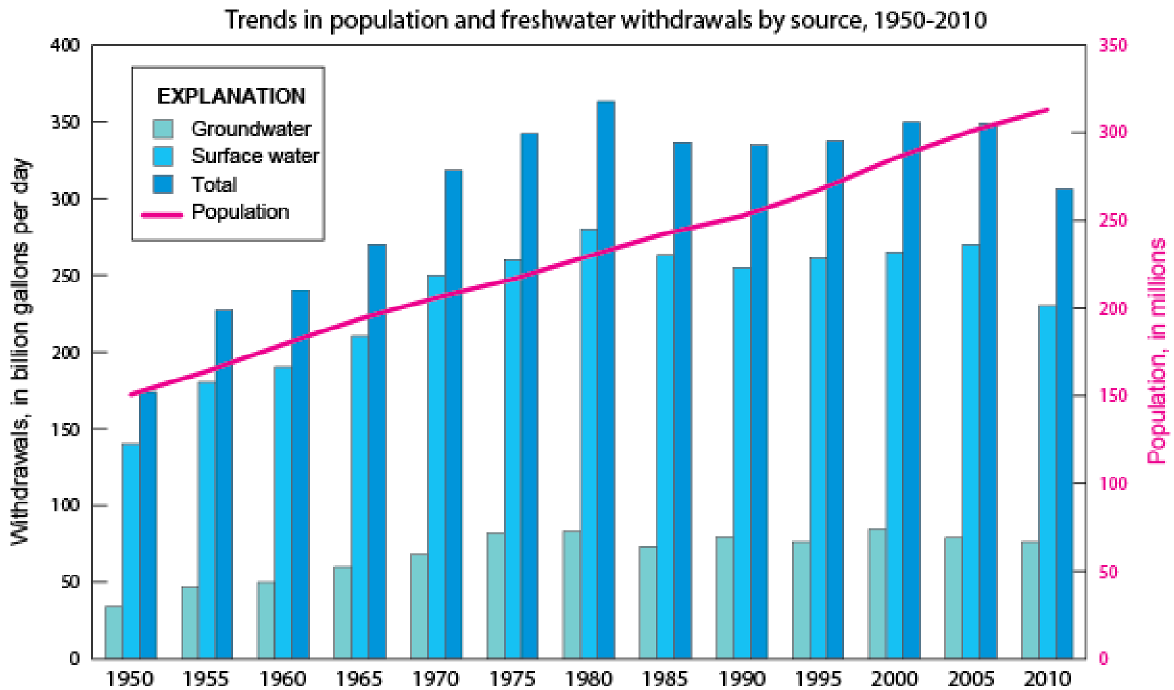


Figure 8.17: Both groundwater and surface water withdrawals had increased over time until 1980 when the withdrawals peaked and stabilized.

Water Scarcity and Availability

There is enough fresh water on Earth to supply every human being with enough drinking water. The main problem we face with regards to water is that it is unevenly distributed, polluted, mismanaged and wasted. Tony Allan, the author of Virtual Water, asserts that water follows money. This refers to the fact that rich countries and societies with money and affluence have more access to safe drinking water even when they live in regions without much water. It also means that areas with large supplies of water can still have water scarcity if they lack the financial resources to build the infrastructure to supply people with safe clean drinking water. Water scarcity is caused by the demand for water being greater than the supply. Scarcity can be defined as either **physical scarcity** or **economic scarcity**.

Physical water scarcity is a situation where there is an actual shortage of water, regardless of quality or infrastructure. It is estimated that about 1.2 million people around the world are experiencing physical water scarcity. **Economic scarcity** is a condition where countries lack the financial resources and/or infrastructure to supply their citizens with reliable safe drinking water. About 1.6 billion people are experiencing economic water shortage; most of them live in less industrialized countries. For a lot of places in the world, scarcity is a transient condition that can be reduced or eliminated by installing the right infrastructure. The major problem in less industrialized countries is the lack of political, financial, and physical structures to provide water to everyone. A few rich people in these countries get the clean water while the majority of the people who cannot afford to pay for it are left out. Examples of such communities include many villages in Africa, Asia, and South America. **Figure 8.18** shows communities in south east Kenya that are experiencing severe water shortages primarily due to lack of infrastructure. Women in these communities must walk long distances to get untreated and contaminated water for drinking and other household needs.

Figure 8.18: Communities in southeast Kenya without ready access to safe drinking water. (A) Groundwater in the area is too salty for consumption. B) Maasai women in Amboseli National Park collecting water from a wetland. (C) Women in Magwede village in SE Kenya walking long distances to get water from a Kiosk. D) Children collecting water in Bungule Village from a water kiosk that is only open for about an hour every day. *Photo credit: Jonathan Levy, Sam Mutiti and Christine Mutiti*

Water Quality (pollution)

Water pollution is a major problem facing many of our surface water and groundwater sources. Contamination can both be natural due to geologic or meteorological events and anthropogenic (human causes). Human sources of contamination can be categorized as either point source or nonpoint source. **Point-source pollution** is water pollution coming from a single point, such as a sewage-outflow pipe. **Non-point source (NPS) pollution** is pollution discharged over a wide land area such as agricultural runoff and urban stormwater runoff, not from one specific location. Non-point source pollution contamination occurs when rainwater, snowmelt, or irrigation washes off plowed fields, city streets, or suburban backyards. As this runoff moves across the land surface, it picks up soil particles and pollutants, such as nutrients and pesticides.

Types of Water Pollution

Contamination of water resources comes in the form of chemical, biological, and physical pollution. **Chemical pollution** includes things such as toxic metals, organic compounds, acidic waters from mining activities and industry, pharmaceuticals and many other chemical compounds from industries and wastewater treatment plants. Another form of chemical pollution is radioactive waste which has a significant potential to cause harm to living things. Most of the radioactive pollution comes from agricultural practices such as tobacco farming, where radioactive phosphate fertilizer is used. **Physical pollution** includes sediment pollution, trash thrown in the water bodies, thermal and other suspended load. Temperature typically affects the metabolism of aquatic fauna in a negative way and can encourage eutrophication. **Biological pollution** usually refers to pathogenic bacteria, viruses, and parasitic protozoa. Common pathogenic microbes introduced into natural water bodies are pathogens from untreated sewage or surface runoff from intensive livestock grazing. Biological pollution is a common cause of illness and death in less industrialized countries where population density, water scarcity and inadequate sewage treatment combine to cause widespread parasitic and bacterial diseases.

Sources of water pollution

Most of the common inorganic chemical water pollutants are produced by non-point sources, mainly intensive agriculture, and high-density urban areas. Specific inorganic chemicals and their major sources are: ammonium nitrate and a host of related phosphate and nitrogen compounds used in agricultural fertilizers; heavy metals (present in urban runoff and mine tailings area runoff). However, some inorganic contaminants such as chlorine and related derivatives are produced from point sources, ironically employed in water treatment facilities. Moreover, some of the large dischargers of heavy metals to aquatic environments are fixed point industrial plants.

High concentrations of nitrogen (N) and phosphorus (P) in water can cause **eutrophication**. You are seeing this whenever you notice the greenish tint to the water in our local streams and rivers during low-flow times, or if you have ever seen a green farm pond. These nutrients are primarily coming from:

- treated wastewater (laden with P and N) being dumped into the river from sewage plants,
- agricultural areas where farmers allow livestock direct access to the stream, and
- agricultural areas where there is intense fertilizer application, and from landscapes (homes, gardens, golf courses) with fertilizer runoff.

The N and P act as fertilizers in the water and promote algae blooms. As the algae dies, it is decomposed by aerobic bacteria in the water. These bacteria use up the oxygen in the water and the low dissolved oxygen (DO) levels can results in "fish kills" where large numbers of fish, and other aquatic life, die because of suffocation. The dead zone in the Gulf of Mexico is a huge area of low DO that has a large negative impact on the fishing industry along the Gulf Coast near the mouth of the Mississippi River. The dead zone occurs annually when fertilizers, from farm fields in the Midwest, wash down the Mississippi river.

Improper storage and use of automotive fluids produce common organic chemicals causing water pollution. These chemicals include methanol and ethanol (present in wiper fluid); gasoline and oil compounds such as octane, nonane (overfilling of gasoline tanks); most of these are considered non-point sources since their pathway to watercourses is mainly overland flow.

However, leaking underground and above ground storage tanks can be considered point sources for some of these chemicals, and even more toxic organic compounds such as perchloroethylene. Grease and fats (such as lubrication and restaurant effluent) can be either point or non-point sources depending upon whether the restaurant releases grease into the wastewater collection system (point source) or disposes of such organics on the exterior ground surface or transports to large landfills.

The most significant **physical pollutant** is excess sediment in runoff from agricultural plots, clear-cut forests, improperly graded slopes, urban streets, and other poorly managed lands, especially when steep slopes or lands near streams are involved. Other **physical pollutants** include a variety of plastic refuse products such as packaging materials; the most pernicious of these items are ring shaped objects that can trap or strangle fish and other aquatic fauna (**Figure 8.14**). Other common physical objects are timber slash debris, waste paper and cardboard. Finally, power plants and other industrial facilities that use natural water bodies for cooling are the main sources of thermal pollution.

Groundwater can also become contaminated from both natural and anthropogenic sources of pollution. Naturally occurring contaminants are present in the rocks and sediments. As groundwater flows through sediments, metals such as iron and manganese are dissolved and may later be found in high concentrations in the water. Industrial discharges, urban activities, agriculture, groundwater withdrawal, and disposal of waste all can affect groundwater quality. Contaminants from leaking fuel tanks or fuel or toxic chemical spills may enter the groundwater and contaminate the aquifer. Pesticides and fertilizers applied to lawns and crops can accumulate and migrate to the water table.

Leakage from septic tanks and/or waste-disposal sites also can contaminate ground water. A septic tank can introduce bacteria to the water, and pesticides and fertilizers that seep into farmed soil can eventually end up in water drawn from a well. Or, a well might have been placed in land that was once used as a garbage or chemical dump site.

Water Management

Pollution control begins with testing and monitoring of water quality. Water quality is usually monitored using easy to measure indicators such as pH, specific conductance (commonly referred to as conductivity), temperature, fecal and total coliform bacteria, dissolved oxygen, macroinvertebrates, and algae. Polluted sites typically have reduced DO levels, lower pH (more acidic), higher nutrient levels, more bacteria, and higher temperatures compared to less impacted or pristine sites.

Non-point source control relates mostly to land management practices in the fields of agriculture, mining and urban design and sanitation. Agricultural practices leading to the greatest improvement of sediment control include: contour grading, avoidance of bare soils in rainy and windy conditions, polyculture farming resulting in greater vegetative cover, and increasing fallow periods. Minimization of fertilizer, pesticide and herbicide runoff is best accomplished by reducing the quantities of these materials, as well as applying fertilizers during periods of low precipitation. Other techniques include avoiding of highly water soluble pesticides and herbicides, and use of materials that have the most rapid decay times to benign substances.

The main water pollutants associated with mines and quarries are aqueous slurries of minute rock particles, which result from rainfall scouring exposed soils and also from rock washing and grading activities. Runoff from metal mines and ore recovery plants is typically contaminated by the minerals present in the native rock formations. Control of this runoff is chiefly achieved by preventing rapid runoff and designing mining operations that avoid tailings either on steep slopes or near streams.

In the case of urban stormwater control, good urban planning and design can minimize stormwater runoff. By reducing impermeable surfaces (pavement that doesn't allow water through), then cities can reduce the amount of surface water runoff the carries pollutants into surface water and causes flooding. Additionally, the use of native plant and xeriscape techniques reduces water use and water runoff, and minimizes the need for pesticides and nutrients. Regarding street maintenance, a periodic use of street sweeping can reduce the sediment, chemical and rubbish load into the storm sewer system

The two common approaches to water management fall under either voluntary programs or the regulatory program. The regulatory approach has been very successful in controlling and reducing point source pollution, which was the focus of regulations when they were first introduced. Voluntary programs, together with new amendments to regulations, have had great success in increasing conservation and reducing diffuse nonpoint source pollution. One of the most widely used voluntary programs is **Watershed Management** while the regulatory approach is centered on the Clean Water Act (CWA).

Watershed Management

The watershed management approach recognizes that water contamination problems are complex and not localized to a section of a river. Water pollution problems are caused by multiple activities within the watershed and, therefore, require holistic approaches in the entire **watershed**. A **watershed** (drainage basin or catchment) is an area of land that drains to a single outlet and is separated from other watersheds by a drainage divide. Rainfall that falls in a watershed will generate runoff (if not trapped or infiltrated into groundwater) to that watershed's outlet. Topographic elevation is used to define a watershed boundary. A focal point of water management plans is the Best Management Practices (BMPs) section. BMPs are designed to consider all of the various uses of water, maximize conservation and minimize pollution.

The regulatory approach

Water management through policy and laws seeks to clean up polluted water, prevent further pollution and apply punitive measures for polluters. In the US water-related regulations go as far back as 1899 with the Rivers and Harbors Act, also known as the Refuse Act that prohibited the dumping of solid waste and obstruction of waterways. This regulation, however, did not include waste flowing from streets and sewers. In 1948 another regulation, the Federal Water Pollution Act (which is the basis of the Clean Water Act) was enacted. This regulation covered contamination from sewage outfalls. It was created to reduce contamination of both interstate groundwater and surface waters. Through this regulation funding was made available to states and local governments for water quality management.

One of the major water-related regulations in the US is the Clean Water Act (CWA) of 1972. The regulation was very comprehensive with lots of programs and empowered the Environmental Protection Agency (EPA) to create goals, and objective laws for its implementation. The legislation has programs for both point and nonpoint source pollution. One other major piece of regulation governing water was the 1974 Safe Drinking Water Act (SDWA).

In 1974, amended in 1986, the SDWA was enacted to establish standards for many chemical constituents for public water supplied by public water agencies. In the regulations, maximum contaminant level goals (MCLG), which are non-enforceable and maximum contaminant levels (MCLs) that are enforceable where created. MCLG are what would be ideal and desirable while MCL are what should be attained in any drinking water supplied by a public municipal agency. For any carcinogen, the MCLG is 0 even though many contaminants have MCLs and detection limits in the parts per billion (ppb) range. Some of them (e.g. dioxin) have MCLs in the parts per trillion (ppt). To give you a sense of how small this ppt is, it is the same as 0.4 mm divided by the distance to the moon.

A Closer Look at the Clean Water Act

The 1972 Clean Water Acts was an overhaul of the 1948 Federal Pollution Control Act. The current regulation includes numerous programs for water quality improvement and protection. The EPA works with its federal, state and tribal regulatory partners to monitor and ensure compliance with clean water laws and regulations in order to protect human health and the environment. The Clean Water Act is the primary federal law governing water pollution. One of the objectives of the CWA was to restore and maintain the integrity of the nation's physical, chemical, and biological waters quality. The ultimate goals of the act are to establish zero pollutant discharge, as well as fishable & swimmable waters in the country. One main component of the CWA is regulations on industrial and municipal discharges into navigable US waters. The act is designed to be a partnership between states and the federal government. The federal government sets the agenda and standards while the state carries out the implementation of the law. States also have the power to set standards that are more stringent than the federal standards if needed. Under the CWA, discharge into US waters is only legal if authorized by a permit. Perpetrators of the law can be punished using administrative, civil, or criminal charges. The second component of the act is providing funding for constructing municipal waste water treatment plants and other projects to improve water quality (Title II and Title VI).

The act covers both point sources (discharge from sources such as pipes) and nonpoint sources (pollution from diffuse sources such as stormwater runoff). Point sources are explicitly covered under section 402, National Pollutant Discharge Elimination System (NPDES). This section requires industries and municipalities to get permits from the EPA before discharging into US waters. The permits require the use of control technology to reduce and prevent pollution.

Water in Crisis (case studies)

- You instructor will assign you a specific case study for the course if needed.

Bibliography

Biology and Concepts in Biology texts (OpenStax)

EPA. (2013). Clean Water: Lakes. http://water.epa.gov/type/lakes/. Last updated on Tuesday, July 30, 2013

Fetter C.W. Jr. Applied Hydrogeology, 4th Edition. Upper Saddle River, New Jersey: Prentice Hall. 2000. Print

Hogan, C. 2014. Water pollution. Retrieved from http://www.eoearth.org/view/article/51cbef2a7896bb431f69cd56

Howard Perlman, The USGS Water Science School. 2015. Surface Water Use in the United States, 2005. http://water.usgs.gov/edu/wusw.html. Last Modified: Thursday, 30-Jul-2015

Howard Perlman, The USGS Water Science School. 2015. The Worlds Water. http://water.usgs.gov/edu/graphics/earthwheredistribution.gif. Last Modified: Thursday, 30-Jul-2015

Howard Perlman. The USGS Water Science School: Aquifers. http://water.usgs.gov/edu/earthgwaquifer.html. Last modified Thursday, 30-Jul-2015 14:17:07

James L., Sipes. Sustainable Solutions for Water Resources.Hoboken, New Jersey: John Wiley and Sons Inc, 2010. Print.

John C. Manning. Principles of applied hydrology 3rd, Edition. Upper Saddle River, New Jersey: Prentice Hall, 1996. Print.

Kenneth, M. Brooks, Peter, F. Fflolliott and Joseph, A. Magner. Hydrology & Management of Watersheds, 4th Edition. Hoboken, New Jersey: Wiley-Blackwell , 2012. Print

Martin R. Hendriks. Introduction to Physical Hydrology.Oxford: Oxford University Press, 2010. Print

The World Oceans. 2015. 5 Oceans of the World. http://theworldsoceans.com/ Retrieved July 30th 2015.

Thomas V. Cech Principles of Water Resources: History, Development, Management, and Policy, 3rd Edition.Wiley and Sons Inc. 2009. Print

USGS Water-Use Web Team. 2015. http://water.usgs.gov/watuse/wuglossary.html. Page Last Modified: Wednesday, 11-Mar-2015

Withgott, j. & Laposata, m. *Essential Environment;* the science behind the stories. 4th Edition. New York City, New York. Pearson 2012. Print