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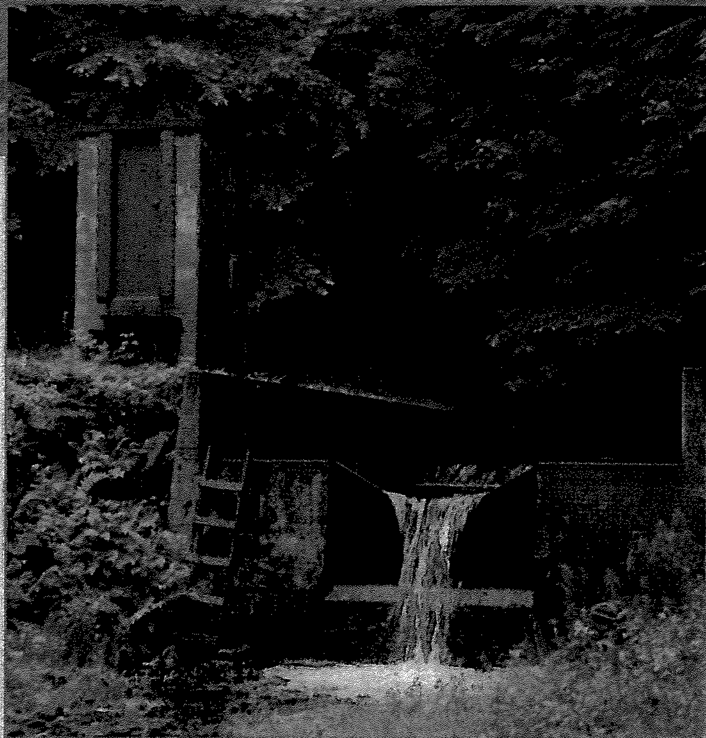
Ecosystems and the Physical Environment



Courtesy Hubbard Brook Experimental Forest

Catchment at Hubbard Brook Experimental Forest. Ecologists who study stream and river systems use catchments (or weirs) to measure the quantity and mineral content of water flowing from a watershed.

Ecosystem processes such as energy flow, the cycling of nutrients, and the effects of natural and human-induced disturbances—for example, air pollution, tree harvesting, and land-use changes—can be studied in both the laboratory and the field. Some ecosystem studies are of particular value because they are long term. Beginning in the late 1950s and continuing to the present, the **Hubbard Brook Experimental Forest (HBEF)**, a 3100-hectare (7750-acre) reserve in the White Mountain National Forest in New Hampshire, has been the site of numerous studies that address the hydrology (e.g., precipitation, surface runoff, and groundwater flow), biology, geology, and chemistry of forests and associated aquatic ecosystems. HBEF is one of the National Science Foundation's 26 long-term ecological research sites.

Experiments at HBEF are often based on field observations. For example, salamander populations surveyed in 1970 have been resurveyed in recent years. Other studies involve controlled experiments. In 1978, scientists added dilute sulfuric acid to a small stream in HBEF to study the effects of acidification. They compared its chemistry and biology to a similar stream that was not manipulated. This experiment was of practical value because *acid deposition*, a form of air pollution, has acidified numerous lakes and streams in industrialized countries.

Another area of research at HBEF explores the effects of **deforestation**, the clearance of large expanses of forest for agriculture or other uses, on stream ecosystems. When a forest is cleared, the water and minerals that drain into streams increase dramatically. The photograph shows a V-notched dam called a *catchment*, constructed across a stream at the bottom of a valley so scientists can measure water volume and chemical components that flow from the ecosystem. Outflow is generally measured in two separate ecosystems, one of which serves as a control and one of which is experimentally manipulated.

These studies demonstrate that deforestation causes soil erosion and leaching of essential minerals, both of which result in decreased soil fertility. Summer temperatures in streams running through deforested areas are warmer than in shady streams running through control forests. Many stream organisms do not fare well in deforested areas, in part because they are adapted to cooler temperatures.

Detailed ecosystem studies such as those at HBEF also contribute to our practical knowledge about how to maintain water quality, wildlife habitat, and productive forests. **Ecosystem management,** a conservation approach that emphasizes restoring and maintaining the quality of an entire ecosystem rather than the conservation of an individual species, makes use of such knowledge.

This chapter examines the physical components of Earth as a complex system—the interactions and connections of Earth's ecosystems with the abiotic, physical environment on which all life depends. We focus on cycles of matter, solar radiation, the atmosphere, the ocean, weather and climate (including hurricanes), and internal planetary processes (including those that cause earthquakes, tsunamis, and volcanoes).

In Your Own Backyard...

Identify an ecosystem near your home that has been affected by humans and is in need of ecosystem management. What land-use changes have altered this particular ecosystem?

The Cycling of Materials within Ecosystems

LEARNING OBJECTIVES

- Describe the main steps in each of these biogeochemical cycles: carbon, nitrogen, phosphorus, sulfur, and hydrologic.

Chapter 3 described how energy flows in one direction through an ecosystem. In contrast, matter, the material of which organisms are composed, moves through systems in numerous cycles from one part of an ecosystem to another—from one organism to another and from living organisms to the abiotic environment and back again (**Figure 4.1**). These **biogeochemical cycles** involve biological, geologic, and chemical interactions.

Five biogeochemical cycles of matter—carbon, nitrogen, phosphorus, sulfur, and hydrologic (water)—are representative of all biogeochemical cycles. These five cycles are particularly important to organisms because these materials make up the chemical compounds of cells. Carbon, nitrogen, and sulfur are elements that form gaseous compounds, whereas water is a compound that readily evaporates; these four cycles have components that move over long distances in the atmosphere with relative ease. Phosphorus does not form gaseous compounds; as a result, only local cycling occurs easily for that element. Humans are affecting all these cycles on both local and global scales; we conclude our examination of each cycle with a discussion of these important issues.

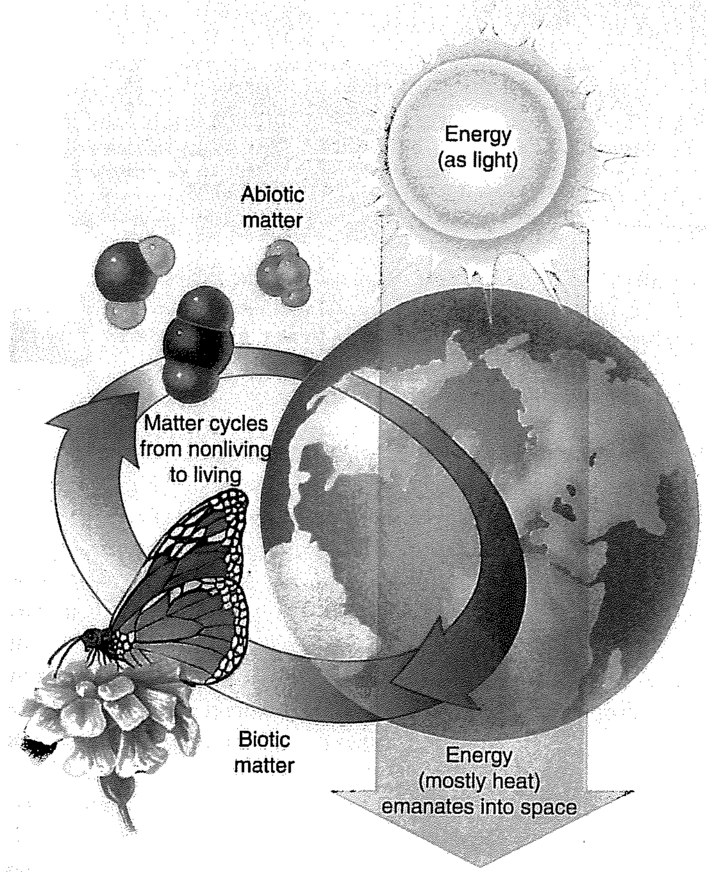


Figure 4.1 Earth's system of energy and matter. Although energy flows one way through ecosystems, matter continually cycles from the abiotic to the biotic components of ecosystems and back again.

THE CARBON CYCLE

Proteins, carbohydrates, and other molecules essential to life contain carbon, so organisms must have carbon available to them. Carbon is found in the atmosphere as a gas, carbon dioxide (CO_2). Carbon is present in the ocean in several forms: dissolved carbon dioxide—that is, carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-)—and dissolved organic carbon from decay processes. Carbon is also present in sedimentary rocks such as *limestone*, which consists primarily of calcium carbonate, $CaCO_3$ (see discussion of the rock cycle in Chapter 15). The global movement of carbon between organisms and the abiotic environment—including the atmosphere, ocean, and sedimentary rock—is known as the **carbon cycle** (**Figure 4.2**).

carbon cycle The global circulation of carbon from the environment to living organisms and back to the environment.

During **photosynthesis**, plants, algae, and certain bacteria remove CO_2 from the air and fix (incorporate) it into chemical compounds such as sugar. Plants use sugar to make other compounds. Thus, photosynthesis incorporates carbon from the abiotic environment into the biological compounds of producers. Those compounds are usually used as fuel for **cellular respiration** by the producer that made them, by a consumer that eats the producer, or by a decomposer that breaks down the remains of the producer or consumer. Thus, cellular respiration returns CO_2 to the atmosphere. A similar carbon cycle occurs in aquatic ecosystems between aquatic organisms and carbon dioxide dissolved in the water.

Sometimes the carbon in biological molecules is not recycled back to the abiotic environment for a long time. A large amount of carbon is stored in the wood of trees, where it may stay for several hundred years or even longer. In addition, millions of years ago, vast coal beds formed from the bodies of ancient trees that did not decay fully before they were buried. Similarly, the organic compounds of unicellular marine organisms probably gave rise to the underground deposits of oil and natural gas that accumulated in the geologic past. Coal, oil, and natural gas, called **fossil fuels** because they formed from the remains of ancient organisms, are vast deposits of carbon compounds, the end products of photosynthesis that occurred millions of years ago (see Chapter 11). The carbon in coal, oil, natural gas, and wood can return to the atmosphere by burning, or **combustion**. In combustion, organic molecules are rapidly oxidized—combined with oxygen—and converted into CO_2 and water, with an accompanying release of heat and light.

The Carbon-Silicate Cycle On a geologic time scale involving millions of years, the carbon cycle interacts with the silicon cycle in the **carbon-silicate cycle**. The first step of the cycle involves chemical *weathering processes*. Atmospheric CO_2 dissolves in rainwater to form carbonic acid (H_2CO_3), which is a weak acid. As the slightly acidic rainwater moves through the soil, carbonic acid dissociates to form hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). The hydrogen ions enter silicate-rich minerals such as feldspar and change their chemical composition, releasing calcium

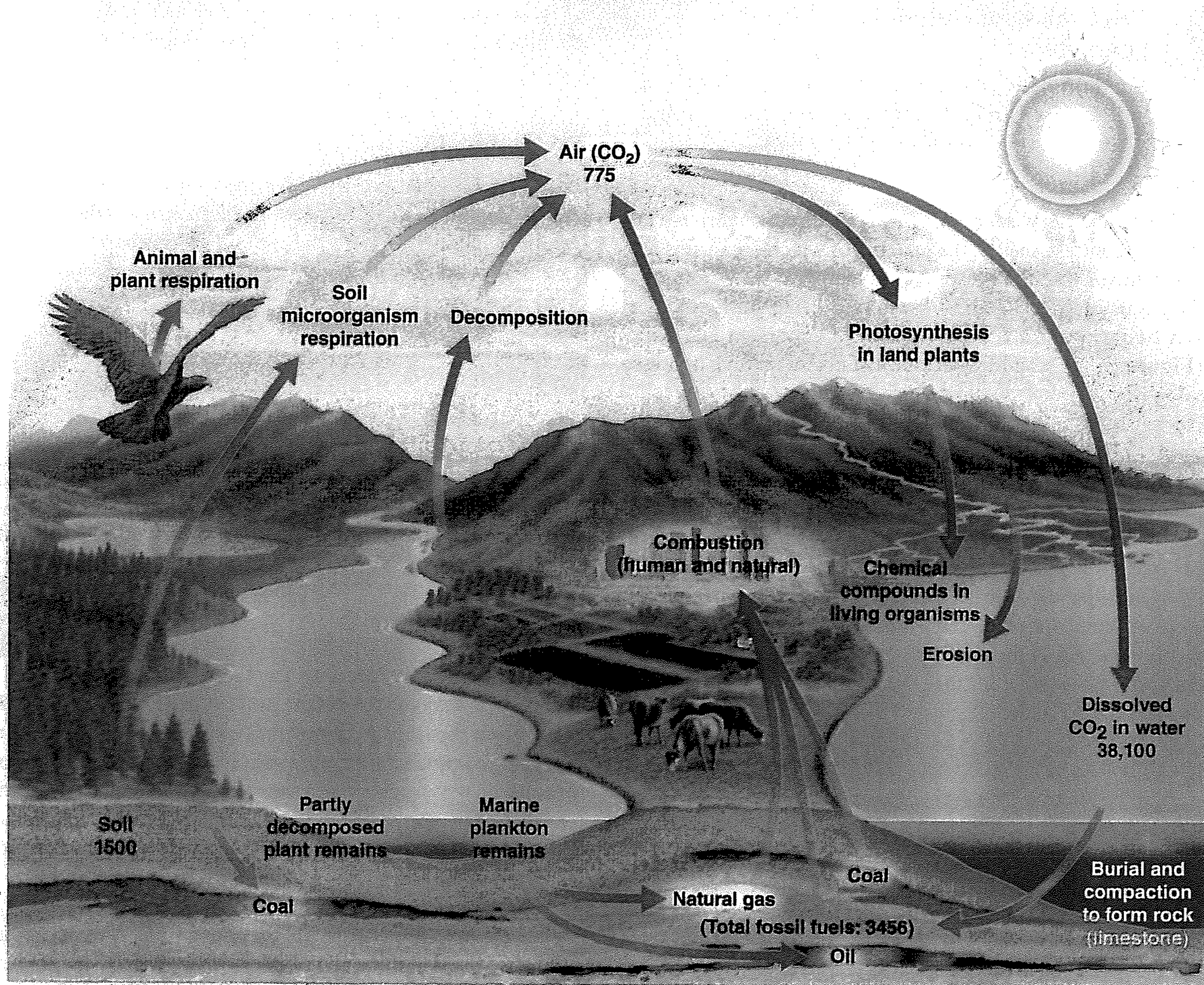


Figure 4.2 The carbon cycle. Sedimentary rocks and fossil fuels hold almost all of Earth's estimated 10^{23} g of carbon. The values shown for some of the active pools in the global carbon budget are expressed as 10^{15} g of carbon. For example, the soil contains an estimated 1500×10^{15} g of carbon. How does the carbon cycle influence global climate? (Carbon Dioxide Information Analysis Center, based on data from W.M. Post, Oak Ridge National Laboratory).

ions (Ca^{2+}). The calcium and bicarbonate ions wash into surface waters and eventually reach the ocean.

Microscopic marine organisms incorporate Ca^{2+} and (HCO_3^-) into their shells. When these organisms die, their shells sink to the ocean floor and are covered by sediments, forming calcium carbonate deposits several kilometers thick. The deposits are eventually cemented to form limestone, a sedimentary rock. Earth's crust is active; over millions of years, sedimentary rock on the seafloor may lift to form land surfaces. The summit of Mount Everest, for example, is composed of sedimentary rock. Limestone exposed by the process of geologic uplift slowly erodes as a result of chemical and physical weathering processes, returning CO_2 to the water and atmosphere to participate in the carbon cycle once again.

Alternatively, the geologic process of *subduction* (discussed later in the chapter) buries the carbonate deposits. The increased heat and pressure of deep burial partially melt the sediments, releasing CO_2, which rises in volcanoes and is vented into the atmosphere.

Human-Induced Changes to the Carbon Cycle Human activities are increasingly disturbing the balance of biogeochemical cycles, including the carbon cycle. Since the end of the 18th century, the advent of the Industrial Revolution, industrial society has used a lot of energy, most of which we have obtained by burning increasing amounts of fossil fuels—coal, oil, and natural gas. This trend, along with a greater combustion of wood as a fuel and the burning of large sections of tropical forests, has shifted carbon from underground deposits to the atmosphere. In the 1700s, CO_2 made up 0.029% of the atmosphere; it now makes up 0.04%, and some scientists project it will be up to 0.06% (double the preindustrial level) by the end of this century. Numerous studies indicate that the increase of CO_2 in the atmosphere (see Figure 20.2) is causing human-induced global climate change. Global climate changes include increasing temperatures, a rise in sea level, altered precipitation patterns, increased wildfires, flooding, drought, heat waves, extinctions of organisms, and agricultural disruption. It has begun to displace people from coastal areas; eventually, millions of people could be displaced.

THE NITROGEN CYCLE

Nitrogen is crucial for all organisms because it is an essential part of biological molecules such as proteins and nucleic acids (for example, DNA). At first glance, a shortage of nitrogen available to organisms would seem impossible. The atmosphere is 78% nitrogen gas (N_2), a two-atom molecule. But each nitrogen molecule is so stable (it has three covalent bonds linking the two atoms) that it does not readily combine with other elements. Atmospheric nitrogen must first be broken apart before the nitrogen atoms can combine with other elements to form proteins and nucleic acids. The **nitrogen cycle**, in which nitrogen cycles between the abiotic environment and organisms, has five steps: nitrogen fixation, nitrification, assimilation, ammonification, and denitrification (**Figure 4.3**). Bacteria are exclusively involved in all these steps except assimilation.

nitrogen cycle The global circulation of nitrogen from the environment to living organisms and back to the environment.

The first step in the nitrogen cycle, **nitrogen fixation**, is the conversion of gaseous nitrogen to ammonia (NH_3). The process gets its name from the fact that nitrogen is fixed into a form that organisms can use; *fixed* nitrogen refers to nitrogen chemically combined with hydrogen, oxygen, or carbon. Combustion, volcanic action, lightning discharges, and industrial processes, all of which supply enough energy to break apart atmospheric nitrogen, fix considerable nitrogen. Nitrogen-fixing bacteria, including cyanobacteria, carry out biological nitrogen fixation in soil and aquatic environments; they employ the enzyme *nitrogenase* to split atmospheric nitrogen and combine the resulting nitrogen atoms with hydrogen. Nitrogenase functions only in the absence of

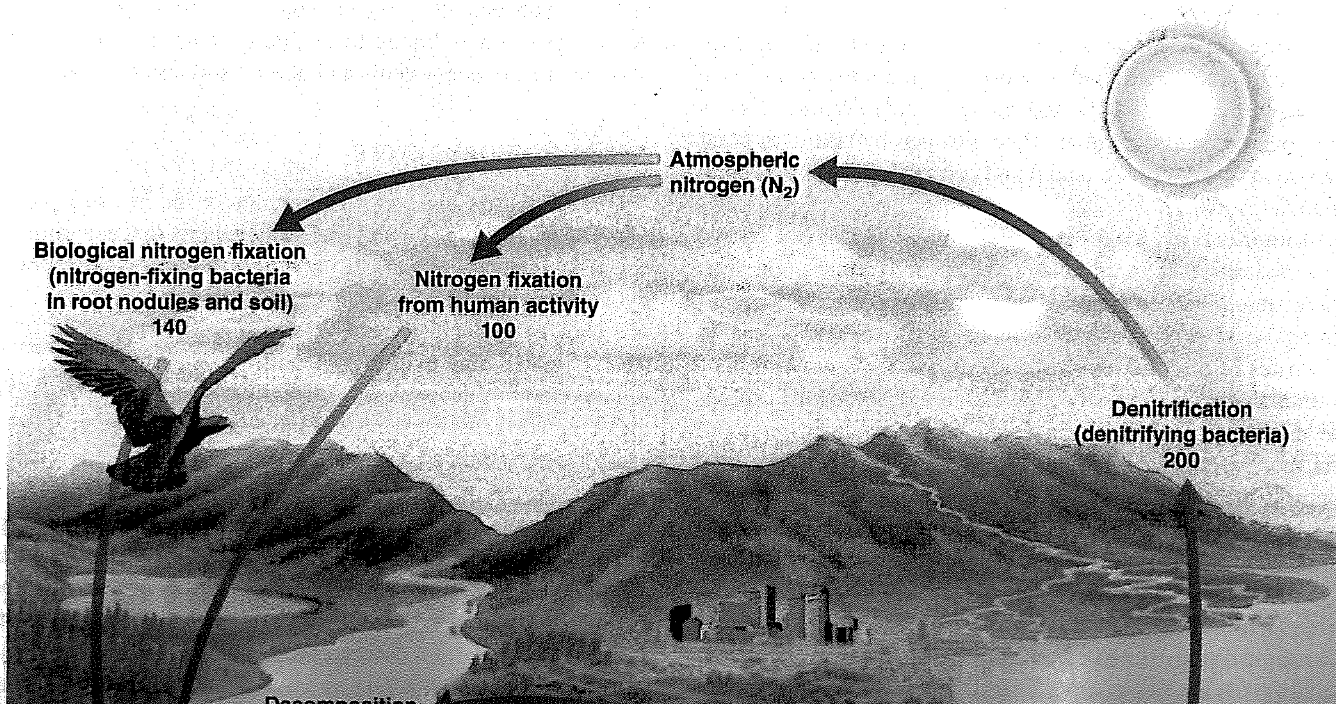


Figure 4.3 The nitrogen cycle. The atmosphere holds the largest pool of nitrogen, 4×10^{21} g. The values shown for some of the active pools in the global nitrogen budget are expressed as 10^{12} g of nitrogen per year. For example, each year humans fix an estimated 100×10^{12} g of nitrogen. (Values from W.H. Schlesinger, *Biogeochemistry: An Analysis of Global Change*, 2nd edition. Academic Press, San Diego, 1997, and based on several sources)

oxygen, and the bacteria that use nitrogenase must insulate it from oxygen by some means.

Some nitrogen-fixing bacteria live beneath layers of oxygen-excluding slime on the roots of certain plants. Other important nitrogen-fixing bacteria, *Rhizobium*, live inside special swellings, or nodules, on the roots of legumes such as beans or peas and some woody plants (see the Chapter 5 discussion of mutualism). The relationship between *Rhizobium* and its host plants is mutualistic: The bacteria receive carbohydrates from the plant, and the plant receives nitrogen in a form it can use. In aquatic environments, cyanobacteria perform most nitrogen fixation. Filamentous cyanobacteria have special oxygen-excluding cells that function as the sites of nitrogen fixation.

The conversion of ammonia (NH_3) or ammonium (NH_4^+, formed when water reacts with ammonia) to nitrate (NO_3^-) is **nitrification**. Soil bacteria perform nitrification, a two-step process. First, soil bacteria convert ammonia or ammonium to nitrite (NO_2^-). Then other soil bacteria oxidize nitrite to nitrate. The process of nitrification furnishes these bacteria, called nitrifying bacteria, with energy.

In **assimilation**, plant roots absorb nitrate (NO_3^-), ammonia (NH_3), or ammonium (NO_4^+) and incorporate the nitrogen of these molecules into plant proteins and nucleic acids. When animals consume plant tissues, they assimilate nitrogen by taking in plant nitrogen compounds (amino acids) and converting them to animal compounds (proteins).

Ammonification is the conversion of biological nitrogen compounds into ammonia (NH_3) and ammonium ions (NO_4^+). Ammonification begins when organisms produce nitrogen-containing waste products such as urea (in urine) and uric acid (in the wastes of birds). These substances, as well as the nitrogen compounds that occur in dead organisms, are decomposed, releasing the nitrogen into the abiotic environment as ammonia. The bacteria that perform this process both in the soil and in aquatic environments are called ammonifying bacteria. The ammonia produced by ammonification enters the nitrogen cycle and is once again available for the processes of nitrification and assimilation.

Denitrification is the reduction of nitrate (NO_3^-) to gaseous nitrogen. Denitrifying bacteria reverse the action of nitrogen-fixing and nitrifying bacteria by returning nitrogen to the atmosphere. Denitrifying bacteria prefer to live and grow where there is little or no free oxygen. For example, they are found deep in the soil near the water table, a nearly oxygen-free environment.

Human-Induced Changes to the Nitrogen Cycle From a systems perspective, human activities have disturbed the balance of the global nitrogen cycle. During the 20th century, humans doubled the amount of fixed nitrogen entering the global nitrogen cycle, primarily through the application of fertilizer composed of fixed nitrogen. Several lines of scientific evidence suggest that terrestrial ecosystems enriched with nitrogen have fewer plant species than unenriched terrestrial ecosystems.

Precipitation washes nitrogen fertilizer into rivers, lakes, and coastal areas, where it stimulates the growth of algae. As these algae die, their decomposition by bacteria robs the water of dissolved oxygen, which in turn causes many fishes and other aquatic organisms to die of suffocation. An excess of nitrogen and other nutrients from fertilizer runoff has caused large oxygen-depleted *dead zones* in about 150 coastal areas around the world. (Chapter 21 discusses the dead zone in the Gulf of Mexico.) In addition, nitrates from fertilizer can leach (dissolve and wash down) through the soil and contaminate groundwater. Many people drink groundwater, and nitrate-contaminated groundwater is dangerous to drink, particularly for infants and small children. Nitrate reduces the oxygen-carrying capacity of a child's blood.

Another human activity that affects the nitrogen cycle is the combustion of fossil fuels. When fossil fuels are burned—in automobiles, for example—the high temperatures of combustion convert some atmospheric nitrogen to **nitrogen oxides**, which produce **photochemical smog**, a mixture of air pollutants that injures plant tissues, irritates eyes, and causes respiratory problems. Nitrogen oxides react with water in the atmosphere to form acids that leave the atmosphere as **acid deposition** and cause the pH of surface waters (lakes and streams) and soils to decrease (see Chapter 19). Acid deposition is linked to declining plant and animal populations in aquatic ecosystems and altered soil chemistry on land.

THE PHOSPHORUS CYCLE

Phosphorus does not form compounds in the gaseous phase and does not appreciably enter the atmosphere (except during dust storms). In the **phosphorus cycle**, phosphorus cycles from the land to sediments in the ocean and back to the land (**Figure 4.4**).

phosphorus cycle The global circulation of phosphorus from the environment to living organisms and back to the environment.

As water runs over apatite and other minerals containing phosphorus, it gradually wears away the surface and carries off inorganic phosphate (PO_4^{3-}) molecules. The erosion of phosphorus-containing minerals releases phosphorus into the soil, where plant roots absorb it in the form of inorganic phosphates. Once in cells, phosphates are incorporated into biological molecules such as nucleic acids and ATP (adenosine triphosphate, an organic compound important in energy-transfer reactions in cells). Animals obtain most of their required phosphate from the food they eat, although in some localities drinking water contains a substantial amount of inorganic phosphate. Phosphorus released by decomposers becomes part of the soil's pool of inorganic phosphate for plants to reuse. As in carbon, nitrogen, and other biogeochemical cycles, phosphorus moves through the food web as one organism consumes another.

Phosphorus cycles through aquatic communities in much the same way that it does through terrestrial communities. Dissolved phosphorus enters aquatic communities through absorption and assimilation by algae and plants, which are then consumed by plankton and larger organisms. A variety of fishes and mollusks eat these in turn. Ultimately, decomposers that break down wastes and dead organisms release inorganic phosphorus into the water, where it is available for aquatic producers to use again.

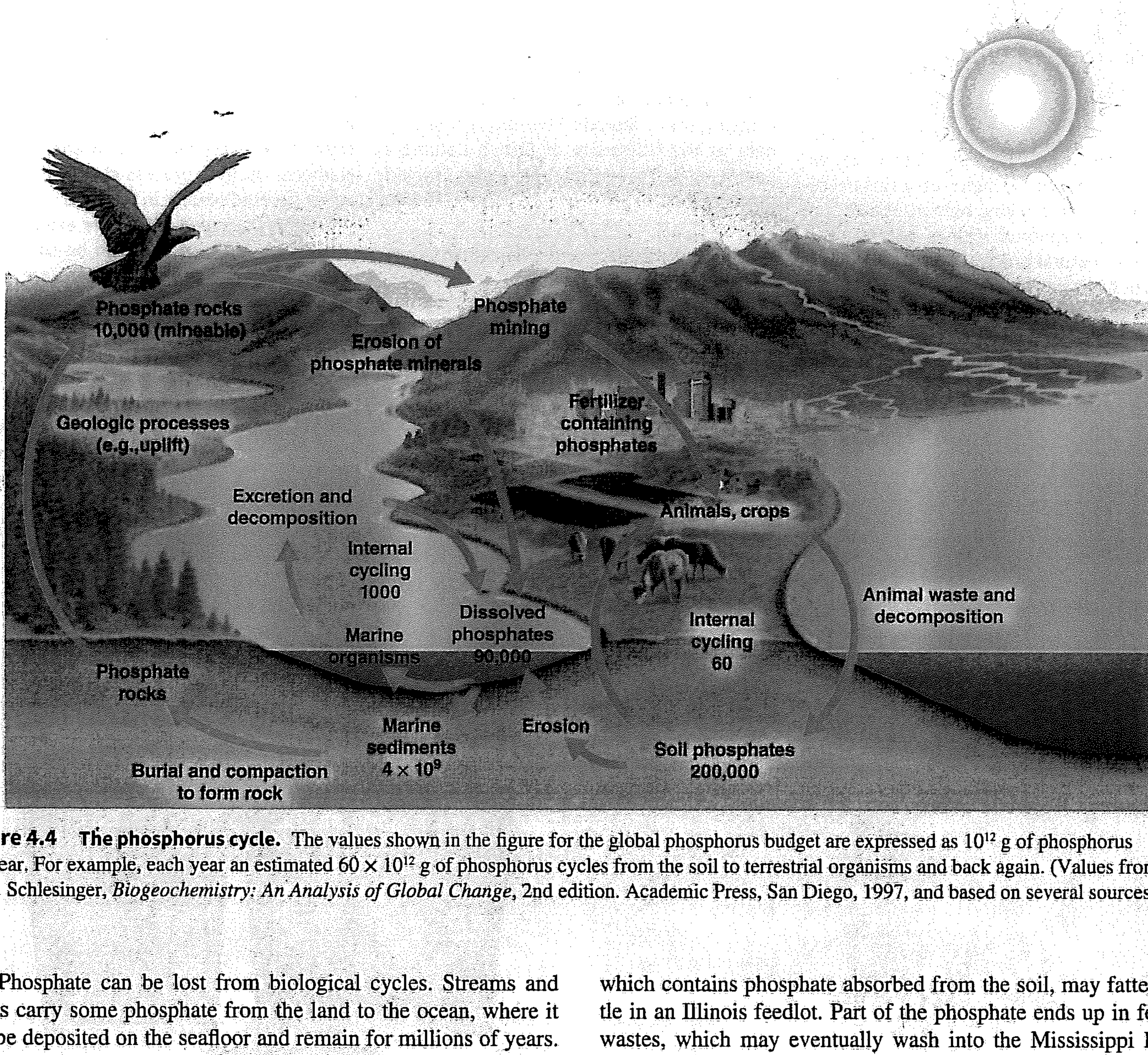


Figure 4.4 The phosphorus cycle. The values shown in the figure for the global phosphorus budget are expressed as 10^{12} g of phosphorus per year. For example, each year an estimated 60×10^{12} g of phosphorus cycles from the soil to terrestrial organisms and back again. (Values from W.H. Schlesinger, *Biogeochemistry: An Analysis of Global Change*, 2nd edition. Academic Press, San Diego, 1997, and based on several sources)

Phosphate can be lost from biological cycles. Streams and rivers carry some phosphate from the land to the ocean, where it can be deposited on the seafloor and remain for millions of years. The geologic process of uplift may someday expose these seafloor sediments as new land surfaces, from which phosphate will once again erode.

A small portion of the phosphate in the aquatic food web finds its way back to the land. Seabirds that eat fishes and other marine animals may defecate on land where they roost. Guano, the manure of seabirds, contains large amounts of phosphate and nitrate. Once on land, these minerals are available for the roots of plants to absorb. The phosphate contained in guano may enter terrestrial food webs in this way, although the amounts involved are quite small.

Human-Induced Changes to the Phosphorus Cycle Humans affect the phosphorus cycle by accelerating the long-term loss of phosphorus from the land. For example, corn grown in Iowa, which contains phosphate absorbed from the soil, may fatten cattle in an Illinois feedlot. Part of the phosphate ends up in feedlot wastes, which may eventually wash into the Mississippi River. When people consume beef from the cattle, more of the phosphate ends up in human wastes that are flushed down toilets into sewer systems. Because sewage treatment rarely removes them, phosphates cause water-quality problems in rivers, lakes, and coastal areas. For practical purposes, phosphorus that washes from the land into the ocean is permanently lost from the terrestrial phosphorus cycle (and from further human use), for it remains in the ocean for millions of years. Also, phosphorus is a limiting nutrient to plants and algae in certain aquatic ecosystems. Thus, excess phosphorus from fertilizer or sewage can contribute to enrichment of the water and lead to undesirable changes (recall the discussion of Lake Washington in Chapter 1). "Meeting the Challenge: Recycling Phosphorus from Sewage" examines one approach to conserving phosphorus.

MEETING THE CHALLENGE

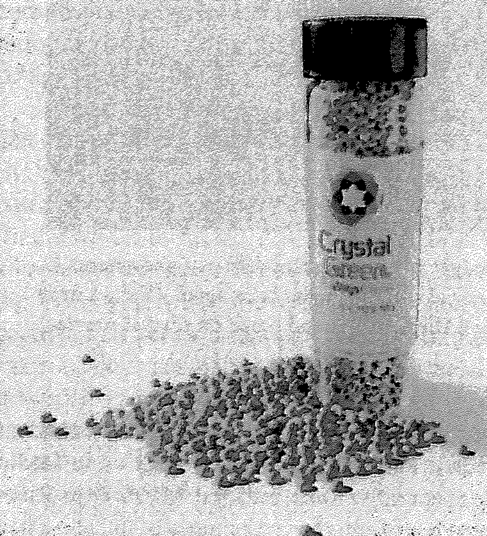
Recycling Phosphorus from Sewage

Phosphorus is a critical component of fertilizer used in agriculture. Without phosphorus, we would not produce the high crop yields necessary to feed the growing human population. Currently, phosphorus rock is being mined faster than natural processes can replenish it. If we continue consuming phosphorus at our present rate, it could be depleted early in the 22nd century.

One way to conserve essential phosphate is to recycle it. Much of the phosphate originally mined to produce fertilizer ends up in sewage—both human and animal waste. In sewage treatment plants, a precipitate separates from the solution as bacteria degrade the organic material in sewage. This precipitate, known as *struvite*, consists of phosphorus, magnesium, and ammonium, all critical plant nutrients. However, struvite is a sticky solid that adheres to pipes, clogging them. **Donald Mavinic**, a civil engineer at the University of British Columbia, partnered with several businesses, including Ostara Nutrient Recovery Technologies, Inc., to develop the technology to efficiently remove the struvite and recover phosphorus during the water treatment process. The phosphorus is sold as Crystal Green®, small, white prills (part a of the figure). For their contributions, Mavinic and his business colleagues received the 2010 Canadian Synergy Award for Innovation.

By late 2014, seven commercial waste water treatment plants were producing Crystal Green in Canada, the United States, and the United Kingdom, including operations in Slough, Berkshire, UK; Saskatoon, Saskatchewan; Portland, Oregon; Suffolk, Virginia; York, Pennsylvania; and Madison, Wisconsin. Other plants are in the planning stage, notably one in Chicago, which will be the world's largest nutrient recovery facility, and another in the Netherlands. This process cleans up polluted water (treated sewage in York and Suffolk both enter the Chesapeake Bay, for example) *and* produces a product that can be sold. In the York plant, for example, the prills are sold to JR Peters, Inc., a Pennsylvania fertilizer company that blends the prills with other plant nutrients and sells it under the label "Jack's ClassiCote with Crystal Green" (part b of the figure).

This is an example of a financially advantageous solution to a previously serious water pollution problem. Such a system, in which profitable uses are found for another company's wastes, is an example of sustainable manufacturing (see Chapter 15).



(a) Crystalline prills (small pearl-like granules) of Crystal Green®, a renewable, slow-release fertilizer. Chemically, the prills consist of 5% nitrogen, 28% phosphorus, and 10% magnesium.

(b) Fertilizer with Crystal Green®. The phosphorus in Crystal Green® is slow-release, which means that more gets absorbed by plant roots and less runs off to pollute waterways.

THE SULFUR CYCLE

sulfur cycle The global circulation of sulfur from the environment to living organisms and back to the environment.

Scientists are still piecing together how the global **sulfur cycle** works. Most sulfur is underground in sedimentary rocks and minerals (e.g., gypsum and anhydrite), which over time erode to release sulfur-containing compounds into the ocean (**Figure 4.5**). Sulfur gases enter the atmosphere from natural sources both in the ocean and on land. Sea spray delivers sulfates (SO_4^{2-}) into the air, as do forest fires and dust storms (desert soils are rich in calcium sulfate, $CaSO_4$). Volcanoes release both hydrogen sulfide (H_2S), a poisonous gas with a smell of rotten eggs, and sulfur oxides (SO_x). Sulfur oxides include sulfur dioxide (SO_2), a choking, acrid gas, and sulfur trioxide (SO_3).

Sulfur gases comprise a minor part of the atmosphere and are not long-lived because atmospheric sulfur compounds are reactive. Hydrogen sulfide reacts with oxygen to form sulfur oxides, and sulfur oxides react with water to form sulfuric acid (H_2SO_4). Although the total amount of sulfur compounds present in the atmosphere at any given time is relatively small, the total annual movement of sulfur to and from the atmosphere is substantial.

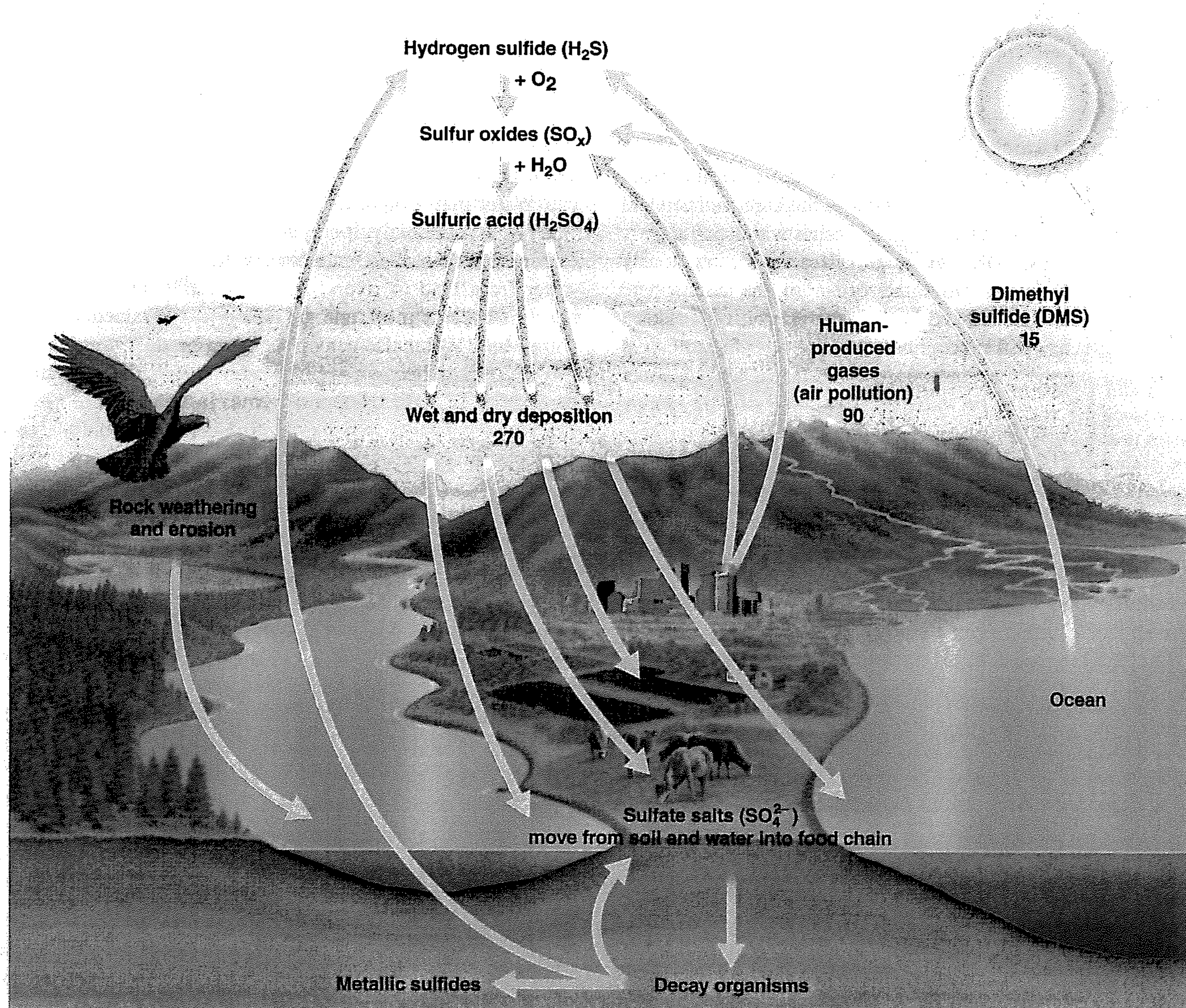


Figure 4.5 The sulfur cycle. The largest pool of sulfur on the planet is sedimentary rocks, which contain an estimated 7440×10^{18} g of sulfur. The second-largest pool is the ocean, which contains 1280×10^{18} g of sulfur. The values shown in the figure for the global sulfur budget are expressed in units of 10^{12} g of sulfur per year. For example, the ocean emits an estimated 15×10^{12} g of sulfur per year as the gas dimethyl sulfide. (Values from W.H. Schlesinger, *Biogeochemistry: An Analysis of Global Change*, 2nd edition. Academic Press, San Diego, 1997, and based on several sources)

A tiny fraction of global sulfur is present in living organisms, where it is an essential component of proteins. Plant roots absorb sulfate (SO_4^{2-}) and assimilate it by incorporating the sulfur into plant proteins. Animals assimilate sulfur when they consume plant proteins and convert them to animal proteins. In the ocean, certain marine algae release large amounts of a compound that bacteria convert to dimethyl sulfide, or DMS (CH_3SCH_3). DMS, known for its pungent odor, is released into the atmosphere, where it helps condense water into droplets in clouds and may affect weather and climate. In the atmosphere, DMS is converted to sulfate, most of which is deposited into the ocean.

As in the nitrogen cycle, bacteria drive the sulfur cycle. In freshwater wetlands, tidal flats, and flooded soils, which are oxygen-deficient, certain bacteria convert sulfates to hydrogen sulfide gas, which is released into the atmosphere, or to metallic sulfides, which are deposited as rock. In the absence of oxygen, other bacteria perform an ancient type of photosynthesis that uses hydrogen sulfide instead of water. Where oxygen is present, the resident bacteria oxidize sulfur compounds to sulfates.

Human-Induced Changes to the Sulfur Cycle Coal, and to a lesser extent oil, contains sulfur. When these fuels are burned in power plants, factories, and motor vehicles, sulfur dioxide, a major cause of acid deposition, is released into the atmosphere. Sulfur dioxide is also released during the smelting of sulfur-containing ores of such metals as copper, lead, and zinc. Pollution abatement, such as scrubbing smokestack gases to remove sulfur oxides, has reduced the amount of sulfur emissions in some countries in recent years. Global sulfur emissions peaked in 2006 then declined between 2006 and 2011, in part due to new control efforts in China, as well as to declines in Europe and North America.

THE HYDROLOGIC CYCLE

Life would be impossible without water, which makes up a substantial part of the mass of most organisms. All forms of life, from bacteria to plants and animals, use water as a medium for chemical reactions as well as for the transport of materials within and among cells. In the **hydrologic cycle**, water continuously circulates from the ocean to the atmosphere to the land and back to the ocean. It provides a renewable supply of purified water for terrestrial organisms and results in a balance among water in the ocean, on the land, and in the atmosphere (**Figure 4.6**). Water moves from the atmosphere to the land and ocean in the form of precipitation—rain, snow, sleet, or hail. When water evaporates from the ocean surface and from soil, streams, rivers, and lakes on land, it forms clouds in the atmosphere. In addition, **transpiration**, the loss of water vapor from land plants, adds water to the atmosphere. Roughly 97% of the water a plant's roots absorb from the soil is transported to the leaves, where it is transpired.

ɿydrologic cycle The global circulation of water from the environment to living organisms and back to the environment.

Water may evaporate from land and reenter the atmosphere directly. Alternatively, it may flow in rivers and streams to coastal estuaries, where fresh water meets the ocean. The movement of water from land to rivers, lakes, wetlands, and, ultimately, the ocean is called **runoff**, and the area of land drained by runoff is a **watershed**. Water also percolates, or seeps, downward through the soil and rock to become **groundwater**, which is fresh water stored

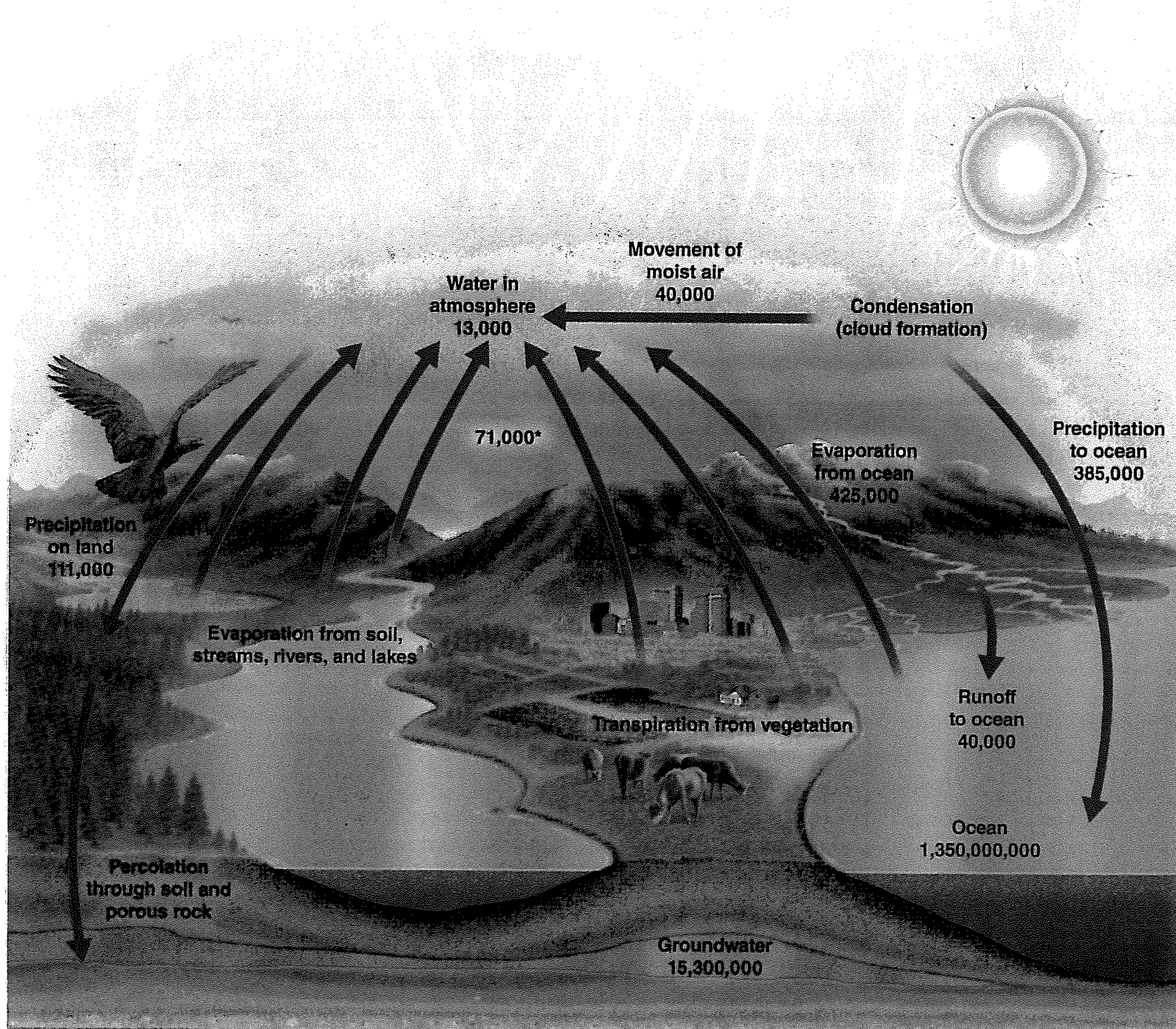


Figure 4.6 The hydrologic cycle. Estimated values for pools in the global water budget are expressed as km³, and the values for movements (associated with arrows) are in km³ per year. The starred value (71,000 km³ per year) includes both transpiration from plants and evaporation from soil, streams, rivers, and lakes. (Values from W.H. Schlesinger, *Biogeochemistry: An Analysis of Global Change*, 2nd edition. Academic Press, San Diego, 1997, and based on several sources)

in underground caverns and porous layers of rock. Groundwater may reside in the ground for hundreds to many thousands of years, but eventually it supplies water to the soil, vegetation, streams and rivers, and the ocean.

Regardless of its physical form—solid, liquid, or vapor—or its location, every molecule of water moves through the hydrologic cycle. Tremendous quantities of water are cycled annually between Earth and its atmosphere. The volume of water entering the atmosphere each year is about 389,500 km^3 (95,000 mi^3). Approximately three-fourths of this water reenters the ocean directly as precipitation; the remainder falls on land.

Human-Induced Changes to the Hydrologic Cycle Some research suggests that air pollution may weaken the global hydrologic cycle. **Aerosols**—tiny particles of air pollution consisting mostly of sulfates, nitrates, carbon, mineral dusts, and smokestack ash—are produced largely from fossil-fuel combustion and the burning of forests. Once in the atmosphere, aerosols enhance the scattering and absorption of sunlight in the atmosphere and cause clouds to form. Clouds formed in aerosols are less likely to release their precipitation. As a result, scientists think aerosols affect the availability and quality of water in some regions. Climate change caused by CO_2 is also altering the global hydrologic cycle by increasing glacial and polar ice-cap melting and by increasing evaporation in some areas.

We have explored how living things depend on the abiotic environment to supply energy and essential materials (in biogeochemical cycles). Let us now consider five additional aspects of the physical environment that affect organisms: solar radiation, the atmosphere, the ocean, weather and climate, and internal planetary processes.

REVIEW

1. What roles do photosynthesis, cellular respiration, and combustion play in the carbon cycle?
2. What are the five steps of the nitrogen cycle?
3. How does the phosphorus cycle differ from the carbon, nitrogen, and sulfur cycles?
4. What sulfur-containing gases are found in the atmosphere?

Solar Radiation

LEARNING OBJECTIVE

- Summarize the effects of solar energy on Earth's temperature, including the influence of albedos of various surfaces.

The sun makes life on Earth possible. It warms the planet, including the atmosphere, to habitable temperatures. Without the sun's energy, the temperature would approach absolute zero (−273°C) and all water would freeze, even in the ocean. The sun powers the hydrologic cycle, carbon cycle, and other biogeochemical cycles and is the primary determinant of climate. Photosynthetic organisms capture the sun's energy and use it to make the food molecules required by almost all forms of life. Most of our fuels—wood, oil, coal, and natural gas—represent solar energy captured by photosynthetic organisms. Without the sun, almost all life would cease.

The sun's energy is the product of a massive nuclear fusion reaction and is emitted into space in the form of electromagnetic radiation—especially visible light and infrared and ultraviolet radiation, which are not visible to the human eye (see Figure 3.5). Approximately one-billionth of the total energy released by the sun strikes our atmosphere, and of this tiny trickle of energy, a minute part operates the biosphere.

Clouds and the atmosphere, and, to a lesser extent, surfaces (especially snow, ice, and the ocean) reflect about 30% of the solar radiation (also called *insolation*) that falls on Earth (**Figure 4.7**). Glaciers and ice sheets have high **albedos** and reflect 80% to 90% of the sunlight hitting their surfaces. At the other extreme, asphalt pavement and buildings have low albedos and reflect 10% to 15%, whereas the ocean and forests reflect only about 5%.

albedo The proportional reflectance of solar energy from Earth's surface, commonly expressed as a percentage.

As shown in Figure 4.7, the remaining 70% of the solar radiation that falls on Earth is absorbed and runs the hydrologic cycle, drives winds and ocean currents, powers photosynthesis, and warms the planet. Ultimately, all this energy is lost through the continual radiation of long-wave infrared energy (heat) into space.

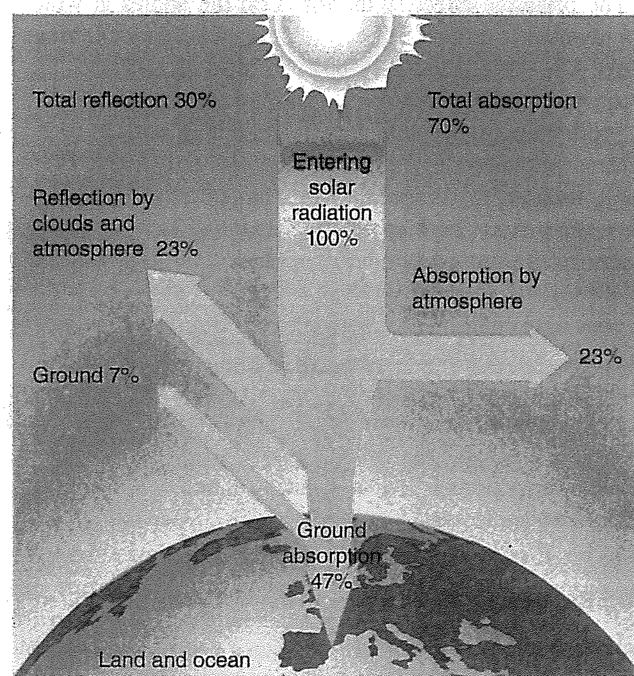
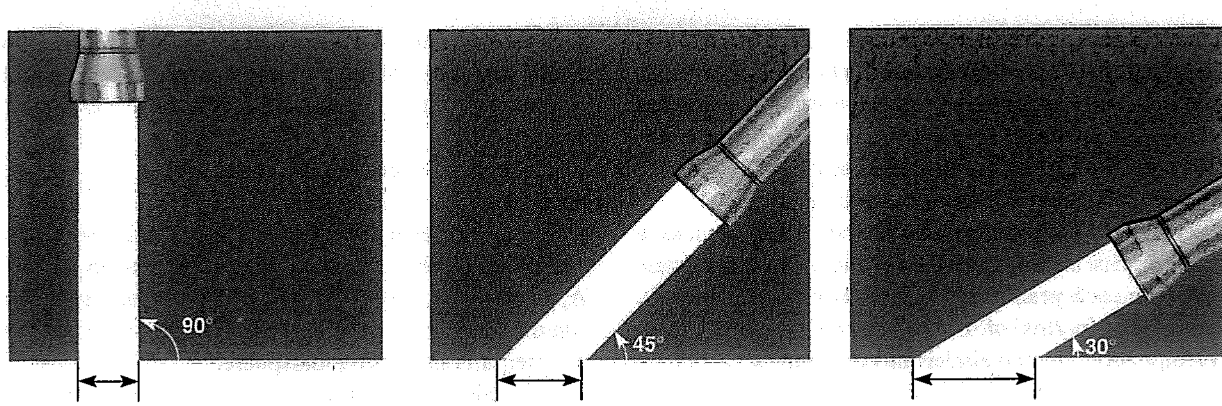


Figure 4.7 Fate of solar radiation that reaches Earth. Most of the sun's energy never reaches Earth. The solar energy that reaches Earth warms the planet's surface, drives the hydrologic cycle and other biogeochemical cycles, produces our climate, and powers almost all life through the process of photosynthesis. (Based on data from K.E. Trenberth, J.T. Fasullo, and J. Kiehl, Earth's Global Energy Budget. *American Meteorological Society*, March 2009.)



(a) One unit of light is concentrated over 1 unit of surface area.

(b) One unit of light is dispersed over 1.4 units of surface area.

(c) One unit of light is dispersed over 2 units of surface area.

Figure 4.8 Solar intensity and latitude. The angle at which the sun's rays strike Earth varies from one geographic location to another, a result of Earth's spherical shape and its inclination on its axis. Sunlight (represented by the flashlight) that shines vertically near the equator is concentrated on Earth's surface (in a). As one moves toward the poles (see b and c), the light hits the surface more and more obliquely, spreading the same amount of radiation over larger and larger areas.

TEMPERATURE CHANGES WITH LATITUDE

The most significant local variation in Earth's temperature is produced because the sun's energy does not reach all places uniformly. A combination of Earth's roughly spherical shape and the tilt of its axis produces variation in the exposure of the surface to the sun's energy.

The principal effect of the tilt is on the angles at which the sun's rays strike different areas of the planet at any one time (**Figure 4.8**). On average, the sun's rays hit vertically near the equator, making the energy more concentrated and producing higher temperatures. At higher latitudes, the sun's rays hit more obliquely; as a result, their energy is spread over a larger surface area. Also, rays of light entering the atmosphere obliquely near the poles pass through a deeper envelope of air than does light entering near the equator. This causes more of the sun's energy to be scattered and reflected back to space, which in turn further lowers temperatures near the poles. Thus, solar energy that reaches polar regions is less concentrated, and temperatures are lower.

TEMPERATURE CHANGES WITH THE SEASONS

Seasons are determined primarily by Earth's inclination on its axis. Earth's inclination on its axis is 23.5 degrees from a line drawn perpendicular to the orbital plane. During half of the year (March 21 to September 22) the Northern Hemisphere tilts toward the sun, and during the other half (September 22 to March 21) it tilts away from the sun (**Figure 4.9**). The orientation of the Southern Hemisphere is just the opposite at these times. Summer in the Northern Hemisphere corresponds to winter in the Southern Hemisphere.

REVIEW

1. How does the sun affect temperature at different latitudes? Why?
2. What is albedo?

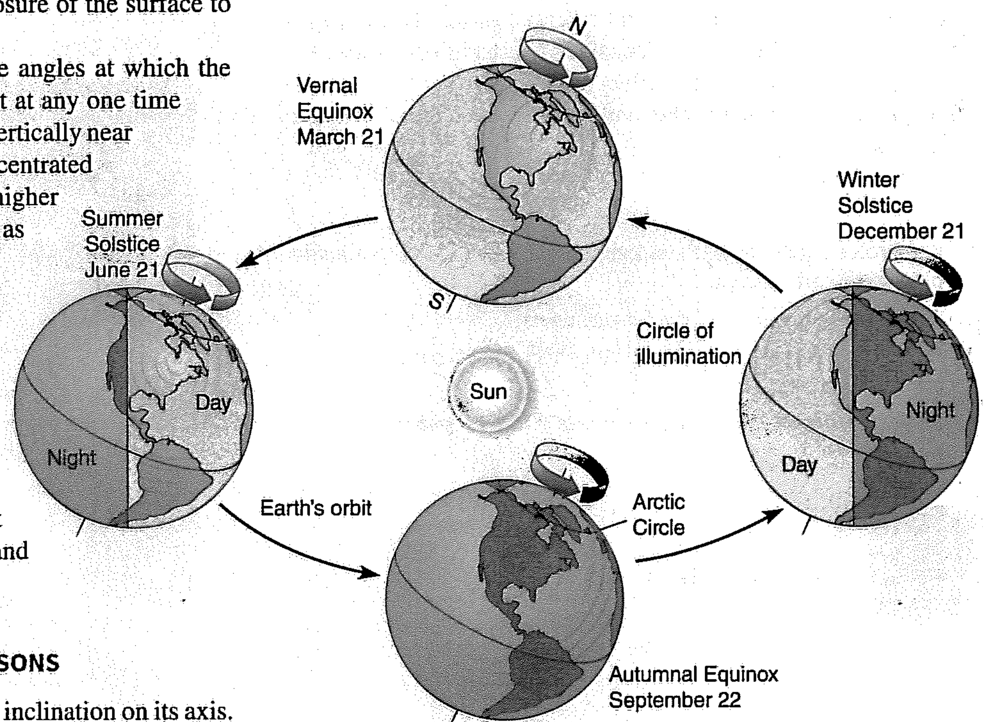


Figure 4.9 Progression of seasons. Earth's inclination on its axis remains the same as it travels around the sun. The sun's rays hit the Northern Hemisphere obliquely during its winter months and more directly during its summer. In the Southern Hemisphere, the sun's rays are oblique during its winter, which corresponds to the Northern Hemisphere's summer. At the equator, the sun's rays are approximately vertical on March 21 and September 22.

The Atmosphere

LEARNING OBJECTIVES

- Describe the four layers of Earth's atmosphere: troposphere, stratosphere, mesosphere, and thermosphere.
- Discuss the roles of solar energy and the Coriolis effect in producing atmospheric circulation.

The atmosphere is an invisible layer of gases that envelops Earth. Oxygen (21%) and nitrogen (78%) are the predominant gases in the atmosphere, accounting for about 99% of dry air. Other gases, including argon, carbon dioxide, neon, and helium, make up the remaining 1%. In addition, water vapor and trace amounts of various air pollutants, such as methane, ozone, dust particles, microorganisms, and chlorofluorocarbons (CFCs), are present in the air. The atmosphere becomes less dense as it extends outward into space; as a result of gravity, most of the atmosphere's mass is found near Earth's surface (**Figure 4.10**).

The atmosphere performs several ecologically important functions. It protects Earth's surface from most of the sun's ultraviolet radiation and X-rays, as well as from lethal amounts of cosmic rays from space. Without this shielding by the atmosphere, most life would cease to exist. While the atmosphere protects Earth from high-energy radiation, it allows visible light and some infrared radiation to penetrate, and these warm the surface and the lower atmosphere. This interaction between the atmosphere and solar energy is responsible for weather and climate.

Organisms depend on the atmosphere, but they maintain and, in certain instances, modify its composition. Over hundreds of millions of years, photosynthetic organisms converted what was once a carbon dioxide-rich atmosphere to one in which oxygen is the second most common component after nitrogen. A balance between oxygen-producing photosynthesis and oxygen-using respiration maintains the current level of oxygen.

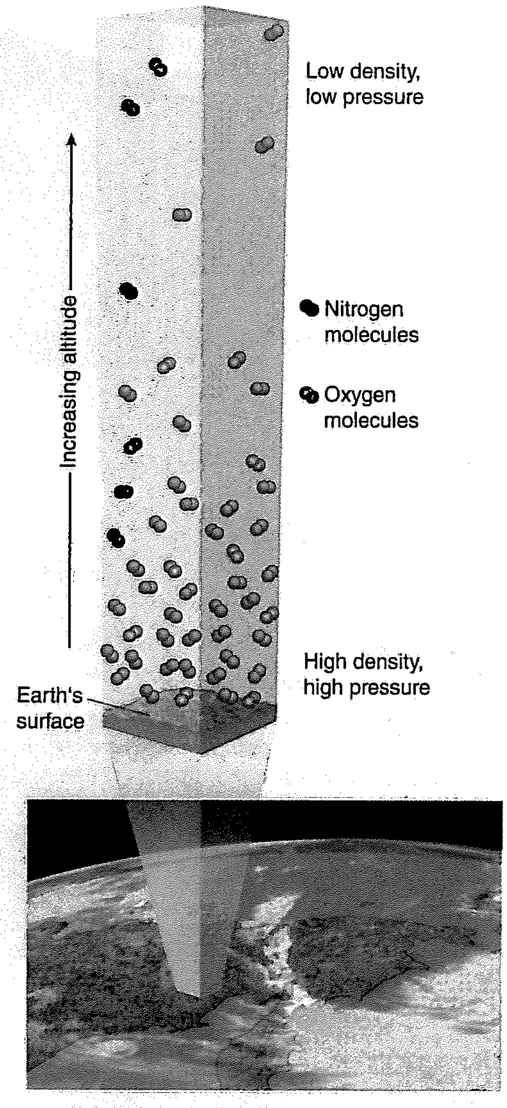


Figure 4.10 Density of the atmosphere. Earth's atmosphere decreases in density and pressure with increasing altitude. The force of gravity is responsible for attracting more air molecules closer to Earth's surface.

LAYERS OF THE ATMOSPHERE

The atmosphere is composed of a series of four concentric layers—the troposphere, stratosphere, mesosphere, and thermosphere (**Figure 4.11**). These layers vary in altitude and temperature with latitude and season. The **troposphere** extends to a height of approximately 12 km (7.5 mi). The temperature of the troposphere decreases with increasing altitude by about 6°C (11°F) for every kilometer. Weather, including turbulent wind, storms, and most clouds, occurs in the troposphere.

troposphere The ...er of the atmosphere closest to Earth's surface.

In the next layer of atmosphere, the **stratosphere**, there is a steady wind but no turbulence. Little water is found in the stratosphere, and the temperature is more or less uniform (−45°C to −75°C) in the lower stratosphere; commercial jets fly here. The stratosphere extends from 12 km to 50 km (7.5 mi to 30 mi) above Earth's surface and contains a layer of ozone critical to life because it absorbs much of the sun's damaging ultraviolet radiation. The absorption of ultraviolet radiation by the ozone layer heats the air, and so temperature increases with increasing altitude in the stratosphere.

stratosphere The ...er of the atmosphere ...d directly above the troposphere.

The **mesosphere**, the layer of atmosphere directly above the stratosphere, extends from 50 km to 80 km (30 mi to 50 mi) above Earth's surface. Temperatures drop steadily in the mesosphere to the lowest in the atmosphere—as low as −138°C.

The **thermosphere** extends from 80 km to 480 km (50 mi to 300 mi) above Earth's surface and is very hot. Gases in the thin air of the thermosphere absorb X-rays and short-wave ultraviolet radiation. This absorption drives the few molecules present to great speeds, raising their temperature in the process to 1000°C or more. The aurora, a colorful display of lights in dark polar skies, is produced when charged particles from the sun hit oxygen or nitrogen molecules in the thermosphere. The thermosphere is important

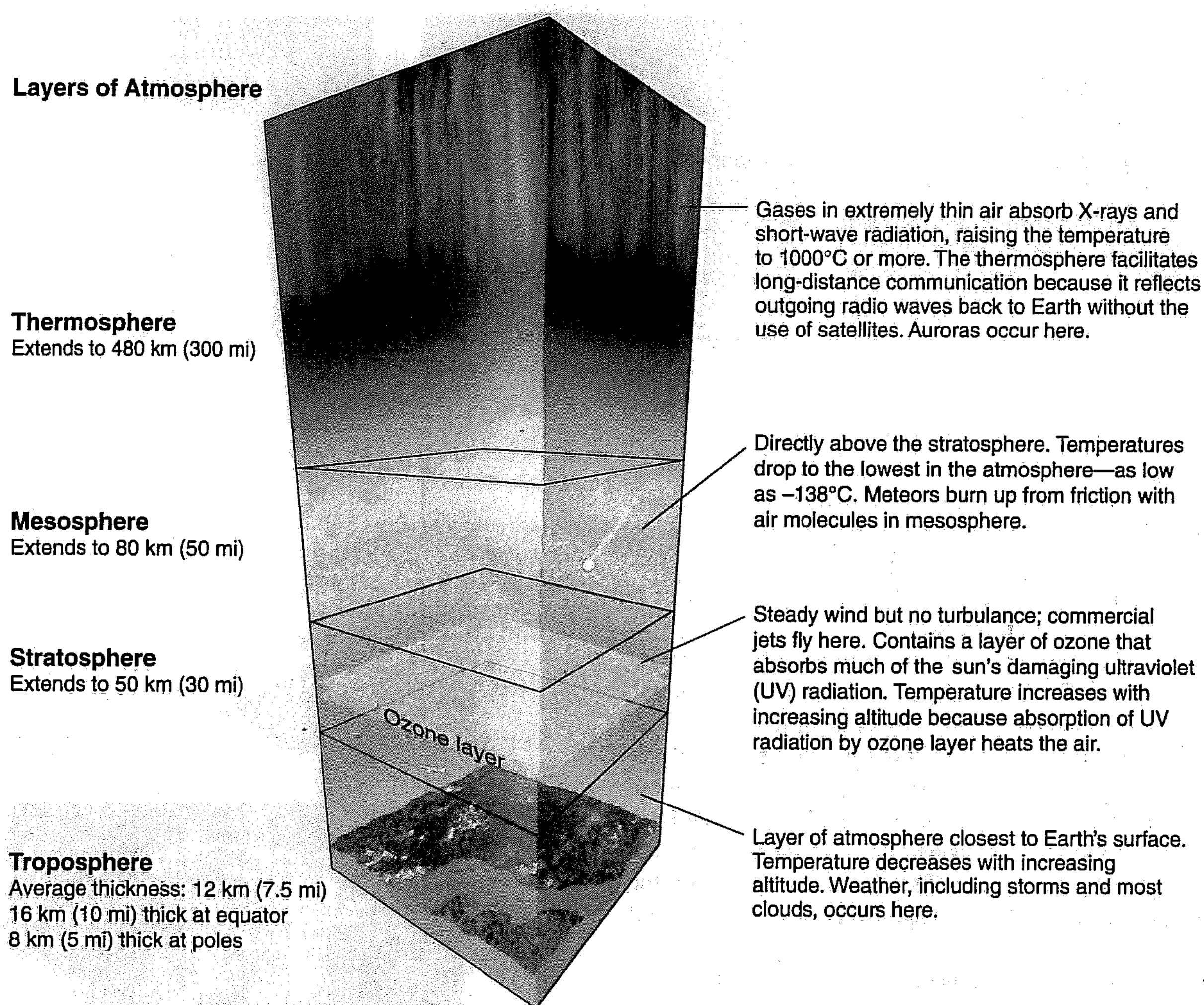


Figure 4.11 Layers of the atmosphere. The troposphere is closest to Earth's surface. The stratosphere is above the troposphere, followed by the mesosphere and thermosphere.

in long-distance communication because it reflects outgoing radio waves back to Earth without the aid of satellites.

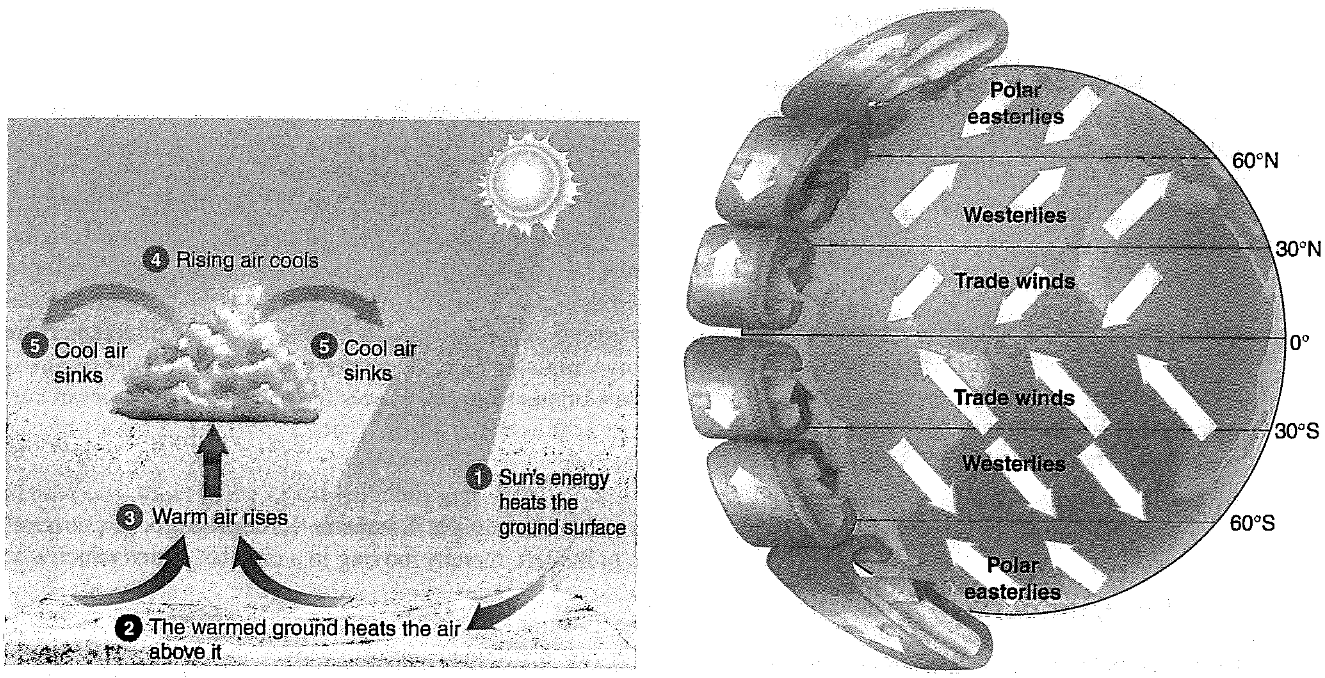
ATMOSPHERIC CIRCULATION

In large measure, differences in temperature caused by variations in the amount of solar energy reaching different locations on Earth drive the circulation of the atmosphere. The warm surface near the equator heats the air in contact with it, causing this air to expand and rise in a process known as *convection* (**Figure 4.12**). As the warm air rises, it cools and then sinks again. Much of it recirculates almost immediately to the same areas it has left, but the remainder of the heated air splits and flows in two directions toward the poles. The air chills enough to sink to the surface at about 30 degrees north and south latitudes. This descending air splits and flows over the surface in two directions. Similar upward movements of warm air and its subsequent flow toward the poles occur at higher latitudes farther from the equator. At the poles, the cold polar air sinks and flows toward the lower latitudes, generally beneath the sheets of warm air that simultaneously flow toward the poles. The constant motion of air transfers heat from the equator toward the poles, and as the air returns, it cools the land over which it passes. This continuous turnover moderates temperatures over Earth's surface.

Surface Winds In addition to its global circulation patterns, the atmosphere exhibits complex horizontal movements commonly called **winds**. The nature of wind, with its gusts, eddies, and lulls, is difficult to understand or predict. It results in part from differences in atmospheric pressure and from Earth's rotation.

Atmospheric gases have weight and exert a pressure that is, at sea level, about 1013 millibars (14.7 lb per in.^{2}). Air pressure is variable, changing with elevation, temperature, and humidity. Winds tend to blow from areas of high atmospheric pressure to areas of low pressure, and the greater the difference between the high- and low-pressure areas, the stronger the wind.

Earth's rotation influences the direction of wind. Earth rotates from west to east, which causes the east-west movements of surface winds to deflect from their straight-line paths. The moving air swerves to the right of the direction in which it is traveling in the



(a) In atmospheric convection, heating of the ground surface heats the air, producing an updraft of less dense, warm air. The convection process ultimately causes air currents that mix warmer and cooler parts of the atmosphere.

(b) Atmospheric circulation transports heat from the equator to the poles (left side). The heated air rises at the equator, travels toward the poles, and cools in the process so that much of it descends again at around 30 degrees latitude in both hemispheres. At higher latitudes, air circulation is more complex.

Figure 4.12 Atmospheric circulation.

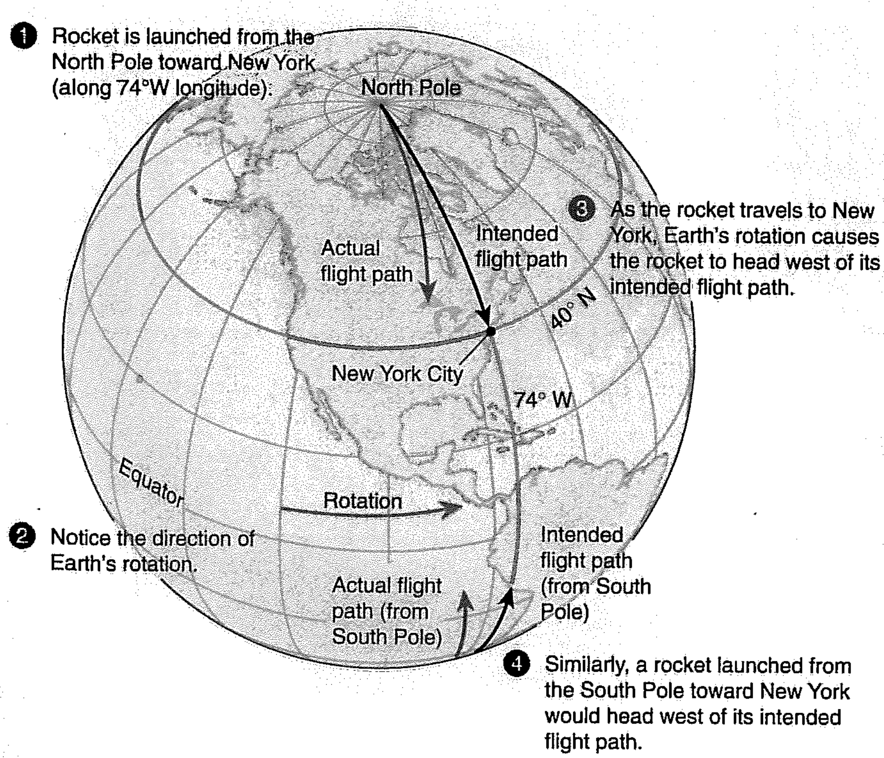


Figure 4.13 Coriolis effect. Viewed from the North Pole, the Coriolis effect appears to deflect winds and ocean currents to the right. From the South Pole, the deflection appears to be to the left. (Adapted from A.F. Arbogast. *Discovering Physical Geography*. Hoboken, NJ: John Wiley & Sons, Inc., 2007.)

Northern Hemisphere and to the left of the direction in which it is traveling in the Southern Hemisphere (**Figure 4.13**). This tendency is the result of the **Coriolis effect**. The Coriolis effect is greater at higher latitudes and negligible at the equator. Air moving eastward or westward at the equator is not deflected from its path.

Coriolis effect The influence of Earth's rotation, which tends to turn fluids (air and water) toward the right in the Northern Hemisphere and toward the left in the Southern Hemisphere.

The atmosphere has three **prevailing winds** (see **Figure 4.12b**). Prevailing winds that generally blow from the northeast near the North Pole or from the southeast near the South Pole are **polar easterlies**. Winds that generally blow in the midlatitudes from the southwest in the Northern Hemisphere or from the northwest in the Southern Hemisphere are **westerlies**. Tropical winds that generally blow from the northeast in the Northern Hemisphere or from the southeast in the Southern Hemisphere are called **trade winds**.

prevailing winds Major surface winds that blow more or less continually.

REVIEW

1. What is the outermost layer of the atmosphere? Which layer of the atmosphere contains the ozone that absorbs much of the sun's ultraviolet radiation?
2. What basic forces determine the circulation of the atmosphere?

The Global Ocean

LEARNING OBJECTIVES

- Discuss the roles of solar energy and the Coriolis effect in producing global water flow patterns, including gyres.
- Define *El Niño–Southern Oscillation (ENSO)* and *La Niña*, and describe some of their effects.

The global ocean is a huge body of salt water that surrounds the continents and covers almost three-fourths of Earth's surface. It is a single, continuous body of water, but geographers divide it into four sections separated by the continents: the Pacific, Atlantic, Indian, and Arctic Oceans. The Pacific Ocean is the largest: It covers one-third of Earth's surface and contains more than half of Earth's water.

PATTERNS OF CIRCULATION IN THE OCEAN

The persistent prevailing winds blowing over the ocean produce surface-ocean water **currents (Figure 4.14)**. The prevailing winds generate **gyres**, large circular ocean currents that often encompass an entire ocean basin. In the North Atlantic Ocean, the tropical trade winds tend to blow toward the west, whereas the westerlies in the midlatitudes blow toward the east. This helps establish a clockwise gyre in the North Atlantic. That is, the trade winds produce the westward North Atlantic Equatorial Current in the tropical North Atlantic Ocean. When this current reaches the North American continent, it is deflected northward, where the westerlies begin to influence it. As a result, the current flows eastward in the midlatitudes until it reaches the landmass of Europe. Here some water is deflected toward the pole and some toward the equator. The water flowing toward the equator comes under the influence of trade winds again, producing the circular gyre. Although surface-ocean currents and winds tend to move in the same direction, there are many variations to this general rule.

The Coriolis effect influences the paths of surface-ocean currents just as it does the winds. Earth's rotation from west to east causes surface-ocean currents to swerve to the right in the Northern Hemisphere, helping establish the circular, clockwise pattern of water currents. In the Southern Hemisphere, ocean currents swerve to the left, thereby moving in a circular, counterclockwise pattern.

The position of landmasses affects ocean circulation. The ocean is not distributed uniformly over the globe: The Southern Hemisphere has more water than the Northern Hemisphere **(Figure 4.15)**. The circumpolar (around the pole) flow of water in the Southern Hemisphere—called the Southern Ocean—is almost unimpeded by landmasses.

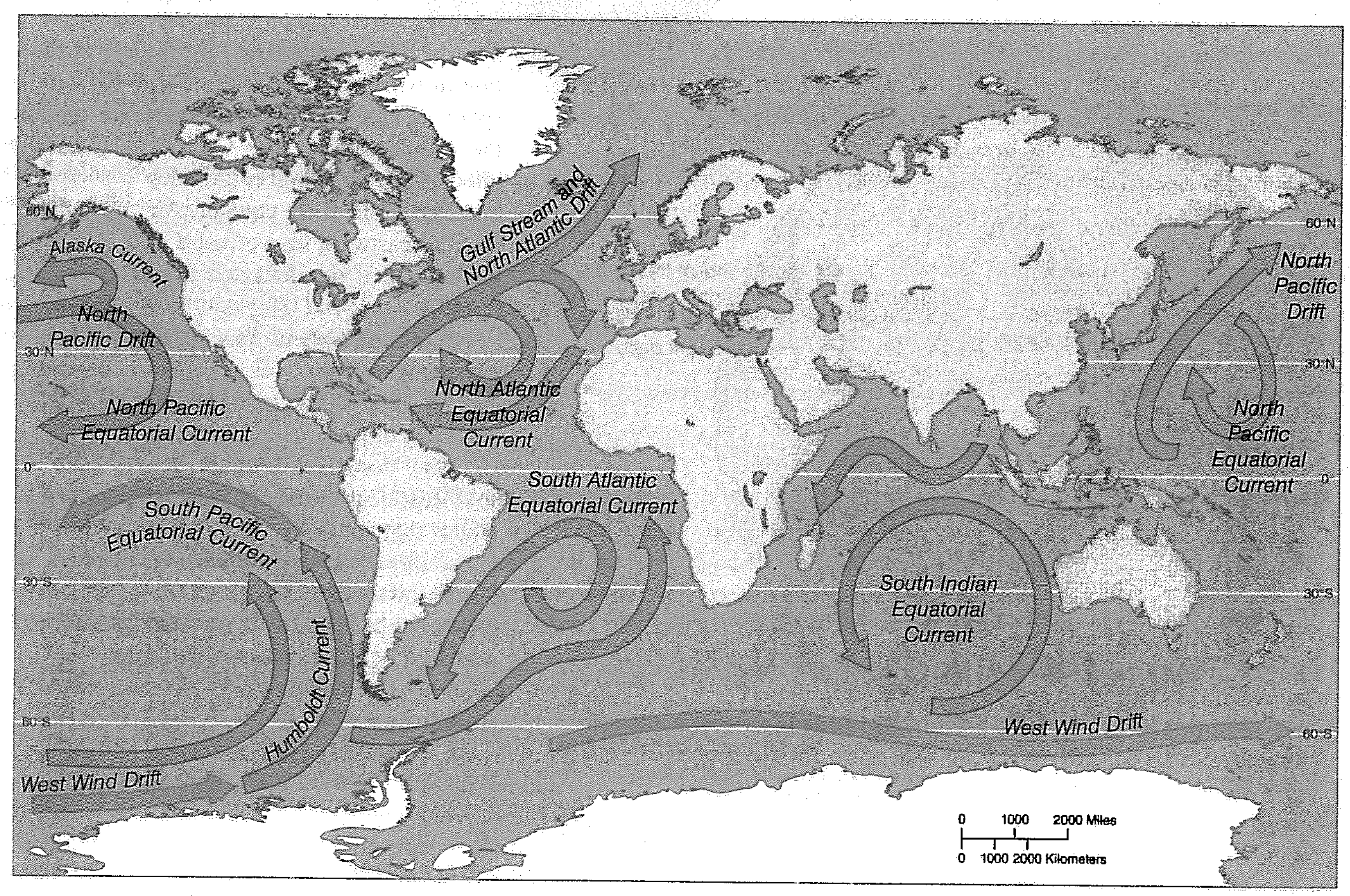
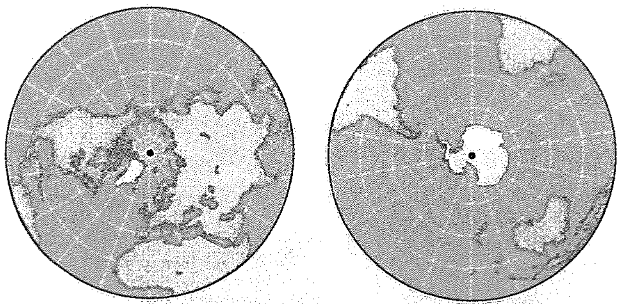


Figure 4.14 Surface-ocean currents. Winds largely cause the basic pattern of ocean currents. The main ocean current flow—clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere—results partly from the Coriolis effect.



(a) The Northern Hemisphere as viewed from the North Pole.

(b) The Southern Hemisphere as viewed from the South Pole. Ocean currents are freer to flow in a circumpolar manner in the Southern Hemisphere.

Figure 4.15 Ocean and landmasses in the Northern and Southern Hemispheres.

VERTICAL MIXING OF OCEAN WATER

The varying **density** (mass per unit volume) of seawater affects deep-ocean currents. Cold, salty water is denser than warmer, less salty water. (The density of water increases with decreasing temperature down to 4°C.) Colder, salty ocean water sinks and flows under warmer, less salty water, generating currents far below the surface. Deep-ocean currents often travel in different directions and at different speeds than do surface currents, in part because the Coriolis effect is more pronounced at greater depths. **Figure 4.16** shows the circulation of shallow and deep currents—the **ocean conveyor belt**—that moves cold, salty deep-sea water from higher to lower latitudes. Note that the Atlantic Ocean gets its cold, deep water from the Arctic Ocean, whereas the Pacific and Indian Oceans get theirs from the water surrounding Antarctica.

The ocean conveyor belt affects regional and possibly global climate. As the Gulf Stream and North Atlantic Drift (see Figure 4.14) push into the North Atlantic, they deliver an immense amount of heat from the tropics to Europe. As this shallow current transfers its heat to the atmosphere, the water becomes denser and sinks. The deep current flowing southward in the North Atlantic is, on average, 8°C (14°F) cooler than the shallow current flowing northward.

Evidence from seafloor sediments and Greenland ice indicates that the ocean conveyor belt shifts from one equilibrium state to another in a relatively short period (a few years to a few decades). The present ocean conveyor belt reorganized between 11,000 and 12,000 years ago. During this period, heat transfer to the North Atlantic stopped, global temperatures dropped, and both North America and Europe experienced conditions of intense cold. The exact causes and effects of such large shifts in climate are not currently known, but many scientists are concerned that human activities may unintentionally affect the link between the ocean conveyor belt and global climate. The circulation of the conveyor belt in the North Atlantic Ocean could potentially stop as global warming

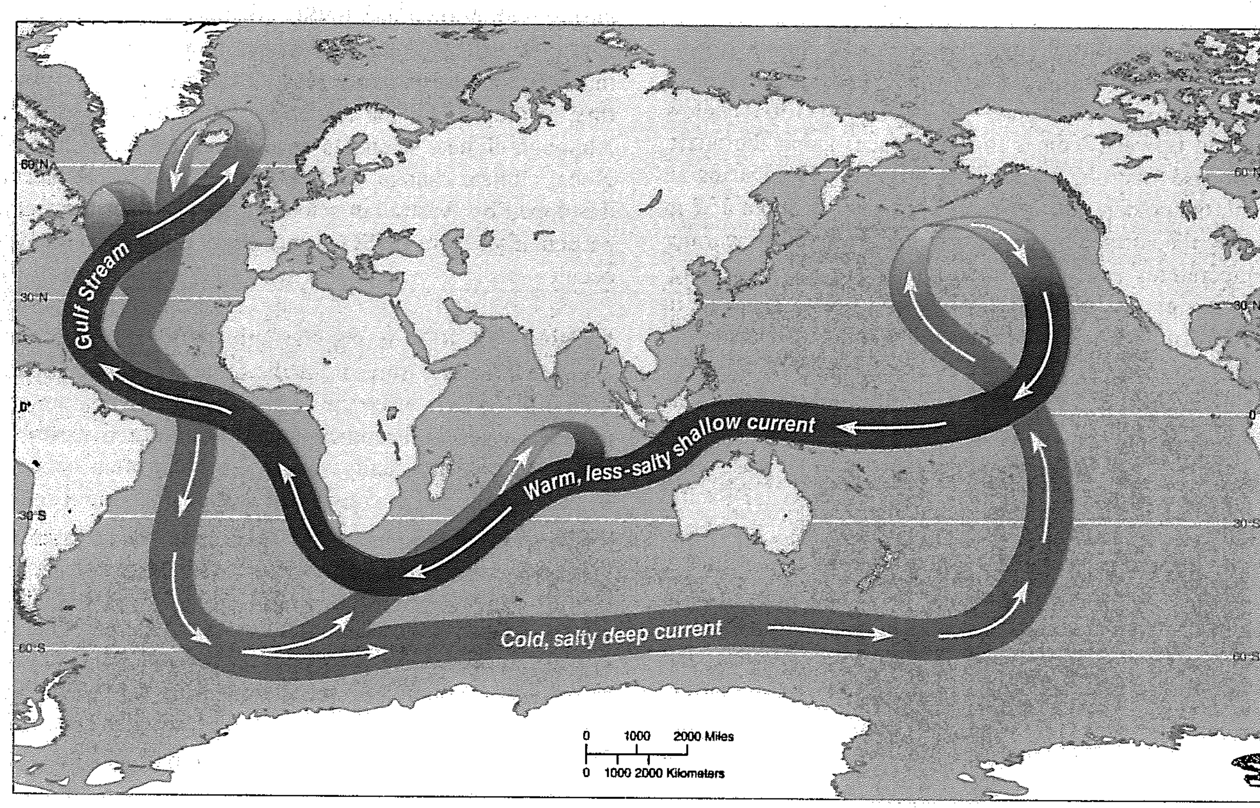
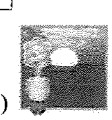


Figure 4.16 Ocean conveyor belt. This loop consists of both warm, shallow water and cold, deep water. The ocean conveyor belt is responsible for the relatively warm climate in Europe. Changes to the conveyor belt could cause climate changes around the world. How might climate warming trigger a mini ice age in Europe? (After W.S. Broecker, "The Great Ocean Conveyor." *Oceanography*, Vol. 4, 1991.)



causes ice in Greenland to melt. (Melting ice would dilute the cold, salty water so that it doesn't sink.) Some scientists have suggested that this change could lead to a mini ice age in northern Europe. Oceanographers are trying to better understand this phenomenon by measuring the Atlantic Ocean circulation using moored instruments at various depths.

OCEAN INTERACTIONS WITH THE ATMOSPHERE

The ocean and the atmosphere are strongly linked, with wind from the atmosphere affecting the ocean currents and heat from the ocean affecting atmospheric circulation. One of the best examples of the interaction between ocean and atmosphere is the **El Niño–Southern Oscillation (ENSO**, or simply **El Niño)** event, which is responsible for much of Earth's interannual (from one year to the next) climate variability.

El Niño–Southern Oscillation (ENSO) A periodic, large-scale warming of surface waters of the tropical eastern Pacific Ocean that affects both ocean and atmospheric circulation patterns.

Normally, westward-blowing trade winds restrict the warmest waters to the western Pacific near Australia. Every three to seven years, however, the trade winds weaken, and the warm mass of water expands eastward to South America, increasing surface temperatures in the eastern Pacific. Ocean currents, which normally flow westward in this area, slow down, stop altogether, or even reverse and go eastward. The name for this phenomenon, **El Niño** (Spanish, "the boy child"), refers to the Christ child because the warming usually reaches the fishing grounds off Peru just before Christmas. El Niños typically last from one to two years.

El Niño can devastate the fisheries off South America. Normally, the colder, nutrient-rich deep water—where remains of dead aquatic organisms decompose—is about 40 m (130 ft) below the surface and **upwells** (comes to the surface) along the coast, partly in response to strong trade winds (**Figure 4.17**). During an ENSO event, the colder, nutrient-rich deep water is about 152 m (500 ft) below the surface in the eastern Pacific, and the warmer surface temperatures and weak trade winds prevent upwelling. The lack of nutrients in the water results in a severe decrease in the populations of anchovies and other marine fishes. During the 1982–1983 ENSO, one of the worst ever recorded, the anchovy population decreased by 99%. However, other species, such as shrimp and scallops, thrive during an ENSO event.

ENSO alters global air currents, directing unusual and sometimes dangerous weather to areas far from the tropical Pacific (**Figure 4.18**). By one estimate, the 1997–1998 ENSO, the strongest on record, caused more than 20,000 deaths and $33 billion in property damages worldwide. It resulted in heavy snows in parts of the western United States and ice storms in eastern Canada; torrential rains that flooded Peru, Ecuador, California, Arizona, and Western Europe; and droughts in Texas, Australia, and Indonesia. An ENSO-caused drought particularly hurt Indonesia: Fires, many deliberately set to clear land for agriculture, burned out of control and destroyed an area as large as the state of New Jersey.

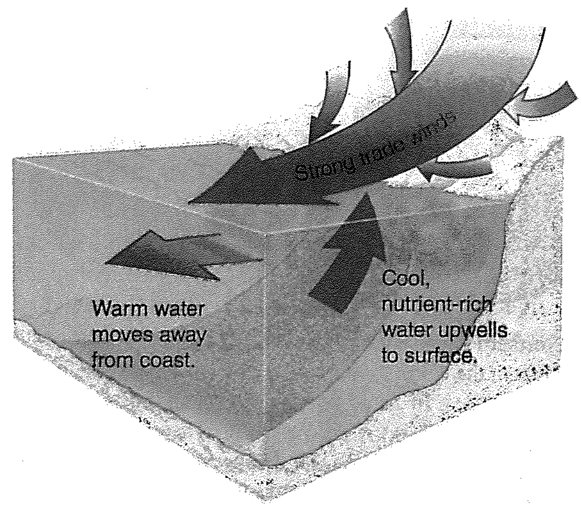
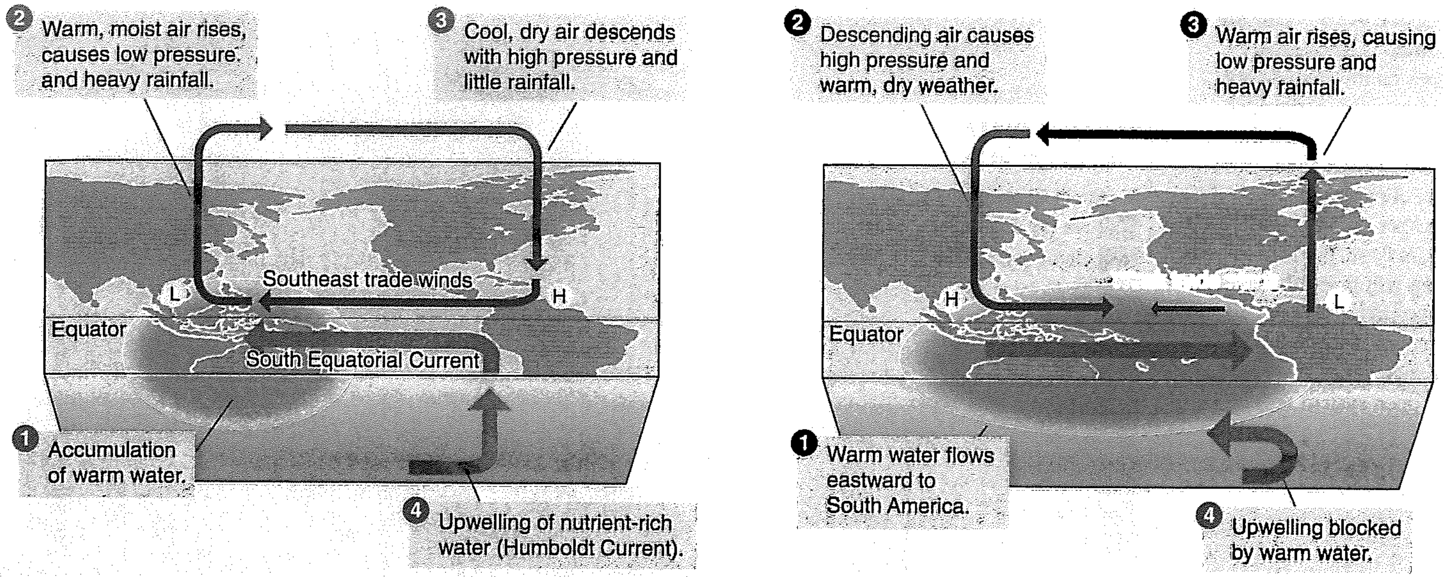


Figure 4.17 Upwelling. Coastal upwelling, where deeper waters come to the surface, occurs in the Pacific Ocean along the South American coast. Upwelling provides nutrients for microscopic algae, which in turn support a complex food web. Coastal upwelling weakens considerably during years with El Niño events, temporarily reducing fish populations.

Climate scientists observe and monitor sea-surface temperatures and winds to better understand and predict ENSO events. The **TAO/TRITON array** consists of 70 moored buoys in the tropical Pacific Ocean. These instruments collect oceanic and weather data during both normal and ENSO conditions. Satellites transmit the data to scientists on shore, who can now predict ENSO events as much as six months in advance. Such forecasts give governments time to prepare for the extreme weather associated with ENSO. Although climate scientists have found it difficult to predict how global climate change might affect El Niño, some recent models developed by Australian scientists suggest that the frequency of particularly severe ENSO events might double as climate changes occur.

La Niña El Niño is not the only periodic ocean temperature event to affect the tropical Pacific Ocean. **La Niña** (Spanish, "the little girl") occurs when the surface-water temperature in the eastern Pacific Ocean becomes unusually cool and westbound trade winds become unusually strong. La Niña often occurs after an El Niño event and is considered part of the natural oscillation of ocean temperature.

During the spring of 1998, the surface water of the eastern Pacific cooled 6.7°C (12°F) in just 20 days. Like El Niño, La Niña affects weather patterns around the world, but its effects are more difficult to predict. In the contiguous United States, La Niña typically causes wetter than usual winters in the Pacific Northwest, warmer weather in the Southeast, and drought conditions in the Southwest. Atlantic hurricanes are stronger and more numerous during a La Niña event.



(a) **Normal climate conditions.** ENSO events depend on the relationship of atmospheric circulation to surface-water flow in the Pacific. Normal conditions occur when strong easterly flow pushes warm water into the western Pacific.

(b) **ENSO conditions.** An ENSO event occurs when easterly flow weakens, allowing warm water to collect along the South American coast. Note the relationship between precipitation and the location of pressure systems. During an ENSO event, northern areas of the contiguous United States are typically warmer during winter, whereas southern areas are cooler and wetter.

Figure 4.18 El Niño–Southern Oscillation (ENSO). ENSO events drastically alter the climate in many areas remote from the Pacific Ocean.

REVIEW

1. How are the sun's energy, prevailing winds, and surface-ocean currents related?
2. What is the El Niño–Southern Oscillation (ENSO)? What are some of its global effects?

Weather and Climate

LEARNING OBJECTIVE

- Distinguish between weather and climate, and briefly discuss regional precipitation differences.
- Contrast tornadoes and tropical cyclones.

Weather refers to the conditions in the atmosphere at a given place and time; it includes temperature, atmospheric pressure, precipitation, cloudiness, humidity, and wind. Weather changes from one hour to the next and from one day to the next. **Climate** refers to the typical patterns of weather that occur in a place over a period of years.

The two most important factors that determine an area's climate are temperature—both average temperature and temperature extremes—and precipitation—average precipitation, seasonal distribution, and variability. Other climate factors include wind, humidity, fog, and cloud cover. Depending on their layers, altitude, and density, clouds can absorb or reflect sunlight and can retain the planet's outgoing heat; details of the effects clouds have on climate have not yet been resolved. Lightning is an important aspect of climate in some areas because it starts fires.

Day-to-day variations, day-to-night variations, and seasonal variations in climate factors are important dimensions of climate that affect organisms. Latitude, elevation, topography, vegetation, distance from the ocean, and location on a continent or other landmass influence temperature, precipitation, and other aspects of climate. Unlike weather, which changes rapidly, climate usually changes slowly, over hundreds or thousands of years.

Earth has many climates, and because each stays relatively constant for many years, organisms have adapted to them. The many kinds of organisms on Earth are here in part because of the large number of climates—from cold, snow-covered polar climates to tropical climates where it is hot and rains almost every day. A German botanist and climatologist, **Wladimir Köppen**, developed in the early part of the 20th century the most widely used system for classifying climates. **Figure 4.19** shows a world climate map modified from Köppen. Note that there are six climate zones—humid equatorial, dry, humid temperate, humid cold, cold polar, and highland climate—and that each is subdivided into climate types. For example, the three types of humid temperate climates are no dry season, dry winter, and dry summer.

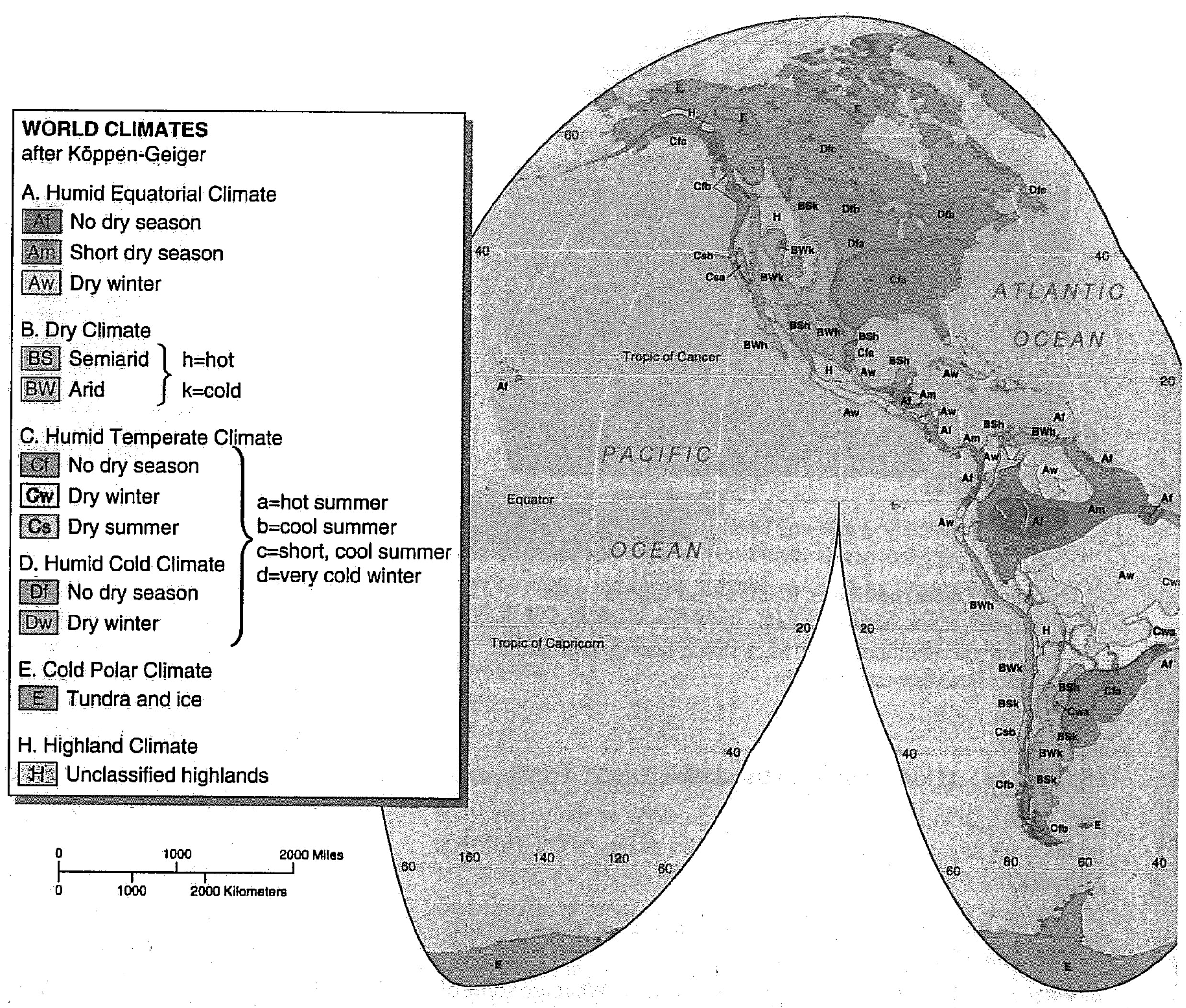


Figure 4.19 Climate zones. The boundary lines on this map do not indicate abrupt changes in climate. Instead, they are transition zones from one climate zone to another. In the next 50 years or so, the Köppen map will probably have to be revised to take into account global climate change. (Based on Köppen system.)

PRECIPITATION

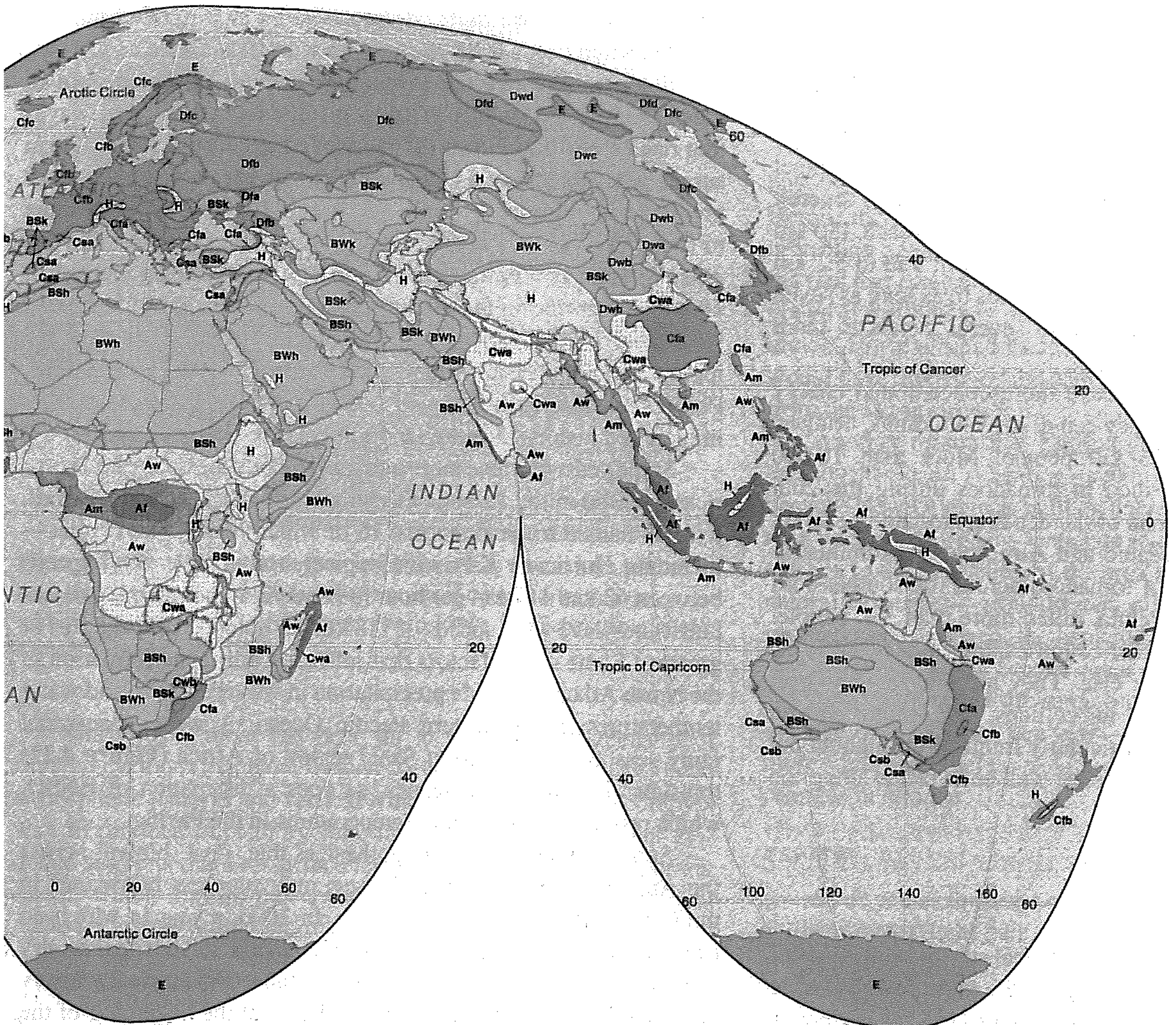
Precipitation refers to any form of water, such as rain, snow, sleet, and hail, that falls from the atmosphere. Precipitation varies from one location to another and has a profound effect on the distribution and kinds of organisms present. One of the driest places on Earth is in the Atacama Desert in Chile, where the average annual rainfall is 0.05 cm (0.02 in.). In contrast, Mount Waialeale in Hawaii, Earth's wettest spot, receives an average annual precipitation of 1200 cm (472 in.).

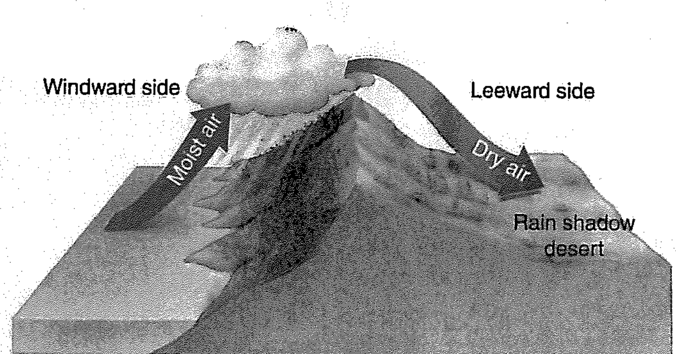
Differences in precipitation depend on several factors. The heavy rainfall of some areas of the tropics results mainly from the equatorial uplift of moisture-laden air. High surface-water temperatures cause the evaporation of vast quantities of water from tropical parts of the ocean, and prevailing winds blow the resulting moist air over landmasses. Heating of the air over a land surface that was warmed by the sun causes moist air to rise. As it rises, the air cools, and its moisture-holding ability decreases (cool air holds less water vapor than warm air). When the air reaches its saturation point—when it cannot hold any additional water vapor—clouds form and water is released as precipitation. The air eventually returns to Earth on both sides of the equator near the Tropics of Cancer and Capricorn (latitudes 23.5 degrees north and 23.5 degrees south, respectively). By then, most of its moisture has precipitated, and the dry air returns to the equator. This dry air makes little biological difference over the ocean, but its lack of moisture over land produces some of the great tropical deserts, such as the Sahara Desert.

Long journeys over landmasses dry the air. Near the windward (the side from which the wind blows) coasts of continents, rainfall is heavy. In temperate areas, continental interiors are usually dry because they are far from the ocean, which replenishes water in the air passing over it.

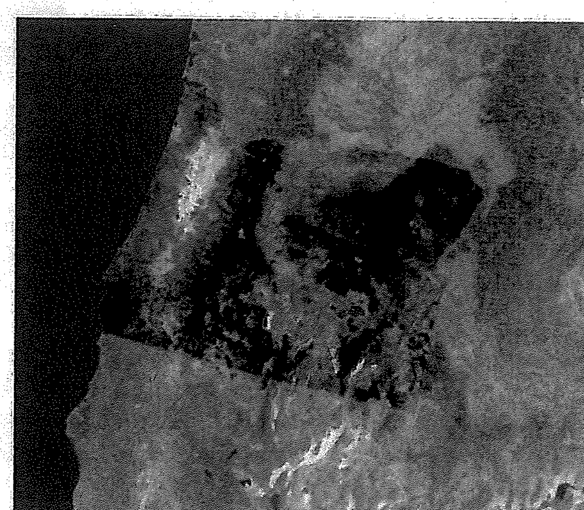
Mountains, which force air to rise, remove moisture from humid air. The air cools as it gains altitude, clouds form, and precipitation occurs, primarily on the windward slopes of the mountains. As the air mass moves down on the other side of the mountain, it is warmed, thereby lessening the chance of precipitation of any remaining moisture. This situation exists on the West Coast of North America, where precipitation falls on the western slopes of mountains close to the coast. The dry land on the side of the mountains away from the prevailing wind—in this case, east of the mountain range—is a **rain shadow** (**Figure 4.20**).

rain shadow Dry conditions, often on a regional scale, that occur on the leeward side of a mountain barrier; the passage of moist air across the mountains removes most of the moisture.





(a) Prevailing winds blow warm, moist air from the windward side. Air cools as it rises, releasing precipitation so that dry air descends on the leeward side.



Earth Satellite Corporation / Science Source

(b) A true-color satellite image of Oregon contrasts the lush vegetation in the moist western region and the more barren arid region to the east of the Cascade Range, which is located in the rain shadow of those mountains.

Figure 4.20 Rain shadow.

TORNADOES

A tornado is a powerful, rotating funnel of air associated with severe thunderstorms. Tornadoes form when a mass of cool, dry air collides with warm, humid air, producing a strong updraft of spinning air on the underside of a cloud. The spinning funnel becomes a tornado when it descends from the cloud and touches the ground. Wind velocity in a strong tornado may reach 480 km per hour (300 mi per hour). Tornadoes range from 1 m to 3.2 km (2 mi) in width. They last from several seconds to as long as seven hours and travel along the ground from several meters to more than 320 km (200 mi).

On a local level, tornadoes have more concentrated energy than any other kind of storm. They can destroy buildings, bridges, and freight trains. Tornadoes kill people: More than 10,000 people in the United States died in tornadoes during the 20th century. In spring of 2011—one of the deadliest tornado years on record with the National Oceanic and Atmospheric Administration (NOAA)—an outbreak of tornadoes across the southeastern states, from Oklahoma to Virginia, killed more than 300 people. Although tornadoes occur in other countries, the United States has more tornadoes than anywhere else. They are most common in the spring months, when Arctic air collides with warm air from the Gulf of Mexico. They are particularly frequent throughout the Great Plains and midwestern states, as well as in states along the Gulf of Mexico coast.

TROPICAL CYCLONES

Tropical cyclones are giant, rotating tropical storms with winds of at least 118 km per hour (73 mi per hour); the most powerful have wind velocities greater than 250 km per hour (155 mi per hour). They form as strong winds pick up moisture over warm surface waters of the tropical ocean and start to spin as a result of Earth's rotation. The spinning causes an upward spiral of massive clouds as air is pulled upward (**Figure 4.21**). Known as *hurricanes* in the Atlantic, *typhoons* in the Pacific, and *cyclones* in the Indian Ocean, tropical cyclones are most common during summer and autumn months, when ocean temperatures are warmest.

Tropical cyclones are destructive when they hit land, not so much from strong winds as from resultant storm surges, waves that rise as much as 7.5 m (25 ft) above the ocean surface. Storm surges cause property damage and loss of life. Some hurricanes produce torrential rains. Hurricane Mitch, the deadliest hurricane to occur in the Western Hemisphere in at least 200 years, hit the Atlantic coast of Central America in 1998 and caused more than 10,000 deaths during the flooding and landslides that followed. In November 2013, Typhoon Haiyan (known as Yolanda in the Philippines) hit Southeast Asia and killed more than 6000 people in the Philippines. Haiyan is believed to be the strongest tropical cyclone in recorded history to make landfall.

Some years produce more hurricanes than others. The 2005 hurricane season in the Atlantic Ocean was the most active on record, with 28 named tropical storms, 15 of which became hurricanes—including Hurricane Katrina. (Tropical storms have wind speeds between 63 and 117 km per hour [39 and 72 mi per hour], whereas hurricanes have wind speeds of 118 km per hour [73 mi per hour] or greater.) Some of the factors that influence hurricane formation in the North Atlantic include precipitation in western Africa and water temperatures in the eastern Pacific Ocean. A wetter-than-usual rainy season in the western Sahel region of Africa (**Figure 4.22**) translates into more hurricanes, as does a dissipation of ENSO, which results in cooler water temperatures in the Pacific.

Some climatologists hypothesize that dust blown across the Atlantic from the Sahara Desert may suppress hurricanes in the Caribbean and western Atlantic. In 2006, a year in which no tropical storms crossed the Atlantic Ocean to form hurricanes, dry weather and high winds in North Africa caused an unusually heavy amount of dust to blow across the Atlantic at the beginning of the hurricane season. The dust blocked some of the sunlight, resulting in cooler air and water temperatures; also, the dryness of the dust and the high winds that blew it across the Atlantic may have suppressed hurricane formation. Similar events are believed to have played a role in a quiet Atlantic hurricane season in 2013.

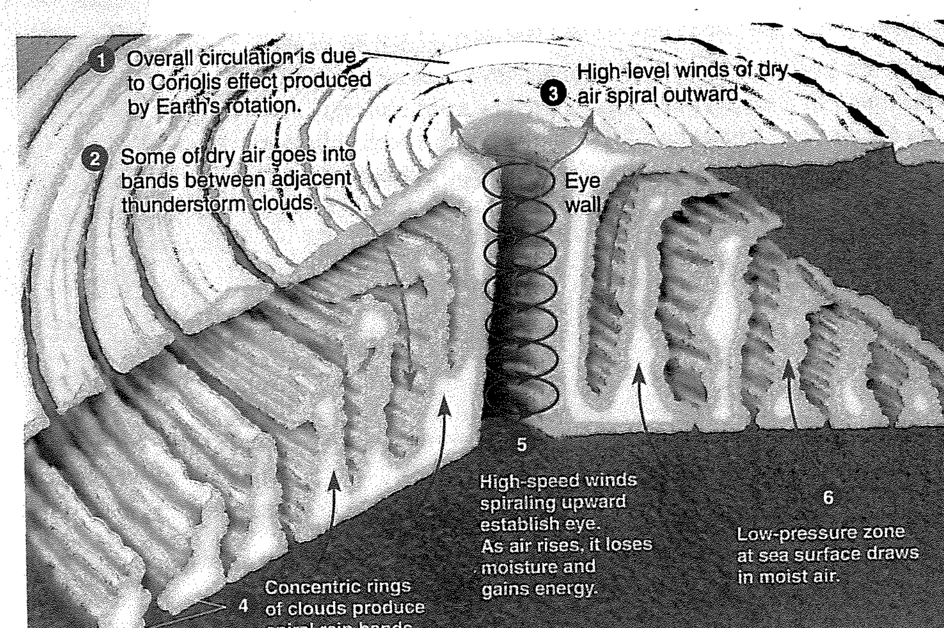


Figure 4.21 Structure of a cyclone. The numbered processes all take place concurrently. Scientists think that cyclones are becoming stronger as Earth's climate continues to warm.

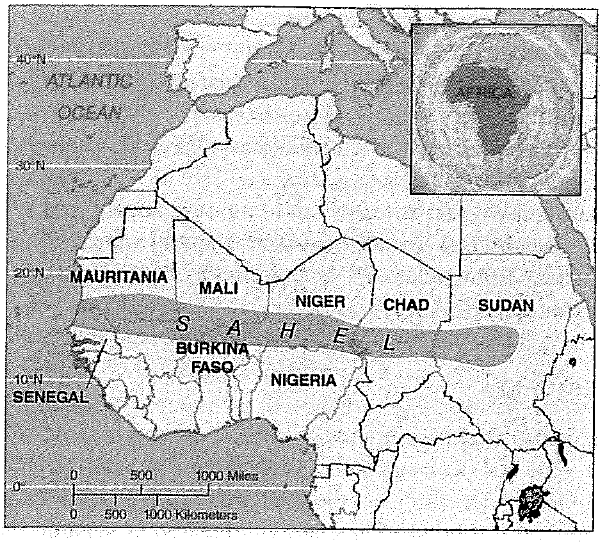


Figure 4.22 The Sahel region in Africa. This area is a transition zone between the Sahara Desert to the north and the moist, tropical rainforest to the south. During the 1970s to 1990s, the Sahel experienced a major drought.

Since 1970, there has been an increase in the intensity of tropical cyclones that have formed. Several factors, such as global atmospheric patterns and vertical wind shear, interact in a complex way to produce tropical cyclone intensity. However, recent evidence suggests that sea-surface temperature is the most important factor, which implies that as the global climate warms, tropical cyclones are becoming more intense (see Chapter 20).

CASE IN POINT

HURRICANE KATRINA

Hurricane Katrina, which hit the north-central Gulf coast along Louisiana, Mississippi, and Alabama in August 2005, was one of the most devastating storms in U.S. history. It produced a storm surge that caused severe damage to the city of New Orleans as well as to other coastal cities and towns in the region. The high waters caused levees and canals to fail, flooding 80% of New Orleans and many nearby neighborhoods.

Most people are aware of the catastrophic loss of life and property damage caused by Katrina. Here we focus on how humans have altered the geography and geology of the New Orleans area in ways that have impaired a balanced natural system and exacerbated the storm damage. This discussion is applicable to many of the world's cities located on river deltas; these cities are also vulnerable to storms and flooding.

The Mississippi River delta formed over millennia from sediments deposited at the mouth of the river. New Orleans is ideally located for industry as well as for sea and river commerce, but the city's development has disrupted delta-building processes. Over the years, engineers have constructed a system of canals to aid navigation and levees to control flooding, since the city is at or below sea level. The canals allowed salt water to intrude and kill the fresh-water marsh vegetation. The levees prevented the deposition of sediments that remain behind after floodwaters subside. (The sediments are now deposited into the Gulf of Mexico.) Under natural conditions, these sediments replenish and maintain the delta, building up coastal wetlands.

As the city grew, new development took place on wetlands—bayous, waterways, and marshes—that were drained and filled in. Before their destruction, these coastal wetlands provided some protection against flooding from storm surges. We are not implying that had Louisiana's wetlands been intact, New Orleans would not have suffered any damage from a hurricane of Katrina's magnitude. However, had these wetlands been largely unaltered, they would have moderated the damage by absorbing much of the water from the storm surge.

Another reason that Katrina devastated New Orleans is that the city has been subsiding (sinking) for many years, primarily because New Orleans is built on unconsolidated sediment (no bedrock underneath). Many wetlands scientists also attribute this subsidence to the extraction of the area's rich supply of underground natural resources—groundwater, oil, and natural gas. As these resources are removed, the land compacts, lowering the city. New Orleans and nearby coastal areas are subsiding an average of 11 mm each year. At the same time, sea level has been rising an average of 1–2.5 mm per year—with some scientists estimating more dramatic increases—in part because of human-induced changes in climate. ■

REVIEW

1. How do you distinguish between weather and climate? What are the two most important climate factors?
2. Distinguish between tornadoes and tropical cyclones.

Internal Planetary Processes

LEARNING OBJECTIVE

- Define *plate tectonics* and explain its relationship to earthquakes and volcanic eruptions.

Planet Earth consists of layers of different composition and rock strength (**Figure 4.23**). Earth's outermost rigid rock layer (the **lithosphere**) is composed of seven large plates, plus a few smaller ones, that float on the **asthenosphere** (the region of the mantle where rocks become hot and soft). Landmasses are situated on some of these plates. As the plates move horizontally across Earth's surface, the continents change their relative positions. **Plate tectonics** is the study of the dynamics of Earth's lithosphere—that is, the movement of these plates.

plate tectonics The study of the processes by which the lithospheric plates move over the asthenosphere.

Any area where two plates meet—a **plate boundary**—is a site of intense geologic activity (**Figure 4.24**). Three types of plate boundaries—divergent, convergent, and transform—exist; all three types occur both in the ocean and on land. Two plates move apart at a **divergent plate boundary**. When two plates move apart, a ridge of molten rock from the mantle wells up

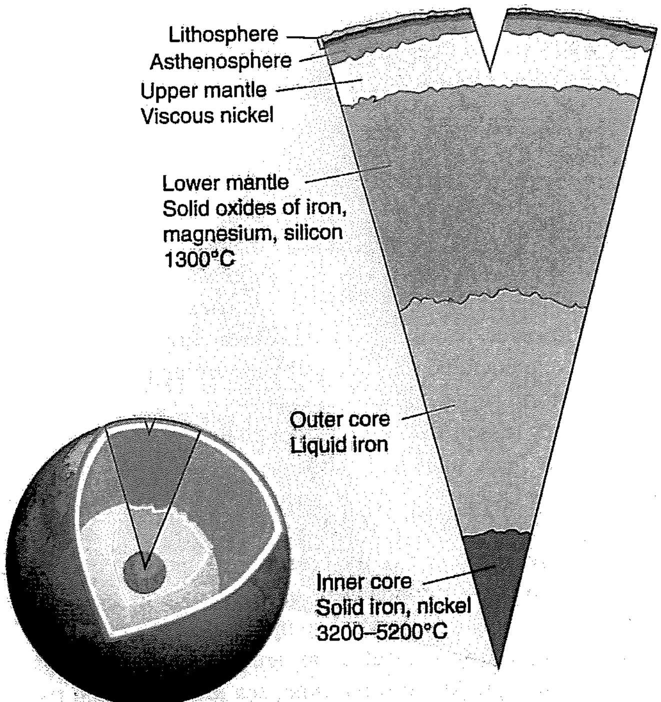


Figure 4.23 Earth's internal structure. A slice through Earth reveals layers of different composition and density.

between them; the ridge continually expands as the plates move farther apart. The Atlantic Ocean is growing as a result of the buildup of lava along the Mid-Atlantic Ridge, where two plates are diverging.

When two plates collide at a **convergent plate boundary**, one of the plates sometimes descends under the other in the process of **subduction**. Convergent collision can also form a mountain range; the Himalayas formed when the plate carrying India converged into the plate carrying Asia. At a **transform plate boundary**, plates move horizontally in opposite but parallel directions. On land, such a boundary is often evident as a long, thin valley due to erosion along the fault line.

Earthquakes and volcanoes are common at plate boundaries. Both the San Francisco area, noted for its earthquakes, and the volcano Mount Saint Helens in Washington State are situated where two plates meet.

EARTHQUAKES

Forces inside Earth sometimes push and stretch rocks in the lithosphere. The rocks absorb this energy for a time, but eventually, as the energy accumulates, the stress is too great and the rocks suddenly shift or break. The energy—released as **seismic waves**, vibrations that spread through the rocks rapidly in all directions—causes one of the most powerful events in nature, an earthquake. Most earthquakes occur along **faults**, fractures where rock moves forward and backward, up and down, or from side to side. Fault zones are often found at plate boundaries.

For example, the Caribbean region is prone to earthquakes due to movements between the North American, South American, and Caribbean plates. Puerto Rico, Jamaica, the Dominican Republic, Martinique, and Guadeloupe have had earthquakes greater than magnitude 7 in the past. In January 2010, an earthquake with a moment magnitude of 7.0 struck in an area approximately 25 km (16 mi) from Port-au-Prince, the capital of Haiti. (Moment magnitude is discussed later in this section.) About 230,000 people were killed, making it one of the deadliest earthquakes on record.

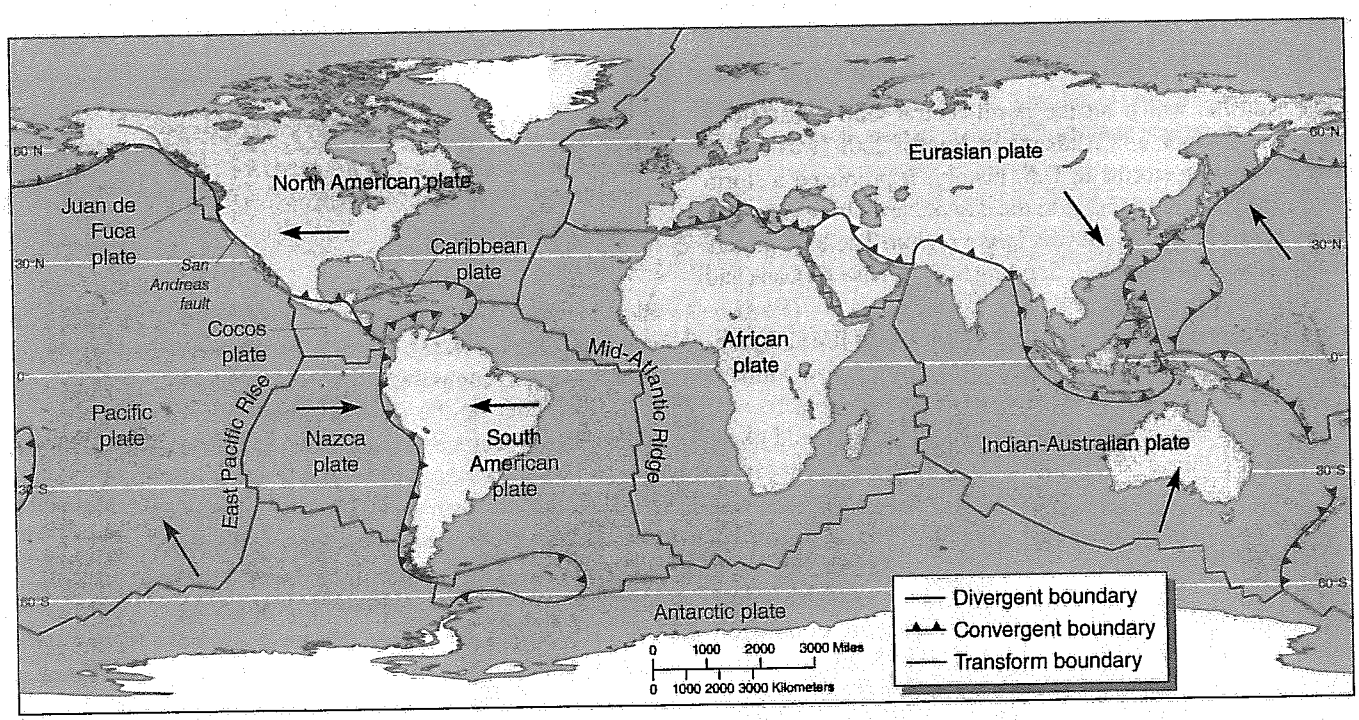


Figure 4.24 Plates and plate boundary locations. Seven major independent plates move horizontally across Earth's surface: African, Eurasian, Indian-Australian, Antarctic, Pacific, North American, and South American. Arrows show the directions of plate movements. The three types of plate boundaries are explained in the text.

Most of these people died due to the structural collapse of poorly constructed buildings. About 1 million people whose homes were destroyed became refugees.

The site where an earthquake begins, often far below the surface, is the focus (**Figure 4.25**). Directly above the focus, at Earth's surface, is the earthquake's epicenter. When seismic waves reach the surface, they cause the ground to shake. Buildings and bridges collapse, and roads break. One of the instruments used to measure seismic waves is a seismograph, which helps seismologists (scientists who study earthquakes) determine where an earthquake started, how strong it was, and how long it lasted. In 1935, Charles Richter, a California seismologist, invented the *Richter scale,* a measure of the magnitude of energy released by an earthquake. Each unit on the Richter scale represents about 30 times more released energy than the unit immediately below it. As an example, a magnitude 8 earthquake is 30 times more powerful than a magnitude 7 earthquake and 900 times more powerful than a magnitude 6 earthquake. The Richter scale makes it easy to compare earthquakes, but it tends to underestimate the energy of large quakes.

Although the public is familiar with the Richter scale, seismologists typically do not use it. There are several ways to measure the magnitude of an earthquake, just as there are several ways to measure the size of a person (for example, height, weight, and amount of body fat). Most seismologists use a more accurate scale, the *moment magnitude scale*, to measure earthquakes, especially those larger than magnitude 6.5 on the Richter scale. The moment magnitude scale calculates the total energy that a quake releases.

Seismologists record more than 1 million earthquakes each year. Some of these are major, but most are too small to be felt, equivalent to readings of about 2 on the Richter scale. A magnitude 5 earthquake usually causes property damage. On average, about every five years, a great earthquake occurs with a reading of 8 or higher. Such quakes usually cause massive property destruction and kill large numbers of people. Few people die directly because of the seismic waves; most die because of building collapses or fires started by ruptured gas lines.

Landslides and tsunamis are some of the side effects of earthquakes. A **landslide** is an avalanche of rock, soil, and other debris that slides swiftly down a mountainside. In 2008, a powerful earthquake struck in a mountainous area in Sichuan Province, China. The quake and powerful aftershocks triggered massive landslides and the structural collapse of many buildings. About 70,000 people were killed, and more than 1.5 million people whose homes were destroyed became refugees.

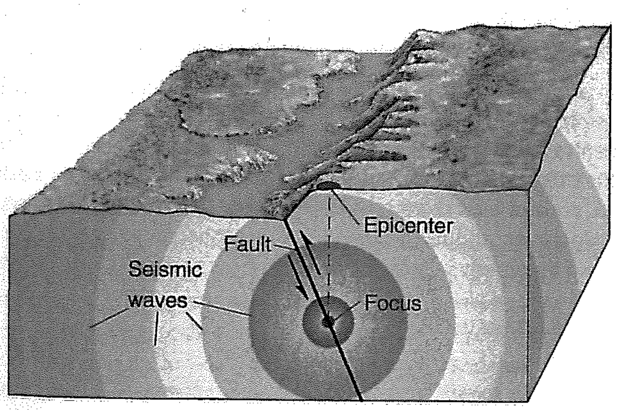


Figure 4.25 Earthquakes. Earthquakes occur when plates along a fault suddenly move in the opposite direction relative to each other. This movement triggers seismic waves that radiate through the crust.

A **tsunami**, a giant sea wave caused by an underwater earthquake, volcanic eruption, or landslide, sweeps through the water at more than 750 km (450 mi) per hour. Although a tsunami may be only about 1 m high in deep-ocean water, it can build to a wall of water 30 m (100 ft) high—as high as a 10-story building—when it comes ashore, often far from where the original earthquake triggered it. Tsunamis have caused thousands of deaths. Colliding tectonic plates in the Indian Ocean triggered tsunamis in 2004 that killed more than 230,000 people in South Asia and Africa. Not only did the tsunamis cause catastrophic loss of life and destruction of property, but also they resulted in widespread environmental damage. Salt water that moved inland as far as 3 km (1.9 mi) polluted soil and groundwater. Oil and gasoline from overturned cars, trucks, and boats contaminated the land and poisoned wildlife. Coral reefs and other offshore habitats were also damaged or destroyed.

In March 2011, an earthquake with a magnitude of 8.9 hit Japan. This earthquake, the strongest ever recorded in Japan, also triggered a disastrous tsunami. Other tsunamis generated by the earthquake hit coastal areas of several Pacific Rim countries, although they caused substantially less damage than in Japan. The death toll in Japan numbered in the thousands and would have been worse except that Japan is one of the best prepared of all nations to face earthquake disasters. Japan lies on a seismically active junction of several tectonic plates. (See Chapter 11 for a discussion of damage to Japan's nuclear power plants from the quake.)

ENVIRONEWS

Mangroves and Natural Disasters in Asia

One rarely hears of forests saving human lives, but that was the case during the December 2004 tsunami in the Indian Ocean. The World Conservation Union compared the death toll in two coastal Sri Lankan villages, one with extensive mangrove forests, and the other deforested. (Mangroves are often cut down to build tourist resorts or aquaculture facilities.) The village with intact mangrove vegetation recorded 2 deaths from the tsunami, whereas the other settlement had almost 6,000 deaths. Similarly, the damage generated in the Philippines by Typhoon Haiyan in November 2013 was much less in an area where mangroves had been replanted compared to deforested areas. One of the many valuable ecosystem services that mangroves provide is to act as a barrier to storm surges and tsunamis. Based on this information, many Asian countries are replanting some deforested coastal areas with mangroves.

VOLCANOES

The movement of tectonic plates on the hot, soft rock of the asthenosphere causes most volcanic activity. In places, the rock reaches the melting point, forming pockets of molten rock, or **magma**. When one plate slides under or away from an adjacent plate, magma may rise to the surface, often forming volcanoes. Magma that reaches the surface is called **lava**.

Volcanoes occur at three locations: at subduction zones, at spreading plates, and above hot spots. Subduction zones within the Pacific Basin have given rise to hundreds of volcanoes around Asia and the Americas in the region known as the "ring of fire." Plates that spread apart also form volcanoes: Iceland is a volcanic island that formed along the Mid-Atlantic Ridge. The Hawaiian Islands have a volcanic origin, but they did not form at plate boundaries. This chain of volcanic islands is thought to have formed as the Pacific plate moved over a **hot spot**, a rising plume of magma that flowed from deep within Earth's rocky mantle through an opening in the crust (**Figure 4.26**).

The largest volcanic eruption in the 20th century occurred in 1991 when Mount Pinatubo in the Philippines exploded. Despite the evacuation of more than 200,000 people, 338 deaths occurred, mostly from the collapse of buildings under the thick layer of wet ash that blanketed the area. The volcanic cloud produced when Mount Pinatubo erupted extended upward some 48 km (30 mi). We are used to hearing about human activities affecting climate, but many significant natural phenomena, including volcanoes, also affect global climate. The magma and ash ejected into the atmosphere when Mount Pinatubo erupted blocked much of the sun's warmth and caused a slight cooling of global temperatures for a year or so.

REVIEW

1. What are tectonic plates and plate boundaries?
2. Where are earthquakes and volcanoes commonly located, and why?

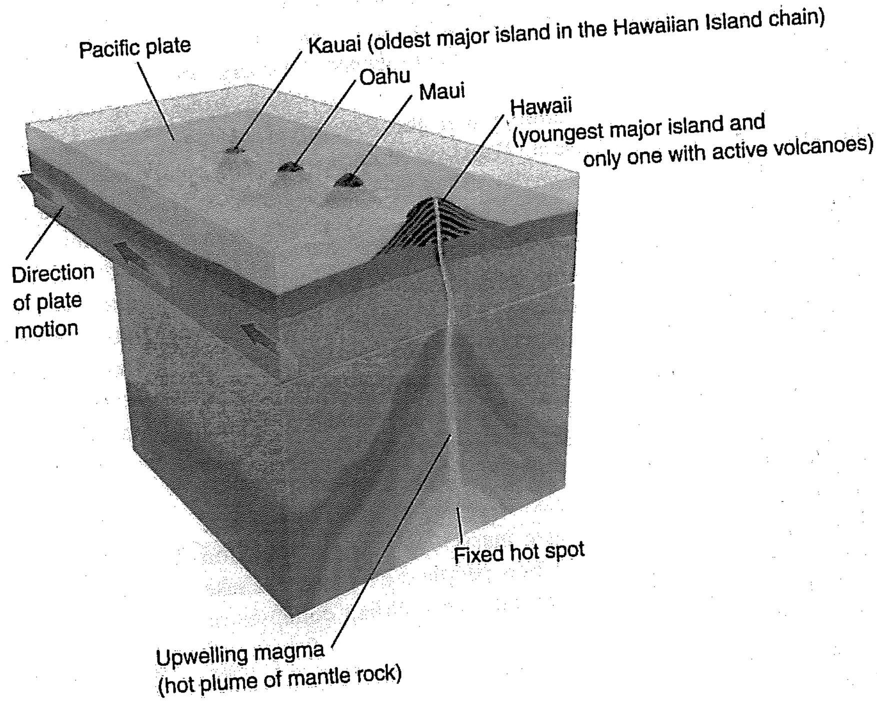


Figure 4.26 Hawaiian hot spot. The hot spot does not move because it is at the top of a rising plume of magma. The islands formed as the Pacific plate moved over the hot spot. Kauai is the oldest Hawaiian island, and Hawaii is the youngest.

ENERGY AND CLIMATE CHANGE

The Carbon Cycle

As we discussed earlier in the chapter, human activities are increasingly disturbing the balance of the carbon cycle. As human demand for fossil energy increases, emissions of the greenhouse gas CO_2 increase. This means carbon that had been captured through photosynthesis over millions of years is being released through combustion (rather than cellular respiration) over a couple of centuries. Plants cannot recapture this carbon through photosynthesis quickly enough to keep the atmospheric CO_2 concentration from increasing. We can only reduce the rate at which the CO_2 concentration increases by reducing emissions.

Many countries traditionally dependent on fossil fuels are developing and implementing policies that could significantly reduce emissions of greenhouse gases. However, so far the countries that emit the most CO_2, including the United States, have not adopted federal regulations; all U.S. control efforts are either voluntary or regulated at the state level. Moreover, about half the global greenhouse gas emissions are produced by rapidly industrializing countries such as China and India. Stabilizing atmospheric CO_2 will thus require major efforts by individuals in all countries throughout this century.

REVIEW OF LEARNING OBJECTIVES WITH SELECTED KEY TERMS

- **Describe the main steps in each of these biogeochemical cycles: carbon, nitrogen, phosphorus, sulfur, and hydrologic.**

1. In the **carbon cycle**, carbon enters plants, algae, and cyanobacteria as carbon dioxide (CO_2), which is incorporated into organic molecules by **photosynthesis**. **Cellular respiration** by plants, by animals that eat plants, and by decomposers returns CO_2 to the atmosphere, making it available for producers again. **Combustion** and weathering also return CO_2 to the atmosphere.
2. In the **nitrogen cycle**, **nitrogen fixation** is the conversion of nitrogen gas to ammonia. **Nitrification** is the conversion of ammonia or ammonium to nitrate. **Assimilation** is the biological conversion of nitrates, ammonia, or ammonium into nitrogen-containing compounds by plants; the conversion of plant proteins into animal proteins is also part of assimilation. **Ammonification** is the conversion of organic nitrogen to ammonia and ammonium ions. **Denitrification** converts nitrate to nitrogen gas.
3. The **phosphorus cycle** has no biologically important gaseous compounds. Phosphorus erodes from rock as inorganic phosphates, and plants absorb it from the soil. Animals obtain phosphorus from their diets, and decomposers release inorganic phosphate into the environment.
4. In the **sulfur cycle**, most sulfur occurs as rocks or as sulfur dissolved in the ocean. Sulfur-containing gases, which include hydrogen sulfide, sulfur oxides, and dimethyl sulfide (DMS), comprise a minor part of the atmosphere and are not long-lived. A tiny fraction of sulfur is present in the proteins of living organisms. Bacteria drive the sulfur cycle.
5. The **hydrologic cycle**, which continuously renews the supply of water essential to life, involves an exchange of water among the land, the atmosphere, and organisms. Water enters the atmosphere by evaporation and **transpiration** and leaves the atmosphere as precipitation. On land, water runs off to lakes, rivers, and the ocean or filters through the ground. **Groundwater** is stored in underground caverns and porous layers of rock.

- **Summarize the effects of solar energy on Earth's temperature, including the influence of albedos of various surfaces.**

Of the solar energy that reaches Earth, 30% is immediately reflected away and the remaining 70% is absorbed. **Albedo** is the proportional reflectance of solar energy from Earth's surface, commonly expressed as a percentage. Glaciers and ice sheets have high albedos, and the ocean and forests have low albedos. Ultimately, all absorbed solar energy is radiated into space as infrared (heat) radiation. A combination of Earth's roughly spherical shape and the tilt of its axis concentrates solar energy at the equator and dilutes solar energy at higher latitudes.

- **Describe the four layers of Earth's atmosphere: troposphere, stratosphere, mesosphere, and thermosphere.**

The **troposphere** is the layer of the atmosphere closest to Earth's surface; weather occurs in the troposphere. The **stratosphere**, found directly above the troposphere, contains a layer of ozone that absorbs much of the sun's damaging ultraviolet radiation. The **mesosphere**, found directly above the stratosphere, has the lowest temperatures in the atmosphere. The **thermosphere** has steadily rising temperatures because the air molecules there absorb high-energy X-rays and short-wave ultraviolet radiation.

- **Discuss the roles of solar energy and the Coriolis effect in producing atmospheric circulation.**

Variations in the amount of solar energy reaching different places on Earth largely drive atmospheric circulation. Atmospheric heat transfer from the equator to the poles produces a movement of warm air toward the poles and a movement of cool air toward the equator, moderating the climate. The atmosphere also exhibits **winds**, complex horizontal movements that result in part from differences in atmospheric pressure and from the Coriolis effect. The **Coriolis effect** is the influence of Earth's rotation, which tends to deflect fluids (air and water) toward the right in the Northern Hemisphere and toward the left in the Southern Hemisphere.

- **Discuss the roles of solar energy and the Coriolis effect in producing global water flow patterns, including gyres.**

Surface-ocean **currents** result largely from prevailing winds, which, in turn, are generated from solar energy. Other factors that contribute to ocean currents include the Coriolis effect, the position of landmasses, and the varying **density** of water. **Gyres** are large, circular ocean current systems that often encompass an entire ocean basin. Deep-ocean currents often travel in different directions and at different speeds than do surface currents. The present circulation of shallow and deep currents, known informally as the **ocean conveyor belt**, affects regional and possibly global climate.

- **Define *El Niño–Southern Oscillation (ENSO)* and *La Niña*, and describe some of their effects.**

El Niño–Southern Oscillation (ENSO) is a periodic, large-scale warming of surface water of the tropical eastern Pacific Ocean that affects both ocean and atmospheric circulation patterns. ENSO results in unusual weather in areas far from the tropical Pacific. During a **La Niña** event, surface water in the eastern Pacific becomes unusually cool.

- **Distinguish between weather and climate, and briefly discuss regional precipitation differences.**

Weather refers to the conditions in the atmosphere at a given place and time, whereas **climate** refers to the typical patterns of weather conditions that occur in a place over a period of years. Temperature and precipitation largely determine an area's climate. Precipitation is greatest where warm air passes over the ocean, absorbing moisture, and is then cooled, such as when mountains force humid air upward.

- **Contrast tornadoes and tropical cyclones.**

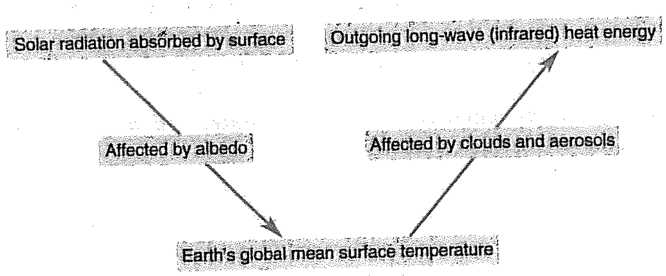
A **tornado** is a powerful, rotating funnel of air associated with severe thunderstorms. A **tropical cyclone** is a giant, rotating tropical storm with high winds. Tropical cyclones are called hurricanes in the Atlantic, typhoons in the Pacific, and cyclones in the Indian Ocean.

- **Define *plate tectonics* and explain its relationship to earthquakes and volcanic eruptions.**

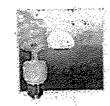
Plate tectonics is the study of the processes by which the lithospheric plates move over the asthenosphere. Earth's lithosphere (outermost rock layer) consists of seven large plates and a few smaller ones. As the plates move horizontally, the continents change their relative positions. **Plate boundaries** are sites of intense geologic activity, such as mountain building, volcanoes, and earthquakes.

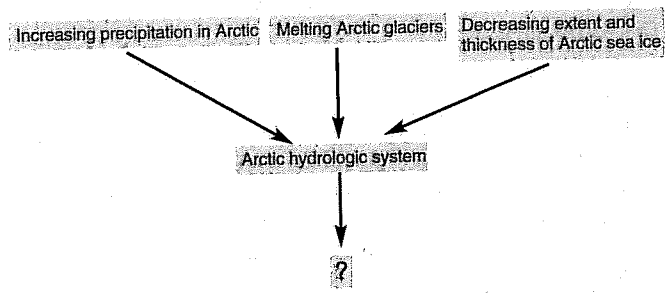
Critical Thinking and Review Questions

1. Briefly describe some of the long-term ecological research conducted at Hubbard Brook Experimental Forest (HBEF). What are some of the environmental effects observed in the deforestation study at HBEF?
2. What is a biogeochemical cycle? Why is the cycling of matter essential to the continuance of life?
3. How might deforestation at HBEF alter the biogeochemical cycles involving that ecosystem?
4. Describe how organisms participate in each of these biogeochemical cycles: carbon, nitrogen, phosphorus, and sulfur.
5. What is the basic flow path of the nitrogen cycle?
6. A geologist or physical geographer would describe the phosphorus cycle as a *sedimentary pathway*. What does that mean?
7. Explain why Earth's temperature changes with latitude and with the seasons. Why is it unlikely that the winter Olympics—typically held in February—would take place in the mountains of New Zealand?
8. What are the two lower layers of the atmosphere? Cite at least two differences between them.
9. Describe the general directions of atmospheric circulation.
10. What is a gyre, and how are gyres produced?
11. How does ENSO affect climate on land?
12. What are some of the environmental factors that produce areas of precipitation extremes, such as rain forests and deserts?
13. The system encompassing Earth's global mean surface temperature can be diagrammed as follows: Explain each part of this system.



14. How are tornadoes and tropical cyclones alike? How do they differ?
15. Relate the locations of earthquakes and volcanoes to plate tectonics.
16. Examine the following changes that have been identified in the Arctic hydrologic system in the past few decades. Predict the effect of these changes on the salinity in the North Atlantic Ocean.





17. What ENSO effects are made fun of in the cartoon below?

By cartoonist Bob Bierman, Copyright Simon Fraser University

Food for Thought

You prepare a small community garden plot and decide to plant peas, tomatoes, and green peppers. How will your green-thumb efforts contribute to any of the biogeochemical cycles, and how will those cycles involve your vegetable patch? Will your choice of plants determine the role your garden plays in any of the cycles?

Peter Walton Photography / Getty Images

6

Major Ecosystems of the World

Burning forest litter and sun flare near Bogong, Victoria, Australia

A wildfire is any unexpected fire that burns in grass, shrub, and forest areas. Whether started by lightning or humans, wildfires are often a significant environmental force. Those areas most prone to wildfires have wet seasons followed by lengthy dry seasons. Vegetation grows and accumulates during the wet season and then dries out enough during the dry season to burn easily. At the peak of a wildfire season in the American West, where extensive lands are prone to fire, hundreds of new wildfires can break out each day (**see photograph**).

Fires were part of the natural environment long before humans appeared, and plants in many terrestrial ecosystems that we discuss in this chapter have adapted to fire. African savannas, California chaparrals, North American grasslands, and pine forests of the southern United States are some fire-adapted ecosystems. For example, fire helps maintain grasses as the dominant vegetation in grasslands by removing fire-sensitive hardwood trees. Grasses adapted to wildfire have underground stems and buds unaffected by a fire; after fire kills the aerial (aboveground) parts, the untouched underground parts send up new sprouts. Fire-adapted trees such as bur oak and ponderosa pine have thick, fire-resistant bark; other trees, such as jack pines, depend on fire to open their cones and release the seeds.

Climate change affects rainfall patterns, generally leading to more intense droughts. Partly because of climate change, more frequent and more intense wildfires occur in the western United States as well as other parts of the world. The wildfire season is longer and drier due to an increase in spring and summer temperatures, which causes mountain snows to melt more quickly.

Human interference affects the frequency and intensity of wildfires. If fire is excluded from a fire-adapted ecosystem, organic litter (such as brush and slender trees) accumulates. When a fire does occur, it burns hotter and climbs into the upper canopies of trees. Called *crown fires*, these fires shoot flames high into the air, and wind pushes the flames to nearby trees. Many recent fires in the western United States have been caused in part by decades of fire suppression. Fire suppression efforts continue in many areas because more and more expensive homes have been built in and around fire-adapted ecosystems.

Prescribed burning is an ecological management tool in which the organic litter is deliberately burned under controlled conditions before it accumulates to dangerous levels. Prescribed burns also suppress fire-sensitive trees, thereby maintaining the natural fire-adapted ecosystem. Fire management experts agree that prescribed burns reduce the damage but do not prevent all fires.

In this chapter, we consider Earth's major ecosystems, both aquatic ecosystems and those on land. We consider how the physical environment, such as presence or absence of wildfires, influences each ecosystem.

In Your Own Backyard...

Many wildfires occur today in places where fire used to be uncommon. Research online to find out how many wildfires occurred in your state in the past year. How many of these were considered severe? Are prescribed fires used to manage any ecosystems in your state?

Earth's Major Biomes

LEARNING OBJECTIVES

- Define *biome* and briefly describe the nine major terrestrial biomes: tundra, boreal forest, temperate rain forest, temperate deciduous forest, temperate grassland, chaparral, desert, savanna, and tropical rain forest.
- Identify one human food in each of the biomes discussed.
- Explain the similarities and the changes in ecosystems observed with increasing elevation and increasing latitude.

Earth has many **climates** based primarily on temperature and precipitation differences. Characteristic organisms have adapted to each climate. A **biome** is quite large in area and encompasses many interacting ecosystems (**Figure 6.1**; also see Figures 4.19 for the world's major climates and Figure 14.8 for the world's major soil types). In terrestrial ecology, a biome is considered the next level of ecological organization above those of community, ecosystem, and landscape.

e A large, relatively ict terrestrial region vith similar climate, ılants, and animals, gardless of where it occurs in the world.

Near the poles, temperature is generally the overriding climate factor (sometimes considered a limiting resource; see Chapter 5), whereas in temperate and tropical regions, precipitation becomes more significant than temperature (**Figure 6.2**). Light is relatively plentiful in most biomes, except in certain environments such as the rainforest floor, or polar regions, where days are short or nonexistent in winter. Other abiotic factors to which certain biomes are sensitive include temperature extremes as well as rapid temperature changes, fires, floods, droughts, and strong winds.

We now consider nine major biomes and how humans are affecting them: tundra, boreal forest, temperate rain forest, temperate deciduous forest, temperate grassland, chaparral, desert, savanna, and tropical rain forest.

TUNDRA: COLD BOGGY PLAINS OF THE FAR NORTH

Tundra (also called **arctic tundra**) occurs in the extreme northern latitudes wherever the snow melts seasonally (**Figure 6.3**). The Southern Hemisphere has no equivalent of the arctic tundra because it has no land in the corresponding latitudes. **Alpine tundra** is a similar ecosystem located in the higher elevations of mountains, above the tree line. Alpine tundra can occur at any latitude, even in the tropics.

tundra The treeless biome in the far north that consists of boggy plains covered by lichens and small plants such as mosses; has harsh, very cold winters and extremely short summers.

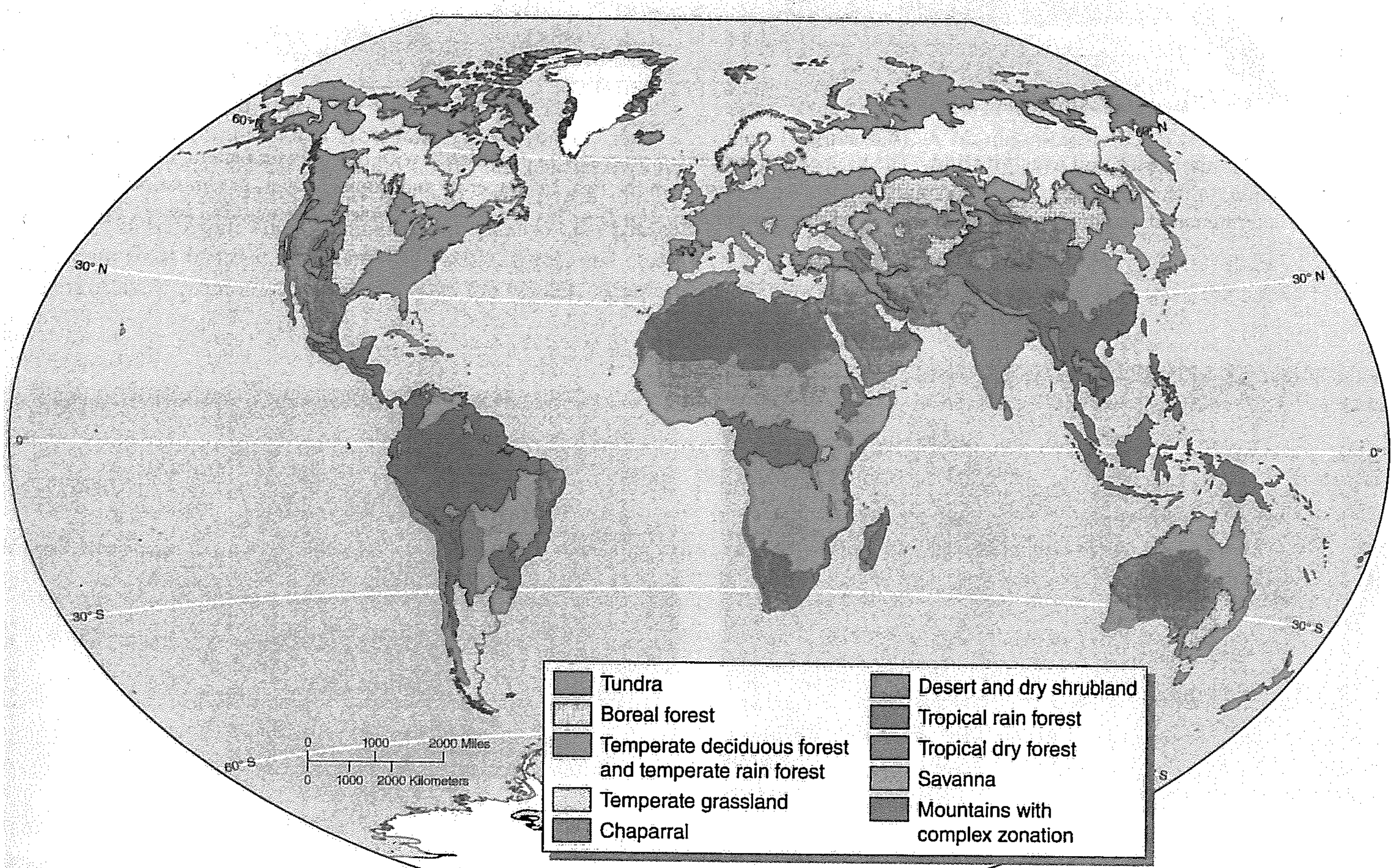


Figure 6.1 Distribution of the world's terrestrial biomes. Although sharp boundaries are shown in this highly simplified map, biomes actually blend together at their boundaries. (Based on data from the World Wildlife Fund)

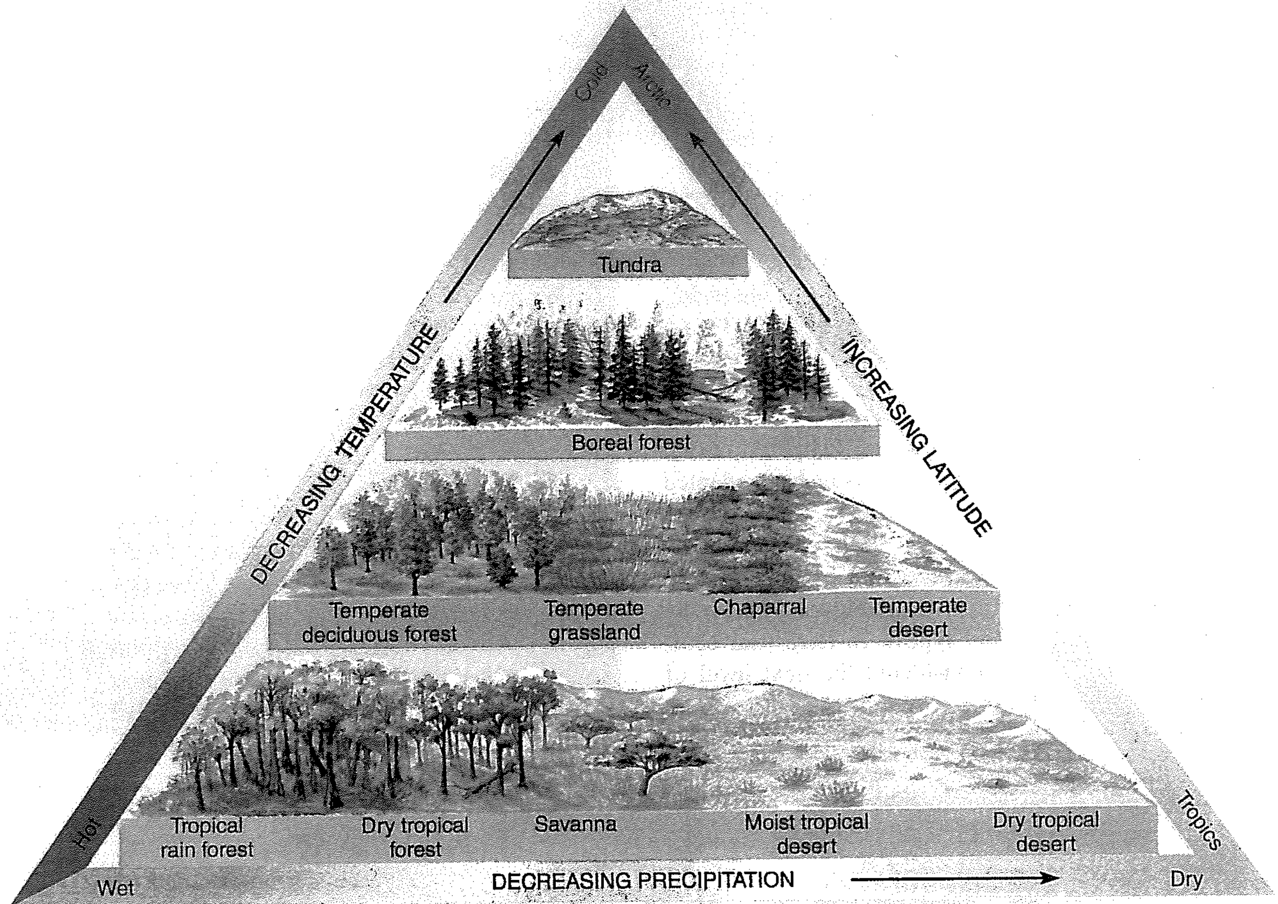


Figure 6.2 Temperature and precipitation. The biomes are distributed primarily in accordance with two climate factors, temperature and precipitation. In the higher latitudes, temperature is the more important of the two. In temperate and tropical zones, precipitation is a significant determinant of community composition. (Based on L. Holdridge, *Life Zone Ecology*. Tropical Science Center, San Jose, Costa Rica [1967])

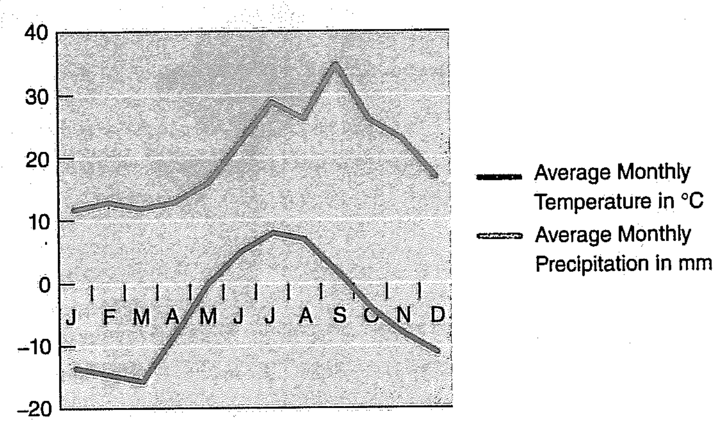


Figure 6.3 Arctic tundra. Only small, hardy plants grow in the northernmost biomes that encircles the Arctic Ocean. Photographed in Greenland. Climate graph shows monthly temperature (blue line) and precipitation data (red line) for Ilulissat, Greenland. Climate graphs provide a useful comparison of various climates. During how many months each year is the Greenland tundra at or above freezing? If climate warming continues, how might this climate graph change in 50 years?

Arctic tundra has long, harsh winters and short summers. Although the growing season, with its warmer temperatures, is short (from 50 to 160 days, depending on location), the days are long. Little precipitation (10 to 25 cm, or 4 to 10 in., per year) falls over much of the tundra, most of it during the summer months.

Most tundra soils are geologically young because they formed when glaciers retreated after the last ice age. (Glacier ice, which occupied about 29% of Earth's land during the last ice age, began retreating about 17,000 years ago. Today, glacier ice occupies about 10% of the land.) Tundra soils are usually nutrient-poor and have little organic litter, such as dead leaves and stems, animal droppings, and remains of organisms. Although the soil melts at the surface during the summer, tundra has a layer of **permafrost**, permanently frozen ground that varies in depth and thickness. The thawed upper zone of soil is usually waterlogged during the summer because permafrost interferes with drainage. Permafrost limits the depth that roots penetrate, thereby preventing the establishment of most woody species. The limited precipitation in combination with low temperatures, flat topography (surface features), and the permafrost layer produces a landscape of broad, shallow lakes and ponds, sluggish streams, and bogs.

Tundra has low **species richness** (the number of different species) and low **primary productivity** (the rate at which energy is accumulated; see the section on ecosystem productivity in Chapter 3). Few plant species occur, but individual species often exist in great numbers. Mosses, lichens (such as reindeer moss), grasses, and grasslike sedges dominate tundra. No readily recognizable trees or shrubs grow except in sheltered locations, where dwarf willows, dwarf birches, and other dwarf trees are common. As a rule, tundra plants seldom grow taller than 30 cm (12 in.).

The year-round animal life of the tundra includes lemmings, voles, weasels, arctic foxes, snowshoe hares, ptarmigan, snowy owls, and musk oxen. These animals are adapted to the extreme cold, with coats of thick fur. Lemmings, voles, hares, and musk oxen consume plant material throughout the winter, whereas weasels, foxes, ptarmigan, and owls are efficient predators on the lemmings and other small herbivores. In the summer, caribou migrate north to the tundra to graze on sedges, grasses, and dwarf willow. Dozens of bird species migrate north in summer to nest and feed on abundant insects. Mosquitoes, blackflies, and deerflies occur in great numbers during summer.

Tundra regenerates slowly after it has been disturbed. Even hikers can cause damage. Oil and natural gas exploration and military use have caused long-lasting injury, likely to persist for hundreds of years, to large portions of the arctic tundra (see Chapter 11, Case in Point: The Arctic National Wildlife Refuge). Agriculture is not generally possible within tundra regions, and humans who live on tundra rely primarily on fish and game for their nutrition.

Climate change is beginning to affect the arctic tundra. As the permafrost melts, conifer trees (cone-bearing evergreens) are replacing tundra vegetation. The trees have a lower albedo (reflectivity) than snow, ice, or tundra vegetation, causing additional warming, an example of a *positive feedback mechanism*. In addition, the permafrost line is moving northward, another result of enhanced climate warming. Methane, a greenhouse gas, is trapped in permafrost and releases into the atmosphere when permafrost melts, thereby further enhancing climate change.

BOREAL FORESTS: CONIFER FORESTS OF THE NORTH

Just south of the tundra is the **boreal forest** (also called **taiga**, pronounced tie'guh). The boreal forest stretches across North America and Eurasia, covering approximately 11% of Earth's land (**Figure 6.4**). A biome comparable to the boreal forest is not found in the Southern Hemisphere; as with arctic tundra, there is no land in the corresponding southern latitudes.

boreal forest A region of coniferous forest (such as pine, spruce, and fir) in the Northern Hemisphere; located just south of the tundra.

Winters are extremely cold and severe, although not as harsh as in the tundra. The growing season of the boreal forest is

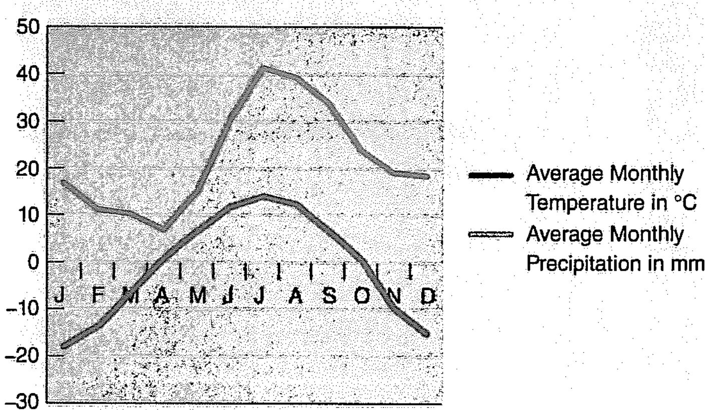


Figure 6.4 Boreal forest. These coniferous forests occur in cold regions of the Northern Hemisphere adjacent to the tundra. Photographed in Autum in Yukon, Canada. Climate graph shows monthly temperature (blue line) and precipitation data (red line) for Whitehorse, Yukon Territory, Canada. How does average monthly precipitation vary with average monthly temperature?

somewhat longer than that of the tundra. Boreal forest receives little precipitation, perhaps 50 cm (20 in.) per year, and its soil is typically acidic and mineral-poor, with a deep layer of partly decomposed pine and spruce needles at the surface. Permafrost is patchy and, where found, is often deep under the soil. Boreal forest has numerous ponds and lakes in water-filled depressions that were dug by grinding ice sheets during the last ice age.

Black and white spruces, balsam fir, eastern larch, and other conifers dominate the boreal forest, although deciduous trees (trees that shed their leaves in autumn), such as aspen and birch, may form striking stands. Conifers have many drought-resistant adaptations, such as needlelike leaves with a minimal surface area for water loss. Such an adaptation lets conifers withstand the northern winter months when roots cannot absorb water because the ground is frozen.

The animal life of the boreal forest consists of some larger species such as caribou, which migrate from the tundra to the boreal forest for winter; wolves; bears; and moose. Most mammals are medium-sized to small, including rodents, rabbits, and fur-bearing predators such as lynx, sable, and mink. Most species of birds are abundant in the summer but migrate to warmer climates for winter. Wildlife ecologists estimate that one of every three birds in the United States and Canada spends its breeding season in the boreal forests of North America. Insects are abundant, but few amphibians and reptiles occur except in the southern boreal forest.

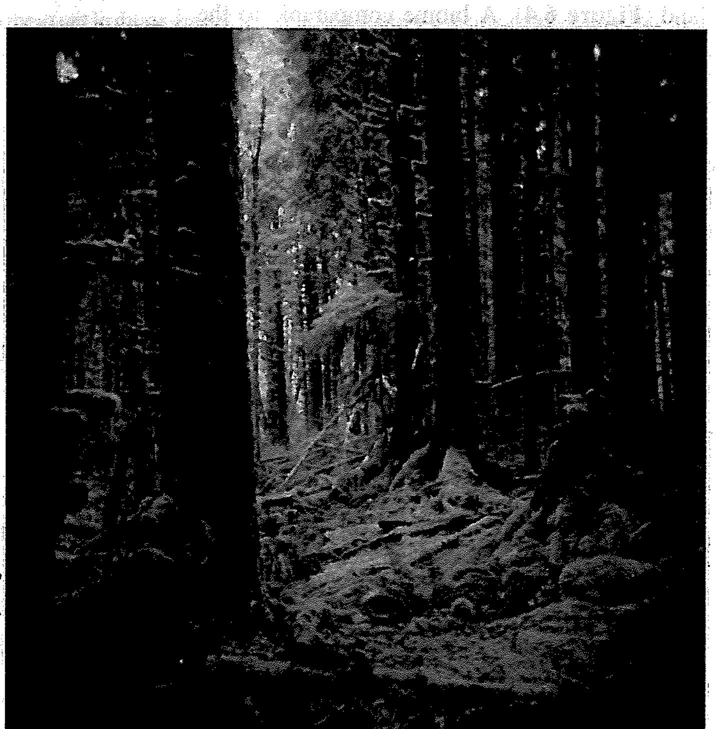
Most of the boreal forest is not well suited to agriculture because of its short growing season and mineral-poor soil. However, the boreal forest yields lumber, pulpwood for paper products, animal furs, and other forest products. Currently, boreal forest is the world's primary source of industrial wood and wood fiber, and extensive logging of certain boreal forests has occurred. Mining, drilling for gas and oil, and farming have also contributed to loss of boreal forest. (See Chapter 17 for a discussion of deforestation of this biome.) As in tundra, humans living in the boreal forest biome primarily rely on animal nutrition, though pine nuts, berries from some shrubs, and some wetland plant species, such as cattail, can provide supplements to human diets in this area.

TEMPERATE RAIN FORESTS: LUSH TEMPERATE FORESTS

A coniferous **temperate rain forest** occurs on the northwest coast of North America. Similar vegetation exists in southeastern Australia and in southern South America. Annual precipitation in this biome is high, more than 127 cm (50 in.), and is augmented by condensation of water from dense coastal fogs. The proximity of temperate rain forest to the coastline moderates the temperature so that the seasonal fluctuation is narrow: Winters are mild and summers are cool. Temperate rain forest has relatively nutrient-poor soil, although its organic content may be high. Needles and large fallen branches and trunks accumulate on the ground as litter that takes many years to decay and release nutrient minerals to the soil.

temperate rain forest A coniferous biome with cool weather, dense fog, and high precipitation.

The dominant plants in the North American temperate rain forest are large evergreen trees such as western hemlock, Douglas fir, western red cedar, Sitka spruce, and western arborvitae (**Figure 6.5**). Temperate rain forests are rich in epiphytic vegetation (see commensalism, Chapter 5)—smaller plants that grow on the trunks and branches of large trees. Epiphytes in this biome are mainly mosses, club mosses, lichens, and ferns, all of which also carpet the ground. Squirrels, wood rats, mule deer, elk, numerous bird species, and several species of amphibians and reptiles are common temperate rainforest animals. Edible plant species for humans include cattail, fireweed, salmonberry, and stinging nettle; numerous edible mushrooms also are available in this biome.



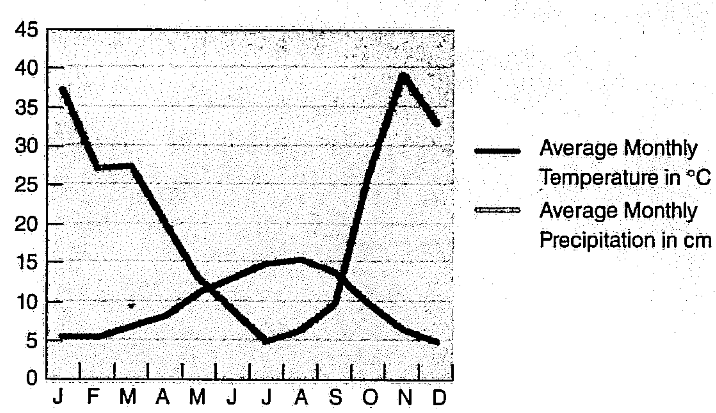


Figure 6.5 Temperate rain forest. This temperate biome has large amounts of precipitation, particularly during winter months. Photographed in Olympic National Park in Washington State. Climate graph shows monthly average temperature (blue line) and precipitation data (red line) for Olympic National Park. What is the range of average monthly temperatures for this biome, and how does it compare to the range of average monthly temperatures in the boreal forest (Figure 6.4)? (data from The Weather Channel)

Temperate rain forest is a rich wood producer, supplying us with lumber and pulpwood. It is also one of the world's most complex ecosystems in terms of species richness. When the logging industry harvests old-growth forest, companies typically replant the area with a **monoculture** (a single species) of trees harvested in 40- to 100-year cycles. The old-growth forest ecosystem, once harvested, never has a chance to regrow through succession. A small fraction of the original old-growth temperate rain forest in Washington, Oregon, and northern California remains untouched. These stable forest ecosystems provide biological habitats for many species, including about 40 endangered and threatened species. The issues surrounding old-growth forests of the Pacific Northwest were explored in the Chapter 2 introduction. Old-growth forest also supports fish habitat in streams and rivers; many Pacific northwest fish species, such as coho and chinook salmon, are extremely valuable and nutritious food sources for humans.

TEMPERATE DECIDUOUS FORESTS: TREES THAT SHED THEIR LEAVES

nperate deciduous rest A forest biome occurs in temperate as with a moderate nt of precipitation.

Hot summers and cold winters are characteristic of the **temperate deciduous forest**, which occurs in temperate areas where precipitation ranges from about 75 to 150 cm (30 to 60 in.) annually. Typically, the soil of a temperate deciduous forest consists of a topsoil rich in organic material and a deep, clay-rich lower layer. As organic materials decay, mineral ions are released. Ions not absorbed by tree roots **leach** (filter) into the clay.

The trees of the temperate deciduous forest form a dense canopy that overlies saplings and shrubs. Broad-leaved hardwood trees, such as oak, hickory, maple, and beech, dominate temperate deciduous forests of the northeastern and mideastern United States (**Figure 6.6**). These trees lose their foliage annually. In the southern areas of the temperate deciduous forest, the number of broad-leaved evergreen trees, such as magnolia, increases. Historically, the American chestnut tree was an important food source for both humans and wildlife within the eastern deciduous forest. Other food trees in this biome include nuts (hickory, beech), fruit (pawpaw), as well as sugar maple (syrup) and sassafras (tea). Many understory plants, ranging from berries (blueberry, blackberry) to roots (ginseng, ginger) also act as human food sources in deciduous forest. Humans living in temperate deciduous forest have a high level of dietary diversity available from the surrounding ecosystem.

Temperate deciduous forests originally contained a variety of large mammals, such as puma, wolves, and bison, which are now absent, plus deer, coyote, bears, and many small mammals and birds. In Europe and North America, logging and land clearing for farms, tree plantations, and cities have removed much of the original temperate deciduous forest. Where it has regenerated, temperate deciduous forest is often in a seminatural state modified by recreation, invasive weeds, livestock foraging, and timber harvest. Many forest organisms have successfully become reestablished in these returning forests.

Worldwide, deciduous forests were among the first biomes converted to agricultural use. In Europe and Asia, many soils that

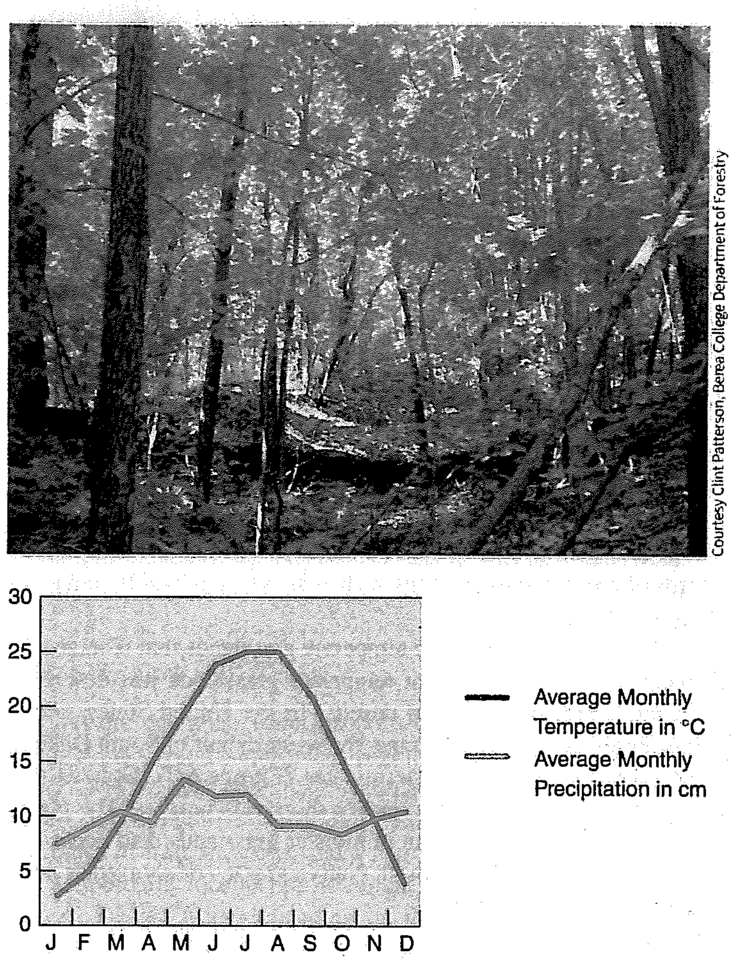


Figure 6.6 Temperate deciduous forest. Abundant and diverse deciduous trees produce nuts, fruit, and seeds and support a wide variety of herbivorous insects and birds. Leaves drop to the ground in fall, supporting a host of detritivores in soil. Photographed in Berea College Forest, in Kentucky. Climate graph shows monthly average temperature (blue line) and precipitation data (red line) for Berea, Kentucky. What is the range of average monthly temperatures for this biome, and how does it compare to the range of average monthly temperatures in the boreal forest (Figure 6.4)? (data from The Weather Channel)

originally supported deciduous forests have been cultivated by traditional agricultural methods for thousands of years without a substantial loss in fertility. During the twentieth century, intensive agricultural practices were widely adopted; these, along with overgrazing and deforestation, have contributed to the degradation of some agricultural lands. Most damage to farmland has happened since the end of World War II (see Chapters 17 and 18).

GRASSLANDS: TEMPERATE SEAS OF GRASS

temperate grasslands A grassland with hot summers, cold winters, and less rainfall than the temperate deciduous forest biome.

Summers are hot, winters are cold, and rainfall is often uncertain in **temperate grasslands**. Annual precipitation averages 25 to 75 cm (10 to 30 in.). Grassland soil has considerable organic material because the aerial portions of many grasses die off each winter or in wildfires and contribute to the organic content of the soil, whereas the roots and rhizomes (underground stems) survive. The roots and rhizomes eventually die and add to the soil's organic material. Many grasses are sod formers—that is, their roots and rhizomes form a thick, continuous underground mat. Although few trees grow except near rivers and streams, grasses grow in great profusion in the deep, rich soil. Periodic wildfires help maintain grasses as the dominant vegetation in grasslands.

Moist temperate grasslands, or *tallgrass prairies*, occur in the United States in parts of Illinois, Iowa, Minnesota, Nebraska, Kansas, and other Midwestern states. Several species of grasses that, under favorable conditions, grow as tall as a person on horseback dominate tallgrass prairies. The land was originally covered with herds of grazing animals, such as pronghorn elk and bison. The principal predators were wolves, although in sparser, drier areas coyotes took their place. Smaller animals included prairie dogs and their predators (foxes, black-footed ferrets, and various birds of prey), grouse, reptiles such as snakes and lizards, and great numbers of insects.

Shortgrass prairies are temperate grasslands that receive less precipitation than the moist temperate grasslands just described but more precipitation than deserts. In the United States, shortgrass prairies occur in Montana, the western half of South Dakota, and parts of other Midwestern states (**Figure 6.7**). Grasses that grow knee-high or lower dominate shortgrass prairies. The plants grow in less abundance than in moister grasslands, and occasionally some bare soil is exposed. Native grasses of shortgrass prairies are drought-resistant.

The North American grassland, particularly the tallgrass prairie, was well suited to agriculture. More than 90% has vanished under the plow, and the remaining prairie is so fragmented that almost nowhere can you see what Native Americans experienced prior to the arrival of European settlers in the Midwest. Today, the tallgrass prairie is considered North America's rarest biome. The rich soils in this biome enabled the North American Midwest, Ukraine, and other moist temperate grasslands to become the breadbaskets of the world, because they provide ideal growing conditions for crops such as corn and wheat, which are also grasses. At the same time, when annual crops replace perennial plant mixtures, seasonally bare ground is vulnerable to erosion. For example, the 1930s Dust Bowl occurred when plowed, bare land remained bare due to drought, and wind blew visible amounts of United States prairie soil as far as Europe. Many ecologists and agricultural scientists are working to understand how grasslands can more sustainably support growth of food crops.

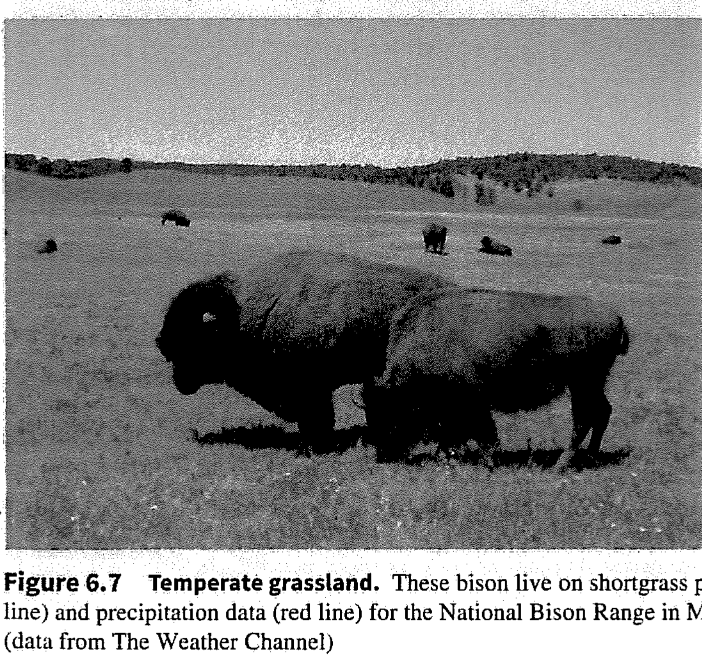
CHAPARRAL: THICKETS OF EVERGREEN SHRUBS AND SMALL TREES

Some hilly temperate environments have mild winters with abundant rainfall combined with hot, dry summers. Such **Mediterranean climates**, as they are called, occur in the area around the Mediterranean Sea as well as in the North American Southwest, southwestern and southern Australia, central Chile, and southwestern South Africa. On mountain slopes of southern California, this Mediterranean-type community is known as **chaparral**. Chaparral soil is thin and often not fertile. Frequent fires occur naturally in this environment, particularly in late summer and autumn.

chaparral A biome with mild, moist winters and hot, dry summers; vegetation is typically small-leaved evergreen shrubs and small trees.

Chaparral vegetation looks strikingly similar in different areas of the world, even though the individual species are not the same. Chaparral usually has a dense growth of evergreen shrubs but may contain short, drought-resistant pine or scrub oak trees that grow 1 to 3 m (3.3 to 9.8 ft) tall (**Figure 6.8**). During the rainy winter season, the environment is lush and green, but the plants lie dormant during the summer. Trees and shrubs often have hard, small, leathery leaves that resist water loss.

Many plants in this biome are fire-adapted and grow best in the months following a fire. Such growth is possible because fire releases nutrient minerals from aerial parts of the plants that burned. Fire does not kill the underground parts and seeds of many plants, and with the new availability of essential nutrient minerals, the plants sprout vigorously during winter rains. Mule deer, wood rats, chipmunks, lizards, and many species of birds are common animals of the chaparral.



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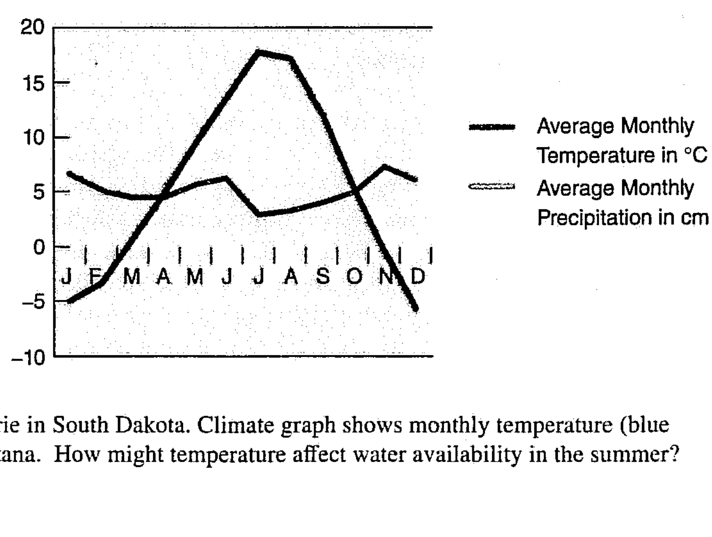


Figure 6.7 Temperate grassland. These bison live on shortgrass prairie in South Dakota. Climate graph shows monthly temperature (blue line) and precipitation data (red line) for the National Bison Range in Montana. How might temperature affect water availability in the summer? (data from The Weather Channel)

Earl Scott / Science Source

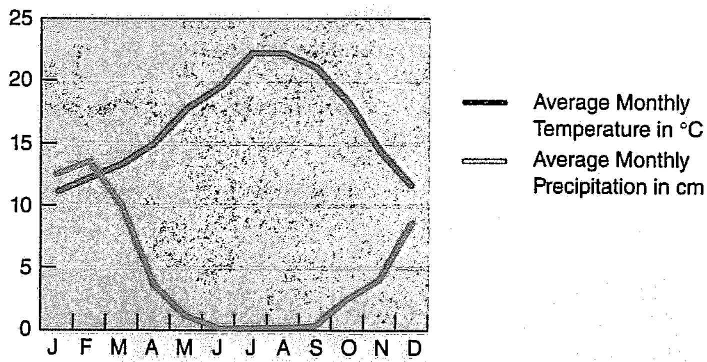


Figure 6.8 Chaparral. This chaparral in California is a fire-adapted habitat. Climate graph shows monthly temperature (blue line) and precipitation data (red line) for the Santa Ynez Valley. How do rainfall and temperatures conspire to increase the likelihood of summer wildfires? (data from The Weather Channel)

Chaparral landscapes are not suitable for most agriculture, although some trees (olive, carob) are particularly adapted to growing on chaparral soils. Vineyards may also thrive in chaparral regions, since grapes are vulnerable to fungal diseases, which do not thrive in arid environments. Among livestock, sheep and goats are better suited to this type of landscape and vegetation than cattle, because their hooves do less damage to the fragile soils.

The fires that occur in California chaparral are quite costly to humans when they consume expensive homes built on the hilly chaparral landscape (see Environews). Unfortunately, efforts to prevent the naturally occurring fires sometimes backfire. Removing the chaparral vegetation, whose roots hold the soil in place, causes other problems; witness the mudslides that sometimes occur during winter rains in these areas.

ENVIRONEWS

Using Goats to Fight Fires

California has about 6000 wildfires each year, and they are becoming increasingly expensive and dangerous to manage because so many people are building homes amid fire-vulnerable chaparral. For one thing, the topography is so steep that firefighters often cannot use mechanized equipment and must be transported to fires by helicopters. Fearing that prescribed burns will get out of control, local governments, such as those of Oakland, Berkeley, Monterey, and Malibu, are increasingly employing a low-tech method to reduce the fuel load—goats.

A herd of 350 goats can denude an entire acre of heavy brush in about a day, but using them entails advance organization and support. First, botanists must walk the terrain to put fences around any small trees and rare or endangered plants; fencing keeps the goats from eating those plants.

Goats are an excellent tool for fire management because they preferentially browse woody shrubs and thick undergrowth—the exact fuel that causes disastrous fires. Fires that occur in areas after goats have browsed there are much easier to contain.

DESERTS: ARID LIFE ZONES

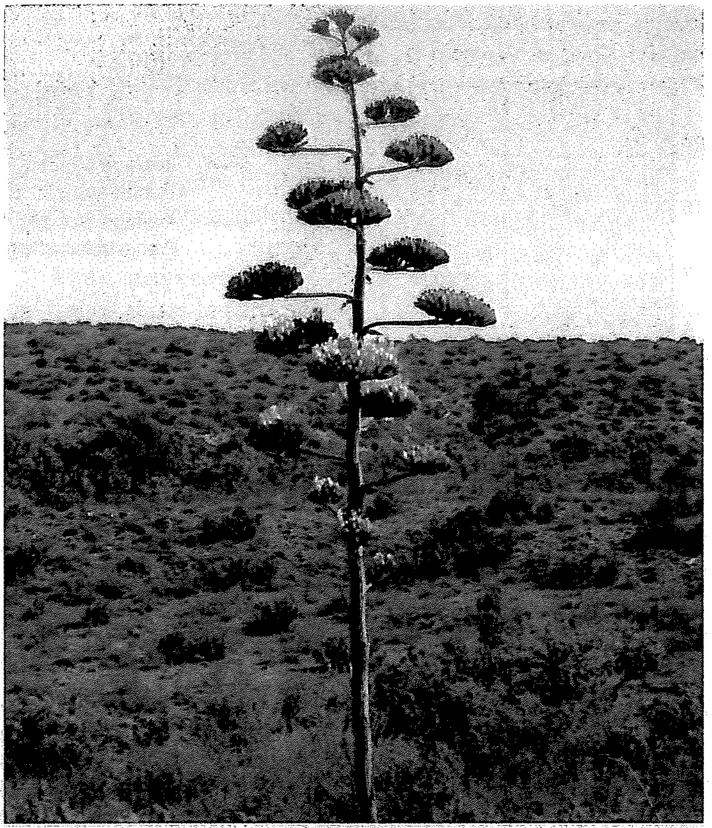
desert A biome in which the lack of precipitation limits plant growth; deserts are found in both temperate and subtropical regions.

Deserts are dry areas found in both temperate (*cold deserts*) and subtropical regions (*warm deserts*). The low water vapor content of the desert atmosphere results in daily temperature extremes of heat and cold, and a major change in temperature occurs in a single 24-hour period. Deserts vary depending on the amount of precipitation they receive, which is generally less than 25 cm (10 in.) per year. As a result of sparse vegetation, desert soil is low in organic material but is often high in mineral content, particularly the salts sodium chloride ($NaCl$), calcium carbonate ($CaCO_3$), and calcium sulfate ($CaSO_4$). In some regions, such as areas of Utah and Nevada, the concentration of certain soil minerals reaches levels toxic to many plants. Lithium, an element valuable for use in batteries and medicines, is found in deserts, such as the Atacama Desert in northern Chile.

Plant cover is so sparse in deserts that much of the soil is exposed. Both perennials (plants that live for more than two years) and annuals (plants that complete their life cycles in one growing season) occur in deserts. However, annuals are common only after rainfall. Plants in North American deserts include cacti, yuccas, Joshua trees, and sagebrushes (**Figure 6.9**).

Inhabitants of deserts are strikingly adapted to the demands of their environment. Desert plants tend to have reduced leaves or no leaves, an adaptation that conserves water. In cacti such as the giant saguaro, the stem, which expands accordion-style to store water, carries out photosynthesis; the leaves are modified into spines, which discourage herbivores. Other desert plants shed their leaves for most of the year, growing only during the brief moist season. Many desert plants are provided with spines, thorns, or toxins to resist the heavy grazing pressure often experienced in this food- and water-deficient environment.

Desert animals tend to be small. During the heat of the day, they remain under cover or return to shelter periodically, whereas at night they come out to forage or hunt. In addition to desert-adapted insects, there are a few desert amphibians (frogs



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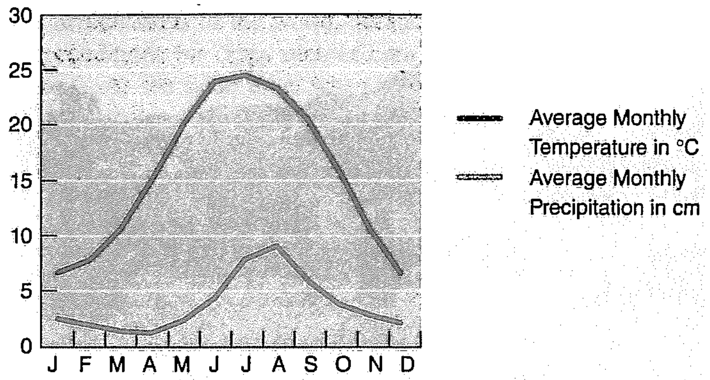


Figure 6.9 **Desert.** This century plant (*Agave americana*) is flowering near Carlsbad Cavern, New Mexico, in May. The plant has succulent leaves with a waxy coating that reduces water loss. Climate graph shows monthly temperature (blue line) and precipitation data (red line) for Carlsbad Canyon. If plants have the highest water needs during flowering and seed set, when might you expect to find flowers in this desert? (data from The Weather Channel)

and toads) and many desert reptiles, such as the desert tortoise, desert iguana, Gila monster, and Mojave rattlesnake. Desert mammals include rodents such as gerbils and jerboas in African and Asian deserts and kangaroo rats in North American deserts. There are also mule deer and jackrabbits in these deserts, oryxes in African deserts, and kangaroos in Australian deserts. Carnivores such as the African fennec fox and some birds of prey, especially owls, live on the rodents and jackrabbits. During the driest months of the year, many desert insects, amphibians, reptiles, and mammals tunnel underground, where they remain inactive.

Some human cultures, such as the Navaho and Pueblo people, have been able to survive on desert agriculture. Agriculture in desert regions is most sustainable when conserved rainfall, rather than groundwater, is used for crops. Some varieties of corn and beans are relatively drought tolerant. Crops such as pearl millet and sorghum use less water, enabling them to be cultivated successfully in some desert regions. Sheep tolerate drought far better than cattle, and can be grazed in some deserts.

Humans have altered North American deserts in several ways. People who drive across the desert in off-road vehicles inflict environmental damage. When the top layer of desert soil is disturbed, erosion occurs more readily, and less vegetation grows to support native animals. Certain cacti and desert tortoises are rare as a result of poaching. Houses, factories, and farms built in desert areas require vast quantities of water, which is imported from distant areas. Increased groundwater consumption by many desert cities has caused groundwater levels to drop. Aquifer depletion in U.S. deserts is particularly critical in southern Arizona and southwestern New Mexico.

SAVANNA: TROPICAL GRASSLANDS

Savanna occurs in areas of low rainfall or seasonal rainfall with prolonged dry periods. The temperatures in tropical savannas vary little throughout the year, and seasons are regulated by precipitation, not by temperature as they are in temperate grasslands. Annual precipitation is 76 to 150 cm (30 to 60 in.). Savanna soil is somewhat low in essential nutrient minerals, in part because it is strongly leached—that is, many nutrient minerals have filtered down out of the topsoil. Savanna soil is often rich in aluminum, which resists leaching, and in some places the aluminum reaches levels toxic to many plants. Although the African savanna is best known, savanna also occurs in South America and northern Australia.

savanna A tropical grassland with widely scattered trees or clumps of trees.

Savanna has wide expanses of grasses interrupted by occasional trees such as acacia, which bristle with thorns that provide protection against herbivores. Both trees and grasses have fire-adapted features, such as extensive underground root systems, that let them survive seasonal droughts as well as periodic fires.

Spectacular herds of hoofed mammals—such as wildebeest, antelope, giraffe, zebra, and elephants—occur in the African savanna (**Figure 6.10**). Large predators, such as lions and hyenas, kill and scavenge the herds. In areas of seasonally varying rainfall, the herds and their predators may migrate annually.

Savannas are rapidly being converted into rangeland for cattle and other domesticated animals, which are replacing the big herds of wild animals. Half of the Cerrado (savanna) in central Brazil has been converted to cropland and pastures since 1970. The problem is more acute in Africa because it has the most

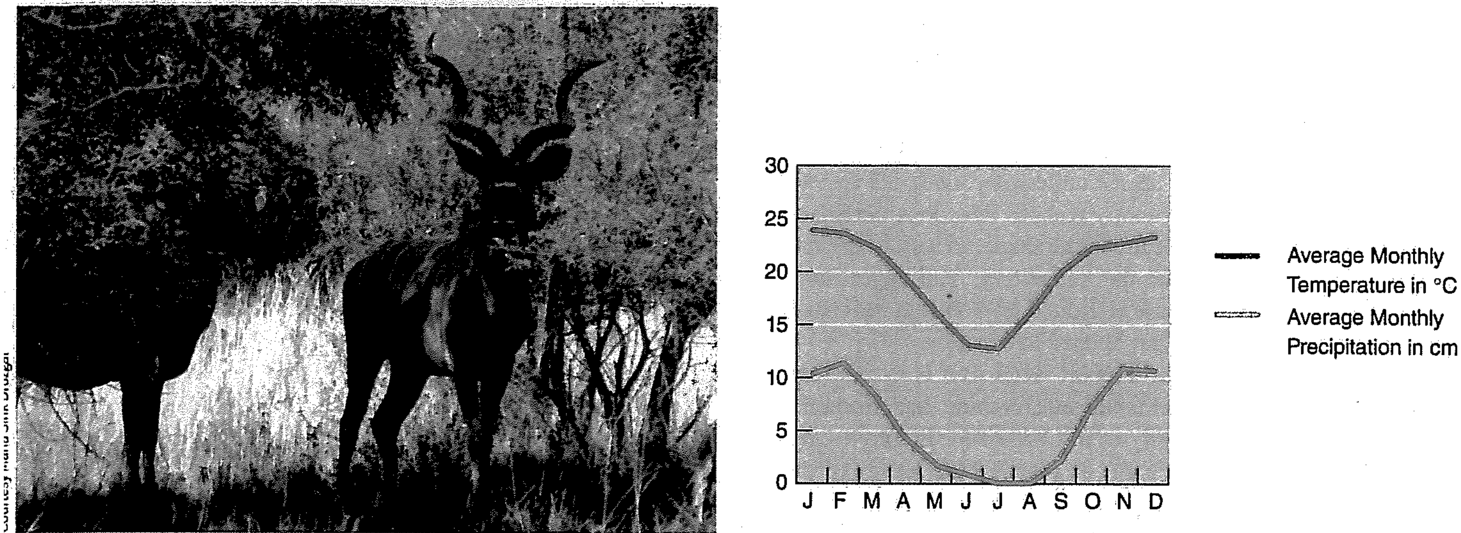


Figure 6.10 Savanna. The greater kudu (*Tragelaphus strepsiceros*) is one of many grazers who inhabit this grassland biome. These kudu were photographed in South Africa. Climate graph shows monthly temperature (blue line) and precipitation data (red line) for Pretoria, South Africa. In what months would savanna be most sensitive to overgrazing? (data from World Weather Online)

rapidly growing human population of any continent. In some places, severe overgrazing (see Chapter 17) and harvesting of trees for firewood have converted savanna to desert, a process called **desertification.**

TROPICAL RAIN FORESTS: LUSH EQUATORIAL FORESTS

pical rain forest A species-rich forest that occurs where climate is warm and moist throughout the year.

Tropical rain forests occur where temperatures are warm throughout the year and precipitation occurs almost daily. The annual precipitation of a tropical rain forest is typically from 200 to 450 cm (80 to 180 in.). Much of this precipitation comes from locally recycled water that enters the atmosphere by trees' transpiration (loss of water vapor from plants).

Tropical rain forest commonly occurs in areas with ancient, highly weathered, mineral-poor soil. Little organic matter accumulates in such soils because bacteria, fungi, and detritus-feeding ants and termites decompose organic litter quite rapidly. Roots and mycorrhizae quickly absorb nutrient minerals from the decomposing material. Thus, nutrient minerals of tropical rain forests are tied up in the vegetation rather than the soil. Tropical rain forests are found in Central and South America, Africa, and Southeast Asia (see Figure 17.10).

Tropical rain forests are very productive—that is, the plants capture a lot of energy by photosynthesis. Of all the biomes, the tropical rainforest is unexcelled in species richness and variety. A person can travel hundreds of meters without encountering two individuals of the same tree species. The trees of tropical rain forests are typically evergreen flowering plants (**Figure 6.11**). Their roots are often shallow and concentrated near the surface in a mat. The root mat catches and absorbs almost all nutrient minerals released from leaves and litter by decay processes. Swollen bases or braces called *buttresses* hold some trees upright and aid in the extensive distribution of the shallow roots.

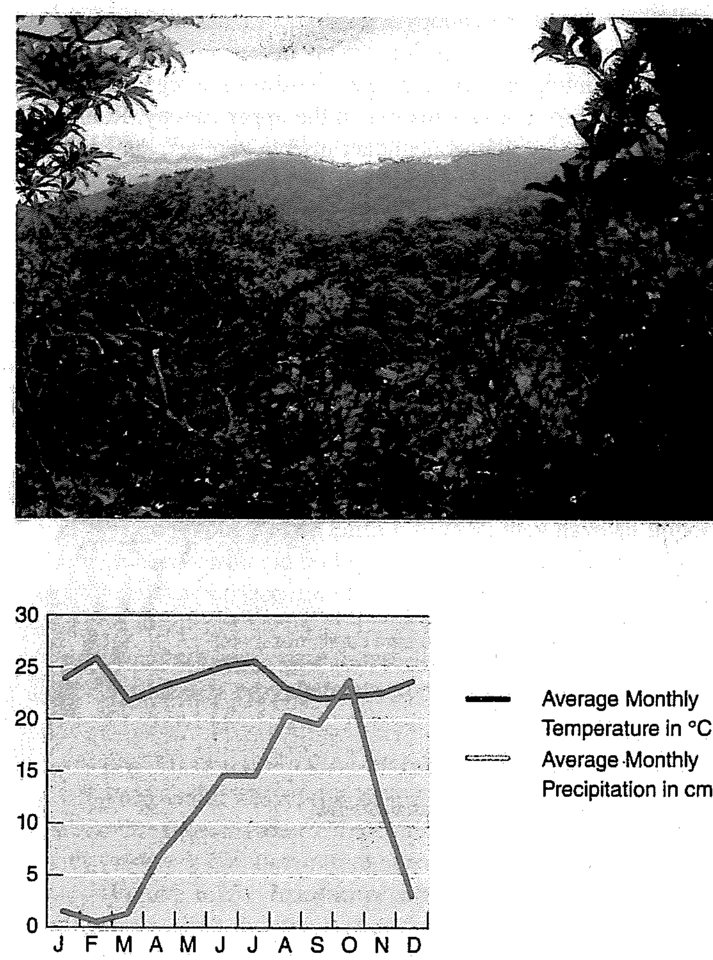


Figure 6.11 Tropical rainforest. This Costa Rican rainforest straddles the Continental Divide. Climate graph shows monthly temperature (blue line) and precipitation data (red line) for Santa Rosa National Park, Costa Rica. Many rainforest leaves have a waxy surface. How could this waxy coating be helpful in both wet and dry seasons? (Brigid Mulloy; data from World Weather Online)

A fully developed tropical rain forest has at least three distinct stories, or layers, of vegetation. The topmost story consists of the crowns of occasional, very tall trees, which are exposed to direct sunlight. The middle story reaches a height of 30 to 40 m (100 to 130 ft) and forms a continuous canopy of leaves that lets in little sunlight to support the sparse understory. Only 2% to 3% of the light bathing the forest canopy reaches the forest understory. Smaller plants specialized for life in the shade, as well as the seedlings of taller trees, compose the understory. The vegetation of tropical rain forests is not dense at ground level except near stream banks or where a fallen tree has opened the canopy.

Tropical rainforest trees support extensive epiphytic communities of plants such as ferns, mosses, orchids, and bromeliads (recall the discussion of epiphytes in Chapter 5). Epiphytes grow in crotches of branches, on bark, or even on the leaves of their hosts, but most use their host trees for physical support, not for nourishment.

Lianas (woody tropical vines), some as thick as a human thigh, twist up through the branches of the huge rainforest trees. Once in the canopy, lianas grow from the upper branches of one forest tree to another, connecting the tops of the trees and providing a walkway for many of the canopy's residents. Lianas and herbaceous vines provide nectar and fruit for many tree-dwelling animals.

Not counting bacteria and other soil-dwelling organisms, most tropical rainforest organisms live in the upper canopy. Rainforest animals include the most abundant insects, reptiles, and amphibians on Earth. The birds, often brilliantly colored, are varied, with some, like parrots, specialized to consume fruit and others, like hummingbirds and sunbirds (Figure 5.16), to consume nectar. Most rainforest mammals, such as sloths and monkeys, live only in the trees and rarely climb to the ground, although some large, ground-dwelling mammals, including elephants, are also found in rain forests.

Although tropical rain forests have an abundance of food species, such as palm fruit, banana, and acai, each grows in low density; plantations of banana or acai are not likely to be sustainable. Biologists know that many rainforest species will become extinct before they are even identified and scientifically described. (See Chapter 17 for more discussion of the ecological impacts of tropical rainforest destruction.)

VERTICAL ZONATION: THE DISTRIBUTION OF VEGETATION ON MOUNTAINS

Hiking up a mountain is similar to traveling toward the North Pole with respect to the major ecosystems encountered (**Figure 6.12**). This elevation-latitude similarity occurs because as one climbs a mountain, the temperature drops just as it does when one travels north. Soils become less rich, because wind and water move dead plant material downhill before it becomes organic matter.

The base of a mountain in Colorado, for example, is covered by deciduous trees, which shed their leaves every autumn. At higher elevations, where the climate is colder and more severe, one might find a coniferous *subalpine forest*, which resembles the northern boreal forest. Higher still, where the climate is quite cold, *alpine tundra* occurs, with vegetation composed of grasses,

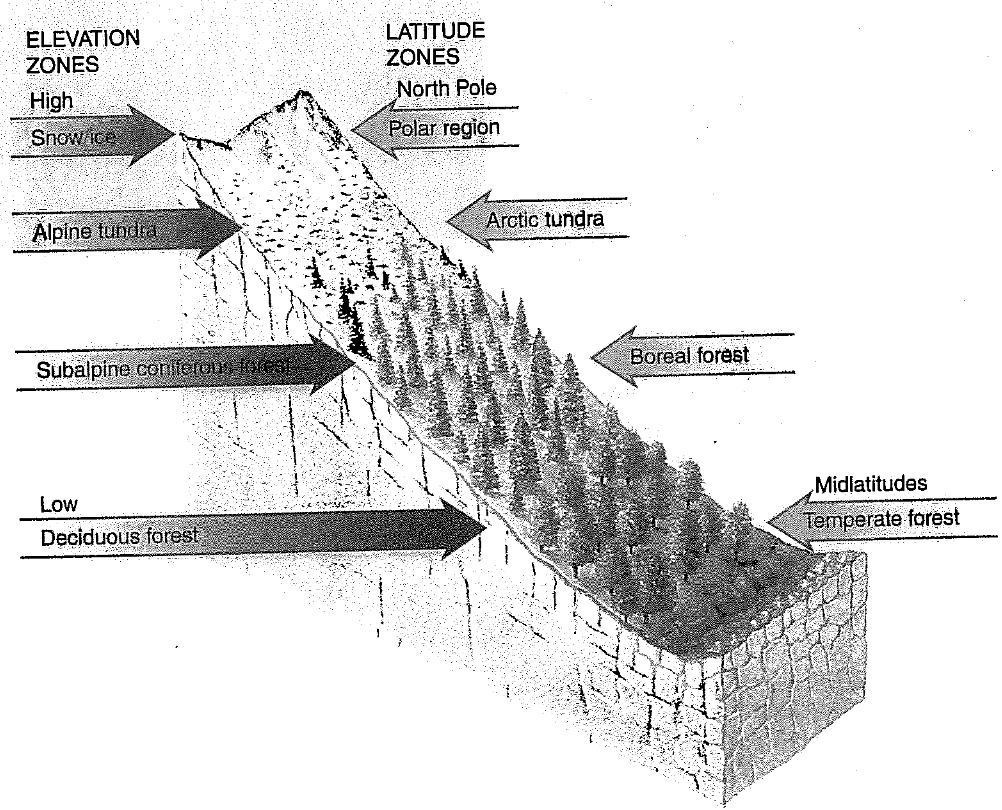


Figure 6.12 Comparison of elevation and latitude zones. The cooler temperatures at higher elevations of a mountain produce a series of ecosystems similar to the boreal forest and tundra biomes.

sedges, and small tufted plants; it is called alpine tundra to distinguish it from arctic tundra. The top of the mountain might have a permanent ice or snow cap, similar to that in the polar land areas.

Important environmental differences between high elevations and high latitudes affect the types of organisms found in each place. Alpine tundra typically lacks permafrost and receives more precipitation than arctic tundra. High elevations of temperate mountains do not have the great extremes in day length associated with the changing seasons in biomes at high latitudes. Furthermore, the intensity of solar radiation is greater at high elevations than at high latitudes. At high elevations, the sun's rays pass through less atmosphere, which filters out less ultraviolet (UV) radiation and results in a greater exposure to UV radiation than occurs at high latitudes. Because of these differences, some kinds of agriculture are possible at high altitude that are not viable at high latitudes; many varieties of potatoes, for example, have been grown for generations in small fields in the Peruvian Andes.

Climate change threatens alpine areas. As the climate warms, many plant and animal species are migrating vertically, where it is cooler. However, vertical migration is limited by mountain heights. Some alpine species are now regionally extinct because the climate zone to which they were adapted would be located at altitudes above the mountaintops.

REVIEW

1. What is a biome? What climate and soil factors produce each of the major terrestrial biomes?
2. Which biome adapts most easily to agriculture? Explain your answer.
3. How does vegetation change with increasing elevation and latitude?

Aquatic Ecosystems

LEARNING OBJECTIVES

- Summarize the important environmental factors that affect aquatic ecosystems.
- Briefly describe the eight aquatic ecosystems: flowing-water ecosystem, standing-water ecosystem, freshwater wetlands, estuary, intertidal zone, benthic environment, neritic province, and oceanic province.
- Identify at least one ecosystem service provided by each aquatic ecosystem.

Aquatic life zones differ from terrestrial biomes in almost all respects. Generally speaking, temperature is somewhat less variable in watery environments because the water itself tends to moderate temperature. Water is obviously not an important limiting factor in aquatic ecosystems, though light is frequently a limiting factor.

The most fundamental division in aquatic ecology is probably between freshwater and saltwater environments. **Salinity**, the concentration of dissolved salts such as sodium chloride (NaCl) in a body of water, affects the kinds of organisms present in aquatic ecosystems, as does the amount of dissolved oxygen. Water greatly interferes with the penetration of light. Floating photosynthetic organisms remain near the water's surface, and vegetation attached to the bottom grows only in shallow water. In addition, low levels of essential nutrient minerals limit the number and distribution of organisms in certain aquatic environments. Other abiotic determinants of species composition in aquatic ecosystems include temperature, pH, and presence or absence of waves and currents.

Aquatic ecosystems contain three main ecological categories of organisms: free-floating plankton, strongly swimming nekton, and bottom-dwelling benthos. **Plankton** are usually small or microscopic organisms that are relatively feeble swimmers. For the most part, they are carried about at the mercy of currents and waves. They cannot swim far horizontally, but some species are capable of large daily vertical migrations and are found at different depths of water depending on the time of day and the season.

Plankton are generally subdivided into two major categories, phytoplankton and zooplankton. **Phytoplankton** are free-floating photosynthetic algae and cyanobacteria that form the base of most aquatic food webs. **Zooplankton** are nonphotosynthetic organisms that include protozoa (animal-like protists), tiny shrimplike crustaceans, and the larval (immature) stages of many animals. In aquatic food webs, zooplankton feed on algae and cyanobacteria and are in turn consumed by newly hatched fish and other small aquatic organisms.

Nekton are larger, more strongly swimming organisms such as fishes, turtles, and whales. **Benthos** are bottom-dwelling organisms that fix themselves to one spot (sponges, oysters, and barnacles), burrow into the sand (worms, clams, and sea cucumbers), or simply walk about on the bottom (crawfish, aquatic insect larvae, and brittle stars).

FRESHWATER ECOSYSTEMS

Freshwater ecosystems include rivers and streams (flowing-water ecosystems), lakes and ponds (standing-water ecosystems), and marshes and swamps (freshwater wetlands). Specific abiotic conditions and characteristic organisms distinguish each freshwater ecosystem. Although freshwater ecosystems occupy a relatively small portion (about 2%) of Earth's surface, they have an important role in the hydrologic cycle: They assist in recycling precipitation that flows as surface runoff to the ocean (see discussion of the hydrologic cycle in Chapter 4). Large bodies of freshwater moderate daily and seasonal temperature fluctuations on nearby land. Freshwater habitats provide homes for many species.

Rivers and Streams: Flowing-Water Ecosystems The nature of a **flowing-water ecosystem** changes greatly between its source (where it begins) and its mouth (where it empties into another body of water) (**Figure 6.13**). *Headwater streams*, the small streams that are the sources of a river, are usually shallow, cool, swiftly flowing, and highly oxygenated. Such streams provide high-quality drinking water, though the landscapes rarely support high-density human populations. In contrast, rivers downstream from the headwaters are wider and deeper, cloudy (they contain suspended particulates), not as cool, slower flowing, and less oxygenated. Rivers make

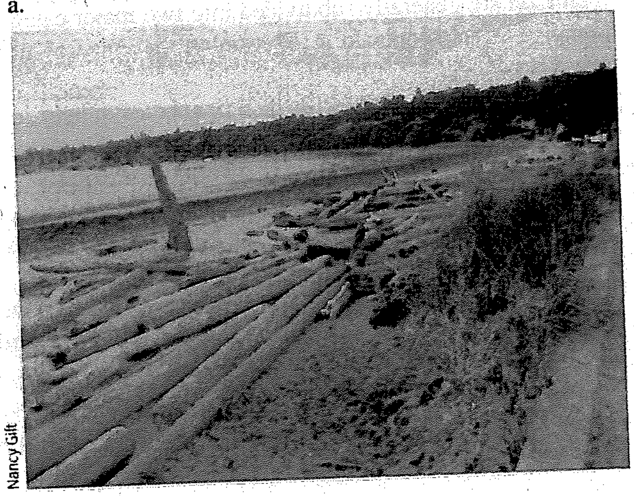
flowing-water ecosystem A freshwater ecosystem such as a river or stream in which the water flows in a current.

Nancy Gilt

a.

Nancy Gilt

b.



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c.

Figure 6.13 Flowing water ecosystem. In the Canadian Rockies, water flow initiates from snow clouds on mountaintop glaciers (a), proceeds through headwater streams (b) and then to rivers, and finally to the ocean at deltas on the coast. (c) (Photos from Yoho National Park, Kicking Horse Pass, and Victoria, British Columbia)

more reliable water sources, though they also typically require more treatment to provide safe drinking water. Along parts of a river or stream, groundwater wells up through sediments on the bottom. This local input of water moderates the water temperature so that summer temperatures are cooler and winter temperatures are warmer than in adjacent parts of the flowing-water ecosystem.

The various environmental conditions in a river system result in many different habitats. The concept of a river system as a single ecosystem with a gradient in physical features from headwaters to mouth is known as the *river continuum concept*. This gradient results in predictable changes in the organisms inhabiting different parts of the river system. For example, in streams with fast currents, the inhabitants may have adaptations such as hooks or suckers to attach themselves to rocks so that they are not swept away. The larvae of blackflies attach themselves with a suction disk located on the end of their abdomen. Some stream inhabitants, such as immature water-penny beetles, may have flattened bodies to slip under or between rocks. Inhabitants such as fish are streamlined and muscular enough to swim in the current. Organisms in large, slow-moving streams and rivers do not need such adaptations, although they are typically streamlined to lessen resistance when moving through water.

Unlike other freshwater ecosystems, streams and rivers depend on the land for much of their energy. In headwater streams, almost all of the energy input comes from detritus, such as dead leaves carried from the land into streams and rivers by wind or surface runoff. Downstream, rivers contain more producers and are less dependent on detritus as a source of energy than are headwaters.

Human activities have several adverse impacts on rivers and streams. Pollution from industry, agriculture, cities, and lawns alters the physical environment and changes the biotic component downstream from the pollution source. A dam causes water to back up, flooding large areas of land and forming a reservoir, which destroys terrestrial habitat. Below the dam, the once-powerful river is often reduced to a relative trickle, which alters water temperature, sediment transport, and delta replenishment and prevents fish migrations. (See Chapter 12 for more discussion of the environmental effects of dams.)

Lakes and Ponds: Standing-Water Ecosystems Zonation characterizes **standing-water ecosystems.** A large lake has three zones: the littoral, limnetic, and profundal zones (**Figure 6.14**). The **littoral zone** is a shallow-water area along the shore of a lake or pond where light reaches the bottom. Emergent vegetation, such as cattails and bur reeds, as well as several deeper-dwelling aquatic plants and algae, live in the littoral zone. The littoral zone is the most productive

standing-water ecosystem A body of fresh water that is surrounded by land and that does not flow; a lake or a pond.

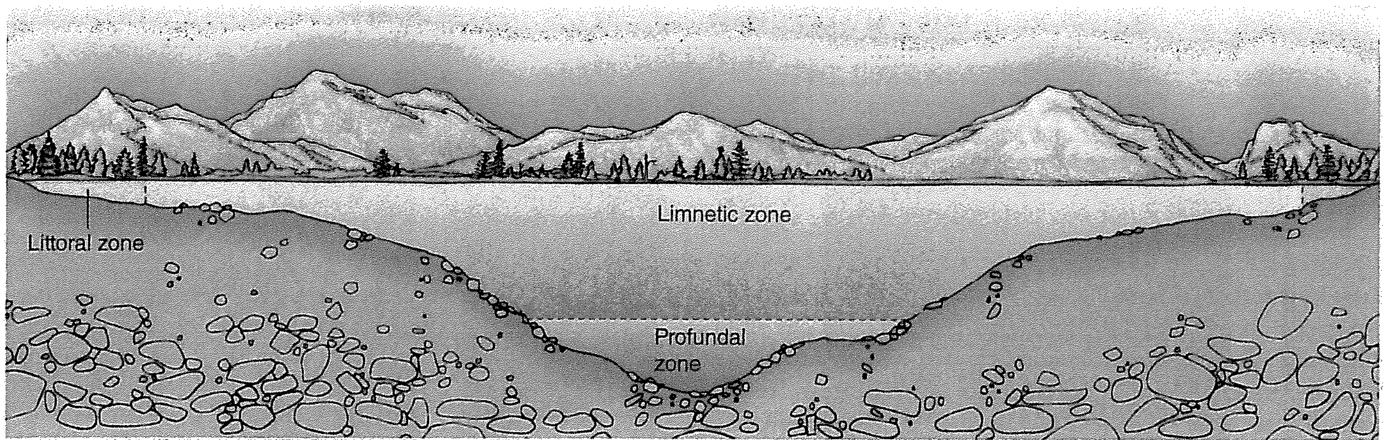


Figure 6.14 Zonation in a large lake. The littoral zone is the shallow-water area around the lake's edge. The limnetic zone is the open, sunlit water away from the shore. The profundal zone, under the limnetic zone, is below where light penetrates.

section of the lake (photosynthesis is greatest here), in part because it receives nutrient inputs from surrounding land that stimulate the growth of plants and algae. Animals of the littoral zone include frogs and their tadpoles; turtles; worms; crayfish and other crustaceans; insect larvae; and many fishes, such as perch, carp, and bass. Surface dwellers such as water striders and whirligig beetles live in still waters. Standing water ecosystems are highly appealing to humans both for the fresh water they provide and for recreational possibilities.

The **limnetic zone** is the open water beyond the littoral zone—that is, away from the shore; it extends down as far as sunlight penetrates to permit photosynthesis. The main organisms of the limnetic zone are microscopic phytoplankton and zooplankton. Larger fishes spend most of their time in the limnetic zone, although they may visit the littoral zone to feed and reproduce. Owing to its depth, less vegetation grows here than in the littoral zone.

The deepest zone, the **profundal zone**, is beneath the limnetic zone of a large lake; smaller lakes and ponds typically lack a profundal zone. Light does not penetrate effectively to this depth, and plants and algae do not live there. Food sinks into the profundal zone from the littoral and limnetic zones. Bacteria decompose dead organisms and other organic material that reach the profundal zone, using up oxygen and liberating the nutrient minerals contained in the organic material. These nutrient minerals are not effectively recycled because there are no producers to absorb and incorporate minerals into the food web. As a result, the profundal zone is both mineral-rich and anaerobic (without oxygen), with few organisms other than anaerobic bacteria occupying it.

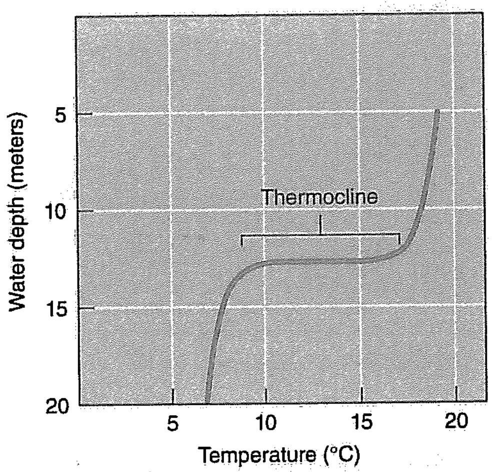
Human effects on lakes and ponds include **eutrophication**, which is nutrient enrichment of a body of water with inorganic plant and algal nutrients like nitrates and phosphates. Although eutrophication can be a natural process, human activities often accelerate it. For example, nutrient levels increase due to the runoff of agricultural fertilizers and discharge of treated or untreated sewage. Soil erosion also increases nutrient loads in lakes and ponds. As eutrophication occurs, the number and kinds of aquatic organisms living in the lake change. Eutrophication of lakes is discussed in detail in Chapter 21 (see Figure 21.2).

Thermal Stratification and Turnover in Temperate Lakes. The marked layering of large temperate lakes caused by how far light penetrates is accentuated by **thermal stratification**, in which the temperature changes sharply with depth. Thermal stratification occurs because the summer sunlight penetrates and warms surface waters, making them less dense. (The density of water is greatest at 4°C. Both above and below this temperature, water is less dense.) In the summer, cool, denser water remains at the lake bottom, separated from the warm, less dense water above by an abrupt temperature transition, the **thermocline** (**Figure 6.15a**). Seasonal distribution of temperature and oxygen (more oxygen dissolves in water at cooler temperatures) affects the distribution of fish in the lake.

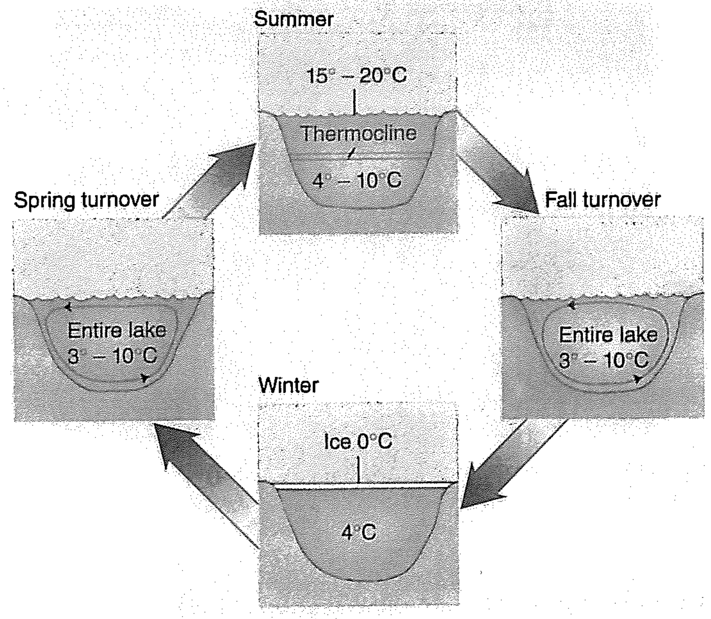
In temperate lakes, falling temperatures in autumn cause **fall turnover**, a mixing of the layers of lake water (**Figure 6.15b**). (Such turnovers are not common in the tropics because the seasonal temperatures do not vary much.) As the surface water cools, its density increases, and eventually it displaces the less dense, warmer, mineral-rich water beneath. The warmer water then rises to the surface where it, in turn, cools and sinks. This process of cooling and sinking continues until the lake reaches a uniform temperature throughout.

When winter comes, the surface water may cool below 4°C, its temperature of greatest density, and if it is cold enough, ice forms. Ice forms at 0°C and is less dense than cold water. Thus, ice forms on the surface, and the water on the lake bottom is warmer than the ice on the surface.

In the spring, **spring turnover** occurs as ice melts and the surface water reaches 4°C. Surface water again sinks to the bottom, and bottom water returns to the surface, resulting in a mixing of the layers. As summer arrives, thermal stratification occurs once again. The mixing of deeper, nutrient-rich water with surface, nutrient-poor water during the fall and spring turnovers brings essential nutrient minerals to the surface and oxygenated water to the bottom. The sudden presence of large amounts of essential nutrient minerals in surface waters encourages the growth of large



(a) Temperature varies by depth during the summer. An abrupt temperature transition, the thermocline, occurs between the upper warm layer and the bottom cold layer.



(b) During fall and spring turnovers, a mixing of upper and lower layers of water brings oxygen to the oxygen-depleted depths of the lake and brings nutrient minerals to the mineral-deficient surface water. During summer months, a layer of warm water develops over cooler, deeper water; no turnover occurs to supply oxygen to deeper water, where the oxygen level drops.

Figure 6.15 Thermal stratification in a temperate lake.

algal and cyanobacterial populations, which form temporary **blooms** (population explosions) in the fall and spring. (Harmful algal blooms such as red tides are discussed in Chapter 7.)

Marshes and Swamps: Freshwater Wetlands **Freshwater wetlands** include marshes, in which grasslike plants dominate, and swamps, in which woody trees or shrubs dominate (**Figure 6.16**). Freshwater wetlands include hardwood bottomland forests (lowlands along streams and rivers that are periodically flooded), prairie potholes (small, shallow ponds that formed when glacial ice melted at the end of the last ice age), and peat moss bogs (peat-accumulating wetlands where sphagnum moss dominates). Wetland soils are waterlogged and anaerobic for variable periods. Most wetland soils are rich in accumulated organic materials, in part because anaerobic conditions discourage decomposition.

freshwater wetland .and that shallow fresh vater covers for at least part of the year and hat has a characteristic soil and water-tolerant vegetation.

Wetland plants are highly productive and provide enough food to support a variety of organisms. Wetlands are valued as a wildlife habitat for migratory waterfowl and many other bird species, beaver, otters, muskrats, and game fishes. Wetlands provide natural flood control because they are holding areas for excess water when rivers flood their banks. The floodwater stored in wetlands then drains slowly back into the rivers, providing a steady flow of water throughout the year. Wetlands serve as groundwater recharging areas. One of their most important roles is to help cleanse water by trapping and holding pollutants in the flooded soil. These important environmental functions are called **ecosystem services** (see Table 5.1).

At one time, wetlands were considered wastelands, areas to fill in or drain so that farms, housing developments, and industrial plants could be built. Because they are breeding places for mosquitoes, wetlands were viewed as a menace to public health. Today, the crucial ecosystem services that wetlands provide are widely recognized. Yet despite some legal protection, wetlands are still threatened by agriculture, pollution, dam construction, and urban and suburban development. In many parts of the United States, we continue to lose wetlands (**Figure 6.17**; also see Chapter 17).

Nancy Gift

Figure 6.16 Freshwater wetland. This lake near Salt Springs, Florida, is surrounded by wetlands. Trees and other plants are adapted to life with continually wet roots and low soil oxygen levels.

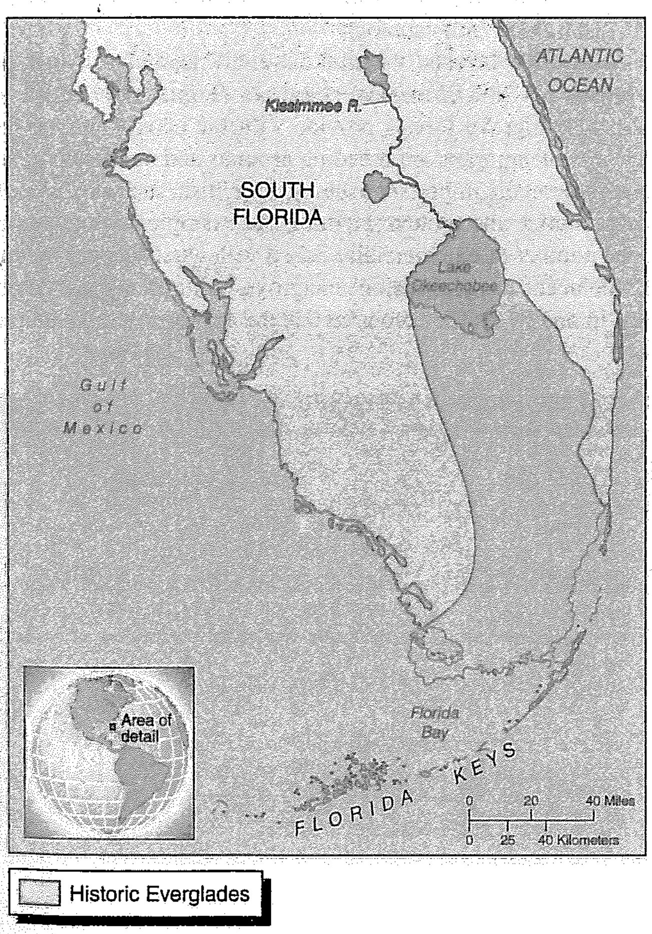
Figure 6.17 What kinds of common threats are faced by wetlands and by endangered species?

CASE IN POINT

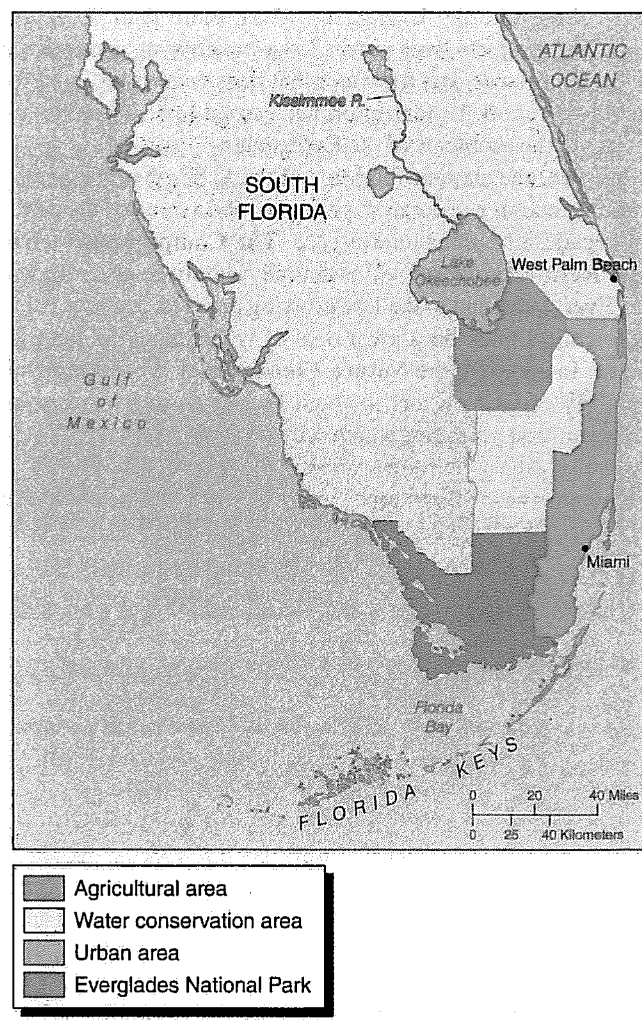
THE EVERGLADES

The Everglades in the southernmost part of Florida is an expanse of predominantly sawgrass wetlands dotted with small islands of trees. At one time, the "river of grass" drifted south in a slow-moving sheet of fresh water from Lake Okeechobee to Florida Bay (**Figure 6.18**). The Everglades is a haven for wildlife such as alligators, snakes, panthers, otters, raccoons, and thousands of wading birds and birds of prey; the Everglades also provide nurseries for a variety of edible and commercially valuable fish. The region's natural wonders were popularized in an environmental classic, *The Everglades: River of Grass*, written by **Marjory Stoneman Douglas** in 1947. The southernmost part of the Everglades is now protected as a national park.

The Everglades today is about half its original size, and it has many serious environmental problems. Most waterbird populations are down 93% in recent decades, and the area is now home to 50 endangered or threatened species and an increasing number of invasive species. Basically, two problems override all others in



(a) Extent of the original Everglades.



(b) The Everglades today.

Figure 6.18 Florida Everglades.

the Everglades today—it receives too little water, and the water it receives is polluted with nutrient minerals from agricultural runoff.

In its original state, water in the Everglades was nutrient-poor. During heavy rains, Lake Okeechobee flooded its banks, creating wetlands that provided biological habitat and helped recharge the Everglades. However, when a hurricane hit the lake in 1928 and many people died, the Army Corps of Engineers built the Hoover Dike along the eastern part of the lake. The Hoover Dike stopped the flooding but prevented the water in Lake Okeechobee from recharging the Everglades. Four canals built by the Everglades Drainage District drained 214,000 hectares (530,000 acres) south of Lake Okeechobee, which was converted to farmland. Fertilizers and pesticides used here make their way to the Everglades, where they alter native plant communities. Phosphorus is particularly harmful because it encourages the growth of nonnative cattails that overrun the native sawgrasses and disrupt the flow of water.

After several tropical storms caused flooding in south Florida in 1947, the Army Corps of Engineers constructed an extensive system of canals, levees, and pump stations to prevent flooding, provide drainage, and supply water to south Florida. These structures diverted excess water to the Atlantic Ocean rather than the Everglades. The resulting lands were drier, which encouraged accelerated urban growth along the east coast and the expansion of agriculture into the Everglades. Thus, more than 80 years of engineering projects have reduced the quantity of water flowing into the Everglades, and the water that does enter is polluted from agricultural runoff. Urbanization has caused loss of habitat, contributing to the problems of the Everglades.

In 1996, the state of Florida and the U.S. government began planning a massive restoration project to undo some of the damage from decades of human interference. **The Comprehensive Everglades Restoration Plan** will eventually supply clean, fresh water to the Everglades and to the fast-growing population of south Florida. Scientists must do a great deal of research as the plan goes forward. In addition, the **Nature Conservancy** is working with a wide array of land owners in south Florida to improve ranching and agricultural practices, which will help increase water quantity and quality. Many questions remain about how best to restore a more natural water flow, repel invasions of foreign species, and reestablish native species. ■

ESTUARIES: WHERE FRESH WATER AND SALT WATER MEET

Several ecosystems may occur where the ocean meets the land: a rocky shore, a sandy beach, an intertidal mudflat, or a tidal **estuary.** Water levels in an estuary rise and fall with the tides; salinity fluctuates with tidal cycles, the time of year, and precipitation. Salinity changes gradually within the estuary, from fresh water at the river entrance to salty ocean water at the mouth of the estuary. Estuarine organisms must tolerate the significant daily, seasonal, and annual variations in temperature, salinity, and depth of light penetration.

estuary A coastal body of water, partly ırrounded by land, with ccess to the open ocean and a large supply of fresh water from a river.

Estuaries are among the most fertile ecosystems in the world, often having a much greater productivity than either the adjacent ocean or the fresh water upriver. This high productivity is brought about by four factors:

1. Nutrients are transported from the land into rivers and creeks that flow into the estuary.
2. Tidal action promotes a rapid circulation of nutrients and helps remove waste products.
3. A high level of light penetrates the shallow water.
4. The presence of many plants provides an extensive photosynthetic carpet and mechanically traps detritus, forming the base of a detritus food web.

Many species, including commercially important fishes and shellfish, spend their larval stages in estuaries among the protective tangle of decaying plants.

Temperate estuaries usually contain **salt marshes**, shallow wetlands dominated by salt-tolerant grasses (see the photograph in the Chapter 3 introduction). Salt marshes have often seemed to be worthless, empty stretches of land to uninformed people. As a result, they have been used as dumps and become severely polluted or have been filled with dredged bottom material to form artificial land for residential and industrial development. A large part of the estuarine environment has been lost in this way, along with many of its ecosystem services, such as biological habitats, sediment and pollution trapping, groundwater supply, and storm buffering. (Salt marshes absorb much of the energy of a storm surge and thereby prevent flood damage elsewhere.) According to the Environmental Protection Agency, estuaries in the United States are in fair to poor condition, with the greatest problems in northeastern and Gulf estuaries.

Mangrove forests, the tropical equivalent of salt marshes, cover perhaps 70% of tropical coastlines (**Figure 6.19**). Like salt marshes, mangrove forests provide valuable ecosystem services. Their interlacing roots are breeding grounds and nurseries for several commercially important fishes and shellfish, such as blue crabs, shrimp, mullet, and spotted sea trout. For example, biologists studied the number of commercially fished yellowtail snapper on coral reefs adjacent to neighboring mangrove-rich and mangrove-poor areas. In one study, they reported that the snapper biomass on reefs

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Figure 6.19 Mangrove forest. Red mangroves (*Rhizophora mangle*) have stiltlike roots that support the tree. These roots grow into deeper water as well as into mudflats exposed by low tide. Many animals live in the protection of the root systems of mangrove forests. Photographed in Belize.

near mangrove-rich areas was two times greater than the biomass near mangrove-poor areas. (Recall from Chapter 3 that *biomass* is an estimate of the mass, or amount, of living material.)

Mangrove branches are nesting sites for many species of birds, such as pelicans, herons, egrets, and roseate spoonbills. Mangrove roots stabilize the submerged soil, thereby preventing coastal erosion, and provide a barrier against the ocean during storms such as hurricanes. Mangroves may be even more effective than concrete seawalls in dissipating wave energy and controlling floodwater from tropical storms. Unfortunately, mangroves are under assault from coastal development, unsustainable logging, and aquaculture (see Figure 18.18). Some countries, such as the Philippines, Bangladesh, and Guinea-Bissau, have lost 70% or more of their mangrove forests.

MARINE ECOSYSTEMS

Although lakes and the ocean are comparable in many ways, there are many physical differences. The depths of even the deepest lakes do not approach those of the ocean trenches, with areas that extend more than 6 km (3.6 mi) below the sunlit surface. Tides and currents exert a profound influence on the ocean. Gravitational pulls of both the sun and the moon usually produce two high tides and two low tides each day along the ocean's coastlines, but the height of those tides varies with the season, local topography, and phases of the moon (a full moon causes the highest tides).

Scientists from many countries use a variety of tools to study the ocean's geology, biology, and physical factors. Some drifting buoys sample surface-water temperatures and wind speeds. Other drifting buoys sink to as much as 2 km (1.2 mi), and then return to the surface to provide satellites with deepwater data. Moored buoys, chained to one spot on the ocean floor, measure wave height, current speeds, and carbon dioxide levels. Fiber-optic cables collect data on the ocean floor, such as crustal dynamics. Ships provide a variety of information, from sampling marine life to using sonar to map the ocean floor. Satellites help to track sea ice, oil spills, and algal blooms. Although scientists monitor many aspects of the ocean, much of the marine world remains a mystery. **Rachel Carson**, best known today for *Silent Spring*, her book on the impact of pesticides, wrote lyrically about the mysteries and science of the ocean in her books *The Edge of the Sea, The Sea Around Us,* and *Under the Sea-Wind.*

The immense marine environment is subdivided into several life zones: the intertidal zone, where organisms live along the shore between high and low tides; the benthic environment, where organisms live on or under the seafloor; and the pelagic environment, where organisms live in the water (**Figure 6.20**). The pelagic environment is, in turn, divided into two provinces based on depth: the neritic and oceanic provinces. The ocean comprises the neritic province, consisting of shallow waters close to shore, and the oceanic province, consisting of the rest of the ocean. The oceanic province overlies the ocean floor at depths greater than 200 m.

The Intertidal Zone: Transition Between Land and Ocean

Although the high levels of light and nutrients, together with an abundance of oxygen, make the **intertidal zone** a biologically productive habitat, it is a stressful one. If an intertidal beach is sandy,

intertidal zone The area of shoreline between low and high tides.

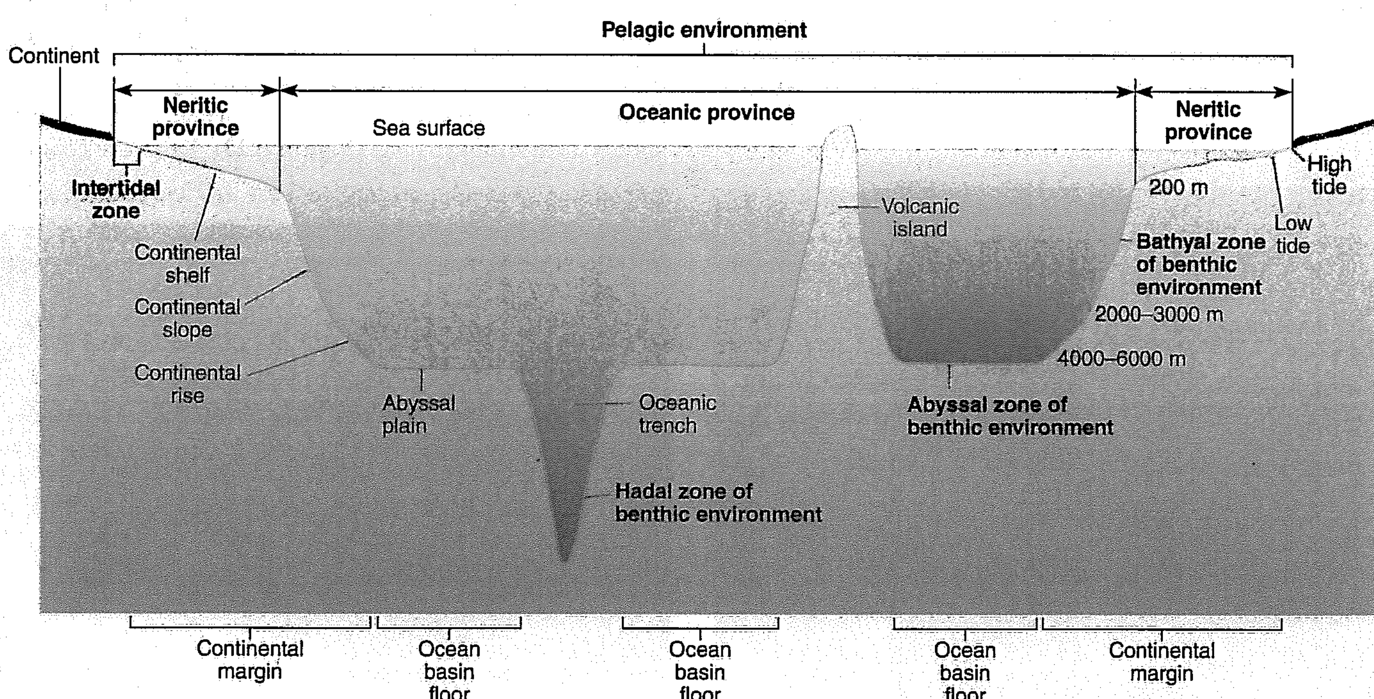

Figure 6.20 Zonation in the ocean. The ocean has three main life zones: the intertidal zone, the benthic environment, and the pelagic environment. The pelagic environment consists of the neritic and oceanic provinces. The neritic province overlies the ocean floor from the shoreline to a depth of 200 m. The oceanic province overlies the ocean floor at depths greater than 200 m. The ocean floor is not a flat expanse; it consists of mountains, valleys, canyons, seamounts, ridges, and trenches. (The slopes of the ocean floor are not typically as steep as shown; they are exaggerated to save space.)

inhabitants must contend with a constantly shifting environment that threatens to engulf them and gives them scant protection against wave action. Consequently, most sand-dwelling organisms, such as mole crabs, are continuous and active burrowers. They usually do not have notable adaptations to survive drying out or exposure because they follow the tides up and down the beach.

A rocky shore provides fine anchorage for seaweeds and marine animals but is exposed to wave action when immersed during high tides and to drying and temperature changes when exposed to air during low tides (**Figure 6.21**). A typical rocky-shore inhabitant has some way of sealing in moisture—perhaps by closing its shell, if it has one—plus a powerful means of anchoring itself to the rocks. Mussels have tough, thread-like anchors secreted by a gland in the foot, and barnacles have special glands that secrete a tightly bonding glue that hardens under water. Rocky-shore intertidal algae, such as rockweed (*Fucus*), usually have thick, gummy coats that dry out slowly when exposed to air, and flexible bodies not easily broken by wave action. Some rocky-shore organisms hide in burrows, under rocks, or in crevices at low tide, and some small crabs run about the splash line.

The intertidal zone, whether sand or rock, takes much of the force of storms such as hurricanes and typhoons. Development of beach areas for housing and recreation is tempting but obviously likely to result in expensive repeated rebuilding efforts.

The Benthic Environment: Seagrass Beds, Kelp Forests, and Coral Reefs Most of the **benthic environment** consists of sediments (mostly sand and mud) where many animals, such as worms and clams, burrow. Bacteria are common in marine sediments and have even been reported in ocean sediments more than 2.5 km (1.5 mi) below the ocean floor.

nthic environment e ocean floor, which ends from the inter- al zone to the deep- ocean trenches.

The deeper parts of the benthic environment are divided into three zones. They are, from shallowest to deepest, the bathyal, abyssal, and hadal zones. The *bathyal benthic zone* is the benthic environment that extends from a depth of 200 to 4000 m (650 ft to 2.5 mi). The *abyssal benthic zone* extends from a depth of 4000 m to a depth of 6000 m (2.5 to 3.7 mi), whereas the *hadal benthic zone* extends from 6000 m to the bottom of the deepest trenches. (Case in Point: Life Without the Sun in Chapter 3 examines the unusual organisms in the deeper part of the benthic environment.) Here we describe shallow benthic communities that are particularly productive—seagrass beds, kelp forests, and coral reefs.

Seagrass Beds. **Sea grasses** are flowering plants adapted to complete submersion in salty ocean water. They occur only in shallow water, to depths of 10 m (33 ft), where they receive enough light to photosynthesize efficiently. Extensive beds of sea grasses occur in quiet temperate, subtropical, and tropical waters (**Figure 6.22**). Eelgrass is the most widely distributed sea grass along the coasts of North America; the largest eelgrass bed in the world is in Izembek Lagoon on the Alaska Peninsula. The most common sea grasses in the Caribbean Sea are manatee grass and turtle grass.

Sea grasses have a high primary productivity and are ecologically important in shallow marine areas. Their roots and rhizomes help stabilize the sediments, reducing surface erosion. Sea grasses provide food and habitat for many marine organisms, including scallops and crabs. In temperate waters, ducks and geese eat sea grasses, whereas in tropical waters, manatees, green turtles, parrot fish, sturgeon, and sea urchins eat them. These herbivores consume only about 5% of the sea grasses. The remaining 95% eventually enters the detritus food web and is decomposed when the sea grasses die. Decomposing bacteria are, in turn, consumed by a variety of animals such as mud shrimp, lugworms, and mullet (a type of fish).

Kelp Forests. **Kelps**, which may reach lengths of 60 m (200 ft), are the largest brown algae (**Figure 6.23**). Kelps are common in

Nancy Gift

Figure 6.21 The intertidal zone. A sandy intertidal zone, with one organism, a seaweed with air bladders, well suited to survive until the next tide, and one organism, a Portugese man o' war, trapped onshore by the falling tide

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Figure 6.22 Seagrass bed. A bivalve mollusk in a seagrass bed in Almeria, Spain. Sea grasses form underwater meadows that are ecologically important for shelter and food for many organisms. Note the many tiny epiphytic algae and invertebrate animals attached to the seagrass blades.

Figure 6.23 Kelp forest. These underwater "forests" support many kinds of aquatic organisms. Photographed off the coast of California.

cooler temperate marine waters of both the Northern and Southern Hemispheres. They are especially abundant in relatively shallow waters (depths of about 25 m, or 82 ft) along rocky coastlines. Kelps are photosynthetic and are the primary food producers for the kelp forest ecosystem. Kelp forests provide habitats for many marine animals. Tube worms, sponges, sea cucumbers, clams, crabs, fishes, and sea otters find refuge in the algal fronds. Some animals eat the fronds, but kelps are mainly consumed in the detritus food web. Bacteria that decompose the kelp remains provide food for sponges, tunicates, worms, clams, and snails. The diversity of life supported by kelp beds almost rivals that found in coral reefs.

Coral Reefs. Coral reefs, built from accumulated layers of calcium carbonate ($CaCO_3$), are found in warm (usually greater than 21°C), shallow seawater. The living portions of coral reefs must grow in shallow waters where light penetrates. Some coral reefs are composed of red coralline algae that require light for photosynthesis. Most coral reefs consist of colonies of millions of tiny coral animals, which require light for the large number of *zooxanthellae*, symbiotic algae that live and photosynthesize in their tissues. In addition to obtaining food from the zooxanthellae that live inside them, coral animals capture food at night with stinging tentacles that paralyze zooplankton and small animals that drift nearby. The waters where coral reefs are found are often poor in nutrients, but other factors are favorable for a high productivity, including the presence of zooxanthellae, a favorable temperature, and year-round sunlight.

Coral reefs grow slowly, as coral organisms build on the calcium carbonate remains of countless organisms before them. On the basis of their structure and underlying geologic features, three kinds of coral reefs exist: fringing reefs, atolls, and barrier reefs (**Figure 6.24**). The most common type of coral reef is the fringing reef. A **fringing reef** is directly attached to the shore of a volcanic island or continent and has no lagoon associated with it. An **atoll** is a circular coral reef that surrounds a central lagoon of quiet water. An atoll forms on top of the cone of a submerged volcano island. More than 300 atolls are found in the Pacific and Indian Oceans, whereas the Atlantic Ocean, which is geologically different from the other two ocean basins, has few atolls. A lagoon of open water separates a **barrier reef** from the nearby land. The world's largest barrier reef is the Great Barrier Reef, which is nearly 2000 km (more than 1200 mi) in length and up to 100 km (62 mi) across. It extends along the northeastern coast of Australia. The second-largest barrier reef is the Mesoamerican Reef in the Caribbean Sea off the coast of Belize, Mexico, and Honduras.

Coral reef ecosystems are the most diverse of all marine environments. They contain thousands of species of fishes and invertebrates, such as giant clams, snails, sea urchins, sea stars, sponges, flatworms, brittle stars, sea fans, shrimp, and spiny lobsters. The Great Barrier Reef occupies only 0.1% of the ocean's surface, but 8% of the world's fish species live there. Competition is intense, particularly for light and space to grow. According to the National Oceanic and Atmospheric Administration (NOAA), fish dependent on coral reefs provide significant protein for at least one billion people worldwide.

Although coral reefs are often found in shallow, tropical waters, many highly diverse reefs are located in cold water. Cold-water coral reefs, which are found on continental shelves,

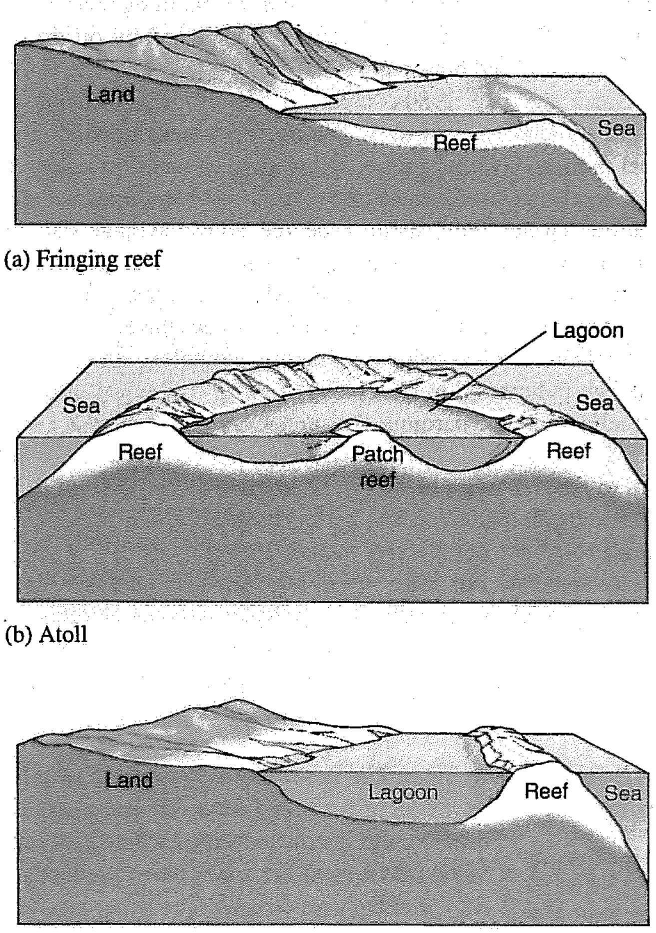

Figure 6.24 Types of coral reefs.

slopes, and seamounts, occur at depths from 50 m to 6 km (164 ft to almost 4 mi). Most of these reefs live in perpetual darkness. Unlike photosynthetic zooxanthellae, these corals rely on capturing prey to supply their food. Like the more familiar shallow-water reefs, cold-water coral reefs are hotbeds of biological diversity. So far, scientists have identified more than 3300 species of cold-water corals.

Coral reefs are ecologically important because they both provide a habitat for many kinds of marine organisms and protect coastlines from shoreline erosion. They provide humans with seafood, pharmaceuticals, and recreational/tourism dollars.

Human Impacts on Coral Reefs. Although coral formations are important ecosystems, they are being degraded and destroyed. Of 109 countries with large reef formations, 90 are damaging them. According to the latest report of the Global Coral Reef Monitoring Network, most coral reefs (61%) face moderate to severe threats due to local human pressures, though some areas (Hawaii, Australia) have done a better job than others at protecting reefs, with less than 20% of reefs there under threat.

How do we harm coral reefs? In some areas, silt washing downstream from clear-cut inland forests has smothered reefs under a layer of sediment. In addition to pollution from coastal runoff, overfishing, fishing with dynamite or cyanide, disease, and coral bleaching are serious threats. Land reclamation, tourism, oil spills, boat groundings, anchor draggings, hurricane damage, ocean dumping, and the mining of corals for building material also take a toll. Cold-water coral reefs are threatened by oil drilling, seabed mining, and bottom trawling.

Since the late 1980s, corals in the tropical Atlantic and Pacific suffered extensive bleaching, in which stressed corals expel their zooxanthellae, becoming pale or white in color. The most likely environmental stressor is warmer seawater temperatures (water only about 1 degree above average can lead to bleaching) and increased ocean acidity due to higher levels of dissolved carbon dioxide. Although many coral reefs have not recovered from bleaching, some have. The coral-zooxanthellae relationship is highly complex and flexible. Research indicates that corals may lose up to 75% of their zooxanthellae without harming the reef. Corals may hold a "secret reserve" of zooxanthellae, not immediately apparent, that allows them to recover when bleached. In addition, corals take in any of several zooxanthella species, perhaps allowing one zooxanthella species to rescue coral when another abandons it. (Some species of zooxanthellae are more stress-resistant than others.) Should seawater, which is naturally slightly basic, become acidified, the calcium carbonate skeletons of coral animals (and shells of crabs, oysters, clams, and many other marine species) would thin or, in extreme cases, dissolve completely away.

The Pelagic Environment: The Vast Marine System The **pelagic environment** consists of all of the ocean water, from the shoreline down to the deepest ocean trenches. It is subdivided into several life zones based on depth and degree of light penetration. The upper reaches of the pelagic environment form the **euphotic zone**, which extends from the surface to a maximum depth of 150 m (488 ft) in the clearest ocean water. Sufficient light penetrates the euphotic zone to support photosynthesis. Large numbers of phytoplankton, particularly diatoms in cooler waters and dinoflagellates in warmer waters, produce food by photosynthesis and are the base of marine food webs. The marine system buffers global temperatures against seasonal temperature changes.

pelagic environment All ocean water, from the shoreline down to the deepest ocean trenches

The two main divisions of the pelagic environment are the neritic and oceanic provinces.

The Neritic Province. Organisms that live in the **neritic province,** the water that overlies the continental shelf, are all floaters or swimmers. Zooplankton (including tiny crustaceans; jellyfish; comb jellies; protists such as foraminiferans; and larvae of barnacles, sea urchins, worms, and crabs) feed on phytoplankton in the euphotic zone. Zooplankton are consumed by plankton-eating nekton such as herring, sardines, squid, baleen whales, and manta rays. These, in turn, become prey for carnivorous nekton such as sharks, toothed whales, tuna, and porpoises (**Figure 6.25**). Nekton are mostly confined to the shallower neritic waters (less than 60 m, or 195 ft, deep), near their food.

neritic province The part of the pelagic environment that overlies the ocean floor from the shoreline to a depth of 200 m (650 ft).

The Oceanic Province. The **oceanic province** is the largest marine environment, comprising about 75% of the ocean's water; the oceanic province is the open ocean that does not overlie the continental shelf. Most of the oceanic province is loosely described as the *deep sea*. (The average depth of the ocean is 4 km, more than 2 mi.) All but the surface waters of the oceanic province have cold temperatures, high hydrostatic pressure, and an absence of sunlight. These environmental conditions are uniform throughout the year.

oceanic province The part of the pelagic environment that overlies the ocean floor at depths greater than 200 m (650 ft).

Most organisms of the deep waters of the oceanic province depend on **marine snow**, organic debris that drifts down into their habitat from the upper, lighted regions of the oceanic province.

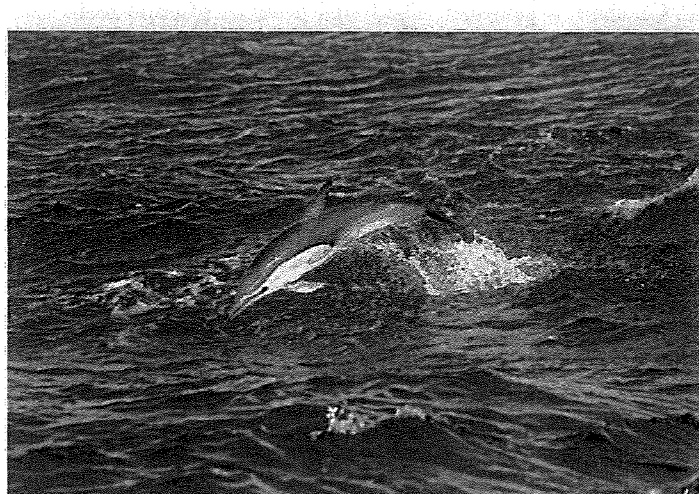

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Figure 6.25 Nekton in the neritic province. A porpoise leaps briefly out of the Pacific Ocean, near the North Island of New Zealand.

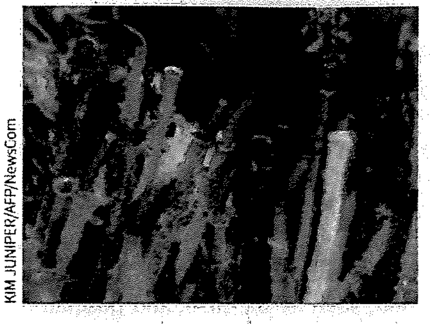


Figure 6.26 Hydrothermal vent community. *Riftia pachyptila* tubeworms and nestled *Bathymodiolus thermophilus* mussels on the East Pacific Rise. This community is on the ocean floor in complete darkness, but produces food using chemosynthesis (like photosynthesis) with heat from a hydrothermal vent.

Organisms of this little-known realm are filter feeders, scavengers, or predators. Many are invertebrates, some of which attain great sizes. The giant squid measures up to 13 m (43 ft) in length, including its tentacles.

Fishes of the deep waters of the oceanic province are strikingly adapted to darkness, high pressure, and scarcity of food. An organism that encounters food infrequently must eat as much as possible when food is available. Adapted to drifting or slow swimming, animals of the oceanic province often have reduced bone and muscle mass. Many of these animals have light-producing organs to locate one another for mating or food capture. The dragon fish has a pocket of red light shining from beneath each eye. Because other species living in the ocean's depths cannot see red light, the dragonfish detects organisms in its surroundings without being seen. (Most animals in the ocean depths are bioluminescent, producing a blue-green light.)

Some deep-sea organisms, however, are producers, using heat from hydrothermal vents as an energy source to fuel a process that chemically parallels photosynthesis. Communities living at hydrothermal vents include clams, mussels, and tubeworms and bacteria living symbiotically within their tissues (**Figure 6.26**). Other organisms, such as barnacles, also live at these vents, in the shelter created by the tubeworms.

National Marine Sanctuaries The United States has set aside **national marine sanctuaries** along the Atlantic, Pacific, and Gulf of Mexico coasts to minimize human impacts and protect unique natural resources and historic sites. These sanctuaries include kelp forests off the coast of California, coral reefs in the Florida Keys, fishing grounds along the continental shelf, and deep submarine canyons, as well as shipwrecks and other sites of historic value (**Figure 6.27**).

The *National Marine Sanctuary Program*, which is part of the National Oceanic and Atmospheric Administration (NOAA), administers the sanctuaries. Like many federal lands, they are managed for multiple purposes, including conservation, recreation, education, mining of some resources, scientific research, and ship salvaging. Commercial fishing is permitted in most of them, although several "no-take" zones exist where all fishing and collecting of biological resources is banned. Several recent studies have shown that these no-take zones for fish promote population increases of individual species as well as species richness (the no-take reserves typically contain 20% to 30% more

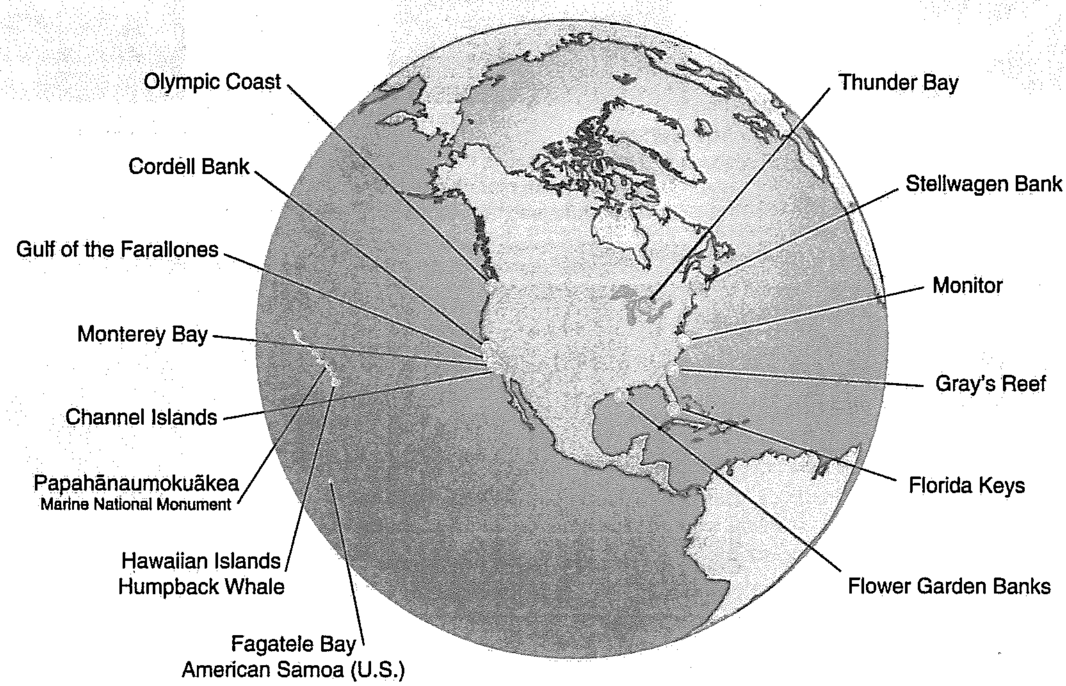


Figure 6.27 National marine sanctuaries. (NOAA)

species than nearby fished areas). The reserves have a spillover effect—that is, they boost populations of fish surrounding their borders.

The National Marine Sanctuary system includes 14 sites—13 national marine sanctuaries and one national monument. In 2006, President George W. Bush established the world's largest protected marine area when he designated the northwestern Hawaiian Islands and surrounding waters—an area almost as large as California—as a national monument. Such a designation provides permanent funding to manage and preserve the area. This protected area is home to thousands of species of seabirds, fishes, marine mammals, and coral reef colonies.

Human Impacts on the Ocean The ocean is so vast that it is hard to visualize how human activities could harm it. Such is the case, however (**Figure 6.28**). The development of resorts, cities, industries, and agriculture along coasts alters or destroys many coastal ecosystems, including mangrove forests, salt marshes, seagrass beds, and coral reefs. Coastal and marine ecosystems receive pollution from land, from rivers emptying into the ocean, and from atmospheric contaminants that enter the ocean via precipitation. Disease-causing viruses and bacteria from human sewage contaminate seafood, such as shellfish, and pose an increasing threat to public health. Millions of tons of trash, including plastic, fishing nets, and packaging materials, find their way into coastal and

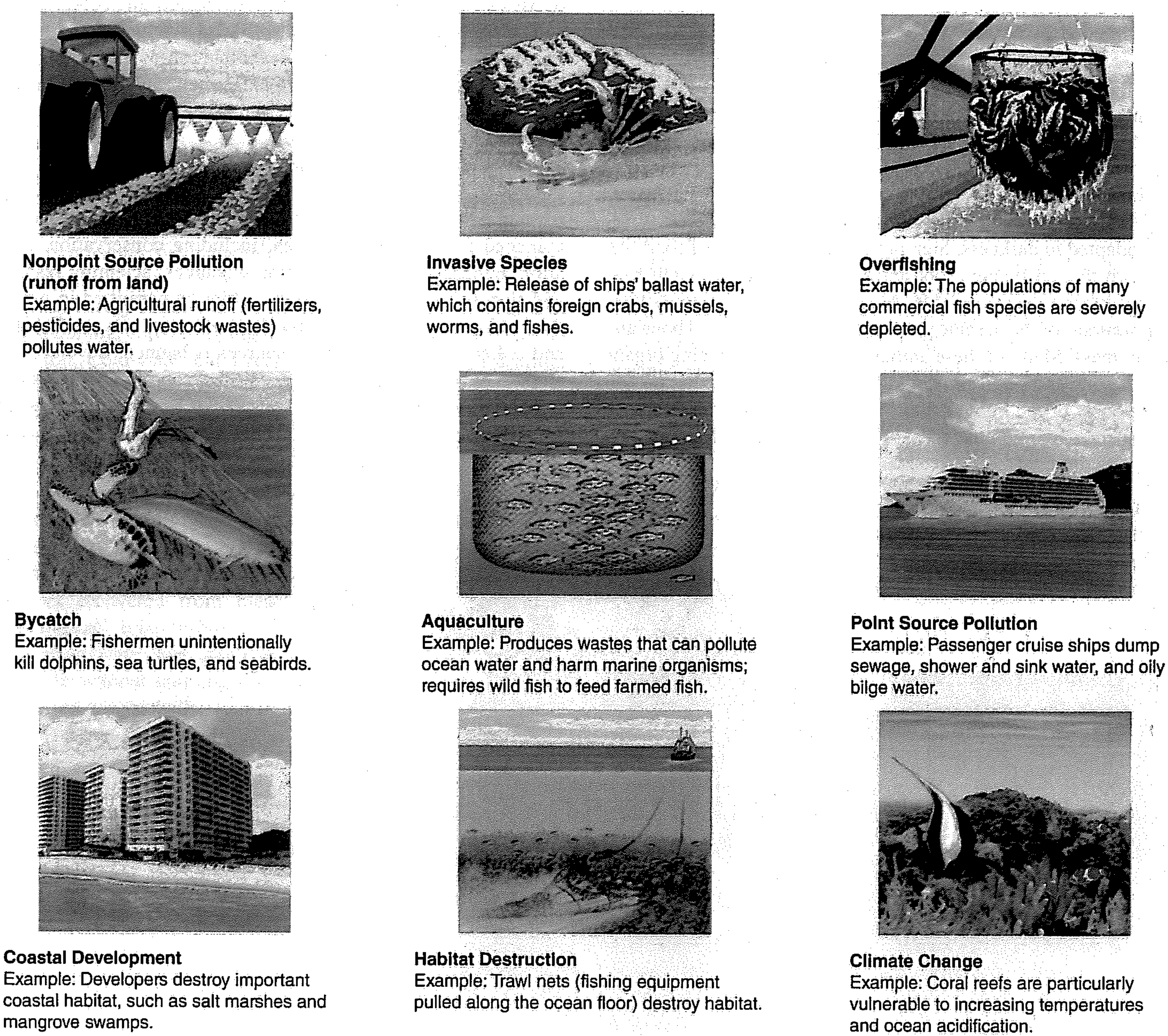


Figure 6.28 Major threats to the ocean. Under which of the major threats would you place the 2010 Deepwater Horizon oil spill in the Gulf of Mexico? (Based on pages 15-16 of S.R. Palumbi, *Marine Reserves: A Tool for Ecosystem Management and Conservation*, Pew Oceans Commission [2003])

marine ecosystems. Some of this trash entangles and kills marine organisms. Less visible contaminants of the ocean include fertilizers, pesticides, heavy metals, and synthetic chemicals from agriculture and industry.

Offshore mining and oil drilling pollute the neritic province with oil and other contaminants. Millions of ships dump oily ballast and other wastes overboard in the neritic and oceanic provinces. Fishing is highly mechanized, and new technologies detect and remove every single fish in a targeted area of the ocean. Scallop dredges and shrimp trawls are dragged across the benthic environment, destroying entire communities with a single swipe.

Conservation groups and government agencies have studied these problems for many years and have made numerous recommendations to protect and manage the ocean's resources. For example, from 2002 to 2003, the Pew Oceans Commission, composed of scientists, economists, fishermen, and other experts, verified the seriousness of ocean problems in a series of seven studies.

The 2004 report by the U.S. Commission on Ocean Policy, the first comprehensive review of federal ocean policy in 35 years, recommended improving the ocean and coasts through improved policy and funding initiatives.

The recommended actions will require billions of dollars and years of effort to be realized.

REVIEW

1. What environmental factors are most important in determining the kinds of organisms found in aquatic environments?
2. How do you distinguish between freshwater wetlands and estuaries? Between flowing-water and standing-water ecosystems? Between the neritic and oceanic provinces?
3. List an ecosystem service provided by each of the aquatic ecosystems.

REVIEW OF LEARNING OBJECTIVES WITH SELECTED KEY TERMS

• Define *biome* and briefly describe the nine major terrestrial biomes: tundra, boreal forest, temperate rain forest, temperate deciduous forest, temperate grassland, chaparral, desert, savanna, and tropical rain forest.

A **biome** is a large, relatively distinct terrestrial region with similar climate, soil, plants, and animals, regardless of where it occurs in the world. **Tundra** is the treeless biome in the far north that consists of boggy plains covered by lichens and small plants such as mosses; tundra has harsh, very cold winters and extremely short summers. **Boreal forest** is a region of coniferous forest (such as pine, spruce, and fir) in the Northern Hemisphere; it is located south of the tundra. **Temperate rain forest** is a coniferous biome with cool weather, dense fog, and high precipitation. **Temperate deciduous forest** is a forest biome that occurs in temperate areas with a moderate amount of precipitation. **Temperate grassland** is grassland with hot summers, cold winters, and less rainfall than the temperate deciduous forest biome. **Chaparral** is a biome with mild, moist winters and hot, dry summers; vegetation is typically small-leaved evergreen shrubs and small trees. **Desert** is a biome in which the lack of precipitation limits plant growth; deserts are found in both temperate and subtropical regions. **Savanna** is tropical grassland with widely scattered trees or clumps of trees. **Tropical rain forest** is a lush, species-rich forest biome that occurs where the climate is warm and moist throughout the year.

• Identify at least one human food that grows well in each of the biomes discussed.

Animal protein, from fishing and hunting, is the primary source of food available in arctic tundra, as well as in boreal forest, though some plants are available in arctic summer. Temperate rain forest fosters edible mushrooms, cattails, and some berries, like salmonberry. Nuts such as hickory, pecan, and chestnut grow in deciduous forest, as well as fruits such as pawpaw. Annual and perennial grasses grow well in prairie biomes. Chaparral can support vineyards and olive orchards. Savanna is best suited for grazing animals, both wild game and livestock. Tropical rainforest ecosystems support a wide variety of fruit (bananas, acai), edible plants, and game animals.

• Explain the similarities and the changes in ecosystems observed with increasing elevation and increasing latitude.

Similar ecosystems are encountered in climbing a mountain (increasing elevation) and traveling to the North Pole (increasing latitude). This elevation-latitude similarity occurs because the temperature drops as one climbs a mountain, just as it does when one travels north.

• Summarize the important environmental factors that affect aquatic ecosystems.

In aquatic ecosystems, important environmental factors include **salinity**, amount of dissolved oxygen, and availability of light for photosynthesis.

• Briefly describe the eight aquatic ecosystems: flowing-water ecosystem, standing-water ecosystem, freshwater wetlands, estuary, intertidal zone, benthic environment, neritic province, and oceanic province.

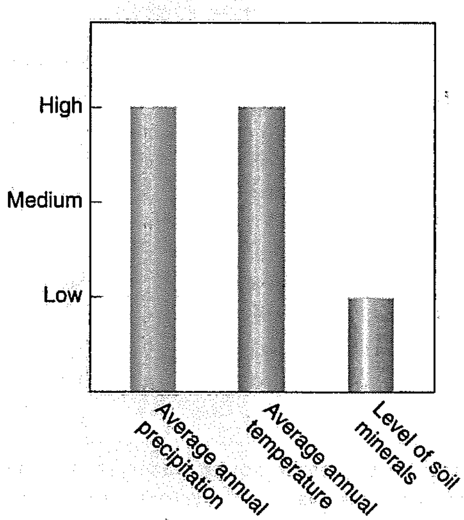
A **flowing-water ecosystem** is a freshwater ecosystem such as a river or stream in which the water flows in a current. A **standing-water ecosystem** is a body of fresh water that is surrounded by land and that does not flow (a lake or a pond). **Freshwater wetlands** are lands that shallow fresh water covers for at least part of the year; wetlands have a characteristic soil and water-tolerant vegetation. An **estuary** is a coastal body of water, partly surrounded by land, with access to the open ocean and a large supply of fresh water from a river. Four important marine environments are the intertidal zone, benthic environment, neritic province, and oceanic province. The **intertidal zone** is the area of shoreline between low and high tides. The **benthic environment** is the ocean floor, which extends from the intertidal zone to the deep-ocean trenches. The **pelagic environment** consists of all of the ocean water, from the shoreline down to the deepest ocean trenches. The two main divisions of the pelagic environment are the neritic and oceanic provinces. The **neritic province** is the part of the pelagic environment that overlies the ocean floor from the shoreline to a depth of 200 m. The **oceanic province** is the part of the pelagic environment that overlies the ocean floor at depths greater than 200 m.

- **Identify at least one ecosystem service provided by each aquatic ecosystem.**

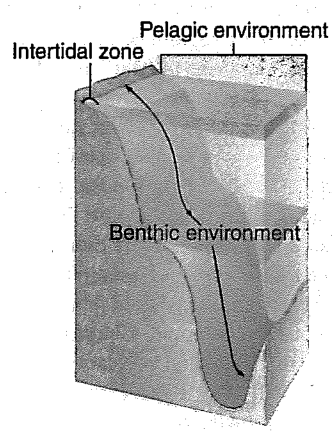
Flowing-water ecosystems provide many people with fresh drinking water, and standing water ecosystems provide habitat for aquatic life as well as opportunities for recreation. Wetlands and estuaries both protect land from heavy rainfall events and storm surges. Intertidal zones offer opportunities for recreation, and protect land from hurricanes and typhoons. Benthic environments (seagrass, kelp forests, and coral reefs) are areas rich in biodiversity, which support nurseries of many commercially valuable fish. Larvae of crabs, as well as herring, sardines, and squid, live in the neritic province. Most commercially valuable fish live in the oceanic province. Both neritic and oceanic provinces help buffer landmasses against temperature changes.

Critical Thinking and Review Questions

1. What two climate factors are most important in determining an area's characteristic biome?
2. Offer a possible reason why the tundra has such a low species richness.
3. Describe representative organisms of the forest biomes discussed in the text: boreal forest, temperate deciduous forest, temperate rain forest, and tropical rain forest.
4. Which biome discussed in this chapter is depicted by the information given below? Explain your answer.



5. In which biome do you live? If your biome does not match a description given in this chapter, how do you explain the discrepancy?
6. Which biomes are best suited for agriculture? Explain why each of the biomes you did not specify is less suitable for agriculture.
7. In biomes less suited for agriculture, what natural food sources are available for humans?
8. Which biome do you think is in greatest immediate danger from human activities? Why?
9. As you walk from the bottom to the top of a mountain, what changes in vegetation would you expect to see?
10. What are two important abiotic factors that affect aquatic ecosystems?
11. Explain the role of freshwater wetlands in water purification.
12. If you were to find yourself on a boat in the Chesapeake Bay, what aquatic ecosystem would you be in? What ecosystem would you be in if you were in the middle of Everglades National Park?
13. Which aquatic ecosystem is often compared to a tropical rain forest? Why?
14. What is the largest marine environment, and what are some of its features?
15. Which of the ocean zones shown would be home to each of the following organisms: lobster, coral, mussel, porpoise, and dragon fish. For those organisms you identified as living in the pelagic environment, are they most likely found in the neritic or oceanic province? Explain your answers.

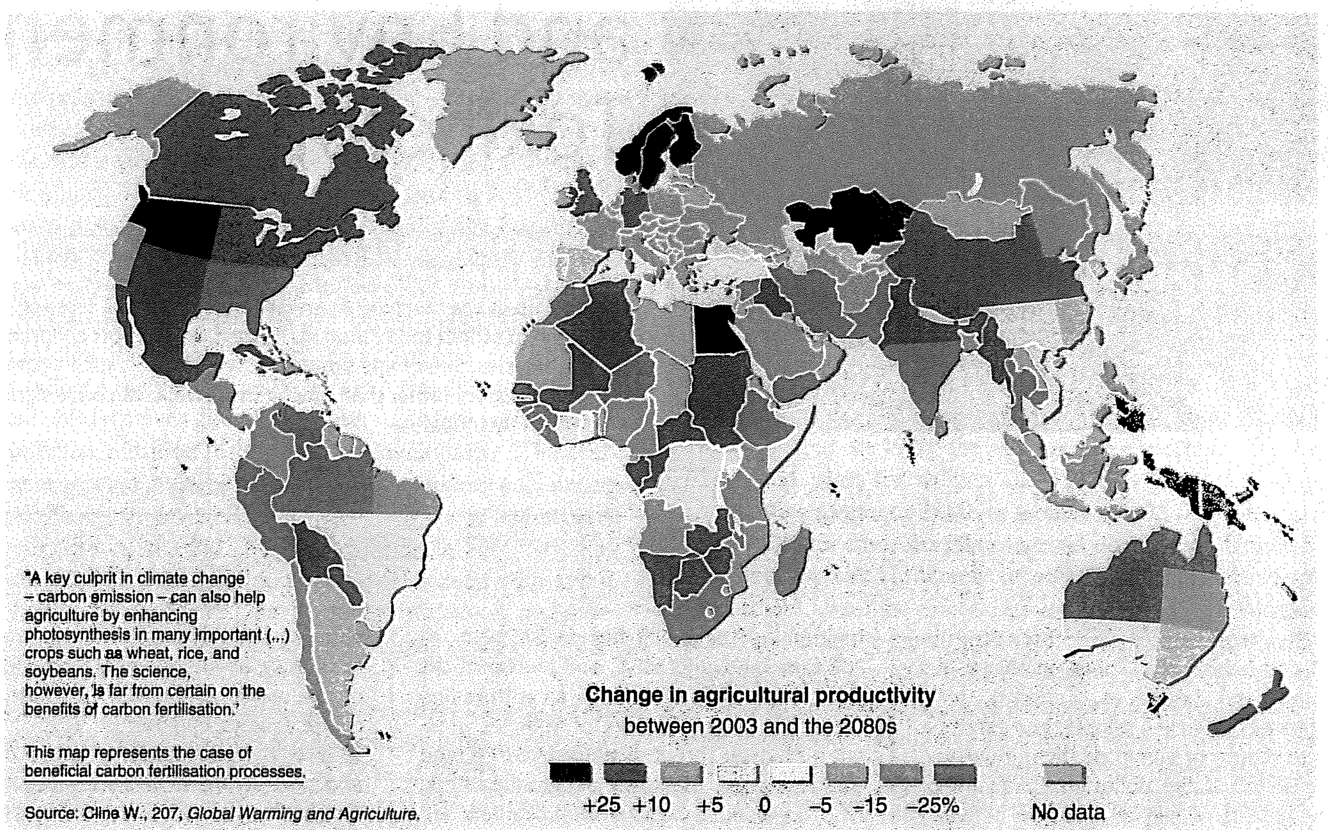


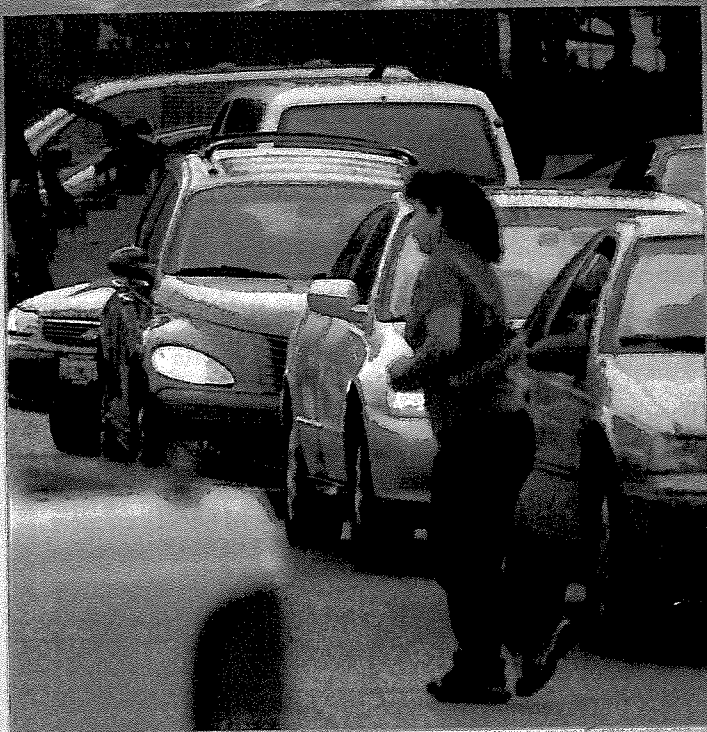
16. What would happen to the organisms in a river with a fast current if a dam was built? Explain your answer.
17. Explain how coral reefs are vulnerable to human activities.
18. Briefly discuss two major human-caused problems in the ocean.
19. Scientists report that in recent years tropical ocean waters have become saltier, whereas polar ocean waters have become less salty. What do you think is a possible explanation for these changes?

Food for Thought

Over the next century, changing temperatures and changes in precipitation are projected to reduce agricultural productivity in some areas and reduce it in others. The figure shows the likely changes in productivity across the globe. Choose a region of interest, and examine how food productivity is likely to change in that region. How might population and trade opportunities change with food productivity?

Projected impact of climate change on agricultural yields





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7

Human Health and Environmental Toxicology

Cars line up in the morning at an elementary school. More children are driven to school today than in the past, when most children walked or rode bicycles. Seemingly simple lifestyle choices, such as driving children to school rather than having them walk, can have significant impacts on their health.

Often, when people think about environment and health, they focus on things like pollution and pesticides. Certainly, toxic substances can sicken people, and there's a need to reduce or eliminate them. However, in the United States, pollution is only one of many aspects of the relationship between healthy people and a healthy environment. How individuals and societies interact with the environment has implications for lifelong physical and mental health. Thinking about humans and the environment functioning as a system allows us to understand where and how changes in the system can improve human and environmental health.

Today, for example, many children in suburban America are driven to school, whereas several decades ago they would have walked or bicycled (**see photograph**). Although this change might seem minor, it represents a dramatic change in how children interact with their environment. They are establishing behaviors that will last a lifetime, with long-term health implications. Effects include reduced exercise, increased pollution and accident risks, and the loss of interaction with the natural and physical world.

Consider a typical U.S. suburban school, with a thousand students. Even if only one-third of students are driven to school—the fraction can be much higher—as many as 300 cars, minivans, SUVs, and pickup trucks may be driving to the school, all at the same time. The large numbers of vehicles present a physical threat to those children (and their parents, siblings, or grandparents) who do walk, especially when drivers are distracted by passengers, other drivers, and cell phones. In addition, hundreds of gasoline-fueled engines idling and accelerating near occupied playgrounds can elevate air pollution levels in areas where children play before each school day begins. Finally, many children who are driven to school on a regular basis miss out on opportunities to experience daily and seasonal changes in weather. Small animals like insects, spiders, and snails go unnoticed, as do the details of trees and grasses.

Children driven to school might otherwise walk a mile or so each day. They miss out on light physical activity that is not made up in other ways. Childhood inactivity is linked to increased adult obesity, which, in turn, is associated with elevated blood pressure, high cholesterol, and a low level of high-density lipoproteins (HDLs, the "good" cholesterol). These conditions harm blood vessels, increasing the risk of stroke, heart disease, and kidney failure. Type 2 diabetes, a dangerous medical condition, is also related to obesity, as are osteoarthritis and cancers of the colon, gallbladder, prostate, kidney, cervix, ovaries, and uterus.

Over the past century, human life spans and general health have improved markedly. This has come from improved medicine and nutrition, a better understanding of causes and treatments of disease, and reductions in poverty. However, recent studies show that life expectancies have decreased among the poor in the United States, in particular among poor women. Understanding the systemic relationship between human health and the natural, physical, and built environment is critical to a future of improved health.

In this chapter, we explore the factors that underlie health and disease in highly developed and developing countries. In future chapters, we will explore a range of related environment–human health interactions.

In Your Own Backyard...

What changes could you make in your daily routines that would both reduce your use of fossil fuels and improve your health?

Human Health

LEARNING OBJECTIVES

- Contrast health issues in highly developed countries with those in less developed countries.
- Explain the difference between endemic and emerging diseases.

Two indicators of human health in a given country are **life expectancy** (how long people are expected to live) and **infant mortality** (how many infants die before the age of one). These health indicators vividly demonstrate the contrasts in health among different nations. In Japan, the average life expectancy for a woman is 86 and for a man, 79. The **infant mortality rate** in Japan is 2.6, which means that fewer than three infants under age one die per 1,000 live births. In contrast, in the East African country Zambia, the average life expectancy is 42 for women and 41 for men. The infant mortality rate in Zambia is 70, which means that 7% of Zambian infants die before reaching the age of one.

Why is there such a difference between these two countries? A Japanese child receives good healthcare, including vaccinations, and has sufficient nutrition for growth and development. The average Japanese woman gives birth to one or two children and, during her pregnancies, can eat well, rest when necessary, and receive medical attention as needed. As Japanese people age, they may develop the chronic degenerative diseases associated with aging, but they have access to quality healthcare, medications, and rehabilitation services. The average person in Japan spends $550 (in U.S. dollars) on medicines each year.

The picture is very different in Zambia. Many Zambian children receive few immunizations and inadequate nutrition for normal growth and development. In 2007, 15% of Zambian children were underweight (down from 28% in 2001). The average Zambian woman is in poor health due to childhood factors. She may give birth to five or six children. Because she does not receive prenatal care, she has an increased risk of death during childbirth. Moreover, one or more of her children will probably die in infancy. The average Zambian spends about $5 on medicines each year. Those Zambians who survive middle age often die prematurely because they lack treatment for the chronic degenerative diseases associated with aging.

Differences in health and healthcare between highly developed and developing countries highlight the effects of different lifestyles and levels of poverty (**Figure 7.1.**). In developing countries, about 146 million children are underweight, and 3 million of these will die this year. Meanwhile, more than 1 billion people are overweight worldwide (compared to 1 billion who are undernourished), and 300 million people are obese. In the highly developed countries of North America and Europe, about 500,000 people will die this year from obesity-related diseases.

Hierry Falise / Getty Images

Figure 7.1 Health Clinic in Bagladesh. This health clinic provides a range of services to Rohingya, a stateless group of Muslims, at the Leda refugee camp.

HEALTH ISSUES IN HIGHLY DEVELOPED COUNTRIES

By many measures, the health of people in the United States and other highly developed countries is good. Improved sanitation during the 20th century reduced many diseases, such as typhoid, cholera, and diarrhea, that previously made people ill or killed them. Many childhood diseases, such as measles, polio, and mumps, have been conquered. In 1900, the average life expectancy for Americans was 51 years for women and 48 years for men. Today, the average life expectancy is 80 for women and 75 for men.

In 1900, the three leading causes of death in the United States were pneumonia and influenza, tuberculosis, and gastritis and colitis (diarrhea); these are infectious diseases caused by microorganisms. Currently, the three leading causes of death in the United States are cardiovascular diseases (of the heart and blood vessels), cancer, and chronic obstructive pulmonary disease (of the lungs); these diseases are noninfectious chronic health problems and are associated with aging. A significant fraction of premature deaths in the United States are caused by poor diet, lack of exercise, and smoking. According to a 2008 study, these factors have led to a reduction in life expectancy of 1.3 years for women in 180 of the poorest U.S. counties and for men in 11 of those counties.

Undernutrition is uncommon in the United States, although about one in six of the elderly are undernourished. However, two related types of malnourishment represent a growing health threat. Many Americans consume inadequate amounts of vitamins, fiber, and essential nutrients. In addition, typical American diets include too many total calories, resulting in a significant obesity problem.

Healthcare professionals use the **body mass index (BMI)** to determine whether a person is overweight or obese. To calculate your BMI, multiply your weight by 703, then divide that number by your height in inches squared:

$$\text{BMI} = (\text{Weight} \times 703) \div \text{Height}^2$$

For example, if you are 5 feet tall and weigh 130 pounds: $130 \times 703 = 91{,}390$. Five feet equals 60 inches, and the square of 60 is 3600. Now you can divide: $91{,}390 \div 3600 = 25.4$.

- If your BMI = 18.5 or less, you are considered underweight.
- If your BMI is from 18.5 to 24.9, you are at a healthy weight.
- If your BMI is between 25 and 29.9, you are overweight.
- If your BMI is 30 or more, you are considered obese.

According to these guidelines, a person whose BMI is 26.7 is considered overweight but not obese.

HEALTH ISSUES IN DEVELOPING COUNTRIES

There is good news and bad news regarding the health and well-being of people in developing countries. Many **endemic diseases**—those that are constantly present in a region or country—are being managed or eliminated. Gradual improvements in sanitation and drinking-water supplies in moderately developed countries are reducing the incidence of diarrheal diseases such as cholera. Mass immunization programs have eliminated smallpox and reduced the risk of polio, yellow fever, measles, and diphtheria in most countries (see Meeting the Challenge: Global Polio Eradication). Despite these gains, malnutrition, unsafe water, poor sanitation, and air pollution still prevail in many less developed countries (**Figure 7.2**). In addition, research suggests that many unhealthy lifestyles associated with developed countries, including smoking, obesity, and diabetes, are increasingly common in less developed countries. **Table 7.1** contains 10 facts that the World Health Organization considers most important about diseases worldwide.

endemic disease A disease that is constantly present, although often varying in prevalence and potency, in a region or population.

Although overall life expectancy worldwide has increased to 69 years, four of the very poorest developing countries (Zambia, Zimbabwe, Lesotho, and Afghanistan) still have life expectancies of 45 years or less. HIV/AIDS, which is managed by medical treatments in much of the world, has reduced life expectancies by more than 20 years in the African countries of Botswana, Lesotho, Swaziland, and Zimbabwe. Worldwide, 34 million people were living with HIV/AIDS worldwide in 2011, and 2.5 million of those were newly infected that year.

According to the World Health Organization, about 10 million children under five years of age die each year, most of whom could be saved with inexpensive treatments. Child mortality is particularly serious in Africa, where 14 countries have higher levels of child mortality today than they did in 1990. Leading causes of death for children in developing countries include malnutrition, lower respiratory tract infections, diarrheal diseases, and malaria. In sub-Saharan Africa, HIV/AIDS is a significant cause of death for many young children.

Robert Caputo/Aurora Photos, Inc.

Figure 7.2 Workers burning trash in Asab, Eritrea. In many developing countries, sorting and burning garbage with little or no protective equipment is common. Workers risk infection, injury, and toxic exposures.

Table 7.1 Ten Facts on the Global Burden of Disease

1. Around 6.6 million children under the age of five died in 2012.
2. Cardiovascular diseases are the leading causes of death in the world.
3. HIV/AIDS is the leading cause of death in Sub-Saharan Africa.
4. Population aging is contributing to the rise in cancer and heart disease.
5. Lung cancer is the most common cause of death from cancer in the world.
6. Complications of pregnancy account for almost 15% of deaths in women of reproductive age worldwide; 99% of these are in developing countries.
7. Mental disorders such as depression are among the 20 leading causes of disability worldwide.
8. Hearing loss, vision problems, and mental disorders are the most common causes of disability.
9. Almost 10% of adults worldwide suffer from diabetes.
10. About 75% of the new infectious diseases affecting humans over the past 10 years were caused by bacteria, viruses, and other pathogens that originated in animals or animal products.

Source: World Health Organization, Global Burden of Disease Study (December 2013).

EMERGING AND REEMERGING DISEASES

At one time, it was mistakenly thought that all infectious diseases either had been or would soon be conquered. We now know this is not true. **Emerging diseases** are infectious diseases that were not previously found in humans; they typically jump from an animal host to the human species. Acquired immune deficiency syndrome (AIDS) demonstrates why we are concerned about emerging disease: About 36 million people have died from HIV/AIDS since the epidemic began, and 34 million people currently live with the disease (see Chapter 8 introduction). HIV/AIDS is now considered endemic in many places. Epidemiologists think the HIV virus jumped from nonhuman primates to humans as long as 100 years ago, perhaps when humans were exposed to contaminated blood when butchering or eating chimpanzees (**Figure 7.3**). Currently, there is an international network of medical personnel looking for—and trying to prevent the spread of—diseases transmitted from monkeys to humans.

Other emerging diseases include Lyme disease, West Nile virus, Creutzfeld-Jakob disease (the human equivalent of mad cow disease), severe acute respiratory syndrome (SARS), Ebola virus, and monkeypox. In addition, new strains of influenza arise each year, some far more deadly than others. To successfully contain an emerging disease, epidemiologists must recognize the symptoms, identify the disease-causing agent, and inform public health authorities. In turn, public health officials must isolate patients with those symptoms and track down all people who have come into contact with the patients. Meanwhile, medical researchers develop treatment strategies and try to determine and eliminate the origins of the disease.

MEETING THE CHALLENGE

Global Polio Eradication

During the 20th century, significant progress was made in eradicating certain infectious diseases caused by viruses. Smallpox, once endemic in many countries, was eliminated worldwide, and polio (more correctly called *poliomyelitis*) was eliminated in North and South America, Europe, Australia, and much of Asia.

Children under the age of five are the main victims of polio, which is spread by contaminated drinking water. The poliovirus attacks the central nervous system (brain and spinal cord), causing paralysis and, in some cases, death. Polio vaccines, first developed in the 1950s, are usually administered orally (by mouth), and a series of four doses is required to provide complete protection to infants. Supplementary doses are given to children under five years of age.

In 1988, polio was endemic in more than 125 countries. Since 1988, the World Health Organization (WHO) has conducted a vigorous campaign to eliminate polio worldwide. For example, a single case of polio reported in Egypt triggered a campaign to vaccinate at least 1 million children there. India is also making significant progress; after an epidemic in 2002, 100 million children were vaccinated! In 2013, there were fewer than 500 polio cases worldwide, down from about 1,600 in 2008.

In Africa, health experts conduct an annual synchronized campaign to vaccinate children during the peak season for polio. However, in 2003, there was a major setback in efforts to eliminate polio in Africa when the Nigerian state of Kano suspended vaccinations because of concerns about vaccine safety. An outbreak of polio occurred in Nigeria, reinfecting areas that were previously polio-free. Polio also spread from northern Nigeria to other African countries, including Sudan, the Central African Republic, Niger, Chad, Mali, Ivory Coast, Cameroon, Burkina Faso, Guinea, Benin, Botswana, Egypt, and Ethiopia, causing the worst epidemic in years.

In 2004, vaccinations resumed in Kano after health officials found a new supplier of the vaccine. Health officials also conducted a synchronized campaign in nearby countries in an effort to contain the virus in Nigeria. However, the quickness with which polio rebounded after suspension of vaccinations vividly demonstrated that serious efforts at both the national and international levels are needed to make polio the second disease to be globally eradicated.

Reemerging diseases are infectious diseases that existed in the past but, for a variety of reasons, are increasing in incidence or in geographic range. The most serious reemerging disease is tuberculosis. People with HIV/AIDS are more susceptible to tuberculosis because their immune systems are compromised. Thus, the HIV/AIDS pandemic has helped fuel the tuberculosis outbreak. Tuberculosis is associated with poverty, and the increased incidence of urban poverty has also contributed to the emergence of tuberculosis. Other important reemerging diseases include yellow fever, malaria, and dengue fever.

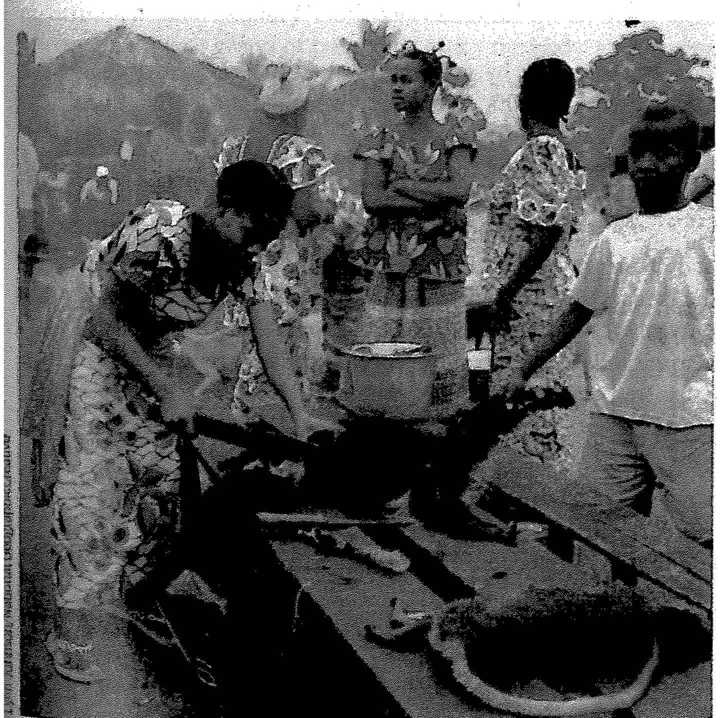


Figure 7.3 Bushmeat. In many parts of Africa and elsewhere, protein is scarce, and monkeys and other bushmeat are an essential part of many diets. Hunting and selling bushmeat potentially exposes hunters, vendors, and others to new diseases. Photographed in Gabon.

One phenomenon responsible for an increased incidence of tuberculosis and other diseases is the evolution of antibiotic-resistant strains of bacteria. Two factors contribute to *antibiotic-resistant bacteria*. First, antibiotics are often overused. People may take unneeded antibiotics, which accelerates the evolution of resistant bacterial strains. Extensive use of antibiotics in the agricultural industry may contribute to this problem.

Second, in some cases antibiotics are underused—rather than completely wiping out a strain, a few individual bacteria are inadvertently allowed to survive, and they are relatively resistant. This can happen at a societal scale, when a few individuals do not get treated, allowing populations of bacteria to survive. It can also happen at the individual level, when a person fails to complete a course of prescribed antibiotics. Failing to complete a prescription can allow some of the most resistant organisms to survive.

Health experts have determined the main factors involved in the emergence or reemergence of infectious diseases. Some of the most important are these:

- Evolution in the infectious organisms, allowing them to move between animal and human hosts
- Evolution of antibiotic resistance in the infectious organisms
- Urbanization, associated with overcrowding and poor sanitation
- A growing population of elderly people who are more susceptible to infection

- Pollution, environmental degradation, and changing weather patterns
- Growth in international travel and commerce
- Poverty and social inequality

CASE IN POINT

INFLUENZA PANDEMICS PAST AND FUTURE

The influenza virus has been a threat to human health for centuries. Every year, one or more new strains of the virus appear and quickly spread around the globe during the flu season, which usually runs from late fall through the winter. In a typical year, anywhere from 5% to 20% of the U.S. population contracts the flu, with symptoms ranging from mild headaches to severe muscle aches, digestive and breathing problems, and high fever. Typically, about 36,000 people in the United States die from the flu each year.

In contrast, a particularly virulent strain during the 1918–1919 flu season may have killed more than 850,000 people in the United States, or nearly 1% of the population of 100 million people. The 1918–1919 flu season corresponded with the end of World War I, a time already characterized by hardships, including hunger and a lack of medicines, as well as a time of unprecedented international travel. The 1918 flu was unusual in that, unlike most strains, it was at least as lethal to healthy people as to the very young, elderly, and infirm.

While individuals can be vaccinated against the flu, successful vaccination requires that researchers predict which influenza strains will appear, successfully prepare enough vaccine for everyone who needs it, and then distribute the vaccine to all those people. In recent years, an increasing fraction of those 65 or older are getting the vaccine (66% in the 2008–2009 flu season, the latest year on record). However, only 33% of those 19 to 49 years old were vaccinated in the same season, which means that a strain similar to that of the 1918–1919 season could be devastating. In addition, such a strain could easily spread around the world via air travel—a scenario envisioned by **Paul Ehrlich** in his 1968 book *The Population Bomb.*

Another recent concern is that of a pandemic of influenza, passing from birds, pigs, or other species to humans. A **pandemic** is a disease that reaches nearly every part of the world and has the potential to infect almost every person. Avian influenza, a strain that appears commonly in birds, tends to be very difficult for humans to contract, since it usually is transferred from bird to human, but not from human to human. It is, however, extremely potent once contracted, with a high fatality rate. A major concern for epidemiologists is the possible evolution of a strain that is easily transferred from human to human—a change that might involve a single genetic mutation. An avian flu pandemic could kill millions, or even billions, of people within a single year.

The swine flu outbreak of 2009 indicates how quickly such a disease can move around the world. The virus, which originated in Mexico, was first identified in April 2009. By early May, it had spread to several dozen countries; by June, it was considered pandemic. The 2009 swine flu strain (referred to as an *H1N1* flu because of its characteristic proteins) has a mixture of human, bird, and swine flu genetic material; H1N1 can be transferred from human to human and between pigs and humans. Two factors prevented the 2009 swine flu from being far more deadly than it was. First, a rapid international response limited its spread, allowing public health officials to prepare to treat the infected. Second, the strain turned out to be less powerful than it could have been. Nonetheless, over 14,000 people worldwide were killed by the 2009 pandemic.

See www.pandemicflu.gov for information on how to be prepared for a flu pandemic. ■

REVIEW

1. What is the average life expectancy for a woman in Japan? A woman in Zambia? Explain the difference.
2. What is the difference between an emerging disease and an endemic disease?

Environmental Pollution and Disease

LEARNING OBJECTIVES

- Summarize the problems associated with chemicals that exhibit persistence, bioaccumulation, and biological magnification in the environment.
- Briefly describe some of the data suggesting that certain chemicals used by humans may also function as endocrine disrupters in animals, including humans.

A 2007 study by researchers at Cornell University suggests that as many as 40% of deaths worldwide are pollution-related. Nonetheless, it is often difficult to establish a direct relationship between environmental pollution and disease (**Figure 7.4**). The relationship is fairly clear for certain pollutants, such as the link between radon and lung cancer (see Chapter 19) or between lead and disorders of the nervous system (see Chapter 21). However, the evidence is less definite for many pollutants, and scientists can only suggest that there is an association between the pollutant and a specific illness. One reason it is so difficult to establish a direct cause and effect is that other factors—such as a person's genetic makeup, diet, level of exercise, and smoking habits—complicate the picture.

Other complications include the fact that certain segments of society are more susceptible than others to adverse health effects from an environmental pollutant. Children are particularly sensitive to pollution, as will be discussed later in this chapter. Other groups at higher risk from pollution include the elderly and people with chronic diseases or compromised immune systems (such as people with HIV/AIDS or those undergoing chemotherapy to treat cancer). Also, people living in poor neighborhoods are often exposed to greater levels of pollution.

Several characteristics of environmental pollutants make them particularly dangerous to both the environment and human health. First, some toxic chemicals persist and accumulate in the

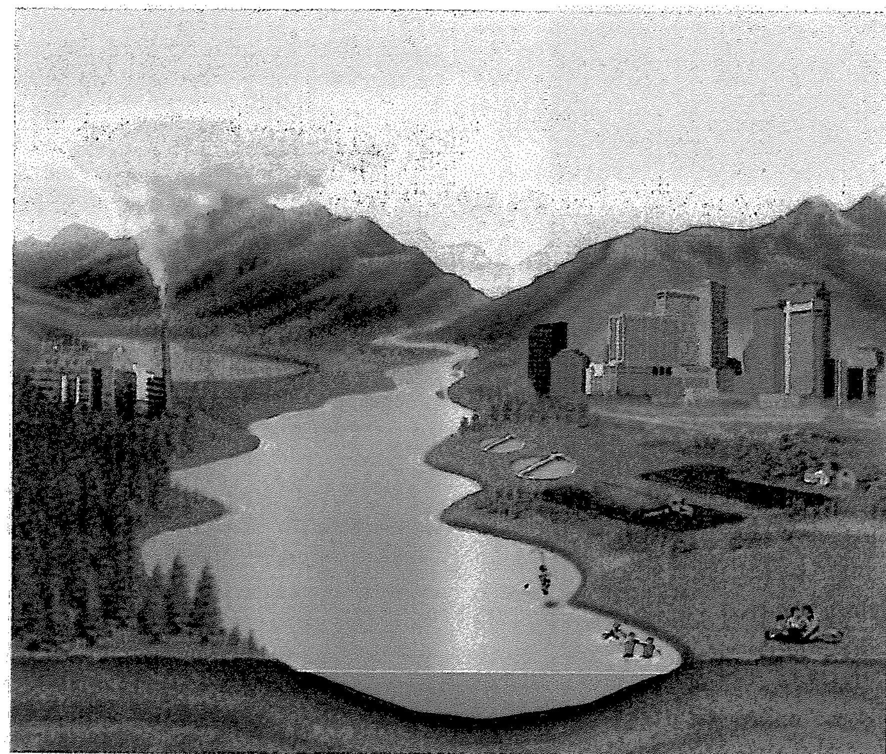


Figure 7.4 Pathways of pollution in the environment. (EPA)

environment and magnify their concentration in the food web. Second, a diverse group of pollutants affect the body's endocrine system, which produces *hormones* to regulate many aspects of body function.

PERSISTENCE, BIOACCUMULATION, AND BIOLOGICAL MAGNIFICATION OF ENVIRONMENTAL CONTAMINANTS

Some toxic substances exhibit persistence, bioaccumulation, and biological magnification. These substances include certain pesticides (such as DDT, or dichlorodiphenyl-trichloroethane), radioactive isotopes, heavy metals (such as lead and mercury), flame retardants (for example, PBDEs, or polybrominated diphenyl ethers), and industrial chemicals (such as dioxins and PCBs, or polychlorinated biphenyls).

The effects of the pesticide DDT on many bird species first demonstrated the problems with these chemicals. Falcons, pelicans, bald eagles, ospreys, and many other birds are sensitive to traces of DDT in their tissues. A substantial body of scientific evidence indicates that one of the effects of DDT on these birds is that they lay eggs with extremely thin, fragile shells that usually break during incubation, causing the chicks' deaths. After 1972, the year DDT was banned in the United States, the reproductive success of many birds improved (**Figure 7.5**).

Three characteristics of DDT contribute to its impact on birds: persistence, bioaccumulation, and biological magnification. It takes many years for some pesticides to break down into less toxic forms. The **persistence** of synthetic pesticides is a result of their novel (not found in nature) chemical structures. Natural decomposers such as bacteria have not yet evolved ways to degrade many synthetic pesticides, so they accumulate in the environment and in the food web.

When a pesticide is not metabolized (broken down) or excreted by an organism, it is simply stored, usually in fatty tissues. Over time, the organism may **bioaccumulate**, or *bioconcentrate*, high concentrations of the pesticide.

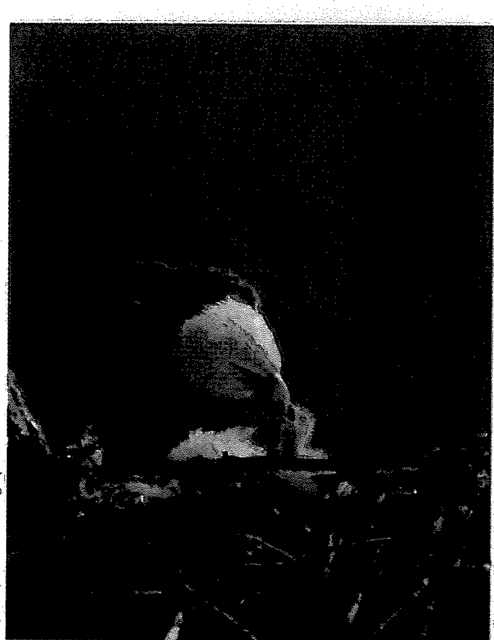
Organisms at higher levels in food webs tend to have greater concentrations of bioaccumulated pesticide stored in their bodies than those lower in food webs. This increase as the pesticide passes through successive levels of the food web is known as **biological magnification**, or *biological amplification*.

As an example of the biological magnification of persistent pesticides, consider a food chain studied in a Long Island salt marsh that was sprayed with DDT over a period of years for mosquito control: algae and plankton → shrimp → American eel → Atlantic needlefish → ring-billed gull (**Figure 7.6**). The concentration of DDT in water was extremely dilute, on the order of 0.00005 part per million (ppm). The algae and other plankton contained a greater concentration of DDT, 0.04 ppm. Each shrimp grazing on

persistence A characteristic of certain chemicals that are extremely stable and may take many years to break down into simpler forms through natural processes.

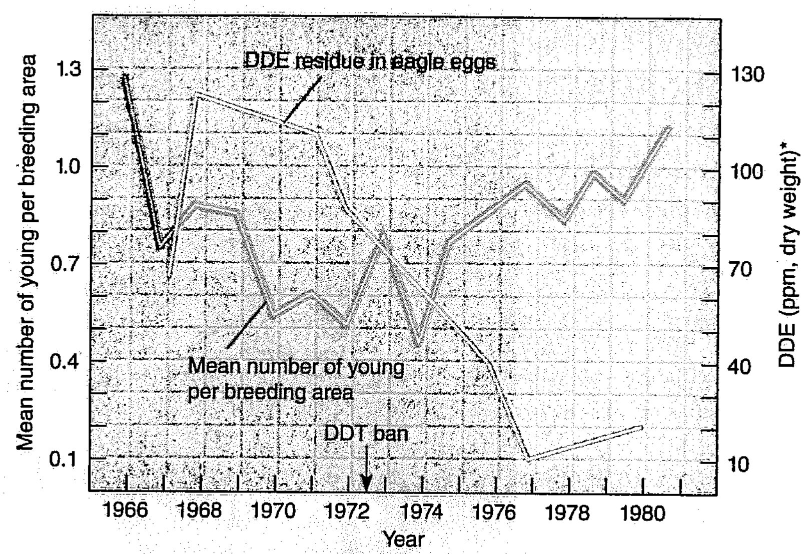
bioaccumulation The buildup of a persistent toxic substance, such as certain pesticides, in an organism's body, often in fatty tissues.

biological magnification The increased concentration of toxic chemicals, such as PCBs, heavy metals, and certain pesticides, in the tissues of organisms that are at higher levels in food webs.



Roy Toft/National Geographic Creative

(a) A bald eagle feeds its chick. Most people know that eagles were on the brink of extinction a few decades ago. However, most people don't understand the scientific research behind the eagles' comeback.



*DDT is converted to DDE in the birds' bodies

(b) A comparison of the number of successful bald eagle offspring with the level of DDT residues in their eggs. DDT was banned in 1972. Note that reproductive success improved after DDT levels decreased. (DDE is a derivative of DDT.) (Reprinted with permission from J. W. Grier, "Ban of DDT and Subsequent Recovery of Reproduction in Bald Eagles." AAAS 1982.)

Figure 7.5 Effect of DDT on birds.

the plankton concentrated the pesticides in its tissues to 0.16 ppm. Eels that ate shrimp laced with pesticide had a pesticide level of 0.28 ppm, and needlefish that ate eels contained 2.07 ppm of DDT. The top carnivores, ring-billed gulls, had a DDT level of 75.5 ppm from eating contaminated fishes. Although this example involves a bird at the top of the food chain, all top carnivores, from fishes to humans, are at risk from biological magnification. Because of this risk, currently approved pesticides in the United States have been tested to ensure they do not persist and accumulate in the environment beyond a level predetermined to be acceptable.

ENDOCRINE DISRUPTERS

Mounting evidence suggests that dozens of industrial and agricultural chemicals—many of which exhibit persistence, bioaccumulation, and biological magnification—are also **endocrine disrupters.** These chemicals, many of which are no longer used in the United States, include

endocrine disrupter A chemical that mimics or interferes with the actions of the endocrine system in humans and wildlife.

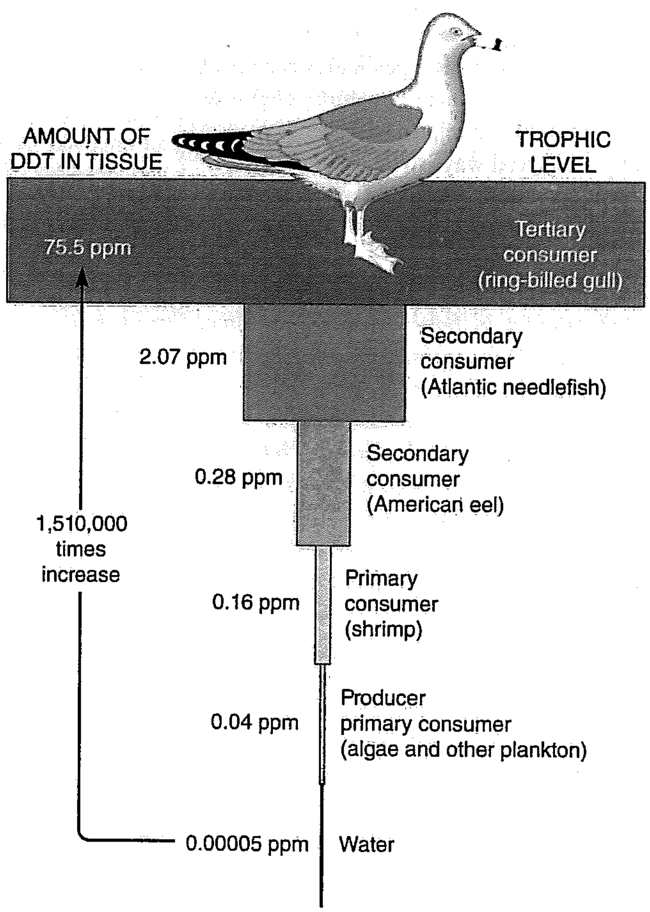


Figure 7.6 Biological magnification of DDT in a Long Island salt marsh. Note how the level of DDT, expressed as parts per million, increased in the tissues of various organisms as DDT moved through the food chain from producers to consumers. The ring-billed gull at the top of the food chain had approximately 1.5 million times more DDT in its tissues than the concentration of DDT in the water. (Based on data from G. M., Woodwell, C. F. Worster, Jr., and P. A. Isaacson. "DDT Residues in an East Coast Sanctuary." *Science* Vol 156 May 12, 1957.)

chlorine-containing industrial compounds known as PCBs and dioxins; the heavy metals lead and mercury; some pesticides such as DDT, kepone, dieldrin, chlordane, and endosulfan; flame retardants (PBDEs); and certain plastics and plastic additives such as phthalates and bisphenol A.

Hormones are chemical messengers produced by organisms in minute quantities to regulate their growth, reproduction, and other important biological functions. Some endocrine disrupters mimic the *estrogens*, a class of female sex hormones, and send false signals to the body that interfere with the normal functioning of the reproductive system. Because both males and females of humans and many other species produce estrogen, endocrine disrupters that mimic estrogen can affect both sexes. Additional endocrine disrupters interfere with the endocrine system by mimicking hormones other than estrogen, such as *androgens* (male hormones such as testosterone) and *thyroid hormones*. Like hormones, endocrine disrupters are active at very low concentrations and, as a result, may cause significant health effects at low doses.

Many endocrine disrupters appear to alter reproductive development in males and females of various animal species. Accumulating evidence indicates that fishes, frogs, birds, reptiles such as turtles and alligators, mammals such as polar bears and otters, and other animals exposed to these environmental pollutants exhibit reproductive disorders and are often left sterile.

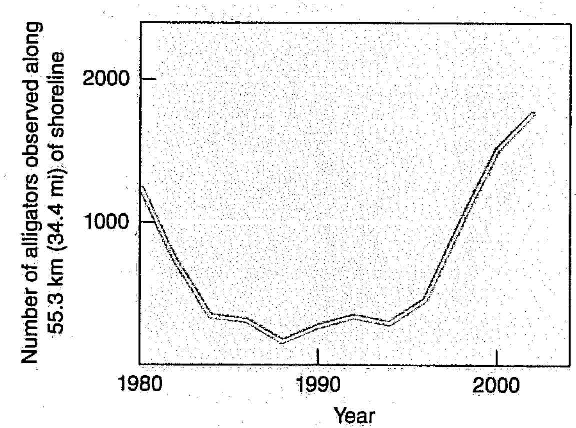
A chemical spill in 1980 contaminated Lake Apopka, Florida's third-largest lake, with DDT and other agricultural chemicals with known estrogenic properties. Male alligators living in Lake Apopka in the years following the spill had low levels of testosterone and elevated levels of estrogen. Their reproductive organs were often feminized or abnormally small. The mortality rate for eggs in this lake was extremely high, which reduced the alligator population for many years (**Figure 7.7**).

Humans may also be at risk from endocrine disrupters, as the number of reproductive disorders, infertility cases, and hormonally related cancers (such as testicular cancer and breast cancer) appears to be increasing. More than 60 studies since 1938 have reported that sperm counts in a total of nearly 15,000 men from many nations, including the United States, dropped by more than 50% between 1940 and 1990. Although only one sperm is needed to fertilize an egg, infertility increases as sperm counts decline. Scientists do not know if this apparent decline and environmental factors are linked, however.

Certain *phthalates*—ingredients of cosmetics, fragrances, nail polish, medications, and common plastics used in a variety of food packaging, toys, and household products—are implicated in birth defects and reproductive abnormalities. Animal studies in which rats are fed large doses of phthalates have shown that these compounds can damage fetal development, particularly of reproductive organs. In humans, exposure to certain phthalates may be correlated to the increase since the 1970s in the incidence of *hypospadias*, a birth defect in which the urethral opening (passageway for urine) is on the underside of the penis instead of at its tip. Certain phthalates are also linked to an increased observance of premature breast development in young girls, typically between 6 and 24 months of age. Other phthalates are of negligible concern, according to the National Toxicology Program's Center for the Evaluation of Risks to Human Reproduction.

Stuart Bauer

(a) A young American alligator (*Alligator mississippiensis*) hatches from eggs taken by University of Florida researchers from Lake Apopka, Florida. Many of the young alligators that hatch have abnormalities in their reproductive systems. This young alligator may not leave any offspring.



(b) Population of juvenile alligators in Lake Apopka after a chemical spill in 1980. (The chemical spill occurred just prior to the 1980 surveys). (Data from A. R. Woodward, Florida Fish and Wildlife Conservation Commission.)

Figure 7.7 Lake Apopka alligators.

Bisphenol A (BPA) is a chemical used in the manufacture of many hard plastic polycarbonate products, including baby bottles, toys, and sport-drink containers. Several studies on animals and a smaller number of studies on humans indicate that BPA is an endocrine disrupter. However, it is unclear how much of the BPA in manufactured products is taken up by our bodies and how much of an effect it can have at those concentrations. Consequently, BPA remains a highly contested regulatory issue: The state of California, the Canadian government, and the European Union have all banned its use in baby bottles, while regulators in the United States and Australia have not.

A Centers for Disease Control and Prevention (CDC) report on a diverse sample of the civilian U.S. population showed the presence of 27 different environmental chemicals—heavy metals, nicotine from tobacco smoke, pesticides, and plastics, many of which are thought to be endocrine disrupters. Nearly every chemical was detected in every participant's body at higher levels than expected. Because scientists had never actually measured 24 of the 28 chemicals in humans before, the study could not say if the levels of various environmental chemicals are increasing or decreasing. However, the study provides a good baseline of the U.S. population's exposure to these compounds against which future studies (the CDC plans to continue the tests) can be compared. The study is also a first step toward determining whether any of these chemicals is the hidden cause of modern illnesses or simply a benign byproduct of modern society.

We cannot make definite links between environmental endocrine disrupters and human health problems at this time because of the limited number of human studies. Human exposure to endocrine-disrupting chemicals must be quantified so that we know exactly how much of each of these chemicals affects various communities. Complicating such assessments is the fact that humans are also exposed to natural hormone-mimicking substances in the plants we eat. Soy-based foods such as bean curd and soymilk, for example, contain natural estrogens.

Congress amended the Food Quality Protection Act and the Safe Drinking Water Act in 1996 to require the U.S. Environmental Protection Agency (EPA) to develop a plan and establish priorities to test thousands of chemicals for their potential to disrupt the endocrine system. In the first round of testing, chemicals are tested to see if they interact with any of five different endocrine receptors. (The body has specially shaped receptors on and in cells to which specific hormones attach. Once a hormone attaches to a receptor, it triggers other changes within the cell.) Chemicals testing positive—that is, binding to one or more types of receptors—are subjected to an extensive battery of tests to determine what specific damages, if any, they cause to reproduction and other biological functions. These tests, which may take decades to complete, should reveal the level of human and animal exposure to endocrine disrupters and the effects of this exposure. (The effects of toxic chemicals, including several endocrine disrupters, are discussed throughout the text.)

REVIEW

1. What are the differences among persistence, bioaccumulation, and biological magnification? How are these chemical characteristics interrelated?
2. How did the 1980 chemical spill in Lake Apopka affect alligators?

Determining Health Effects of Environmental Pollution

LEARNING OBJECTIVES

- Define *toxicant,* and distinguish between acute and chronic toxicities.
- Describe how a dose-response curve helps determine the health effects of environmental pollutants.
- Discuss pesticide risks to children.

The human body is exposed to many kinds of chemicals in the environment. Both natural and synthetic chemicals are in the air we breathe, the water we drink, and the food we eat. *All* chemicals, even "safe" chemicals such as sodium chloride (table salt), are toxic if exposure is high enough. A one-year-old child will die from ingesting about two tablespoons of table salt; table salt is also harmful to people with heart or kidney disease.

The study of **toxicants**, or toxic chemicals, is called *toxicology*. It encompasses the effects of toxicants on living organisms as well as ways to prevent or minimize adverse effects, such as developing appropriate handling or exposure guidelines.

toxicant A chemical with adverse human health effects.

The effects of toxicants following exposure can be immediate (acute toxicity) or prolonged (chronic toxicity). **Acute toxicity,** which ranges from dizziness and nausea to death, occurs immediately to within several days following a single exposure. In comparison, **chronic toxicity** generally produces damage to cells (including cancer) or vital organs, such as the kidneys or liver, following a long-term, low-level exposure to chemicals. Toxicologists know far less about chronic toxicity than they do about acute toxicity, in part because the symptoms of chronic toxicity often mimic those of other chronic diseases.

acute toxicity Adverse effects that occur within a short period after exposure to a toxicant.

chronic toxicity Adverse effects that occur some time after exposure to a toxicant or after extended exposure to the toxicant.

We measure toxicity by the extent to which adverse effects are produced by various doses of a toxicant. A **dose** of a toxicant is the amount that enters the body of an exposed organism. The **response** is the type and amount of damage that exposure to a particular dose causes. A dose may cause death *(lethal dose)* or may cause harm but not death *(sublethal dose)*. Lethal doses, usually expressed in milligrams of toxicant per kilogram of body weight, vary depending on the organism's age, sex, health, metabolism, genetic makeup, and how the dose was administered (all at once or over a period of time). Lethal doses in humans are known for many toxicants because of records of homicides and accidental poisonings.

IDENTIFYING TOXIC SUBSTANCES

One approach scientists use to determine acute toxicity is to administer various doses of a suspected toxicant to laboratory animals, measure the responses, and use these data to predict the chemical effects on humans. The dose lethal to 50% of a population of test animals is the **lethal dose-50%**, or **LD_{50}**. It is usually reported in milligrams of chemical toxicant per kilogram of body weight. LD_{50} is inversely related to the acute toxicity of a chemical: The smaller the LD_{50}, the more toxic the chemical, and, conversely, the greater the LD_{50}, the less toxic the chemical (**Table 7.2**). The LD_{50} is determined for all new synthetic chemicals—thousands are produced each year—as a way of estimating their toxic potential. It is generally assumed that a chemical with a low LD_{50} for several species of test animals is toxic in humans.

The **effective dose-50%**, or **ED_{50}**, is used to evaluate a wide range of biological responses, such as stunted development in the offspring of a pregnant animal, reduced enzyme activity, or onset of hair loss. The ED_{50} causes 50% of a population to exhibit whatever response is under study.

Table 7.2 LD_{50} Values for Selected Chemicals

Chemical	*LD_{50} (mg/kg)**
Aspirin	1750
Ethanol	1000
Morphine	500
Caffeine	200
Heroin	150
Lead	20
Cocaine	17.5
Sodium cyanide	10.0
Nicotine	2.0
Strychnine	0.8

*Administered orally to rats.

Table 7.3 Hypothetical Data Set for Animals Exposed to a Chemical

Number of Animals in Test	*Number of Animals with Cancer*	*Dose (mg/kg/day)*	*Probability of Cancer**
50	0	0.0	0
50	2	5.0	0.04
50	6	10.0	0.12
50	22	20.0	0.44

*The probability of getting cancer at a given dose is the number of animals with cancer at that dose level divided by the total number exposed at that dose level.

One complication of toxicology is that an individual's genes can contribute to that person's response to a specific toxicant. The National Institute of Environmental Health Science has identified several hundred *environmental susceptibility genes*. Subtle differences in these genes affect how the body metabolizes toxicants, making them more or less toxic. Other gene variations allow certain toxicants to bind strongly—or less so—to the genetic molecule DNA. (Generally, when a toxicant binds to our DNA, it is a bad thing.) Genetic variation is one of the most important factors that determine why some people develop lung cancer after years of smoking, but others do not. For example, researchers have identified variations in the P450 gene (which codes for an enzyme) that determine how the body metabolizes some of the cancer-causing chemicals in tobacco smoke.

Traditionally, cancer was the principal disease evaluated in toxicology because many people were concerned about cancer-inducing chemicals in the environment and because cancer is so feared. Environmental contaminants are linked to several other serious diseases, such as birth defects, damage to the immune response, reproductive problems, and damage to the nervous system or other body systems. Although cancer is not the only disease caused or aggravated by toxicants, we focus here on risk assessment as it relates to cancer. Risk assessment for noncancer hazards, such as diseases of the liver, kidneys, or nervous system, is similar to cancer risk assessment.

cology The study the effects of toxic emicals on human health.

idemiology The idy of the effects of oxic chemicals and diseases on human populations.

Toxicology and **epidemiology** are the two most common methods for determining whether a chemical causes cancer. Toxicologists expose laboratory animals such as rats to varying doses of the chemical and see whether they develop cancer. Epidemiologists look at the historical exposures of humans to the same chemical to see whether exposed groups show increased cancer rates. Each of these methods has advantages and disadvantages but even when used together can provide only rough estimates of a chemical's carcinogenic potential.

Toxicology has the advantage that doses are measured and administered in precise amounts. Usually, two, three, or four groups of animals are exposed to different amounts or doses, including a control group that is not exposed. At the end of the experiment (about two years for mice and rats), the animals are dissected, and the ratio of animals with tumors to animals without in each group is recorded. This is used to determine a dose-response curve for the chemical. Doses are converted from animal dose to "equivalent human dose" by comparing body weight and metabolism rates. **Table 7.3** depicts a hypothetical toxicological data set.

Several uncertainties limit comparisons of animal laboratory studies to humans. First, the dose levels in the experiments are typically much, much larger than those faced by humans in the environment, so extrapolation from high-dose effects to low-dose effects can be inaccurate. **Extrapolation** is estimating the expected effects at some dose of interest from the effects at known doses. Second, humans and laboratory animals may process the chemicals in different ways. Third, laboratory animals live only about 2 years, while human life expectancy is around 70 to 80 years. Finally, human exposures are much more sporadic, and humans are exposed to a variety of chemicals that may amplify or offset each other.

Epidemiological studies have an advantage in that they look at people who were actually exposed to the chemical. Ideally, a **cohort**, or group of individuals who were exposed to the chemical, is compared to an otherwise similar group who were not exposed. For example, cohorts exposed to benzene in a variety of industrial settings have clearly had higher levels of leukemia than did similar groups who were not exposed.

Epidemiology has several limitations. First, it is usually difficult to reconstruct, or estimate, historical doses. Second, confounding factors may exist—for example, industry workers may also have been exposed to some other chemical that was not recorded. Third, the individuals in an industrial setting—in the benzene case, healthy males between 18 and 60 years of age—may respond differently to the chemical than would others, such as children or pregnant women.

Epidemiology may be more representative than toxicology, but toxicology is usually more precise. Ideally, epidemiological data and toxicological data are combined to provide a clearer picture of the causes of cancer. In the case of benzene, animal tests confirm the epidemiological finding that benzene is a carcinogen but do not improve our understanding of benzene's potency. **Table 7.4** compares the advantages and disadvantages of epidemiology and toxicology.

Table 7.4 Comparison of Advantages and Disadvantages of Toxicological and Epidemiological Studies

Epidemiology	*Toxicology*	*Advantage*
Human subjects	Typically animal subjects	Epidemiology
Exposure to multiple chemicals	Exposure to a single chemical	Toxicology
Retrospective (backward-looking)	Prospective (forward-looking)	Toxicology
Arbitrary dose ranges	Specified dose ranges	Toxicology
Estimated doses	Administered doses	Epidemiology
Exposed group genetically diverse	Exposed group genetically homogeneous	
Sample size of 100 to 10,000	Sample size of 10 to 100	Epidemiology
Risk to exposed group near or slightly above background rate	Risk to exposed group substantially above background rate	Toxicology

Source: D. M. Hassenzahl and A. Finkel (2008) "Risk Assessment for Environmental and Occupational Health." In Heggenhougen and Quah, *International Encyclopedia of Public Health.*

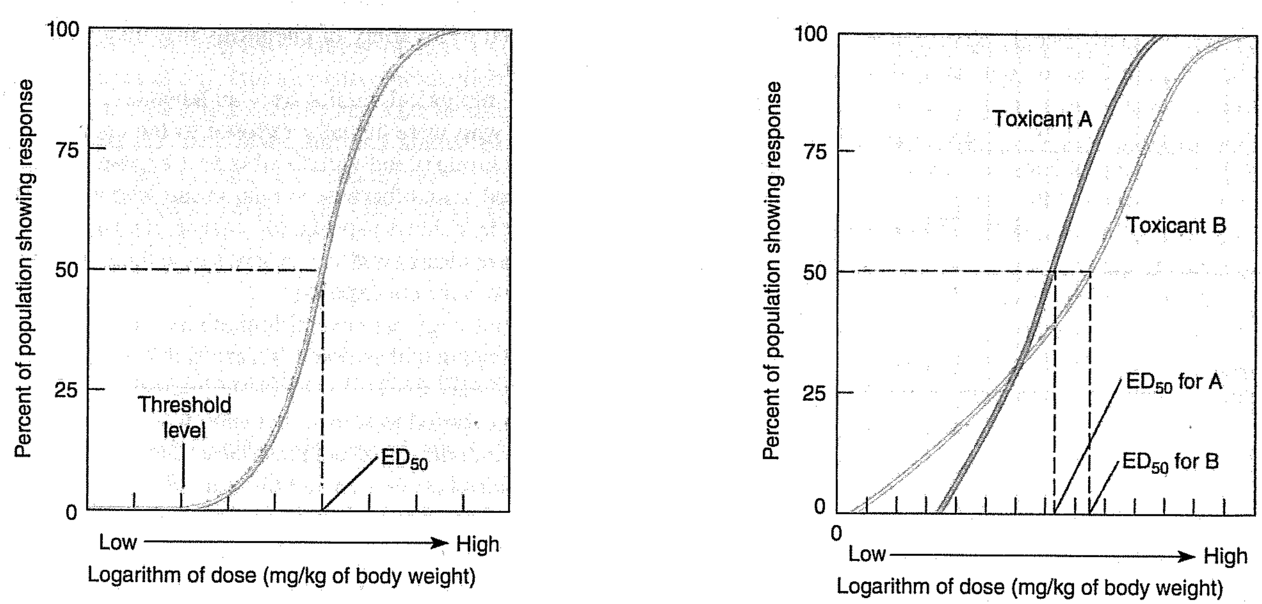
Dose-Response Relationships A **dose-response curve** shows the effect of different doses on a population of test organisms (**Figure 7.8**). Scientists first test the effects of high doses and then work their way down to a **threshold** level, the maximum dose with no measurable effect (or, alternatively, the minimum dose with a measurable effect). Toxicologists often assume that doses lower than the threshold level will not have an effect on the organism and are safe.

Many chemicals are essential to humans and animals in small amounts but toxic at higher levels. Vitamin D is a good example: We know that the human body requires vitamin D to properly absorb calcium and phosphorus. Too much or too little vitamin D can cause a variety of symptoms, including digestive complications. Thus the dose-response relationship between vitamin D and health is U-shaped. While the biological effects of chemicals at low concentrations are difficult to assess, some evidence suggests that a variety of chemicals, including some pesticides and trace metals like cadmium, are healthful in small doses but dangerous at higher levels.

This effect, called **hormesis**, occurs when a small exposure improves health, while a larger exposure causes illness. Hormesis is depicted by the blue line in **Figure 7.9**. In this hypothetical data set, animals exposed to relatively low levels of a chemical were less likely to have tumors than those in the control group, while those with higher chemical exposures had clearly elevated levels of tumors. It is possible that there is a threshold (that is, below some concentration, the chemical does not cause cancer) and that the chemical causes tumors at low levels—but not enough to show up in a test of only a few animals. It is also possible that the chemical has a *hormetic* effect and somehow suppresses tumors.

Some evidence suggests that ionizing radiation—the sort of radiation associated with nuclear waste and radon—may have a hormetic effect. However, most radiation experts conclude that while hormesis is possible, it is more likely that radiation causes cancer even at very low doses.

Chemical Mixtures Humans are frequently exposed to various combinations of chemical compounds. Cigarette smoke contains a mixture of chemicals, as does automobile exhaust. The vast



(a) This hypothetical dose-response curve demonstrates two assumptions of classical toxicology: First, the biological response increases as the dose is increased; second, there is a safe dose—a level of the toxicant at which no response occurs. Harmful responses occur only above a certain threshold level.

(b) Dose-response curves for two hypothetical toxicants, A and B. In this example, toxicant A has a lower effective dose-50% (ED_{50}) than toxicant B. At lower doses, toxicant B is more toxic than toxicant A.

Figure 7.8 Dose-response curves.

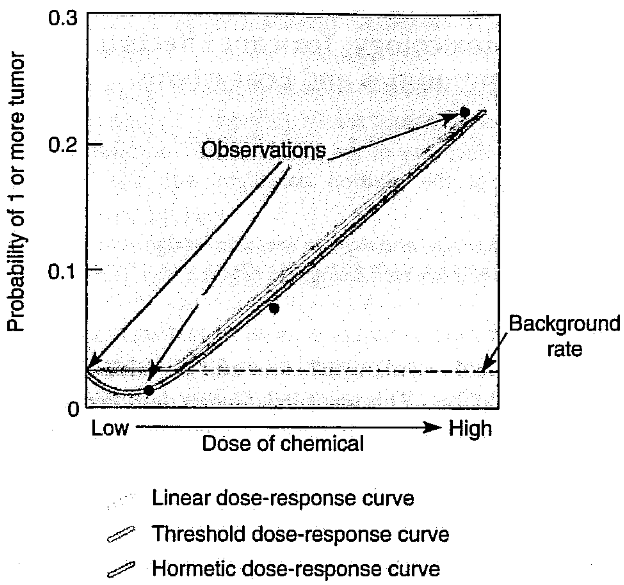


Figure 7.9 Contrasting dose-response relationships. Often, only a few observations are available for the effects of a chemical. In such cases, there may be more than one equally plausible explanation for the relationship between the chemical and the expected health effects at low concentrations. In this case, a small amount of the chemical appears to actually reduce the number of tumors; this could be a real effect, or it could be a random effect. Which dose-response curve do you think best explains these observations: linear (green), threshold (orange), or hormetic (blue)?

majority of toxicological studies are performed on single chemicals rather than chemical mixtures, however, and for good reason. Mixtures of chemicals interact in a variety of ways, increasing the level of complexity in risk assessment. Moreover, too many chemical mixtures exist to evaluate them all.

Chemical mixtures interact by additivity, synergy, or antagonism. When a chemical mixture is **additive**, the effect is exactly what one would expect, given the individual effects of each component of the mixture. If a chemical with a toxicity level of 1 is mixed with a different chemical with a toxicity level of 1, the combined effect of exposure to the mixture is 2. A **synergistic** chemical mixture has a greater combined effect than expected; two chemicals, each with a toxicity level of 1, might have a combined toxicity of 3. An **antagonistic** interaction in a chemical mixture results in a smaller combined effect than expected; for example, the combined effect of two chemicals, each with toxicity levels of 1, might be 1.3.

If toxicological studies of chemical mixtures are lacking, how do scientists assign the effects of chemical mixtures? Risk assessors typically assign risk values to mixtures by additivity—adding the known effects of each compound in the mixture. Such an approach usually underestimates but may sometimes overestimate the risk involved, but it is the best approach currently available. The alternative—waiting for years or decades until numerous studies are designed, funded, and completed—is unreasonable.

CHILDREN AND CHEMICAL EXPOSURE

Children are more susceptible to most chemicals than are adults because their bodies are still developing and are not as effective in dealing with toxicants. In addition, because they weigh less than adults, the same dose of a chemical can be more potent. Consider a toxicant with an LD_{50} of 100 mg/kg. A potentially lethal dose for a child who weighs 11.3 kg (25 lb) is $100 \times 11.3 = 1130$ mg, equal to a scant 1/4 teaspoon if the chemical is a liquid. In comparison, the potentially lethal dose for an adult who weighs 68 kg (150 lb) is 6800 mg, or slightly less than 2 teaspoons. Thus, we must protect children from exposure to environmental chemicals because harmful doses are smaller for children than for adults.

In recent years, people have paid increased attention to the health effects of household pesticides on children because it appears that household pesticides are a greater threat to children than to adults. For one thing, children tend to play on floors and lawns, where they are exposed to greater concentrations of pesticide residues. Also, children, especially when very young, are more likely to put items in their mouths.

The EPA estimates that at least 75% of U.S. homes use pesticide products, such as pest strips, bait boxes, bug bombs, flea collars, pesticide pet shampoos, aerosols, liquids, and powders. Several thousand different household pesticides are manufactured, and these contain over 300 active ingredients and more than 2,500 inert ingredients. Each year, poison control centers in the United States receive more than 130,000 reports of exposure and possible poisoning from household pesticides. More than half of these incidents involve children.

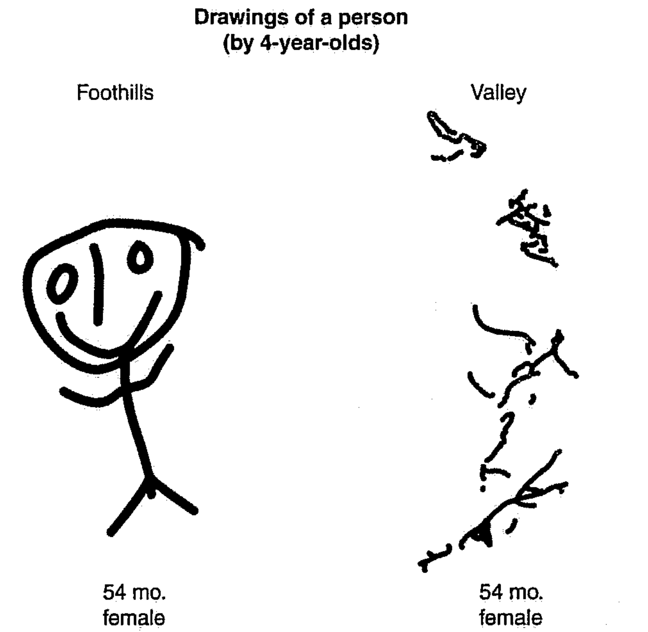
Research supports an emerging hypothesis that exposure to pesticides may affect the development of intelligence and motor skills of infants, toddlers, and preschoolers. One study, published in *Environmental Health Perspectives* in 1998, compared two groups of rural Yaqui Indian preschoolers. These two groups, both of which live in northwestern Mexico, shared similar genetic

ENVIRONEWS

Toxicology Without Animals

There are several reasons why we might want to determine the toxicity of chemicals without using laboratory animals. Regulators are concerned because such studies can take a long time (at least two years for rats and mice) and may still leave questions about the relevance of the findings to human health. Chemical manufacturers are concerned about the cost of such studies as well as the uncertainty in the findings. And many people consider intentionally exposing animals to potentially toxic chemicals unethical.

A recent panel of the National Research Council suggests combining experiments on cells in test tubes with our ever-advancing knowledge of how chemicals interact with each other. This approach allows scientists to determine the *toxicity pathways* by which an individual chemical might (or might not) damage living cells and organs. Several hundred chemicals have already been screened using this technology. Toxicity pathway research is a priority outside the United States as well: By 2013, European cosmetics companies must demonstrate that their products are safe without relying on animal testing.



(a) Most preschoolers who received little pesticide exposure were able to draw a recognizable stick figure.

(b) Most preschoolers who lived in an area where agricultural pesticides were widely used could draw only meaningless lines and circles.

Figure 7.10 Effect of pesticide exposure on preschoolers. A study in Sonora, Mexico, found that Yaqui Indian preschoolers varied in their motor skills on the basis of the degree of pesticide exposure. The children were asked to draw a person. Two representative pieces of art are shown; both are drawn by 4 1/2-year-old girls.

backgrounds, diets, water mineral contents, cultural patterns, and social behaviors. The main difference between the two groups was their exposure to pesticides: One group lived in a farming community (valley) where pesticides were used frequently (45 times per crop cycle) and the other in an adjacent nonagricultural area (foothills) where pesticides were rarely used. When asked to draw a person, most of the 17 children from the low-pesticide area drew recognizable stick figures, whereas most of the 34 children from the high-pesticide area drew meaningless lines and circles (**Figure 7.10**).

A 2010 study in California by the Center for Health Assessment of Mothers and Children of Salinas found that exposure of pregnant women to pesticides has long-term effects on their children. A 10-year study of 600 women showed a correlation between the mother's pesticide exposure and both delayed mental development and pervasive development disorder in their offspring. The research continues to investigate other potential impacts, and a much larger 10,000-person study has recently begun.

REVIEW

1. What is acute toxicity? chronic toxicity?
2. How are potentially toxic chemicals identified?
3. Why are children particularly susceptible to environmental contaminants such as pesticides?

Ecotoxicology: Toxicant Effects on Communities and Ecosystems

LEARNING OBJECTIVES

- Discuss how discovery of the effects of DDT on birds led to the replacement of the dilution paradigm with the boomerang paradigm.
- Define *ecotoxicology*, and explain why knowledge of ecotoxicology is essential to human well-being.

People used to think—and indeed some still do—that "the solution to pollution is dilution." This so-called *dilution paradigm* meant that you could discard pollution into the environment and it would be diluted sufficiently to cause no harm. We know today that the dilution paradigm is not generally valid. This text is full of examples of the failure of the dilution paradigm. For example, recall from Chapter 1 how dumping treated sewage into Lake Washington caused a major water pollution problem. A more serious example, from the perspective of human well-being, is *Love Canal*, a small community in New York State contaminated by toxic waste dumped into a nearby pit by a chemical company (see Chapter 23). To be fair, the chemical company dumped wastes at a time (1942–1953) when the dilution paradigm was still widely accepted. However, failure of the dilution paradigm brought scant consolation to the people living in Love Canal. They had to abandon their homes, and many have had health problems since leaving the contaminated site.

Today, virtually all environmental scientists have rejected the dilution paradigm in favor of the *boomerang paradigm*: What you throw away can come back and hurt you. The boomerang paradigm was adopted during the latter half of the 20th century after several well-publicized events captured the public's attention. Notable among these events was the discovery that the pesticide DDT was accumulating in birds at the top of the food web. The implications were clear that DDT was an unacceptable threat not only to ecosystem health but also potentially to human health.

As a result of the environmental impacts of DDT and the many other environmental problems that have arisen since DDT, a new scientific field—**ecotoxicology**—was born. Ecotoxicology, also called *environmental toxicology*, is an extension of the field of toxicology, which is human-oriented. However, ecotoxicology is also human-oriented in the sense that humans produce the contaminants that adversely affect the environment.

ecotoxicology The study of contaminants in the biosphere, including their harmful effects on ecosystems.

The scope of ecotoxicology is broad—from molecular interactions in the cells of individual organisms to effects on populations (e.g., local extinctions), communities and ecosystems (e.g., loss of species richness), and the biosphere (e.g., global climate change). Expanding knowledge in ecotoxicology provides many examples of linkages between human health and the health of natural systems.

Ecotoxicology helps policy makers determine the costs and benefits of the many industrial and technological "advances" that affect us and the ecosystems on which we depend. However, most environmental regulations are currently based on data for single species. Scientists have only begun to collect data to determine the environmental status of populations, communities, ecosystems, and higher levels of natural systems. Obtaining this higher-level information is complicated because (1) natural systems are exposed to many **environmental stressors** (changes that tax the environment); (2) natural systems must be evaluated for an extended period to establish important trends; and (3) the results must be clear enough for policy makers and the public to evaluate.

CASE IN POINT

THE OCEAN AND HUMAN HEALTH

The ocean is important to us as a source of both food and natural chemical compounds that could benefit human health. These chemicals have potential uses in many areas, including, among others, novel pharmaceuticals, nutritional supplements, agricultural pesticides, and cosmetics. The discovery and development of beneficial marine compounds is in its infancy. Sponges, corals, mollusks, marine algae, and marine bacteria are some of the ocean's organisms that have the potential to provide these natural chemicals. In addition to serving as a source of food and other products, the ocean absorbs many wastes from human-dominated land areas.

Negative Health Impacts of Marine Microorganisms Marine microorganisms occur naturally in every part of the ocean environment. On average, 1 million bacteria and 10 million viruses occur in each milliliter of seawater! These organisms usually perform their ecological roles (such as decomposition) without causing major problems to humans. However, human activities now have a measurable effect on the ocean, including increases in land-based nutrient runoff and pollution and a small rise in ocean temperatures. These changes are causing an increase in the number and distribution of disease-causing microorganisms, particularly bacteria and viruses that pose a significant health threat to humans. (Recall the discussion of the boomerang paradigm.) For example, humans can become ill—or even die if their immune systems are compromised—from drinking water or eating fish or shellfish (such as mussels or clams) contaminated with disease-causing microorganisms associated with human sewage or livestock wastes. Additional research is needed to study links between human-produced pollution and the increase of disease-causing microorganisms in the ocean system.

Scientists have observed an association in Bangladesh between outbreaks of cholera, caused by a waterborne bacterium, and increases in the surface temperature of coastal waters in the Bay of Bengal. The association is an indirect one. Apparently, the increased temperatures encourage the growth of microscopic plankton, which, in turn, produce ideal growing conditions for the cholera bacterium. Tides carry these contaminated waters into rivers that provide drinking water, increasing the risk of cholera in the local population.

Certain species of harmful algae sometimes grow in large concentrations called *algal blooms*. When some pigmented marine algae experience blooms, their great abundance frequently colors the water orange, red, or brown (**Figure 7.11**). Known as **red tides**, these blooms may cause serious environmental harm and threaten the health of humans and animals. Some of the algal species that form red tides produce toxins that attack the nervous systems of fishes, leading to massive fish kills. Waterbirds such as cormorants suffer and sometimes die when they eat the contaminated fishes. The toxins also work their way up the food web to marine mammals and people. In 1997, more than 100 monk seals, one-third of that endangered species' total population, died from algal toxin poisoning off the West African coast. Humans may also suffer if they consume algal toxins, which often bioaccumulate in shellfish or fishes. Even nontoxic algal species may wreak havoc when they bloom, as they shade aquatic vegetation and upset food web dynamics.

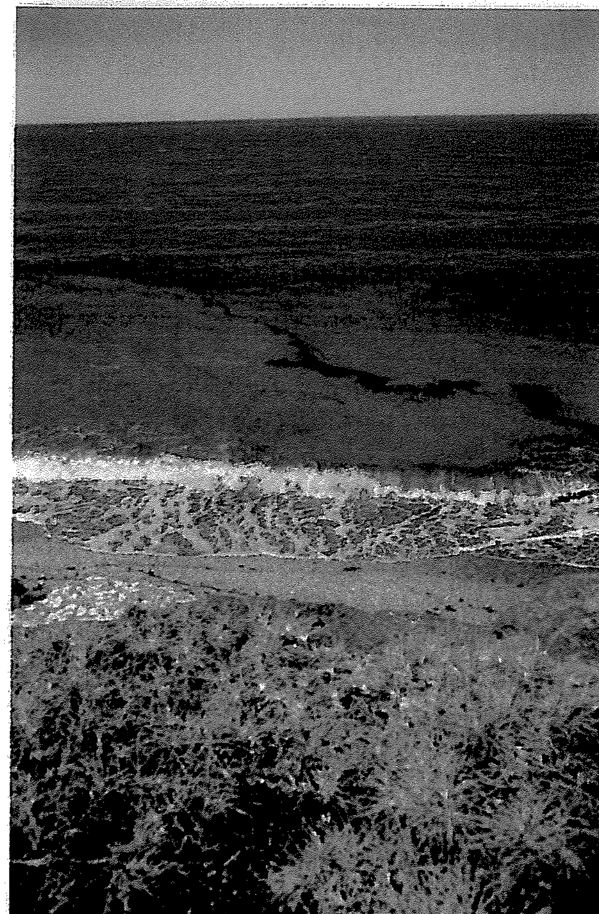

Bill Bachman/Science Source

Figure 7.11 Red tide. The presence of billions of toxic algae color the water. Photographed in the Gulf of Carpentaria, Australia.

No one knows what triggers red tides, which are becoming more common and more severe, but many scientists think the blame lies with coastal pollution. Wastewater and agricultural runoff to coastal areas contain increasingly larger quantities of nitrogen and phosphorus, two nutrients that stimulate algal growth. Changes in ocean temperatures, such as those attributed to global warming, may also trigger algal blooms. In addition, a possible connection exists between red tide outbreaks in Florida's coastal waters and the arrival of dust clouds from Africa. These dust clouds, which sometimes blow across the Atlantic Ocean, enrich the water with iron and appear to trigger algal blooms.

Because we do not know what causes red tides, no control measures are in place to prevent the blooms or to end them when they occur. However, technologies like satellite monitoring and weather-tracking systems allow better prediction of conditions likely to stimulate blooms. ■

REVIEW

1. What environmental catastrophe was largely responsible for replacement of the dilution paradigm with the boomerang paradigm?
2. What is ecotoxicology?

Decision Making and Uncertainty: Assessment of Risks

LEARNING OBJECTIVES

- Define *risk,* and explain how risk assessment helps determine adverse health effects.
- Explain how risk information can improve environmental decisions.
- Define *ecological risk assessment.*

risk The probability that particular adverse effect will result from some exposure or condition.

Throughout this chapter, we have discussed various **risks** to human health and the environment. Each of us makes many risk management decisions every day, most of which are based on intuition, habit, and experience. We make these decisions effectively—after all, most of us make it through each day without getting injured or killed.

However, environmental and health decisions often impact many individuals, and the best choices are not always made on an intuitive level. *Risk analysis* is a tool used to organize how we think about complex environmental systems. When we think about risks from a systems perspective, we can decide which of the following it is most effective to do:

- Change our activities to avoid particular risks altogether.
- Limit the extent to which a particular **hazard** can come into contact with us.
- Limit the extent to which the hazard can harm us.
- Provide some sort of offset or compensation if the hazard causes harm.

hazard A condition that has the potential to cause harm.

For example, consider the risk of injury from car accidents. We can redesign cities to allow people to work near where they live. We can establish rules about how fast people can drive or on which side of the street they drive. We can require seatbelts and airbags so that people who are in accidents don't get hurt as badly. Finally, we can purchase insurance to cover expenses, lost time, and suffering. Risk analysis also allows us to think about the tradeoffs between different activities. For example, we could bicycle instead of driving. This would take more time, and we might have a higher risk of an accident, but we would also get some health benefits from the exercise.

RISK INFORMATION AS A DECISION TOOL

Risk management is the process of identifying, assessing, and reducing risks. **Risk assessment** involves using statistical methods to quantify the risks of a particular action so that these risks can be compared and contrasted with other risks. The four steps involved in risk assessment for adverse health effects are summarized in **Figure 7.12.**

Risk is calculated as the probability that some negative effect or event will occur times the consequences (deaths, injuries,

1 Hazard identification
Does exposure to substance cause increased likelihood of adverse health effect such as cancer or birth defects?

2 Dose-response assessment
What is the relationship between amount of exposure (dose) and seriousness of adverse health effect? A person exposed to a low dose may have no symptoms, whereas exposure to a high dose may result in illness.

3 Exposure assessment
How much, how often, and how long are humans exposed to a substance in question? Where humans live relative to emissions is also considered.

4 Risk characterization
What is probability of individual or population having adverse health effect? Risk characterization evaluates data from dose-reponse assessment and exposure assessment. Risk characterization indicates that Mexican-Americans, many of whom are agricultural workers, are more vulnerable to pesticide exposure than other groups (see photo and graph).


Sisse Brimberg/National Geographic Creative

Agricultural workers have a greater than average exposure to chemicals such as pesticides. (Sisse Brimberg/National Geographic Image Collection)

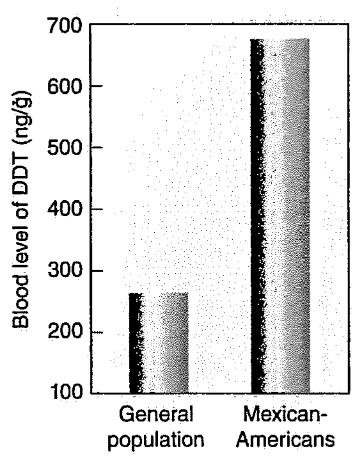


Figure 7.12 The four steps of a risk assessment for adverse health effects. (Adapted from *Science and Judgment in Risk Assessment.* Washington, DC, National Academy Press [1994].)

Table 7.5 Probability of Death by Selected Causes for a U.S. Citizen

Cause of Death	*One-Year Odds**	*Lifetime Odds**
Cardiovascular disease	1 in 300 (3.3×10^{-3})	1 in 4 (2.5×10^{-1})
Cancer, all types	1 in 510 (2.0×10^{-3})	1 in 7 (1.4×10^{-1})
Motor vehicle accidents	1 in 6700 (1.5×10^{-4})	1 in 88 (1.1×10^{-2})
Suicide	1 in 9200 (1.1×10^{-4})	1 in 120 (8.3×10^{-3})
Homicide	1 in 18,000 (5.6×10^{-5})	1 in 240 (4.2×10^{-3})
Killed on the job	1 in 48,000 (2.1×10^{-5})	1 in 620 (1.6×10^{-3})
Drowning in bathtub	1 in 840,000 (1.1×10^{-6})	1 in 11,000 (9.1×10^{-5})
Tornado	1 in 3,000,000 (3.3×10^{-7})	1 in 39,000 (2.6×10^{-5})
Commercial aircraft	1 in 3,100,000 (3.2×10^{-7})	1 in 40,000 (2.5×10^{-5})
Hornet, wasp, or bee sting	1 in 6,100,000 (1.6×10^{-7})	1 in 80,000 (1.3×10^{-5})

*Probability of risk is in parentheses.
Probabilities calculated by L. Berg from multiple sources.

economic losses) if it does occur. Risk is typically reported as a fraction, ranging from 0 (certain not to occur) to 1 (certain to occur). For example, according to the American Cancer Society, in 2002 about 170,000 Americans who smoked died of cancer. This translates into a probability of death of 0.00059 (that is, 5.9×10^{-4}). **Table 7.5** contains probability estimates of death by selected causes in the United States. Note that these are population estimates, are highly uncertain, and most are unequally distributed across the population (e.g., deaths on the job can only occur among the employed, and some jobs are far riskier than others).

Risk assessment is used in several ways for environmental regulation. A regulatory agency may establish a "maximum-risk" standard. For example, the EPA may decide that people should face an additional risk of cancer of no more than 1 in 1 million from trichloroethylene (TCE, a common contaminant) in municipal drinking water. If we know the **cancer potency** of TCE and we know how much water the average person drinks, we can calculate the maximum allowable concentration of TCE.

cer potency An te of the expected increase in cancer ciated with a unit se in exposure to a chemical.

Alternatively, risk managers may be concerned about the expected risk associated with an existing or historical exposure. For example, a company might need to know how much money to set aside to pay medical costs associated with construction workers who were exposed to asbestos. It may be impossible to tell which individuals will contract asbestosis (a lung disease associated with chronic asbestos exposure), but we can estimate the number of disease instances among a large group of individuals.

Many of our decisions about risks have far more to do with our trust in individuals and institutions who manage the risks than with the calculated values of those risks. For example, many people distrust the nuclear industry, which means it doesn't matter how accurately the industry can calculate the risks of a nuclear accident. We worry less about risks that we feel we can control (such as driving or eating) than those outside our control (such as pesticide contamination). We also worry more about things we dread (dying from cancer) than those we don't (bicycling). Effective risk management, then, is not based on calculated risks alone but must also account for intuition, trust, and social conditions.

Cost-Benefit Analysis and Risks Risk assessment can be an important input to **cost-benefit analysis** (see Chapter 2). In a cost-benefit analysis, the estimated cost of some regulation to reduce risk is compared with potential benefits associated with that risk reduction. Cost-benefit analysis is an important mechanism to help decision makers formulate environmental legislation, but it is only as good as the data and assumptions on which it is based. Corporate estimates of the cost to control pollution are often many times higher than the actual cost turns out to be. During the debate over phasing out leaded gasoline in 1971, the oil industry predicted a cost of $7 billion per year during the transition, but the actual cost was less than $500 million per year.

Despite the wide range that often occurs between projected and actual costs, the cost portion of cost-benefit analysis is often easier to determine than are the health and environmental benefits. The cost of installing air pollution–control devices at factories is relatively easy to estimate, but how does one put a price tag on the benefits of a reduction in air pollution? What is the value of reducing respiratory problems in children and the elderly, two groups susceptible to air pollution? How much is clean air worth?

Another problem with cost-benefit analysis is that the risk assessments on which such analyses are based are far from perfect. Even the best risk assessments are based on assumptions that, if changed, could substantially alter the estimated risk. Risk assessment is an uncertain science. Cost-benefit analyses and risk assessments are useful in evaluating and addressing environmental problems, but decision makers must recognize the limitations of these methods when developing new government regulations.

The Precautionary Principle You have probably heard the expression "an ounce of prevention is worth a pound of cure." This statement is the heart of a policy—the **precautionary principle**—advocated by many politicians and environmental activists. According to the precautionary principle, when a new technology or chemical product is suspected of threatening health or the environment, we should undertake precautionary measures even if there is uncertainty about the scope of danger.

precautionary principle The idea that no action should be taken or product introduced when the science is inconclusive but unknown risks may exist.

The precautionary principle may also be applied to existing technologies when new evidence suggests they are more dangerous than originally thought. When observations and experiments suggested that chlorofluorocarbons (CFCs) harm the ozone layer in the stratosphere, the precautionary principle led most countries to phase out these compounds. Studies made after the phase-out supported this step.

To many people, the precautionary principle is common sense, given that science and risk assessment often cannot provide definitive answers to policy makers. The precautionary principle puts the burden of proof on the developers of the new technology or substance, who must demonstrate safety beyond a reasonable doubt.

Although the precautionary principle has been incorporated into decisions in the European Union, the United States, and elsewhere, it has many detractors. Some scientists think that it challenges the role of science and endorses making decisions without the input of science. Advocates of cost-benefit analysis note that the precautionary principle may be extremely expensive or may cause us to hold off on new technologies that are much safer than those already in place.

Some critics contend that the precautionary principle's imprecise definition can reduce trade and limit technological innovations. For example, several European countries made precautionary decisions to ban beef from the United States and Canada because these countries use growth hormones to make cattle grow faster. Europeans contend that the growth hormone might harm humans eating the beef, but the ban, in effect since 1989, is widely viewed as intended to protect their own beef industry.

The rapid expansion of nanotechnology is another area where the precautionary principle might be useful. **Nanotechnology** is the creation of materials and devices on the ultra-small scale of atoms or molecules (**Figure 7.13**). It is increasingly common in a variety of settings, from cosmetics to wastewater treatment to electronics. Because of their very small scale, **nanomaterials** can be environmentally advantageous if they require fewer raw materials than does traditional manufacturing.

However, particles on the nanometer scale (a nanometer is one-billionth of a meter) pose potentially significant but highly uncertain health, safety, and environmental risks. Concerned about this high uncertainty, some policy makers argue that we should take a precautionary approach and avoid using nanotechnologies until they can be shown to be safe. The EPA has decided to regulate nanomaterials that might adversely affect the environment: The burden of proof about product safety will fall on companies that sell nanotechnology.

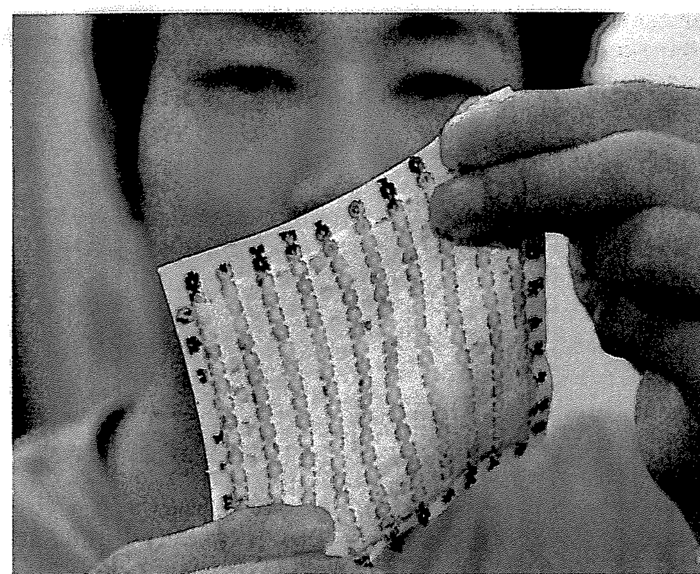

YOSHIKAZU TSUNO/AFP/GettyImages Inc

Figure 7.13 Nanotechnology. Japan's Tokyo University researcher Tsuyoshi Sekitani displays an elastic sheet containing carbon nano tubes which conduct electricity (black part) in the silicon rubber (white base) at his laboratory at the University of Tokyo on August 11, 2008.

Fractional Risk Attribution By one estimate, as many as 150,000 people die each year from health effects associated with climate change, and this rate could reach 300,000 per year by 2030. However, in climate change as well as other environmental cases, it is often difficult to attribute illness, injury, or death to a particular environmental cause. This is the case for first responders (police, firefighters, medical personnel) to the Twin Towers in New York City on September 11, 2001. They were exposed to large amounts of airborne pollutants, and now many of them suffer from cancers and other illnesses. Although we can confidently attribute the increased rate of disease to the exposure, it is very difficult to say which specific cases were caused by the exposure and which would have happened without the exposure. This has created a problem for those first responders, since it is unclear who would be responsible for treating them.

One approach to dealing with this sort of uncertainty is to consider **fractional risk attribution**. This approach allocates the likelihood of each of two or more different possible causes. For example, if there is a doubling of cancers among a group of individuals following some exposure, under fractional risk attribution, we would assign 50% of the "blame" for the cancers to that exposure. We still can't say which cancers were caused by the exposure, but we can say that half of them would not have occurred without it.

This concept could be particularly useful for climate change, where it is difficult to say that any particular weather event was caused by climate change. There is strong evidence that recent record rains, heat, droughts, hurricanes, and other events were caused by the changing climate, but it is impossible to say that any particular death would not have occurred without climate change. We can often estimate the number of various extreme events that would have occurred without climate change, compare this to the number of events that did occur, and use this to estimate the fraction of deaths (as well as property damage, injuries, and illnesses) attributable to climate change.

Risks and Tradeoffs Some threats to our health, particularly from toxic chemicals in the environment, make big news. Other threats, while larger from a risk assessment perspective, go unnoticed. Media reports of risk events and situations are constrained by the need to entertain as well as inform, and most reporters are not trained in science or risk assessment. Consequently, the risks that get the most attention in the media may not be as detrimental as others that get less coverage.

This does not mean that we should ignore chemicals that humans introduce into the environment. Nor does it mean we should discount stories the news media sometimes sensationalize. These stories serve an important role in getting the regulatory wheels of the government moving to protect us as much as possible from the dangers of our technological and industrialized world. They reflect a distrust in the ability of industry and government to manage risks and thereby suggest opportunities to improve those institutions. Quantifying risks is an important step toward reducing them, but it is as important to understand why and how people respond to risks, independent of their magnitudes.

ECOLOGICAL RISK ASSESSMENT

The EPA and other federal and state environmental monitoring groups are increasingly trying to evaluate ecosystem health using methods developed for assessing risks to human health. Detailed guidelines exist for performing **ecological risk assessment (ERA)**. Although it began as an extension of ecotoxicology, ecological risk assessment covers a much broader set of impacts to ecosystems. It includes an assessment of the exposures of a range of plants and animals to **stressors** (potentially adverse conditions) and the range of impacts associated with those stressors.

Such analyses are difficult because effects may occur on a wide scale, from individual animals or plants in a local area to ecological communities across a large region. Given the hazards and exposure levels of human-induced environmental stressors, ecological effects range from good to bad or from acceptable to unacceptable. Using scientific knowledge in environmental decision making is filled with uncertainty because many ecological effects are incompletely understood or difficult to measure. A real need exists to quantify risk to the environmental system and to develop strategies to cope with the uncertainty.

ERA is increasingly used to manage the diverse threats to **watersheds**. For example, the Yellow River delta area in China includes eight distinct ecosystems (saline seepweed beach, reed marsh, freshwater bodies, forest and meadow, prawn pool and salt pan, paddy fields, dry farmland, and human settlement) (**Figure 7.14**). These face a number of stressors, including agricultural water withdrawal, drought, storm surges, flooding, and oil spills. An ERA for the area concluded that a few areas face the greatest probability of negative effects; managers are now using this information to prioritize risk-reduction activities in the delta.

Figure 7.14 Yellow River delta. The Yellow River delta region in China is a highly productive and diverse set of ecosystems that faces multiple human-induced stressors. Ecological risk assessment has guided managers in identifying and dealing with the most vulnerable areas.

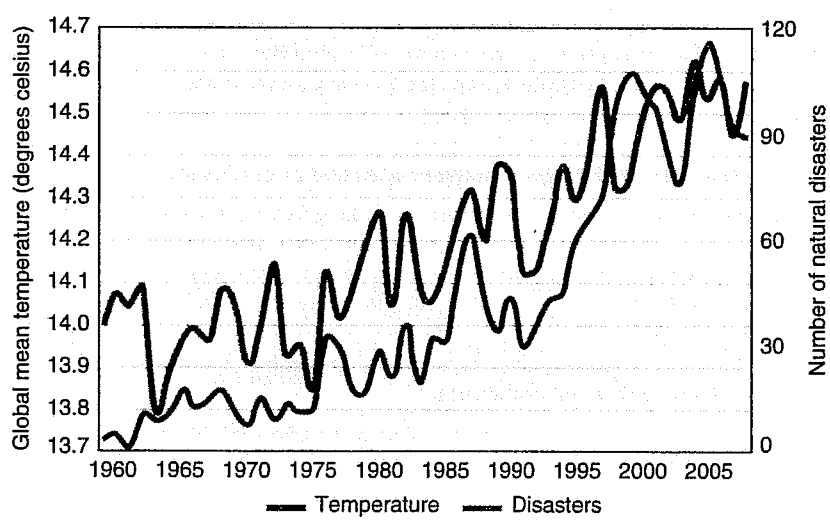
REVIEW

1. What is risk assessment?
2. How does cost-benefit analysis differ from the precautionary principle?
3. When is an ecological risk assessment undertaken?

ENERGY AND CLIMATE CHANGE

Chronic Disease and Acute Illness

Although climate change has already begun to cause human deaths and disease, the number of cases is highly uncertain. As with other hazards, climate change–related deaths and illness include both acute and chronic effects. Acute effects include deaths associated with heat waves in Europe in 2006 and the United States in 2010, extreme weather events like Hurricanes Katrina and Ike, wildfires like those in California in 2008, and other natural disasters (see the figure). Chronic effects include an expanded range for tropical diseases and increased airborne allergens. Not all health effects will be negative; for example, milder winters are likely to lead to fewer cases of influenza.



Global mean temperature and heat-related natural catastrophes, 1960–2010. This figure suggests that the number of heat-related natural catastrophes (such as heat waves and droughts) has increased over the past five decades. What is the ratio of heat-related disasters in 2010 to those in 1960? In 1975?

REVIEW OF LEARNING OBJECTIVES WITH SELECTED KEY TERMS

- **Contrast health issues in highly developed countries with those in less developed countries.**

Cardiovascular diseases, cancer, and chronic obstructive pulmonary disease are health problems in the United States and other highly developed nations; many of these diseases are chronic health problems associated with aging and are caused in part by lifestyle choices involving diet, exercise, and smoking. Child mortality is particularly serious in developing countries, where leading causes of death in children include malnutrition, diarrheal diseases, and malaria.

- **Explain the difference between endemic and emerging diseases.**

Endemic diseases are constantly present in a population or region. Some endemic diseases, such as smallpox and polio, have been controlled worldwide, while others remain common. **Emerging diseases** are those that are relatively new to human populations. Because different strains prevail each year, influenza is often thought of as an emerging disease. AIDS was an emerging disease a few decades ago, but is now endemic in many places.

- **Summarize the problems associated with chemicals that exhibit persistence, bioaccumulation, and biological magnification in the environment.**

Chemicals that exhibit **persistence** are extremely stable and may take many years to break down into simpler forms by natural processes. **Bioaccumulation** is the buildup of a persistent toxic substance, such as certain pesticides, in an organism's body, often in fatty tissues. **Biological magnification** is the increased concentration of toxic chemicals, such as PCBs, heavy metals, and certain pesticides, in the tissues of organisms at higher levels in food webs.

- **Briefly describe some of the data suggesting that certain chemicals used by humans may also function as endocrine disrupters in animals, including humans.**

A chemical spill in 1980 contaminated Lake Apopka, in Florida, with DDT and other agricultural chemicals with estrogenic properties. Male alligators living in Lake Apopka in the years following the spill had low levels of testosterone (an androgen) and elevated levels of estrogen. Their reproductive organs were often feminized or abnormally small, and the mortality rate for eggs was extremely high. Humans may also be at risk from **endocrine disrupters**, as the number of reproductive disorders, infertility cases, and hormonally related cancers (such as testicular cancer and breast cancer) appears to be increasing.

- **Define *toxicant*, and distinguish between acute and chronic toxicities.**

A **toxicant** is a chemical with adverse human health effects. **Acute toxicity** refers to adverse effects that occur within a short period after exposure to a toxicant. **Chronic toxicity** refers to adverse effects that occur some time after exposure to a toxicant or after extended exposure to a toxicant.

- **Describe how a dose-response curve helps determine the health effects of environmental pollutants.**

A **dose-response curve** is a graph that shows the effect of different doses on a population of test organisms. Scientists first test the effects of high doses and then work their way down to a **threshold** level.

- **Discuss pesticide risks to children.**

More than half of all reports of exposure and possible poisoning from household pesticides involve children. Some research suggests that exposure to pesticides may affect the development of intelligence and motor skills of infants, toddlers, and preschoolers.

- **Discuss how discovery of the effects of DDT on birds led to the replacement of the dilution paradigm with the boomerang paradigm.**

A paradigm is a generally accepted understanding of how some aspect of the world works. According to the dilution paradigm, "the solution to pollution is dilution." Environmental scientists reject the dilution paradigm in favor of the boomerang paradigm: What you throw away can come back and hurt you. The boomerang paradigm was adopted after the discovery that the pesticide DDT was accumulating in birds at the top of the food web. The implications were that DDT represented an unacceptable threat to ecosystem health and human health.

- **Define *ecotoxicology,* and explain why knowledge of ecotoxicology is essential to human well-being.**

Ecotoxicology is the study of contaminants in the biosphere, including their harmful effects on ecosystems. Ecotoxicology helps policy makers determine the costs and benefits of the many industrial and technological "advances" that affect us and the ecosystems on which we depend.

- **Define *risk,* and explain how risk assessment helps determine adverse health effects.**

Risk is the probability that a particular adverse effect will result from some exposure or condition. **Risk assessment** is the process of estimating those probabilities and consequences. Risk assessments, when properly performed, provide information about the probability and severity of a risk or set of risks.

- **Explain how risk information can improve environmental decisions.**

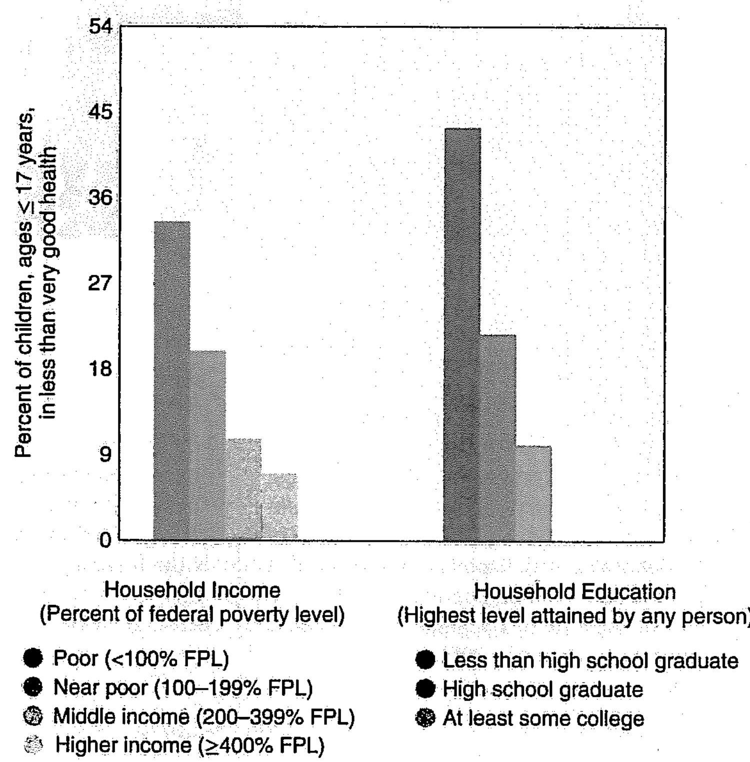
Risk information can be used to inform several different decision approaches. In **risk management**, risks are assessed and described, and policy choices are chosen to reduce known risks. Risk can serve as an input to **cost-benefit analysis**. Uncertainty associated with a risk assessment for a particular product or material might lead us to apply the **precautionary principle** and thus avoid an uncertain but possibly adverse outcome. **Fractional risk attribution** allows us to allocate responsibility for adverse outcomes based on the likely contributors to those outcomes, even when the cause of individual cases cannot be determined.

- **Define *ecological risk assessment*.**

Ecological risk assessment is the process by which the ecological consequences of a range of human-induced **stressors** are estimated.

Critical Thinking and Review Questions

1. What are the three leading causes of death in the United States? How are they related to lifestyle choices?
2. Why are public health researchers concerned about "exporting" health problems associated with developed countries to less developed countries?
3. What accounts for the much lower infant mortality rates in highly developed countries as compared to less developed countries?
4. What was the first viral disease to be globally eradicated? What disease do health officials hope will be eradicated soon?
5. What is a pandemic, and why does the potential for pandemics trouble many public health officials?
6. Distinguish among persistence, bioaccumulation, and biological magnification.
7. How do acute and chronic toxicity differ?
8. What is a dose-response curve? What can it tell us about effects at low doses if experimental information is about high doses?
9. What are the major differences between toxicology and epidemiology? In what ways are they the same? How might decision makers respond when the two approaches lead to different conclusions?
10. Describe the common methods for determining whether a chemical causes cancer.
11. Select one of the two choices to complete the following sentence, and then explain your choice: The absence of certainty about the health effects of an environmental pollutant (is/is not) synonymous with the absence of risk.
12. For each of the following scenarios, suggest whether it would be more appropriate to use cost-benefit analysis, the precautionary principle, or fractional risk attribution. Explain your answers.
    a. Regulating risk associated with mercury from coal-fired power plants
    b. Compensating cancer patients who were exposed to chemicals on the job 20 years earlier
    c. Preparing for climate change–related illnesses in the year 2050
    d. Creating a new policy for nanomaterials in cosmetics and medicines
    e. Preparing for diseases that might transfer from animals to humans in the future
13. How are risk assessments for human health and ecological risk assessments for environmental health alike? How do they differ?
14. Do you expect that a warmer world will improve or worsen human health? Explain your answer.
15. The figure below shows that children's health in the United States is closely linked to both household income and education. Could the environment be one of the factors associated with household income? Household education? Explain.



Household income, education, and children's health in the United States.

Food for Thought

In the first half of the 20th century, the U.S. military had to turn away an unexpectedly large number of potential recruits because they were underweight. In response, the U.S. government developed a policy for providing food to millions of Americans. By the end of the 20th century, the military was turning away potential recruits for being overweight. Discuss what this says about the relationship between caloric intake and a healthy diet. Do government-sponsored food programs in your area promote healthful eating? Explain.

8

The Human Population

KIM LUDBROOK/EPA/Newscom

HIV/AIDS orphans. The orphans of the Chubby Chumbs Fountain of Love orphanage receive their lunch, in Johannesburg, South Africa. Most of these children are AIDS orphans or are HIV positive, or both.

Africa has the most rapidly growing human population of all the continents. Most of Africa's population is concentrated in sub-Saharan Africa (that part of Africa south of the Sahara Desert). Experts currently predict that the sub-Saharan population of 926 million will increase to 1.3 billion by 2025 and is expected to double by 2050.

In spite of these astounding increases, many population experts lowered their estimates of population growth rates in sub-Saharan Africa during the 1990s and early 2000s. Tragically, the estimates were lowered because acquired immune deficiency syndrome (AIDS), caused by the human immune deficiency virus (HIV), is ravaging many countries in the sub-Saharan region. The UN Program on HIV/AIDS estimates that 25 million of the world's 35 million adults and children who are now infected with HIV/AIDS live in sub-Saharan Africa (latest available data). Worldwide, more than 2.3 million people become newly infected with HIV each year, and about 70% of these new infections occur in sub-Saharan Africa. About 15 million children in this region have lost one or both parents to AIDS (see photograph). Many AIDS orphans do not receive adequate education, healthcare, or nutrition.

Despite global progress in expanding the treatment of HIV/AIDS around the world, countries in sub-Saharan Africa are experiencing high death rates from HIV/AIDS, which is the leading cause of death in Africa. The high mortality from HIV/AIDS has caused life expectancies to decline in many African countries. In Swaziland, for example, the average life expectancy declined from a high of about 60 years in the late 1980s to 49 years in 2013. Africa's AIDS crisis has many repercussions beyond a reduced life expectancy. The HIV/AIDS epidemic threatens the economic stability and social support networks of the region and has overwhelmed healthcare systems. Hunger has significantly increased in some countries, owing to the loss of HIV/AIDS-infected agricultural workers; by 2020, the United Nations estimates that AIDS will have killed at least 20% of agricultural workers in southern Africa. Labor shortages are common, and foreign investments have slowed because many investors are wary of the high rate of infection among workers.

The good news is that efforts to improve access to the antiretroviral therapy necessary to treat HIV/AIDS are gaining ground: Globally, the number of people receiving the therapy tripled between 2005 and 2012. In 2012, approximately 61% of the world's individuals living with HIV/AIDS in low- and middle-income countries—including approximately 68% in sub-Saharan Africa—received treatment. HIV/AIDS deaths and new cases recorded annually have both declined, and the average life expectancy has increased slightly. With these welcome improvements in HIV/AIDS treatment, population experts hope that these sub-Saharan countries can focus on improving family planning programs and controlling birth rates.

The HIV/AIDS epidemic is but one factor affecting the human population. In this chapter, we focus on the current state of the human population.

In Your Own Backyard...

What is the "safe-sex" message regarding HIV transmission? Do you think most students at your school are concerned about HIV transmission? Why or why not?

The Science of Demography

LEARNING OBJECTIVES

- Define *demography* and summarize the history of human population growth.
- Identify Thomas Malthus, relate his ideas on human population growth, and explain why he might or might not be correct.
- Explain why it is impossible to answer precisely how many people Earth can support—that is, Earth's carrying capacity for humans.

Demography is the science of human population structure and growth. The application of population statistics is called **demographics**.

demography The applied branch of ›logy that deals with ılation statistics and ıides information on populations of vari- ,countries or groups of people.

Examine **Figure 8.1**, which shows human population growth. Refer back to Figure 5.5 and compare the two curves. The characteristic J curve of exponential population growth shown in Figure 8.1 reflects the decreasing amount of time it has taken to add each additional billion people to our numbers. It took thousands of years for the human population to reach 1 billion, a milestone that occurred around 1800. It took 130 years to reach 2 billion (in 1930), 30 years to reach 3 billion (in 1960), 15 years to reach 4 billion (in 1975), 12 years to reach 5 billion (in 1987), 12 years to reach 6 billion (in 1999), and 12 years to reach 7 billion (in 2011).

One of the first to recognize that the human population cannot increase indefinitely was **Thomas Malthus**, a British economist (1766–1834). He pointed out that human population growth is not always desirable—a view contrary to the beliefs of his day and to those of many people even today—and that the human population can increase faster than its food supply. The inevitable consequences of population growth, he maintained, are famine, disease, and war. Since Malthus's time, the human population has grown from about 1 billion to 7 billion.

At first glance, it appears that Malthus was wrong. Our population has continued to grow because scientific advances have allowed food production to keep pace with population growth. Malthus might ultimately prove correct because we do not know if our increase in food production is *sustainable.* Have we achieved this increase in food production at the environmental cost of reducing the ability of the land to meet the needs of future populations? The truth is that we still do not know if Malthus was wrong or right.

CURRENT AND FUTURE POPULATION NUMBERS

Our world population, which was 7.1 billion in 2012, increased by about 97 million from 2012 to 2013. This increase was not due to an increase in the birth rate *(b)*. In fact, the world birth rate has declined during the past 200 years. Instead, the increase in population was due to a dramatic decrease in the death rate *(d)*, which has occurred primarily because greater food production, better medical care, and improvements in water quality and sanitation practices have increased the life expectancies for a great majority of the global population.

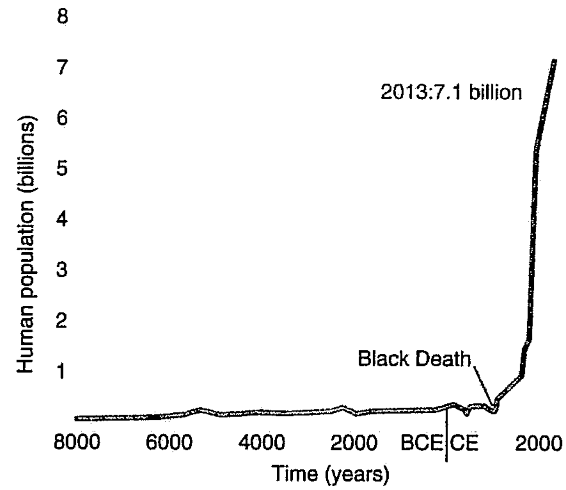


Figure 8.1 Human population growth. During the last 1000 years, the human population has been increasing exponentially. Population experts predict that the population will level out during the 21st century, possibly forming the S curve observed in certain other species. (Black Death refers to a devastating disease, probably bubonic plague, that decimated Europe and Asia in the 14th century.) (Population Reference Bureau)

Although our numbers continue to increase, the world growth rate *(r)* has declined over the past several years, from a peak of 2.2% per year in the mid-1960s to 1.2% per year in 2013. Population experts at the United Nations and the World Bank have projected that the growth rate will continue to decrease slowly until **zero population growth**—when the birth rate equals the death rate—is attained. If this stabilization occurs, it will be clear that human population follows a steep S curve, rather than a J curve. Experts project that zero population growth will occur toward the end of the 21st century. (You may wish to review *r*, *b*, and *d* as well as J and S curves in Chapter 5.)

The United Nations periodically publishes population projections for the 21st century. In its 2012 revision, it forecast that the human population will be between 8.3 billion (its "low" projection) and 10.9 billion (its "high" projection) in the year 2050, with 9.6 billion thought most likely (its "medium" projection; **Figure 8.2**). These estimates take into account both lower projected fertility levels and higher projected mortality from HIV/AIDS. Lower fertility levels result in an aging population; the percentage of the world population over the age of 65 was about 8% in 2013 and is expected to rise. (Population aging is discussed later in this chapter.) Such population projections are "what-if" exercises: Given certain assumptions about future tendencies in the birth rate, death rate, and migration, an area's population can be calculated for a given number of years into the future.

The main unknown factor in any population growth scenario is Earth's **carrying capacity**. Most published estimates of how many people Earth can support range from 4 billion to 16 billion. These estimates vary widely, depending on what assumptions are made about standard of living, resource production and consumption, technological innovations, and waste generation.

carrying capacity The maximum number of individuals of a population that a particular environment can support for an indefinite period, assuming no changes in the environment.

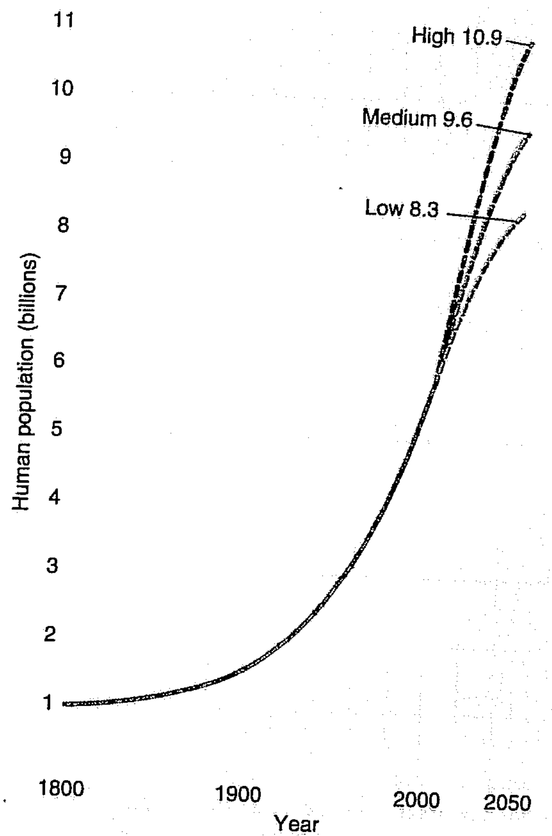


Figure 8.2 Population projections to 2050. In 2012, the United Nations revised its projections of the human population in 2050, each based on different fertility rates. The medium projection was 9.6 billion. How will increasing human population numbers from the present to 2050 affect worldwide energy use? (Data from *World Population Prospects, The 2012 Revision*, UN Population Division)

If we want all people to have a high level of material well-being equivalent to the lifestyles common in highly developed countries, then Earth will clearly support far fewer humans than if everyone lives just above the subsistence level. Earth's carrying capacity for humans is not decided simply by environmental constraints; human choices and values must be factored into the assessment.

HUMAN MIGRATION

Human migration across international borders is a worldwide phenomenon that has escalated dramatically during the past few decades. People migrate in search of jobs or an improved standard of living; to escape war or persecution for their race, religion, nationality, or political opinions; or to join other family members who have already migrated. The increase in the human population has contributed to the current surge in migration, which population experts predict will continue to increase during the next 30 years or so.

Deteriorating environmental conditions and increased competition for jobs, both brought on by unsustainable population growth, may accelerate international migration. Most international migrants relocate in nearby countries. As a result, each continent has its own characteristic flow of international migrants. In North America, for example, the large number of unauthorized migrants entering the United States from Mexico and Central America is a controversial political issue. In the European Union, many guest workers from Morocco, the former Yugoslavia, and Turkey unexpectedly became permanent residents, and cultural differences between natives and nonnatives remain an ongoing concern.

Sometimes economic, political, or environmental problems force people to leave their homelands en masse. According to estimates from the UN High Commissioner for Refugees, there were 15.4 million international refugees at the end of 2012 (latest data available). Countries with large numbers of refugees currently include Afghanistan, Somalia, Iraq, the Syrian Arab Republic, and Sudan. Syrians were poised to pass Afghans to become the world's largest refugee group by the end of 2014, with their numbers expected to exceed 4 million. Most refugees flee to neighboring countries, where many are placed in camps, which are often crowded and sometimes unhygienic.

REVIEW

1. Describe human population growth for the past 200 years.
2. Who was Thomas Malthus, and what were his views on human population growth?
3. When determining Earth's carrying capacity for humans, why is it not enough to just consider human numbers? What else must be considered?

Demographics of Countries

LEARNING OBJECTIVES

- Explain how highly developed and developing countries differ in population characteristics such as infant mortality rate, total fertility rate, and age structure.
- Explain how population growth momentum works.

Whereas world population figures illustrate overall trends, they do not describe other important aspects of the human population story, such as population differences from country to country (**Table 8.1**).

Table 8.1 The World's 10 Most Populous Countries

Country	*2013 Population (in millions)*	*Population Density (per square kilometer)*
China	1357	142
India	1277	388
United States	316	33
Indonesia	249	130
Brazil	196	23
Pakistan	191	230
Nigeria	174	1
Bangladesh	157	1087
Russia	143	8
Japan	127	337

Source: Population Reference Bureau.

As you may recall from Chapter 1, not all countries have the same rate of population increase. Countries can be classified into two groups—highly developed and developing—depending on growth rates, degree of industrialization, and relative prosperity (**Table 8.2**). Note, however, that these categories can be overly simplistic—for example, not taking into account a range of characteristics within countries—yet they help to illustrate differences in population increases.

Nations identified as **highly developed countries** (or *developed countries*), such as the United States, Canada, France, Germany, Sweden, Australia, and Japan, have low rates of population growth and are highly industrialized relative to the rest of the world (**Figure 8.3**). Highly developed countries have the lowest birth rates in the world. Indeed, some countries such as Germany have birth rates just below those needed to sustain their populations and are declining slightly in numbers.

Highly developed countries have low **infant mortality rates**. The infant mortality rate of the United States was 5.9 in 2013, compared with a world rate of 40. Highly developed countries also have longer life expectancies (79 years in the United States versus 70 years worldwide) and high average per capita GNI PPPs ($50,610 in the United States versus $11,690 worldwide). *Per capita GNI PPP* is gross national income (GNI) in purchasing power parity (PPP) divided by midyear population. It indicates the amount of goods and services an average citizen of a particular country could buy in the United States. Perhaps because of high *per capita* GNI PPPs, highly developed countries also have high rates of energy consumption and waste production.

infant mortality rate The number of infant deaths (under age 1) per 1000 live births.

Countries identified as *developing* are grouped into two subcategories, moderately developed and less developed. Mexico, Turkey, Thailand, India, and most South American nations are

Table 8.2 Comparison of 2013 Population Data in Developed and Developing Countries

	Developed	*Developing*	
	(Highly Developed) United States	*(Moderately Developed) Venezuela*	*(Less Developed) Ethiopia*
Fertility rate	1.9	2.4	4.8
Projected population change, 2013–2050*	1.3	1.4	2.0
Infant mortality rate	5.9 per 1000	11.6 per 1000	52 per 1000
Life expectancy at birth	79 years	75 years	62 years
Per capita GNI PPP (2012; U.S. $)**	$50,610	$13,120	$1,140
Women using modern contraception	73%	62%	27%

*Includes fertility, mortality, and migration estimates; 2050 population is presented as a multiple of the 2013 population.
**GNI PPP = gross national income in purchasing power parity.
Source: Population Reference Bureau.

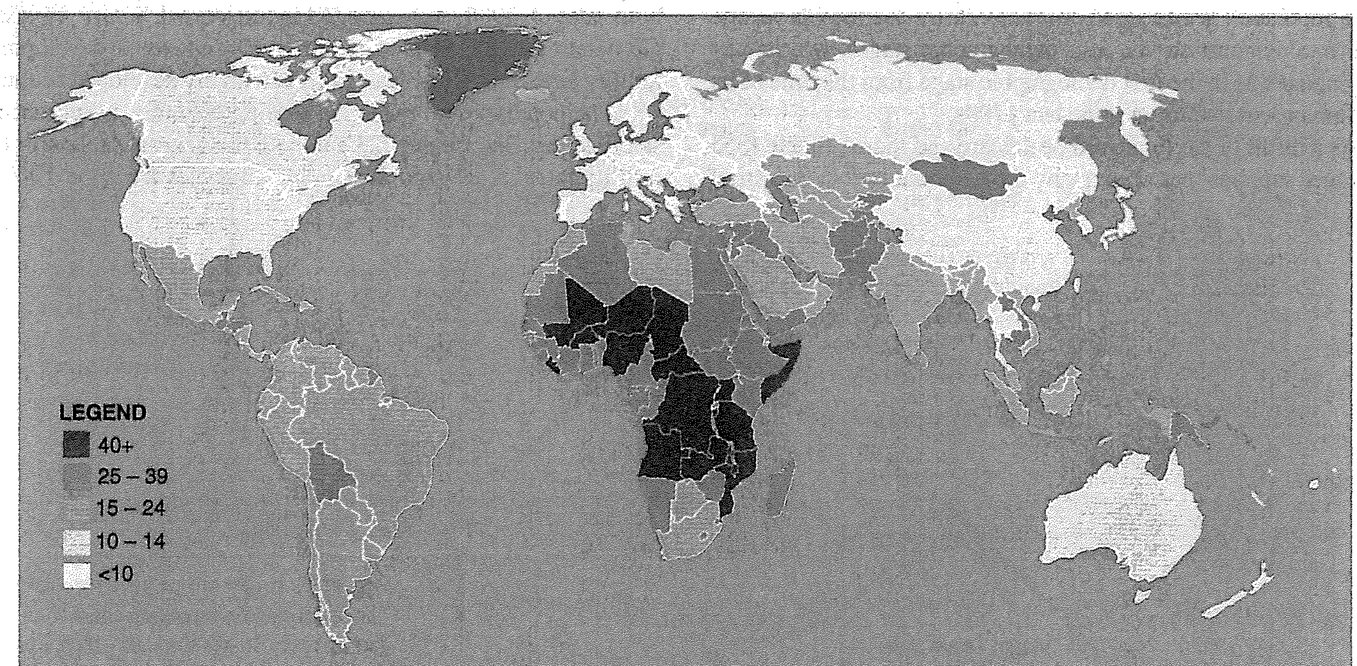


Figure 8.3 Birth rates around the world, 2013. Numbers indicate births per 1000 total population. European nations had the fewest births, and African countries had the most. (Population Reference Bureau)

examples of **moderately developed countries**. Their birth rates and infant mortality rates are higher than those of highly developed countries, but they are declining. Moderately developed countries have a medium level of industrialization, and their average per capita GNI PPPs are lower than those of highly developed countries. Examples of **less developed countries** include Bangladesh, Niger, Ethiopia, Laos, and Cambodia. These countries have the highest birth rates, the highest infant mortality rates, the shortest life expectancies, and the lowest average per capita GNI PPPs in the world. These countries also have lower levels of fossil fuel usage and waste production.

Replacement-level fertility is the number of children a couple must produce to "replace" themselves. Replacement-level fertility is usually given as 2.1 children. The number is greater than 2.0 because some infants and children die before they reach reproductive age. Worldwide, the **total fertility rate (TFR)** is currently 2.5, well above the replacement level.

...al fertility rate (TFR) The average number of children born per ...oman, given the popu... ...on's current birth rate.

DEMOGRAPHIC STAGES

In 1945, Princeton demographer **Frank Notestein** recognized four demographic stages, based on his observations of Europe as it became industrialized and urbanized (**Figure 8.4**). During these stages, Europe converted from relatively high to relatively low birth and death rates. To date, all highly developed and moderately developed countries with more advanced economies have gone through this progression, or **demographic transition**. Demographers generally assume that the same demographic transition will occur in less developed countries as they become industrialized.

In the first stage—the **preindustrial stage**—birth and death rates are high, and population grows at a modest rate. Although women have many children, the infant mortality rate is high. Intermittent famines, plagues, and wars also increase the death rate, so the population grows slowly or temporarily declines. If we use Finland to demonstrate the four demographic stages, we can say that Finland was in the first demographic stage from the time of its first human settlements until the late 1700s.

As a result of the improved healthcare and more reliable food and water supplies that accompany the beginning of an industrial society, the second demographic stage, called the **transitional stage**, has a lowered death rate. The population grows rapidly because the birth rate is still high. Finland in the mid-1800s was in the second demographic stage.

The third demographic stage, the **industrial stage**, is characterized by a decline in birth rate and takes place at some point during the industrialization process. The decline in birth rate slows population growth despite a relatively low death rate. Finland experienced this stage in the early 1900s.

Low birth and death rates characterize the fourth demographic stage, called the **postindustrial stage**. In heavily industrialized countries, people are better educated and more affluent; they tend to desire smaller families, and they take steps to limit family size. The population grows slowly or not at all in the fourth demographic stage. This is the situation in such highly developed countries and groups of countries as the United States, Canada, Australia, Japan, and Europe, including Finland.

Why has the population stabilized in highly developed countries in the fourth demographic stage? The decline in birth rate is associated with an improvement in living standards, although it is not known whether improved socioeconomic conditions have caused a decrease in birth rate or a decrease in birth rate has caused improved socioeconomic conditions. Perhaps both are true. Another reason for the decline in birth rate in highly developed countries is the increased availability of family planning services. Other socioeconomic factors that influence birth rate are increased education, particularly of women, and urbanization of society. We consider these factors in greater detail later in this chapter and in Chapter 9.

We do not know if low birth rates will continue beyond the fourth demographic stage. Low birth rates may be a permanent response to the socioeconomic factors of an industrialized, urbanized society, or they may be a response to the changing roles of women in highly developed countries. Unforeseen changes in the socioeconomic status of women and men in the future may change birth rates. A 2009 study reported in the journal *Nature*, for example, determined that above a certain level of economic development, fertility begins to rise, at least in certain highly developed countries.

The population in many developing countries is approaching stabilization. See **Figure 8.5** and note the general decline in total fertility rates in selected developing countries from the 1960s to

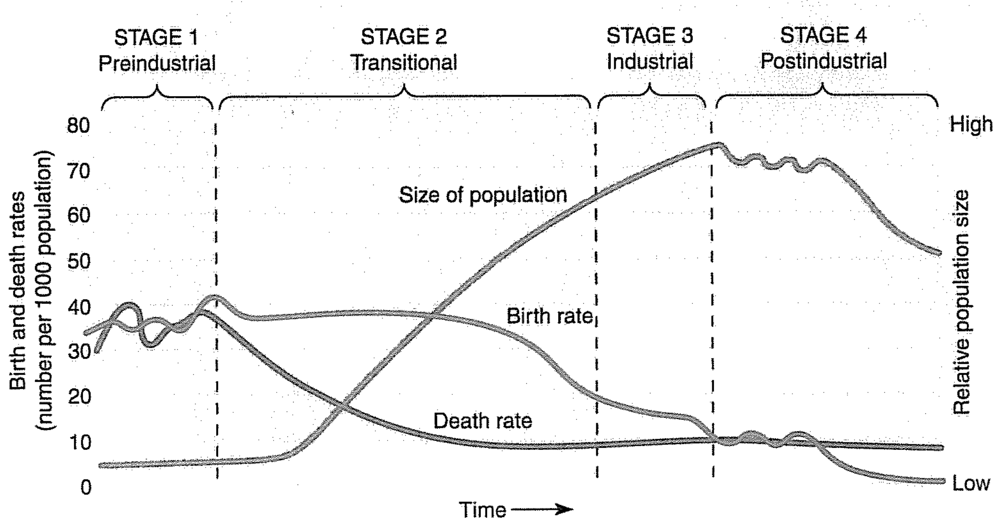


Figure 8.4 Demographic transition. The demographic transition consists of four demographic stages through which a population progresses as its society becomes industrialized. Note that the death rate declines first, followed by a decline in the birth rate.

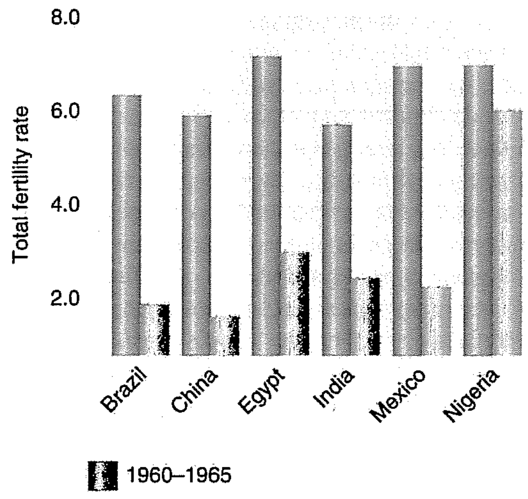


Figure 8.5 Fertility changes in selected developing countries. (Population Reference Bureau)

2013. The total fertility rate in developing countries decreased from an average of 6.1 children per woman in 1970 to 2.6 in 2013. Although the fertility rates in these countries have declined, most still exceed replacement-level fertility. Consequently, the populations in these countries are still increasing. Even when fertility rates equal replacement-level fertility, population growth will still continue for some time. To understand why this is so, let us examine the age structure of various countries.

AGE STRUCTURE

age structure The number and proportion of people at each age in a population.

To predict the future growth of a population, one must know its **age structure**, or distribution of people by age. The number of males and number of females at each age, from birth to death, are represented in an age structure diagram.

The overall shape of an age structure diagram indicates whether the population is increasing, stable, or shrinking. The age structure diagram of a country with a high growth rate, based on a high fertility rate—for example, Ethiopia or Guatemala—is shaped like a pyramid (**Figure 8.6a**). The probability of future population growth is great because the largest percentage of the population is in the prereproductive age group (0 to 14 years of age). A positive **population growth momentum** exists because when all these children mature, they will become the parents of the next generation, and this group of parents will be larger than the previous group. Even if the fertility rate of such a country has declined to replacement level (that is, couples are having smaller families than their parents did), the population will continue to grow for some time. Population growth momentum, which can be positive or negative, explains how the present age distribution affects the future growth of a population.

population growth momentum The potential for future increases or decreases in a population based on the present age structure.

In contrast, the more tapered bases of the age structure diagrams of countries with slowly growing, stable, or declining populations indicate that a smaller proportion of the population will become the parents of the next generation (**Figure 8.6b, c**). The age structure diagram of a stable population, one that is neither growing nor shrinking, demonstrates that the numbers of people at prereproductive and reproductive ages are approximately the same. A larger percentage of the population is older—that is, postreproductive—than in a rapidly increasing population. Many countries in Europe have stable populations. In a population shrinking in size, the prereproductive age group is *smaller* than either the reproductive or postreproductive group. Russia, Ukraine, and Germany are examples of countries with slowly shrinking populations.

An estimated 26% of the global human population is under age 15 (**Figure 8.7a**). When these people enter their reproductive

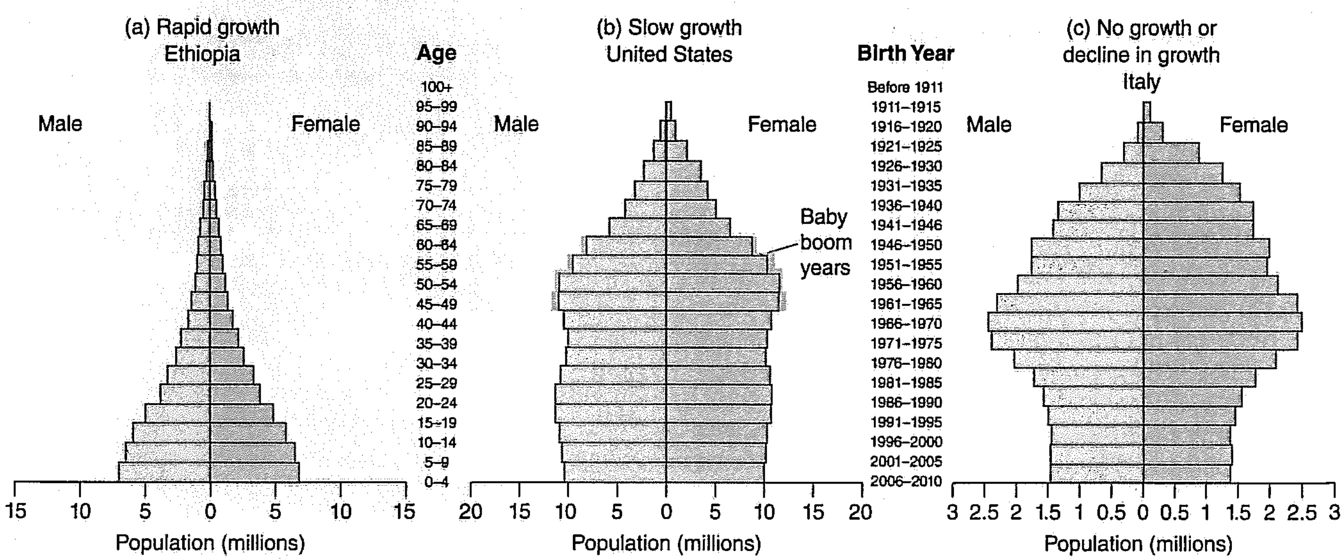
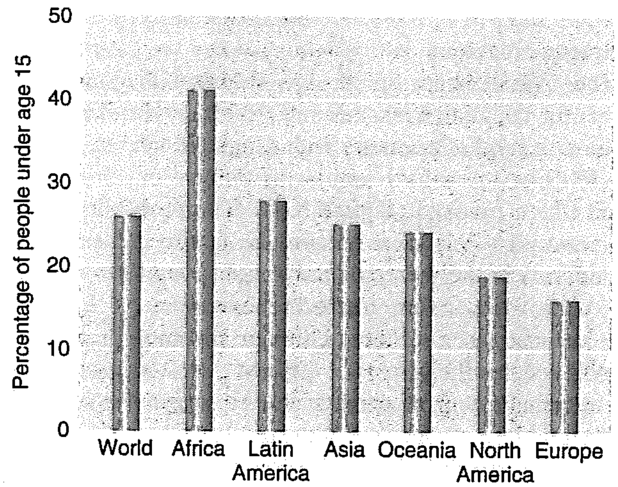
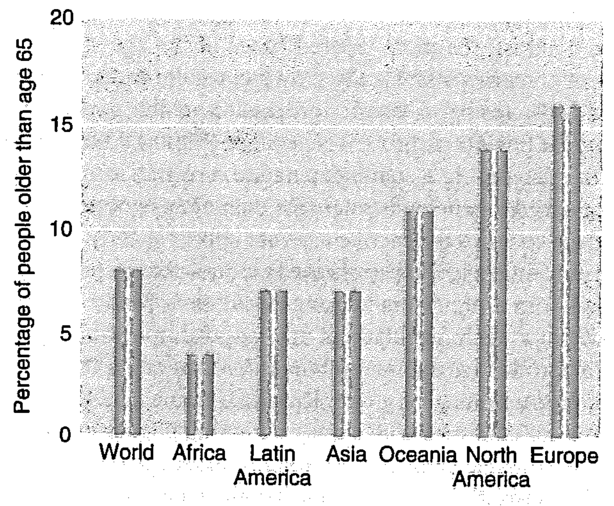


Figure 8.6 Age structure diagrams. Shown are countries with (a) rapid growth (Ethiopia), (b) slow growth (United States), and (c) no growth (Italy) or declining population growth. These age structure diagrams indicate that less developed countries such as Ethiopia have a much higher percentage of young people than do highly developed countries. As a result, less developed countries are projected to have greater population growth than highly developed countries. (UN Department of Economic and Social Affairs Population Division)



(a) Percentages of the population under age 15 for various regions in 2013. The higher this percentage, the greater the potential for population growth when people in this group reach their reproductive years.



(b) Percentages of the population older than 65 in 2013. Lower fertility rates lead to aging populations.

Figure 8.7 Prereproductive and elderly populations in various regions of the world. (Population Reference Bureau)

years, they have the potential to cause a large increase in the growth rate. Even if the birth rate does not increase, the growth rate will increase simply because more people are reproducing.

Since 1950, most of the world population increase has occurred in developing countries—as a result of the younger age structure and the higher-than-replacement-level fertility rates of their populations. In 1950, 67% of the world's population was in developing countries in Africa, Asia (minus Japan), and Latin America. Since 1950, the world's population more than doubled, but most of that growth occurred in developing countries. As a reflection of this fact, in 2013, the number of people in developing countries (including China) had increased to 82.6% of the world population. Most of the population increase during the 21st century will occur in developing countries, largely the result of their younger age structures.

Age Structure: Effects of an Aging Population Declining fertility rates have profound social and economic implications because as fertility rates drop, the percentage of the population that is elderly increases (**Figure 8.7b**). An aging population has a higher percentage of people who are chronically ill or disabled, and these people require more healthcare and other social services. Because the elderly produce less wealth (most are retired or incapable of working), an aging population reduces a country's productive workforce, increases its tax burden, and strains its social security, health, and pension systems. (In general, these systems are "pay-as-you-go," with current workers paying for retirees' benefits and future workers paying for current workers' retirement benefits.)

Consider Japan, which has the world's longest life expectancy—80 for men and 86 for women. Japan's population is declining because of its low fertility rate (1.4 in 2013). Japanese leaders are concerned that there will not be enough young people to support Japan's growing elderly population. To address some of the problems in its workforce, Japan is starting to offer incentives to the elderly to work longer before receiving retirement benefits, and some elderly Japanese have taken on nontraditional jobs to expand their working years (**Figure 8.8**).

Russia's fertility rate is low (1.7 in 2013), and the UN Population Division predicts that Russia's population in 2050 will have declined to 132.4 million (its 2013 population was 143.5 million). Like many countries with declining populations, Russia offers incentives to young couples who choose to have children; these include assisting with maternity leave and helping to pay for childcare when the mother returns to the workplace.

Given that the world population continues to increase, many demographers think that providing incentives to encourage women to have more children is not a good approach. After all, if a given

AP Photo/Katsumi Kasahara

Figure 8.8 Elderly worker in Japan. The population in the town of Kamikatsu, Japan, is dominated by the elderly, many of whom seek to stay employed. One thriving industry in the region, run primarily by elderly women, is the collection of decorative leaves that are sold for use in Japanese cuisine.

country raises its birth rate, it is not only increasing the world population but also contributing to its aging population in the future.

Changes in a population's age structure can affect many social problems (such as crime) that at first glance do not appear to be directly related. Sociologists have observed that in an aging population the crime rate may decline. Most crimes involve young adults between the ages of 18 and 24, and in an aging population, these young adults represent a smaller proportion of the population. According to the U.S. Census Bureau, in the late 1990s, the United States experienced a reduction in the rate of violent crimes, and the aging of the U.S. population was cited as at least one factor. (Like all social problems, the causes of crime are complex.)

Thus, aging populations offer a mixed bag of benefits and problems. No country has been faced with an aging population before now, and we do not know how aging populations will function. Despite the uncertainties, most policy analysts think that countries with higher proportions of elderly will probably have to increase the age of retirement (through incentives that encourage people to work after age 65) and decrease benefits for the elderly. Also, because benefits for the elderly will most certainly decline over time, experts recommend that young people begin saving aggressively for their retirements *early* in their careers instead of after their children have grown.

REVIEW

1. What is total fertility rate? Why do you suppose it is much higher in Mozambique than it is in Sweden?
2. What is population growth momentum?

Population and Quality of Life

LEARNING OBJECTIVES

- Relate carrying capacity to agricultural productivity.
- Relate human population to chronic hunger and food insecurity.
- Describe the relationship between economic development and population growth.

As the 21st century proceeds, it will become increasingly difficult to meet the basic needs (a balanced diet, clean water, decent shelter) of all people, especially in countries that have not achieved population stabilization. About 12% of the world's population live in less developed countries. If their rate of population growth continues, many of these countries will double their populations by 2050.

The social, political, and economic problems resulting from continued population growth in less developed countries sometimes result in internal violence and political collapse. Such violent conflict inevitably affects countries that have already achieved stabilized populations and high standards of living. For this reason, population growth is of concern to the entire world community, regardless of where it occurs.

As our numbers increase during the 21st century, environmental degradation, hunger, persistent poverty, economic stagnation, urban deterioration, and health issues will continue to challenge us. Already, the need for food for the increasing number of people living in environmentally fragile arid lands, such as parts of sub-Saharan Africa, has led to overuse of the land for grazing and crop production. When land overuse occurs in combination with an extended drought, formerly productive lands may decline in agricultural productivity—that is, their carrying capacity may decrease. Although it is possible to reclaim such arid lands, the large number of people and their animal herds trying to live off the land make reclamation efforts difficult. (Carrying capacity as it relates to environmental resistance was introduced in Chapter 5.)

No one knows if Earth can sustainably support the 9.6 billion people that is the UN medium projection for 2050 (see Figure 8.2). It is not even clear that Earth can sustainably support the 7.1 billion people we currently have. We cannot quantify the carrying capacity for humans in any meaningful way, in part because our impact on natural resources and the environment involves more than simply population numbers.

To estimate global carrying capacity for humans, we must make certain assumptions about our *quality* of life. Do we assume that everyone in the world should have the same standard of living as average U.S. citizens currently do? If so, then Earth would support a fraction of the humans it could support if everyone in the world had only the barest minimum of food, clothing, and shelter. Also, we do not know if future technologies would completely alter Earth's sustainable population size. We may have already reached or overextended our carrying capacity, and the numerous environmental problems we are currently experiencing may cause the world population increase to come to a halt or even decline precipitously.

POPULATION AND CHRONIC HUNGER

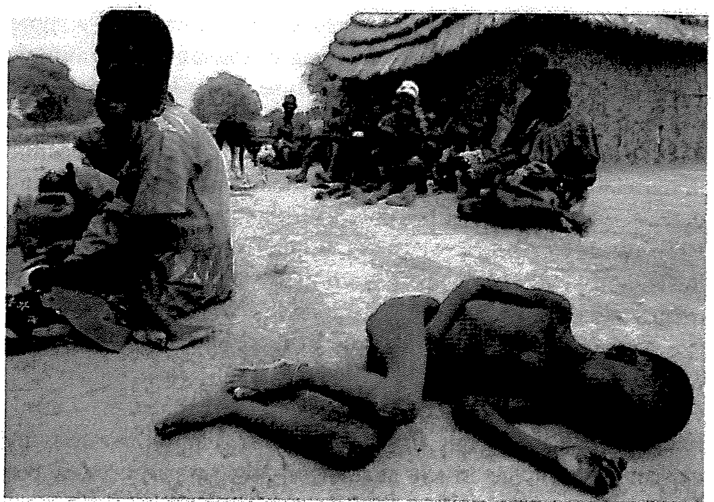
Food security is the condition in which people do not live in hunger or fear of starvation. Many of the world's people—more than 1 billion—do not have food security. These people do not get enough food to thrive; in certain areas of the world, people, especially children, still starve (**Figure 8.9**).

According to the UN Food and Agriculture Organization (FAO), 86 countries are considered low income and food deficient. South Asia and sub-Saharan Africa are the two regions of the world with the greatest **food insecurity**. People with food insecurity live under the threat of starvation. Worldwide, the FAO estimates that as many as 2 billion people face food insecurity intermittently as a result of poverty, drought, or civil strife.

food insecurity The condition in which people live with chronic hunger and malnutrition.

Most of the millions of people who die each year from hunger are not victims of *famine*. Famines are usually attributed to bad weather (droughts or floods), insect outbreaks, armed conflict (which causes a breakdown in social and political institutions), or some other disaster. Famines, which generally receive widespread press coverage, account for between 5% and 10% of the world's hungry people in a given year. The remaining 90% to 95%, which represent people with chronic hunger, receive little attention in the world news.

Chronic hunger, population, poverty, and environmental problems are interrelated, but there is no consensus on the most effective way to stop chronic hunger. Many politicians and economists think the best way to tackle world food problems is to



Antony Njuguna/Reuters/Landov

Figure 8.9 Hunger. A young Sudanese boy collapses from hunger at a food distribution center run by a medical charity. Population growth is not the only reason there is not enough food for all the world's peoples. In Sudan, the underlying cause is ongoing civil strife.

conomic development An expansion in a overnment's economy, viewed by many as the best way to raise the standard of living.

promote the **economic development** of countries that do not produce adequate food supplies for their people. Economic development, which is most effective when associated with stable democratic governments, includes improving roads, extending power grids to isolated rural areas, building schools and medical clinics, and expanding communication networks.

The assumption is that economic development would provide the appropriate technology for the people living in those countries to increase their food production or their food-purchasing ability. Once a country makes these gains, its total fertility rate should decline, helping to lessen the population problem. (Poverty and hunger are revisited in Chapters 18 and 24.)

ECONOMIC EFFECTS OF CONTINUED POPULATION GROWTH

The relationship between economic development and population growth is difficult to evaluate. Population growth affects economic development *and* economic development affects population growth, but the degree to which each affects the other is unclear. Some economists have argued that population growth stimulates economic development and technological innovation. Other economists think a rapidly expanding population hampers developmental efforts. Most major technological advances are now occurring in countries where population growth is low to moderate, an observation that supports the latter point of view.

Are large increases in population a deterrent to economic development? Experts studying the interactions among global problems such as underdevelopment, hunger, poverty, environmental problems, and rapid population growth have concluded that population stabilization alone will not eliminate other world problems. For most of the developing world, however, economic development would profit from slower population growth. Population stabilization will not guarantee higher living standards but will probably promote economic development, which, in turn, will raise the standard of living.

REVIEW

1. How is agricultural productivity related to carrying capacity?
2. How is human population growth related to chronic hunger?
3. How is human population growth related to economic development?

Reducing the Total Fertility Rate

LEARNING OBJECTIVES

- Define *culture* and explain how total fertility rate and cultural values are related.
- Define *gender inequality* and relate the social and economic status of women to total fertility rate.
- Explain how the availability of family planning services affects total fertility rate.

Moving from one place to another used to be a solution for unsustainable population growth, but it is not today. As a species, we have expanded our range throughout Earth, and few habitable areas remain that have the resources to adequately support a major increase in human population. For obvious reasons, increasing the death rate is not an acceptable means of regulating population size. Clearly, the way to control our expanding population is to reduce the number of births. Cultural traditions, women's social and economic status, and family planning all influence the total fertility rate.

CULTURE AND FERTILITY

The values and norms of a society—what is considered right and important and what is expected of a person—are all part of a society's **culture**. A society's culture, which includes its language, beliefs, and spirituality, exerts a powerful influence over individuals by controlling behavior. This control is internalized—that is, it is taken for granted.

culture The ideas and customs of a group of people at a given period; culture, which is passed from generation to generation, evolves over time.

Gender is an important part of culture. Different societies have different gender expectations—that is, varying roles men and women are expected to fill. In parts of Latin America men do the agricultural work, whereas in sub-Saharan Africa this is what women do. With respect to fertility and culture, a couple is expected to have the number of children determined by the cultural traditions of their society.

High total fertility rates are traditional in many cultures. The motivations for having many babies vary from culture to culture, but a major reason for high total fertility rates is high infant and child mortality rates. For a society to endure, it must produce enough children who can survive to reproductive age. If infant and child mortality rates are high, total fertility rates must be high to compensate. Although world infant and child mortality rates are decreasing, culturally embedded fertility levels will take longer to decline. Parents must have enough confidence that the children they already have will survive before they stop having additional babies. Another reason for the lag in fertility decline is cultural: Changing anything traditional, including large family size, usually takes a long time.

Higher total fertility rates in some developing countries are due to the important economic and societal roles of children. In some societies, children usually work in family enterprises such as farming or commerce, contributing to the family's livelihood (**Figure 8.10**). When these children become adults, they provide support for their aging parents.

The International Labour Organization (ILO) estimates that, although child labor has declined in recent years, worldwide, about 144 million children between the ages of 5 and 14 worked in 2012 (the ILO does not count household chores as labor). This estimate represents 11.8% of all children. Almost all of these children live in developing countries. About 38 million child laborers do hazardous work, such as mining and construction, and often suffer from chronic health problems caused by the dangerous, unhealthy workplace conditions to which they are exposed. Children who work long hours do not have childhoods, nor do they receive any education.

In contrast, children in highly developed countries have less value as a source of labor because they attend school and because less human labor is required in an industrialized society. Furthermore, highly developed countries provide many economic and social services for the elderly, so the burden of their care does not fall entirely on their offspring.

Many cultures place a higher value on male children than on female children. In these societies, a woman who bears many sons achieves a high status; the social pressure to have male children keeps the total fertility rate high. For example, the Hindu religion in India traditionally required that parents be buried alongside their son, and having a son still has deep cultural significance in India today.

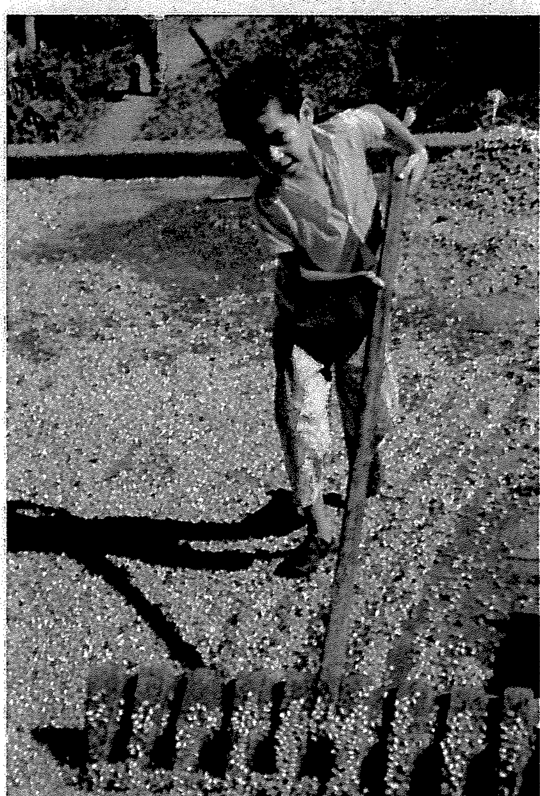


Figure 8.10 Child at work. This young Mexican boy helps his family's agricultural business by spreading coffee beans to dry. In developing countries, total fertility rates are high partly because children traditionally contribute to the family by working. Older children often have wage-producing jobs that add to the family income.

Religious belief systems are another aspect of culture that affects total fertility rates (TFRs). Several studies in the United States point to differences in TFRs among Catholics, Protestants, and Jews. In general, Catholic women have a higher TFR than either Protestant or Jewish women, and women who do not follow any religion have the lowest TFR of all. However, the observed differences in TFRs may not be the result of religious differences alone. Other variables, such as ethnicity (certain religions are associated with particular ethnic groups) and residence (certain religions are associated with urban or with rural living), complicate any generalizations.

THE SOCIAL AND ECONOMIC STATUS OF WOMEN

Gender inequality exists in most societies, although the extent of the gap between men and women varies in different cultures. Gender disparities include the lower political, social, economic, and health status of women compared to men. For example, more women than men live in poverty, particularly in developing countries. In most countries, women are not guaranteed equality in legal rights, education, employment and earnings, or political participation.

gender inequality The social construct that results in women not having the same rights, opportunities, or privileges as men.

Because sons are more highly valued than daughters, girls are often kept at home to work rather than being sent to school. In most developing countries, a higher percentage of women are illiterate than men (**Figure 8.11**). However, definite progress has been made in recent years in increasing literacy in both women and men and in narrowing the gender gap. Fewer young women and men are illiterate than older women and men within a given country.

Worldwide, some 32 million girls in 2010 were not given the opportunity to receive a primary (elementary school) education, although progress has been made: Nearly twice as many girls were out of school in 1999. As of 2010, however, only one-third of countries worldwide reported gender parity in both primary and secondary education. **Gender parity** in education is the right of every child—boy or girl—to attend school. Fewer women than men attend secondary school (high school). In Africa, no more than 50% of women in any country attend secondary school, and in some countries only 2% to 5% are enrolled.

Laws, customs, and lack of education often limit women to low-skilled, low-paying jobs. In such societies, marriage is usually the only way for a woman to achieve social influence and economic security. Thus, the single most important factor affecting high total fertility rates may be the low status of women in many societies. A significant way to address unsustainable population growth is to improve the social and economic status of women. Next, we will examine how marriage age and educational opportunities, especially for women, affect fertility.

Marriage Age and Fertility The total fertility rate is affected by the average age at which women marry, which is determined

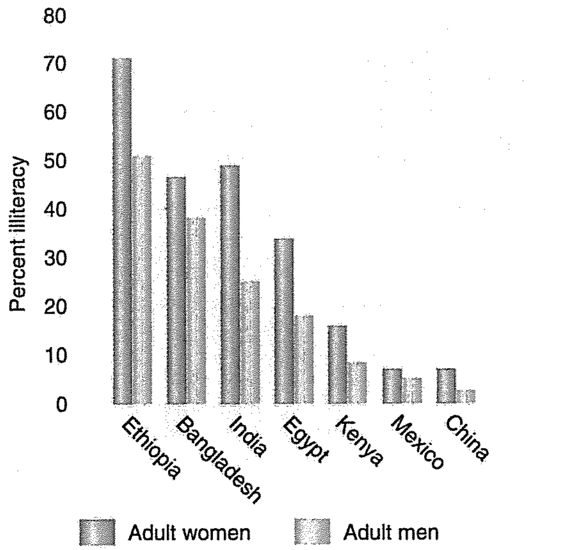


Figure 8.11 Percent illiteracy of men and women in selected developing countries. A higher percentage of women than men are illiterate. (From *CIA World Factbook* 2011)

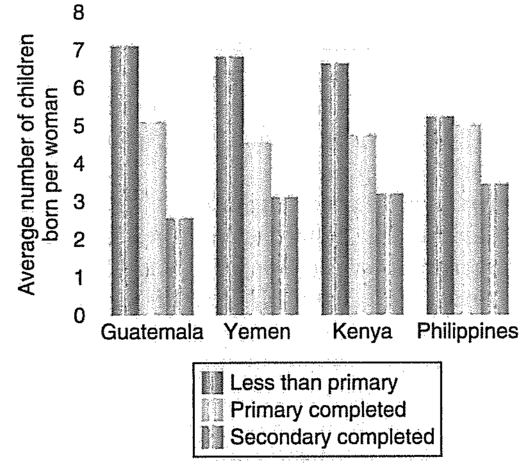


Figure 8.12 Education and fertility. The amount of education a woman receives affects the total number of children she has (TFR). The graph shows TFRs for women with different levels of education in several developing countries. (Adapted from E. Murphy, and D. Carr, *Powerful Partners: Adolescent Girls' Education and Delayed Childbearing*. Population Reference Bureau [2007])

by the laws and customs of the society in which they live. Women who marry are more apt to bear children than women who do not marry, and the earlier a woman marries, the more children she is likely to have.

The percentage of women who marry and the average age at marriage vary widely among different societies, but there is generally a correlation between marriage age and total fertility rate. For example, in Pakistan the average age of a woman at marriage is 17, and the TFR is 3.8. In contrast, in Denmark the average age of a woman at marriage is 32, and the TFR is 1.7.

Educational opportunities and fertility In nearly all societies, women with more education tend to marry later and have fewer children. Studies in dozens of countries show a strong correlation between the average amount of education women receive and the total fertility rate (**Figure 8.12**).

Education increases the probability that women will know how to control their fertility, and it provides them with knowledge to improve the health of their families, which results in a decrease in infant and child mortality. A study in Kenya showed that 10.9% of children born to women with no education died by age 5, as compared with 7.2% of children born to women with a primary education and 6.4% of children born to women with a secondary education.

Education increases women's options, providing ways of achieving status besides having babies. Education may have an indirect effect on total fertility rate as well. Children who are educated have a greater chance of improving their living standards, partly because they have more employment opportunities. Parents who recognize this may be more willing to invest in the education of a few children than in the birth of many children whom they cannot afford to educate. The ability of better-educated people to earn more money may be one of the reasons smaller family size is associated with increased family income.

FAMILY PLANNING SERVICES

Socioeconomic factors may encourage people to want smaller families, but reduction in fertility will not become a reality without the availability of **family planning services**. Traditionally, family planning services have focused on maternal and child health, including prenatal care to help prevent infant and maternal death or disability. However, because of gender inequality and cultural constraints, many women cannot ensure their own reproductive health without the support of their partners. Polls of women in developing countries reveal that many who say they do not want additional children still fail to practice any form of birth control. When asked why they do not use birth control, these women frequently respond that their husbands want additional children.

family planning services Services that enable men and women to limit family size, safeguard individual health rights, and improve the quality of life for themselves and their children.

The governments of most countries recognize the importance of educating people about basic maternal and child healthcare (**Figure 8.13**). Developing countries that have had success in significantly lowering total fertility rates credit many of these results to effective family planning programs. Prenatal care and proper birth spacing make women healthier. In turn, healthier women give birth to healthier babies, leading to fewer infant deaths. Globally, the percentage of women using family planning services to limit family size has increased from less than 10% in the 1960s to 56% today. However, the actual *number* of women not using family planning has increased owing to population growth.

Family planning services provide information on reproductive physiology and contraceptives, as well as the actual contraceptive devices, to those who wish to control the number of children they produce or to space their children's births (**Figure 8.14**). Family planning programs are most effective when they are designed with sensitivity to local social and cultural beliefs. Family planning services do not try to force people to limit their family sizes but, rather, attempt to convince people that small families (and the contraceptives that promote small families) are acceptable and desirable.

Contraceptive use is strongly linked to lower total fertility rates. In Canada, the United States, and Northern Europe, where total fertility rates are at replacement levels or lower, the percentage of married women of reproductive age who use contraceptives is greater than 70%. Fertility declines have occurred in developing countries where contraceptives are readily available. For example, research has shown that 90% of the decrease in fertility in 31 developing countries was a direct result of the increased knowledge and availability of contraceptives. Since the 1970s, use of modern contraceptives in East Asia and many areas of Latin America has increased significantly, and these regions have experienced a corresponding decline in birth rate. In areas where contraceptive use has remained low, such as parts of Africa, there was little or no decline in birth rate.

REVIEW

1. How are high total fertility rates related to the economic roles of children in certain cultures?
2. What appears to be the single most important factor affecting high TFRs?
3. How do family planning services influence TFR?

Government Policies and Fertility

LEARNING OBJECTIVES

- Compare how the governments of China and Mexico have tried to slow human population growth.
- Explain the role of population growth momentum in Mexico's population growth.
- Describe at least four of the Millennium Development Goals that came out of the UN Millennium Summit.

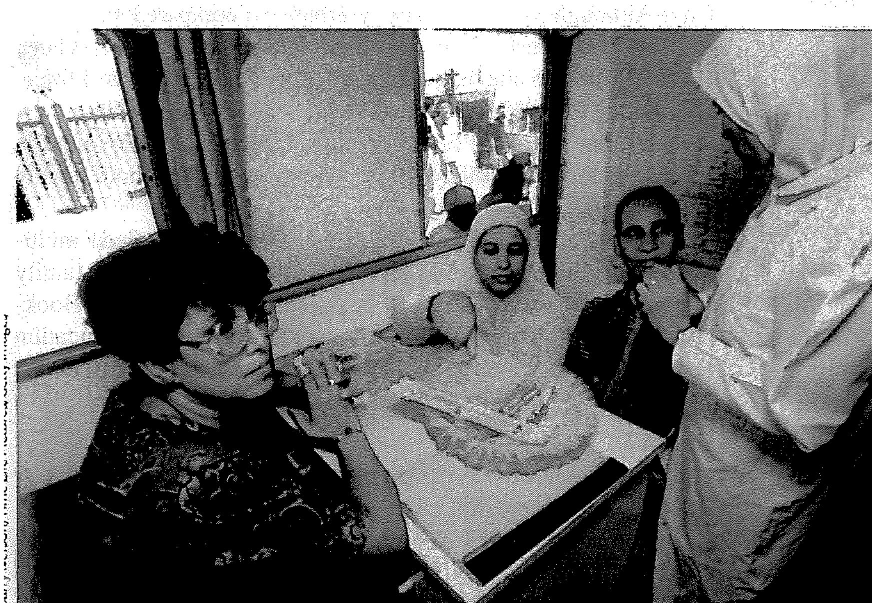


Figure 8.13 Family planning. Women in the rural town of Sinnuris, Egypt, learn about family planning and birth control.

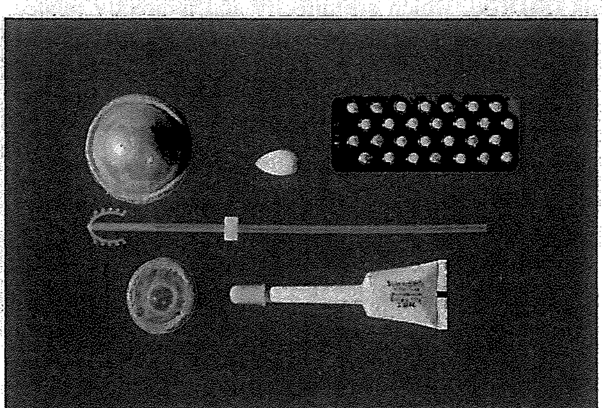


Figure 8.14 Some commonly used contraceptives.

The involvement of governments in childbearing and child rearing is well established. Laws determine the minimum age at which people may marry and the amount of compulsory education. Governments may allot portions of their budgets to family planning services, education, healthcare, old-age security, or incentives for smaller or larger family size. The tax structure, including additional charges or allowances based on family size, influences fertility.

In recent years, the governments of at least 78 developing countries in Africa, Asia, Latin America, and the Caribbean have prioritized limiting population growth. They have formulated policies, such as economic rewards and penalties, to achieve this goal. Most countries sponsor family planning projects, many of which are integrated with healthcare, education, economic development, and efforts to improve women's status. The UN Fund for Population Activities supports many of these activities.

CHINA AND MEXICO: CONTRASTING POPULATION GROWTH MEASURES

China, with a mid-2013 population of 1.36 billion, has the largest population in the world, and its population exceeds the combined populations of all highly developed countries. Recognizing that its rate of population growth had to decrease or the quality of life for everyone in China would be compromised, the Chinese government in 1971 began to pursue birth control seriously. It urged couples to marry later, increase spacing between children, and limit the number of children to two.

In 1979, China instigated an aggressive plan to push the nation into the third demographic stage. Announcements were made for incentives to promote later marriages and one-child families (**Figure 8.15**). Local jurisdictions were assigned the task of reaching this goal. A couple who signed a pledge to limit themselves

Figure 8.15 China's one-child family policy. A billboard campaign in China promotes the one-child family. Note that the billboard features happy parents with a single female child to counteract the traditional preference for boys.

to a single child might be eligible for such incentives as medical care and schooling for the child, cash bonuses, preferential housing, and retirement funds. Penalties were also instituted, including fines and the surrender of all of these privileges if a second child was born.

China's aggressive plan brought about the most rapid and drastic reduction in fertility in the world, from 5.8 births per woman in 1970 to 2.1 births per woman in 1981. However, it was controversial and unpopular because it compromised individual freedom of choice. In some instances, community and governmental pressures induced women who were pregnant with a second child to get an abortion.

Moreover, the disproportionate number of male versus female babies reported born in recent years (120 boys for every 100 girls in 2000), suggested that many expectant parents aborted female fetuses or killed or abandoned newborn baby girls. In China, sons carry on the family name and traditionally provide old-age security for their parents. Thus, sons are valued more highly than daughters are. Demographers project that by the middle of the 21st century, marriageable males will outnumber marriageable females by 1 million.

China's TFR in 2013 was 1.5. The one-child family policy is now relaxed in rural China, where 47% of all Chinese live. China's recent population control program has relied on education, publicity campaigns, and fewer penalties to achieve its goals. In addition, the Chinese government has been running a "Care for Girls" campaign, and legislation has increased the rights of girls (for example, to inherit). China trains population specialists, and thousands of secondary school teachers integrate population education into the curriculum.

Mexico, with a mid-2013 population of 117.6 million, is the second most populous nation in Latin America. (Brazil, with a population of 195.5 million, is the most populous.) Mexico has a tremendous potential for growth because 30% of its population is less than 15 years of age. Even with a low birth rate, positive population growth momentum will cause the population to continue to increase in the future because of the large number of young women having babies. However, the approach taken by Mexico contrasts greatly with China's.

Traditionally, the Mexican government supported rapid population growth, but in the late 1960s the government became alarmed at how rapidly the population was increasing. In 1974, the Mexican government instigated several measures to reduce population growth, such as educational reform, family planning, and healthcare. The time was right for such changes, as many Mexican women were already ignoring the decrees of the pro-growth government and the Roman Catholic Church and purchasing contraceptives on the black market. Mexico has had great success in reducing its fertility level, from 6.7 births per woman in 1970 to 2.2 births per woman in 2013.

Mexico's goal includes both population stabilization and balanced regional development. Its urban population makes up 78% of its total population, and most of these people live in Mexico City. Although Mexico is largely urbanized compared with other developing countries, its urban-based industrial economy has been unable to absorb the large number of people in the workforce. (According to the Mexico office of the ILO, about 1.3 million new workers join Mexico's labor force each year.) Unemployment in Mexico is high, and many Mexicans have migrated, both legally and illegally, to the United States.

Mexico's recent efforts at population control include multimedia campaigns. Popular television and radio shows carry family planning messages, such as "Small families live better." Booklets on family planning are distributed, and population education is integrated into the public school curriculum. Social workers receive training in family planning as part of their education.

CASE IN POINT

THE MILLENNIUM DEVELOPMENT GOALS

In 2000, 189 heads of state met at the UN Millennium Summit to address how to meet the needs of the world's impoverished people. This gathering committed their countries to a global partnership with a plan of action known as the **Millennium Development Goals (MDGs)**, which are directly and indirectly related to the population issues discussed in this chapter. Although the MDGs are lofty, each is attainable; each has measurable indicators that can be used to monitor progress.

- **Goal 1: Eradicate extreme hunger and poverty.** Targets include halving the number of people living on an income of less than U.S. $1 (now scaled to $1.25) a day by 2015, and halving the proportion of people who suffer from hunger. Most analysts believe that reaching this goal will require a firm commitment to family planning to curb unsustainable population growth.
- **Goal 2: Achieve universal primary education.** All boys and girls, regardless of where they live, should enroll in and complete a primary education (grades 1 through 5). Limiting

family size is essential to meeting this goal because children in large families are less likely to enroll in school and more likely to drop out than children in small families.

- **Goal 3: Promote gender equality and empower women.** *Gender equality* means that men and women have equal power and influence in society. One of the central keys to meeting this goal is that all women have the right to determine if and when they will bear children. Goal 3 is also based on eradicating gender disparity in education.
- **Goal 4: Reduce child mortality.** The target is to reduce by two-thirds the mortality rate of infants and children younger than five years of age. Studies have shown that, given the same amount of healthcare, infants born less than 18 months after an older child are two to four times more likely to die than infants born after 36 months. This goal can be achieved by allowing more time between births; access to family planning and gender equality are keys to longer birth spacing.
- **Goal 5: Improve maternal health.** By 2015, the maternal mortality ratio should be reduced by two-thirds. According to the World Health Organization, access to family planning could prevent 150,000 maternal deaths annually. Family planning improves maternal health by reducing the number of unintended pregnancies and the number of unsafe abortions.
- **Goal 6: Combat HIV/AIDS, malaria, and other diseases.** Reduce the spread of HIV/AIDS, malaria, and other important diseases. For example, the use of condoms indirectly reduces mother-to-infant transmission of HIV/AIDS by preventing unintended pregnancies.
- **Goal 7: Ensure environmental sustainability.** This is a multipart goal that includes reversing the loss of natural resources, halving the number of people without sustainable access to safe drinking water and basic sanitation, and improving the lives of at least 100 million people living in slums (see Chapters 9 and 24). Goal 7 focuses both on relieving the increasing pressure on the environment caused by rising populations in developing countries and addressing the consumptive patterns of people living in highly developed countries.
- **Goal 8: Develop a global partnership for economic development.** The financial aspects of the MDGs are encompassed in this goal: providing measures for debt relief for the external debts in developing countries, creating productive jobs for young people, and providing access to affordable medicines in developing countries.

An unprecedented effort has been extended toward reaching these goals, and many targets have been attained or are in reach. For example, the number of people living in extreme poverty has indeed been halved, from 47% of the population in 1990 to 22% in 2010, as has the number of people lacking access to safe drinking water. Yet these are massive problems requiring complex solutions. As then UN Secretary-General **Kofi A. Annan** said, "It takes time to train the teachers, nurses, and engineers; to build the roads, schools, and hospitals; to grow the small and large businesses able to create jobs and income needed." These goals should encourage us all to do our part in improving the human condition (see Meeting the Challenge: The Poverty Action Lab). ■

REVIEW

1. What are the successes and failures of China and Mexico in slowing human population growth?
2. How does population growth momentum affect Mexico's population growth?
3. What are the Millennium Development Goals?

ENVIRONEWS

The Millennium Villages Project

Sometimes international aid to impoverished people does not reach them, or the aid is piecemeal and provides a temporary, Band-Aid approach that quickly loses its effectiveness after the money is spent. The Millennium Villages Project (MVP) is a different approach to fighting poverty. National and local African governments, the Earth Institute at Columbia University, various aid groups, and other participants work with selected communities in rural Africa to help them achieve the Millennium Development Goals. The MVP has affected 400,000 people—across 10 sub-Saharan countries—who live in 79 villages within 12 groups representing the 12 agro-ecological zones and farming systems in Africa. The villages are all located in areas of food insecurity: At least 20% of all children five years of age or younger are underweight.

The MVP is unique in that it involves a coordinated set of interventions in agriculture, nutrition, health, education, energy, water, and the environment. First, a detailed assessment of current conditions is prepared, both to determine what interventions are most needed and to provide a baseline against which future assessments can monitor the effectiveness of the program. The project involves community-led economic development and is based on the premise that rural African communities can improve their standard of living if they are taught and provided with technologies that simultaneously improve agricultural productivity, health, and education. The program provides assistance for at least five years, during which time the management of improvements is transitioned from the aid groups to the villagers themselves.

MEETING THE CHALLENGE

The Poverty Action Lab

Poverty is a complex, seemingly intractable problem related to many factors, of which economic underdevelopment, lack of education, gender inequality, and degradation of land are just a few. Providing resources to help impoverished people improve their standard of living is critical, but what is the most effective way to spend the money?

In 2003, several economics professors at the Massachusetts Institute of Technology started the **Jameel Poverty Action Lab (J-PAL)** to conduct scientifically rigorous, randomized trials of social and anti-poverty programs. The J-PAL trials, which are controlled experiments, are patterned after the randomized trials conducted by pharmaceutical makers when evaluating the safety of new drugs. The scientific results of trials meant to help the poor assist policy makers from nongovernmental organizations, international organizations, and other groups to formulate more effective programs to reduce poverty.

Dozens of trials are under way or have been completed worldwide. In India, for example, poor elementary schoolchildren who were underachieving in math and literacy were given extra help by tutors who worked with the children in small groups (15–20 students) for two years. The tutors were mostly young, local women who had recently finished secondary school. Students in schools without tutors served as a control. Based on achievement tests, low-achieving students with tutors scored significantly higher than students in control schools, particularly in math. Surprisingly, these students also outscored students in a separate, more expensive program using computer-assisted learning. The low cost of hiring young tutors has enabled other school districts in India to expand the program to their schools.

In Kenya, a randomized trial tested whether providing schoolchildren with free deworming treatments and education on worm prevention improved their overall health, nutrition, and educational advancement. This study determined that school attendance improved by 25% when children were dewormed because they were sick less often. Moreover, the entire community's health benefited because the deworming of schoolchildren reduced the transmission of worm eggs to others in the community.

Researchers concluded that the cost of deworming was significantly less than that of other programs aimed at improving school attendance. J-PAL has been extended to study the effectiveness of social programs in the United States and Europe. In an ongoing study in France, for example, where unemployment is high, particularly among youth, university students with lower socioeconomic backgrounds were randomly placed into either treatment or control groups, with the treatment group receiving mentoring, workshops, and interactions with other students. Researchers hope to determine whether such interventions improve young people's employment prospects.

Achieving Population Stabilization

LEARNING OBJECTIVES

- Explain how individuals can adopt voluntary simplicity to mitigate the effects of population growth.

In this chapter, we have considered how population issues exacerbate global problems, including chronic hunger, poverty, and economic underdevelopment. Population stabilization is critically important if we are to effectively tackle these serious problems.

We have discussed many ways in which developing countries can achieve lower population growth rates. Improving access to public health, increasing the average level of education—especially for women, and providing greater employment for women are all critical to controlling population growth. All depend on community and government involvement.

Highly developed nations must face their own population problems, particularly the environmental costs of unsustainable consumption by affluent people (**Figure 8.16**). Policies should be formulated that support reducing the use of resources, increasing the reuse and recycling of materials, and expunging the throwaway mentality. These policies will show that highly developed countries are serious about the issues of rapid population growth and unsustainable consumption at home as well as abroad.

On a personal level, individuals in highly developed countries should examine their own consumptive practices and consider taking steps to reduce them. Individual efforts to reduce material consumption—sometimes called **voluntary simplicity**—are effective collectively and may influence others to reduce unnecessary consumption. Moving from a lifestyle based on accumulation of wealth and the things money can buy to a lifestyle of voluntary simplicity is called *downshifting*.

voluntary simplicity A way of life that involves wanting and spending less.

JEFF ZELEVANSKY/Reuters/Landov/Landov

Figure 8.16 Warehouse shopping. The United States consumes more goods per person than any other country in the world. The large U.S. population, 316 million in 2013, makes unsustainable consumption an even greater problem. Photographed in Union, New Jersey. How is consumption related to energy use?

Voluntary simplicity is not just living frugally. Instead, it involves desiring less of what money can buy. Each person who scales back his or her consumption benefits the environment (see discussion of ecological footprints in Chapter 1). As a result of needing less money, many people who downshift can afford to work fewer hours. People who advocate voluntary simplicity maintain that their lifestyle gives them fewer "things" but more time—time to do volunteer work, experience the natural world, and enjoy relationships.

Before purchasing a product, an individual striving for simplicity should ask if it is really needed. A material lifestyle—two or three cars in the garage, steaks on the grill, a television in every room, and similar luxury items—may provide short-term satisfaction. Such a lifestyle is not as fulfilling in the long term as learning about the world, interacting with others in meaningful ways, and contributing to the improvement of family and community. In the end, a rich life is measured not by what was owned but by what was done for others.

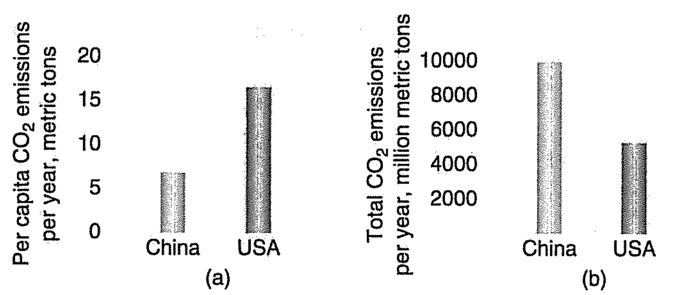
REVIEW

1. How does voluntary simplicity mitigate the effects of population growth?

ENERGY AND CLIMATE CHANGE

Population

Strong scientific evidence links climate change to increasing CO_2 emissions, most of which are produced by burning fossil fuels: coal, oil, and natural gas. Many factors interact among energy, climate, and population, particularly when considering trends in individual countries. *Per capita CO_2 emissions* in China, for example, are quite low compared to per capita emissions in highly developed countries such as the United States [part (a) of the figure]. But China is industrializing rapidly, and industrialization increases CO_2 emissions. Rapid economic development, combined with the huge number of people in China (more than 1.3 billion), has resulted in its *total annual CO_2 emissions* exceeding total annual emissions in the United States [part (b) of the figure]. China has abundant coal reserves, which have become its energy source of choice as its economy expands. Because burning coal produces more *CO_2 emissions per unit of energy* generated than any other source of fuel, China's CO_2 production per unit of energy is also higher than that in the United States.



Data from PBL Netherlands Environmental Assessment Agency, *Trends in Global CO_2 Emissions 2013 Report*

REVIEW OF LEARNING OBJECTIVES WITH SELECTED KEY TERMS

- **Define *demography* and summarize the history of human population growth.**

Demography is the applied branch of sociology that deals with population statistics and provides information on the populations of various countries or groups of people. Although it took thousands of years for the human population to reach 1 billion, it took only 130 years to reach 2 billion (in 1930), 30 years to reach 3 billion (in 1960), 15 years to reach 4 billion (in 1975), 12 years to reach 5 billion (in 1987), 12 years to reach 6 billion (in 1999), and 12 years to reach 7 billion (in 2011). World population continues to increase, but the world growth rate (r) has declined since the mid-1960s.

- **Identify Thomas Malthus, relate his ideas on human population growth, and explain why he might or might not be correct.**

Thomas Malthus, a 19th-century British economist, pointed out that the human population could increase faster than its food supply, resulting in famine, disease, and war. Some people think Malthus was wrong, in part because scientific advances have allowed food production to keep pace with population growth. Malthus may ultimately be correct because we do not know if our increase in food production is sustainable.

- **Explain why it is impossible to answer precisely how many people Earth can support—that is, Earth's carrying capacity for humans.**

Carrying capacity is the maximum number of individuals of a given species that a particular environment can support for an indefinite period, assuming there are no changes in the environment. Estimates of how many people Earth can support vary depending on what assumptions are made about standard of living, resource consumption, technological innovations, and waste generation. If we want all people to have a high level of material well-being equivalent to the lifestyles common in highly developed countries, then Earth will clearly support far fewer humans than if everyone lives just above the subsistence level.

- **Explain how highly developed and developing countries differ in population characteristics such as infant mortality rate, total fertility rate, and age structure.**

Infant mortality rate is the number of infant deaths (under age 1) per 1000 live births. **Total fertility rate (TFR)** is the average number of children born to each woman. **Age structure** is the number and proportion of people at each age in a population. **Highly developed countries** have the lowest infant mortality rates, lowest total fertility rates, and oldest age structure. Developing countries have the highest infant mortality rates, highest total fertility rates, and youngest age structure.

- **Explain how population growth momentum works.**

Population growth momentum is the potential for future increases or decreases in a population based on the present age structure. A country can have replacement-level fertility and still experience population growth if the largest percentage of the population is in the prereproductive years.

- **Relate carrying capacity to agricultural productivity.**

When land overuse occurs, often in combination with an extended drought, formerly productive lands may decline in agricultural productivity—that is, their carrying capacity may decrease.

- **Relate human population to chronic hunger and food insecurity.**

The rapid increase in population exacerbates many human problems, including hunger. **Food insecurity** is the condition in which people live with chronic hunger and malnutrition. The countries with the greatest food shortages have some of the highest **TFRs.**

- **Describe the relationship between economic development and population growth.**

Economic development is an expansion in a government's economy, viewed by many as the best way to raise the standard of living. Most economists think that slowing population growth promotes economic development.

- **Define *culture* and explain how total fertility rate and cultural values are related.**

Culture comprises the ideas and customs of a group of people at a given period; culture, which is passed from generation to generation, evolves over time. The relationship between TFR and culture is complex. Four factors are primarily responsible for high TFRs: high infant and child mortality rates, the important economic and societal roles of children in some cultures, the low status of women in many societies, and a lack of health and family planning services. Culture influences all of these factors.

- **Define *gender inequality* and relate the social and economic status of women to total fertility rate.**

Gender inequality is the social construct that results in women not having the same rights, opportunities, or privileges as men. The single-most important factor affecting high TFRs is the low status of women in many societies.

- **Explain how the availability of family planning services affects total fertility rate.**

Family planning services are services that enable men and women to limit family size, safeguard individual health rights, and improve the quality of life for themselves and their children. TFRs tend to decrease where family planning services are available.

- **Compare how the governments of China and Mexico have tried to slow human population growth.**

In 1979, China began a coercive one-child family policy to reduce TFR. The program is now relaxed in rural China; education and publicity campaigns are used today. In 1974, the Mexican government instigated several measures to reduce population growth, such as educational reform, family planning, and healthcare. Mexico's recent efforts at population control include multimedia campaigns.

- **Explain the role of population growth momentum in Mexico's population growth.**

Even with lower birth rates, Mexico's positive population growth momentum will cause its population to increase because of the large number of young women having babies.

- **Describe at least four of the Millennium Development Goals that came out of the UN Millennium Summit.**

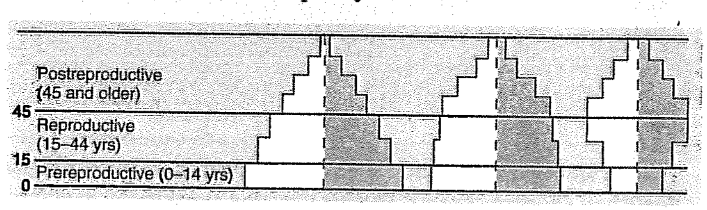
The UN Millennium Summit formed a global partnership with a plan of action, known as the **Millennium Development Goals (MDGs)**. The goals are to eradicate extreme hunger and poverty; achieve universal primary education; promote gender equality and empower women; reduce child mortality; improve maternal health; combat HIV/AIDS, malaria, and other diseases; ensure environmental sustainability; and develop a global partnership for economic development.

- **Explain how individuals can adopt voluntary simplicity to mitigate the effects of population growth.**

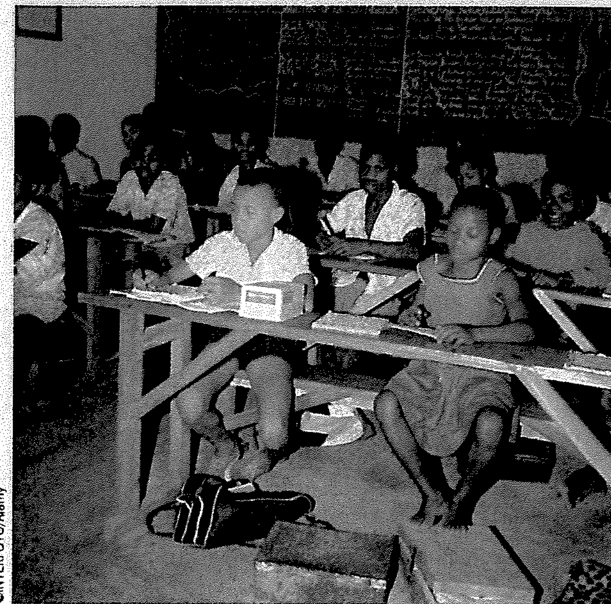
Voluntary simplicity is a way of life that involves wanting and spending less. Each person who scales back unnecessary consumption lessens the effects of population growth.

Critical Thinking and Review Questions

1. What are some of the factors that have contributed to the huge increase in the incidence of AIDS in sub-Saharan Africa? What are some indications that the trend is reversing?
2. What is demography?
3. What was the human population when you were born? When your parents were born?
4. Some people suggest that Malthus's ideas about human population growth outrunning the environment's ability to support it could happen on a global level. How might this happen in countries considered developing? In highly developed countries?
5. Why is it so difficult to apply the biological concept of carrying capacity directly to the human population?
6. What are total fertility rate and infant mortality rate? Which group of countries has the highest total fertility rates? Which group has the highest infant mortality rates?
7. Which population below is more likely to have a positive population growth momentum? Which is more likely to have a negative population growth momentum? Explain your answers.



8. How is carrying capacity of the Earth system related to land degradation and agricultural productivity?
9. What is food insecurity? What regions of the world have the greatest food insecurity?
10. How are population growth and economic development related?
11. How do cultural values affect fertility rate? Give examples.
12. What is voluntary simplicity? How is it related to resource consumption?
13. What is family planning? What considerations must family planning programs take into account if they are to reduce fertility rates?
14. China has the world's second largest economy and includes many highly industrialized regions, yet it is typically classified as a developing nation in large part because of its low per capita GNI PPP. What sorts of challenges described in this chapter does China likely face?
15. Why does Mexico have a positive population growth momentum?
16. What are four Millennium Development Goals that the nations of the world have aspired to? Do you consider them attainable? Why or why not?
17. This photograph shows Nigerian students in a classroom. Why do you think the school has many more boys than girls? How is fertility rate related to educational opportunities for women?



©INTERFOTO/Alamy

18. Discuss this statement: The current human population crisis causes or exacerbates all environmental problems, including energy issues and climate change.

World Population Data Sheet Assignment

Use the Population Reference Bureau's *World Population Data Sheet 2014* from www.prb.org to answer the following questions.

1. What is the estimated world population in billions?
2. What is the current birth rate for the world?
3. Which continent has the highest birth rate, and what is this rate?
4. Which country or countries has/have the highest birth rate, and what is this rate?
5. Which continent has the lowest birth rate, and what is this rate?
6. Which country or countries has/have the lowest birth rate, and what is this rate?
7. What is the current death rate for the world?
8. Which country or countries has/have the highest death rate, and what is this rate?
9. How many countries do not have a positive natural increase (i.e., they are either stable or decreasing in population)? In which regions are they found?
10. Which country or countries has/have the highest infant mortality rate, and what is this rate?
11. Which country or countries has/have the lowest infant mortality rate, and what is this rate?
12. Which country or countries has/have the highest total fertility rate, and what is this rate?
13. Which country or countries has/have the lowest total fertility rate, and what is this rate?
14. Which country or countries has/have the highest percentage of the population under age 15, and what is this percentage?
15. Which country or countries has/have the highest percentage of the population over age 65, and what is this percentage?
16. Which country or countries has/have the longest life expectancy, and what is this figure?
17. Which country or countries has/have the shortest life expectancy, and what is this figure?
18. Which country or countries has/have the highest percentage of the population living in urban areas, and what is this percentage?
19. Which country or countries has/have the highest per capita GNI PPP, and what is this figure?
20. Which country or countries has/have the lowest per-capita GNI PPP, and what is this figure?

Food for Thought

Visit the Millennium Villages website and research the food topics addressed by the many past and ongoing projects in the participating villages. What are the primary concerns tackled in efforts to end hunger and provide a sustainable food supply in the Millennium Villages? How might these problems differ from challenges faced in providing a steady and healthy food supply to the hungry in your community?