CHAPTER 6

The Biogeochemical Cycles

As a result of biogeochemical cycles marine life is plentiful in the Santa Barbara Channel of southern California.

LEARNING OBJECTIVES

Life is composed of many chemical elements, which have to be available in the right amounts, the right concentrations, and the right ratios to one another. If these conditions are not met, then life is limited. The study of chemical availability and biogeochemical cycles—the paths chemicals take through Earth's major systems—is important in solving many environmental problems. After reading this chapter, you should understand . . .

- What the major biogeochemical cycles are;
- How life, over the Earth's history, has greatly altered chemical cycles;
- The major factors and processes that control biogeochemical cycles;
- Why some chemical elements cycle quickly and some slowly;
- How each major component of Earth's global system (the atmosphere, waters, solid surfaces, and life) is involved and linked with biogeochemical cycles;
- How the biogeochemical cycles most important to life, especially the carbon cycle, generally operate;
- How humans affect biogeochemical cycles.

CASE STUDY

Methane and Oil Seeps: Santa Barbara Channel

FIGURE 6.1 **Coal Oil Point, Santa Barbara**, the location of large offshore oil and gas seeps on one of America's most beautiful coastlines. Active oil and gas seeps are located from near the shore to just past offshore platform Holly that has many pumping oil wells.

The Santa Barbara Channel off the shore of southern and central California is home to numerous species, including such marine mammals as dolphins, sea otters, elephant seals, sea lions, harbor seals, and blue, humpback, and gray whales; many birds, including brown pelicans; and a wide variety of fish. The channel is also a region with large oil and gas resources that have been exploited by people for thousands of years.[1,2,3] For centuries, Native Americans who lived along the shoreline collected tar from oil seeps to seal baskets and the planks of their seagoing canoes. During the last century, oil wells on land and from platforms anchored on the seabed have been extracting oil and gas. Oil and gas are hydrocarbons, and as such are part of the global carbon cycle that involves physical, geological, biological, and chemical processes.

The story of oil and gas in the Santa Barbara Channel begins 6–18 million years ago with the deposition of a voluminous amount of fine sediment, enriched with planktonic microorganisms whose bodies sank to the ocean floor and were buried. (*Planktonic* refers to small floating algae and animals.) Over geologic time, the sediment was transformed into sedimentary rock, and the organic material was transformed by heat and pressure into oil and gas. About a million or so years ago, tectonic uplift and fracturing forced the oil and gas toward the surface. Oil and gas seepage has reached the surface for at least 120,000 years and perhaps more than half a million years.

Some of the largest seeps of oil and natural gas (primarily methane) are offshore of the University of California, Santa Barbara, at Coal Oil Point, where about 100 barrels of oil and approximately 57,000 m^3 (2 million cubic feet) of gas are released per day (Figures 6.1 and 6.2). To put the amount of oil in perspective, the 1989 *Exxon Valdez* tanker accident in Prince William Sound released about 250,000 barrels of oil. Thus, the oil seeping from the Coal Oil Point area alone equals one *Exxon Valdez* accident every seven years. This is a tremendous amount of oil to be added to the marine environment.

Sudden emissions of gases create small pits on the seafloor. The gas rises as clouds of bubbles clearly visible at the surface (Figure 6.2b and c). Once at the surface, the oil and gas form slicks that are transported by marine currents and wind. On the seafloor, the heaviest materials form mounds of tar several meters or more in diameter.[3] Some of the thicker tar washes up on local beaches, sometimes covering enough of the water and beach to stick to the bare skin of walkers and swimmers. Tar may be found on beaches for several kilometers to the east.

The emitted hydrocarbon gases contribute to air pollution in the Santa Barbara area. Once in the atmosphere, they interact with sunlight to produce smog, much like the smog produced by hydrocarbon emissions from automobiles in Los Angeles. If all the methane ended up in the atmosphere as hydrocarbons, the contribution to air pollution in Santa Barbara County would be about double the emission rate from all on-road vehicles in Santa Barbara County.

Fortunately for us, seawater has a tremendous capacity to take up the methane, and bacteria in the ocean feed on the methane, releasing carbon dioxide (Figure 6.2a). The ocean and its bacteria thus take care of about half the methane moving up from the seeps. Thanks to microbial decomposition of the methane, only about 1% of the methane that is dissolved in the seawater is emitted into the atmosphere.[1, 2]

Even so, in recent years people have taken action to further control the oil and gas seeps at Coal Oil Point. Two steel seep tents (each 30 m by 30 m) have been placed over some of the methane seeps, and the gas is collected and moved to the shore through pipelines, for use as natural gas. Furthermore, the pumping of oil from a single well from a nearby platform with many wells apparently has reduced emissions of methane and oil from the seeps. What drives methane emission is pressure from below, and pumping from the wells evidently reduces that pressure.

The lesson from the methane and oil seeps at Coal Oil Point is twofold: first, that this part of the carbon cycle is a complex linkage of physical, biological, and chemical processes; and second, that human activity may also play a role. These two concepts will be a recurring theme in our discussion of the major biogeochemical cycles that concern us today.

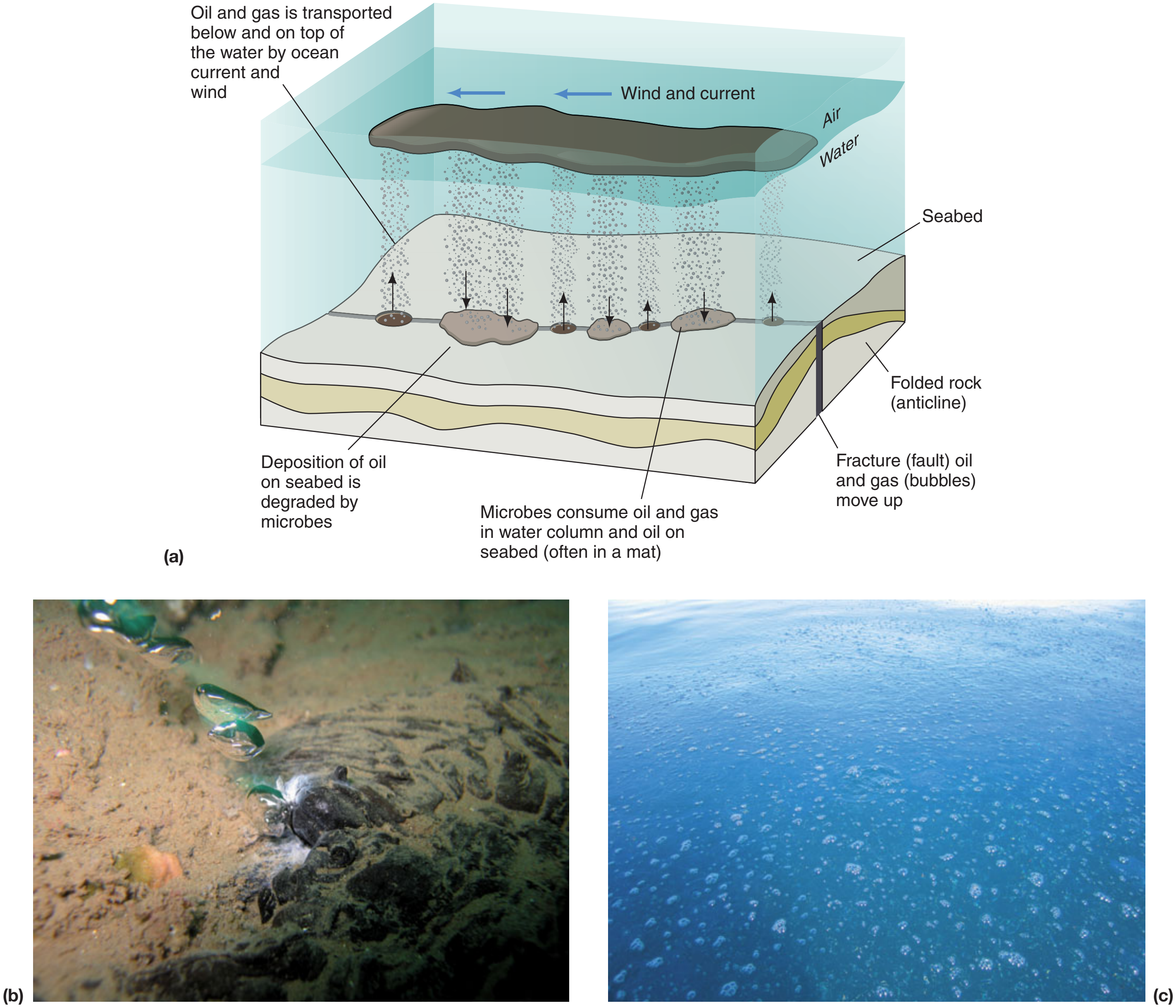


FIGURE 6.2 **(a)** Idealized diagram of physical, chemical, and biological processes with shallow methane and oil seeps; **(b)** small bubbles of methane (~1 cm) from a seep at Coal Oil Point on the seabed; and **(c)** methane bubbles (~1 cm) at the surface. (*Photographs courtesy of David Valentine.*)

6.1 Earth Is a Peculiar Planet

Our planet, Earth, is unique, at least to the extent that we have explored the cosmos. In our solar system, and in the Milky Way galaxy to the extent that we have observed it, Earth is the only body that has the combination of four characteristics: liquid water; water at its triple point (gas, liquid, and solid phases at the same time); plate tectonics; and life (Figure 6.3). (Recent space probes to the moons of Jupiter and Saturn suggest that there may be liquid water on a few of these and perhaps also an equivalent of plate tectonics. And recent studies of Mars suggest that liquid water has broken through to the surface on occasion in the past, causing Earthlike water erosion.)

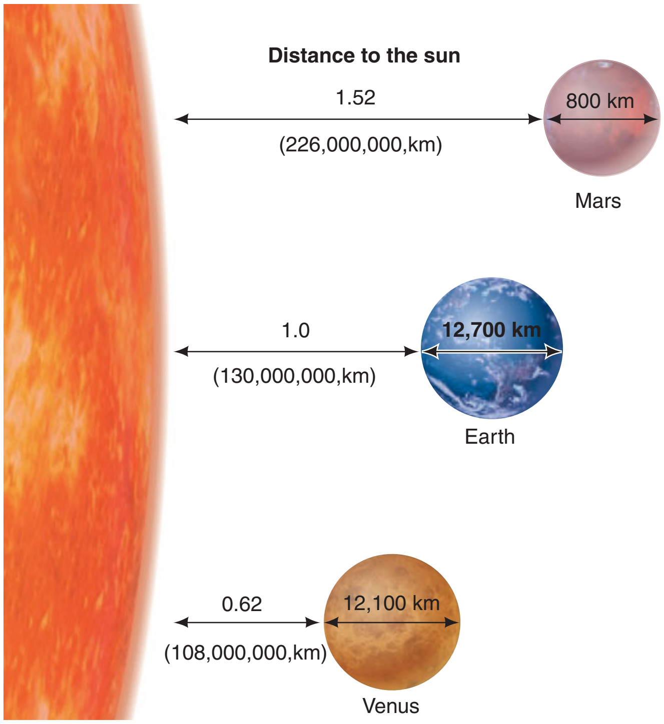
The above discussion leads to consideration of the history of Earth over billions of years. This has prompted some geologists to propose "big history"—to link contemporary history with geologic history, perhaps even going back all the way to the *Big Bang*

12 billion years ago, when our universe was born.[4,5] The main regimes of big history include cosmos, Earth, and life. To this, in the context of environmental science, we add human history.[4,5]

Space Travelers and Our Solar System

Life changes the cycling of chemical elements on Earth and has done so for several billion years.[6] To begin to examine this intriguing effect of life at a global level, it is useful to imagine how travelers from another solar system might perceive our planet. Imagine these space travelers approaching our solar system. They find that their fuel is limited and that of the four inner planets, only two, the second (Venus) and the fourth (Mars), are on their approach path. By chance, and because of differences in the orbits of the planets, the first (Mercury) and the third (Earth) are both on the opposite side of the sun, not easily visible for their instruments to observe or possible for their spacecraft to approach closely. However, they can observe Mars and Venus as they fly by them, and from those observations hypothesize about the characteristics of the planet whose orbit is between those two—Earth (Figure 6.4).

The space travelers' instruments tell them that the atmospheres of Venus and Mars are primarily carbon dioxide, with some ammonia (nitrogen combined with hydrogen) and trace amounts of nitrogen, oxygen, argon, and the other "noble gases"—that is, elements like argon that form few compounds. Since the space travelers understand how solar systems originate, they know that the inner planets are formed by the gathering together of particles as a result of gravitational force. Therefore, they believe that the second, third, and fourth planets should have a similar composition, and this leads them to believe that it is reasonable to assume the third planet will have an atmosphere much like that of Venus and Mars.



Atmosphere	Venus	Earth	Mars
Carbon dioxide	98%	0.03%	96%
Hydrogen	1.9%	73%	2.7%
Oxygen	Trace	21%	0.13%
Argon	0.1%	1%	2%
Total Pressure (bars)	90	1	0.00
Surface temperature	447°C	13°C	−53°C

FIGURE 6.3 **Venus, Earth, and Mars.** These three planets had a common origin and should be similar. They are within a factor of 2 in size and distance from the sun, and the atmospheres of Mars and Venus are similar in chemical makeup. Earth's atmosphere, however, is very different.

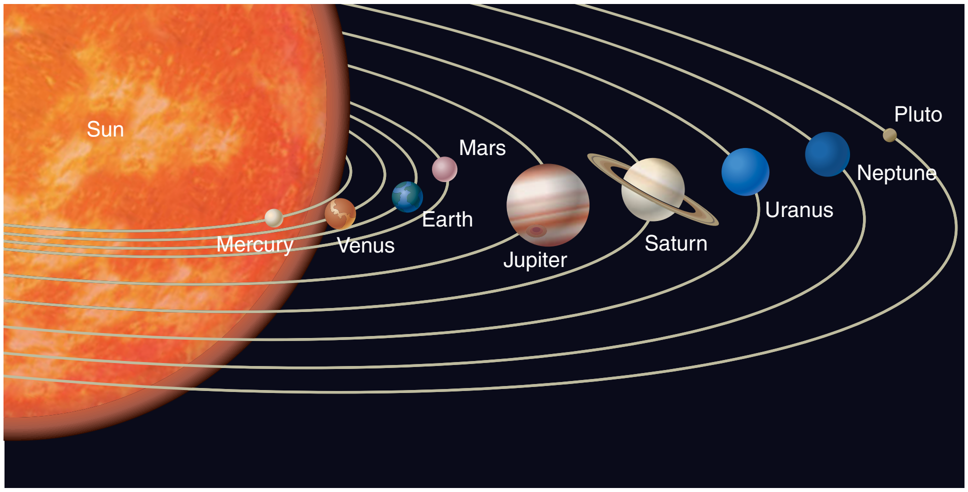


FIGURE 6.4 **Our solar system with the planets (Pluto is not classified as a planet) shown from NASA space probes**. Imagine travel to this system from another and wondering what the third planet was like.

Suppose a later space flight from the same solar system visits ours once again, but this time it is able to approach Earth. Knowing the results of the previous voyage, the new travelers are surprised to discover that Earth's atmosphere is entirely different from those of Venus and Mars. It is composed primarily (78%) of free (molecular) nitrogen (N_2), with about 20% oxygen, a trace of carbon dioxide and other gases, and some argon. What has caused this great difference? Because they are trained in science and in the study of life in the universe, and because they come from a planet that has life, these space travelers recognize the cause immediately: *Earth must contain life.* Life changes its planet's atmosphere, oceans, and upper surfaces. Even without seeing life directly, they know from its atmosphere that Earth is a "living" planet.

The great 20th-century ecologist G. Evelyn Hutchinson described this phenomenon succinctly. The strangest characteristic of Earth's surface, he wrote, is that it is not in thermodynamic equilibrium, which is what would happen if you were able to carry out a giant experiment in which you took Earth, with its atmosphere, oceans, and solid surfaces, and put it into a closed container sealed against the flow of energy and matter. Eventually the chemistry of the air, water, and rocks would come into a chemical and physical fixed condition where the energy was dispersed as heat and there would be no new chemical reactions. Physicists will tell you that everything would be at the lowest energy level, that matter and energy would be dispersed randomly, and nothing would be happening. This is called the **thermodynamic equilibrium**. In this giant experiment, this equilibrium would resemble that in the atmospheres of Mars and Venus, and Earth's atmosphere would be very different from the way it is now.

Life on Earth acts as a pump to keep the atmosphere, ocean, and rocks far from a thermodynamic equilibrium. The highly oxygenated atmosphere is so far from a thermodynamic equilibrium that it is close to an explosive combination with the organic matter on the Earth. James Lovelock, the originator of the Gaia hypothesis, has written that if the oxygen concentration in the atmosphere rose a few percentage points, to around 22% or higher, fires would break out spontaneously in dead wood on Earth's surface.[6] It's a controversial idea, but it suggests how close the present atmosphere is to a violent disequilibrium.[7]

The Fitness of the Environment[8]

Early in the 20th century, a scientist named Lawrence Henderson wrote a book with a curious title: *The Fitness of the Environment.*[9] In this book, Henderson observed that the environment on Earth was peculiarly suited to life. The question was, how did this come about? Henderson sought to answer this question in two ways: first, by examining the cosmos and seeking an answer in the history of the universe and in fundamental characteristics of the universe; second, by examining the properties of Earth and trying to understand how these may have come about.

"In the end there stands out a perfectly simple problem which is undoubtedly soluble," Henderson wrote. "In what degree are the physical, chemical, and general meteorological characteristics of water and carbon dioxide and of the compounds of carbon, hydrogen, and oxygen favorable to a mechanism which must be physically, chemically, and physiologically complex, which must be itself well regulated in a well-regulated environment, and which must carry on an active exchange of matter and energy with that environment?" In other words, to what extent are the nonbiological properties of the global environment favorable to life? And why is Earth so fit for life?

Today, we can give partial answers to Henderson's question. The answers involve recognizing that "environmental fitness" is the result of a two-way process. Life evolved in an environment conducive for that to occur, and then, over time, life altered the environment at a global level. These global alterations were originally problems for existing organisms, but they also created opportunities for the evolution of new life-forms adapted to the new conditions.

The Rise of Oxygen

The fossil record provides evidence that before about 2.3 billion years ago Earth's atmosphere was very low in oxygen (anoxic), much closer to the atmospheres of Mars and Venus. The evidence for this exists in water-worn grains of pyrite (iron sulfide, FeS_2), which appear in sedimentary rocks formed before 2.3 billion years ago. Today, when pure iron gets into streams, it is rapidly oxidized because there is so much oxygen in the atmosphere, and the iron forms sediments of iron oxides (what we know familiarly as rusted iron). If there were similar amounts of oxygen in the ancient waters, these ancient deposits would not have been pyrite—iron combined with sulfur—but would have been oxidized, just as they are today. This tells us that Earth's ancient Precambrian atmosphere and oceans were low in oxygen.

The ancient oceans had a vast amount of dissolved iron, which is much more soluble in water in its unoxidized state. Oxygen released into the oceans combined with the dissolved iron, changing it from a more soluble to a less soluble form. No longer dissolved in the water, the iron settled (precipitated) to the bottom of the oceans and became part of deposits that slowly were turned into rock. Over millions of years, these deposits formed the thick bands of iron ore that are mined today all around Earth, with notable deposits found today from Minnesota to Australia. That was the major time when the great iron ore deposits, now mined, were formed. It is intriguing to realize that very ancient Earth history affects our economic and environmental lives today.

FIGURE 6.5 Banded-iron formations. Photograph of the Grand Canyon showing red layers that contain oxidized iron below layers of other colors that lack the deposited iron.

The most convincing evidence of an oxygen-deficient atmosphere is found in ancient chemical sediments called *banded-iron formations* (Figure 6.5).

These sediments were laid down in the sea, a sea that must have been able to carry dissolved iron—something it can't do now because oxygen precipitates the iron. If the ancient sea lacked free oxygen, then oxygen must also have been lacking in the atmosphere; otherwise, simple diffusion would have brought free oxygen into the ocean from the atmosphere.

How did the atmosphere become high enough in oxygen to change iron deposits from unoxidized to oxidized? The answer is that life changed the environment at a global level, adding free oxygen and removing carbon dioxide, first within the oceans, then in the atmosphere. This came about as a result of the evolution of photosynthesis. In photosynthesis, you will recall, carbon dioxide and water are combined, in the presence of light, to form sugar and free oxygen. But in early life, oxygen was a toxic waste that was eliminated from the cell and emitted into the surrounding environment. Scientists calculate that before oxygen started to accumulate in the air, 25 times the present-day amount of atmospheric oxygen had been neutralized by reducing agents such as dissolved iron. It took about 2 billion years for the unoxidized iron in Earth's oceans to be used up.

Life Responds to an Oxygen Environment

Early in Earth's history, from 4.6 billion years ago until about 2.3 billion years ago, was the oxygen-deficient phase of life's history. Some of the earliest photosynthetic organisms (3.4 billion years ago) were ancestors of bacteria that formed mats in shallow water (Figure 6.6). Photosynthesis became well established by about 1.9 billion years ago, but until sufficient free oxygen was in the atmosphere, organisms could get their energy only by

FIGURE 6.6 Stromatolites. Among the earliest photosynthetic organisms were bacteria that formed these large mounds called stromatolites **(a)**, fossils of which, shown here, have been dated as old as 3.4 billion years. The bacteria grew in long filaments—cells connected to one another in a line—and these formed layers that were infiltrated by sand and clay that washed down from the land into the shallow waters of the bays where this kind of photosynthetic bacteria lived (they took oxygen from water). Over time, the combination of sediments and living and dead bacterial cells formed large mounds. Similar bacteria, if not exactly the same species, still live, and form the same kind of mounds shown here in Shark Bay, Australia **(b)**. The ancient stromatolites were among the organisms that eventually created an oxygen-rich atmosphere.

fermentation, and the only kinds of organisms were bacteria and their relatives called **prokaryotes**. These have a simpler internal cell structure than that of the cells of our bodies and other familiar forms of life, known as **eukaryotes** (Figure 6.7).

Without oxygen, organisms cannot completely "burn" organic compounds. Instead, they can get some energy from what we call fermentation, whose waste products are carbon dioxide and alcohol. Alcohol is a high-energy compound that, for the cell in an oxygenless atmosphere, is a waste product that has to be gotten rid of. Fermentation's low-energy yield to the organism puts limitations on the anaerobic cell. For example:

- Anaerobic cells must be small because a large surface-to-volume ratio is required to allow rapid diffusion of food in and waste out.
- Anaerobic cells have trouble keeping themselves supplied with energy. They cannot afford to use energy to maintain **organelles**—specialized cell parts that function like the organs of multicelled organisms. This means that all anaerobic bacteria were prokaryotes lacking specialized organelles, including a nucleus.
- Prokaryotes need free space around them; crowding interferes with the movement of nutrients and water into and out of the cell. Therefore, they live singly or strung end-to-end in chains. They cannot form three-dimensional structures. They are life restricted to a plane.

For other forms of life to evolve and persist, bacteria had to convert Earth's atmosphere to one high in oxygen. Once the atmosphere became high in oxygen, complete respiration was possible, and organisms could have much more complex structures, with three-dimensional bodies, and could use energy more efficiently and rapidly. Thus the presence of free oxygen, a biological product, made possible the evolution of eukaryotes, organisms with more structurally complex cells and bodies, including the familiar animals and plants. Eukaryotes can do the following:

- Use oxygen for respiration, and because oxidative respiration is much more efficient (providing more energy) than fermentation, eukaryotes do not require as large a surface-to-volume ratio as anaerobic cells do, so eukaryote cells are larger.
- Maintain a nucleus and other organelles because of their superior metabolic efficiency.
- Form three-dimensional colonies of cells. Unlike prokaryotes, aerobic eukaryotes are not inhibited by crowding, so they can exist close to each other. This made possible the complex, multicellular body structures of animals, plants, and fungi.

Animals, plants, and fungi first evolved about 700 million to 500 million years ago. Inside their cells, DNA, the genetic material, is concentrated in a nucleus rather than distributed throughout the cell, and the cell contains organelles such as mitochondria which process energy. With the appearance of eukaryotes and the growth of an oxygenated atmosphere, the **biosphere**—our planet's system that includes and sustains all life—started to change rapidly and to influence more processes on Earth.

In sum, life affected Earth's surface—not just the atmosphere, but the oceans, rocks, and soils—and it still does so today. Billions of years ago, Earth presented a habitat where life could originate and flourish. Life, in turn, fundamentally changed the characteristics of the planet's surface, providing new opportunities for life and ultimately leading to the evolution of us.

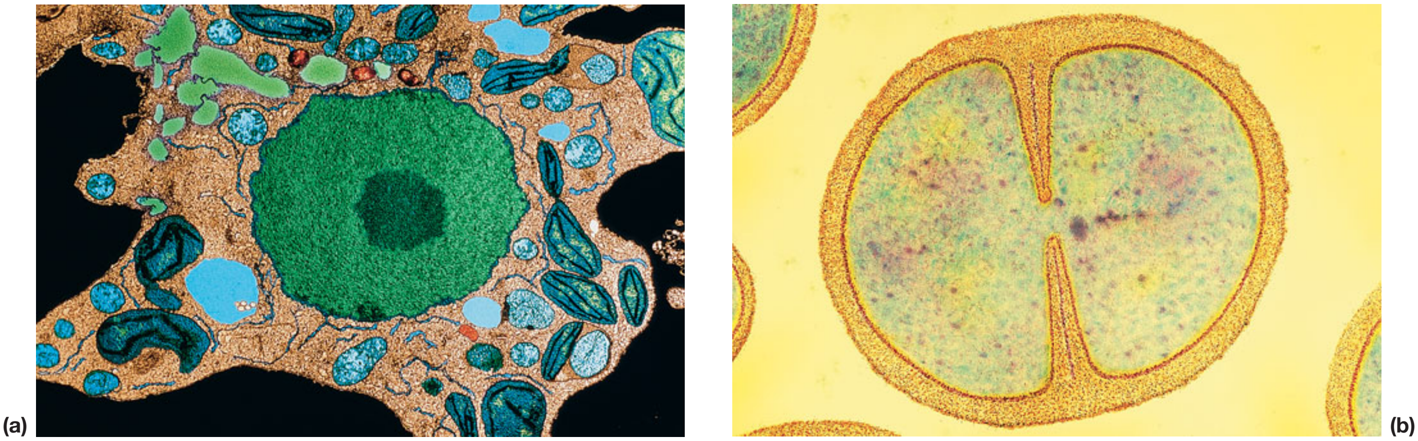


FIGURE 6.7 **Prokaryotes and eukaryotes.** Photomicrograph of **(a)** bacterial (Prokaryote)cell and **(b)** a bacterial (prokaryote) cell. From these images you can see that the eukaryotic cell has a much more complex structure, including many organelles.

6.2 Life and Global Chemical Cycles

All living things are made up of chemical elements (see Appendix D for a discussion of matter and energy), but of the more than 103 known chemical elements, only 24 are required by organisms (see Figure 6.8). These 24 are divided into the **macronutrients**, elements required in large amounts by all life, and **micronutrients**, elements required either in small amounts by all life or in moderate amounts by some forms of life and not at all by others. (*Note*: For those of you unfamiliar with the basic chemistry of the elements, we have included an introduction in Appendix E, which you might want to read now before proceeding with the rest of this chapter.)

The macronutrients in turn include the "big six" elements that are the fundamental building blocks of life: carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur. Each one plays a special role in organisms. Carbon is the basic building block of organic compounds; along with oxygen and hydrogen, carbon forms carbohydrates. Nitrogen, along with these other three, makes proteins. Phosphorus is the "energy element"—it occurs in compounds called ATP and ADP, important in the transfer and use of energy within cells.

Other macronutrients also play specific roles. Calcium, for example, is the structure element, occurring in bones and teeth of vertebrates, shells of shellfish, and wood-forming cell walls of vegetation. Sodium and potassium are important to nerve-signal transmission. Many of the metals required by living things are necessary for specific enzymes. (An enzyme is a complex organic compound that acts as a catalyst—it causes or speeds up chemical reactions, such as digestion.)

For any form of life to persist, chemical elements must be available at the right times, in the right amounts, and in the right concentrations. When this does not happen, a chemical can become a **limiting factor**, preventing the growth of an individual, a population, or a species, or even causing its local extinction.

Chemical elements may also be toxic to some life-forms and ecosystems. Mercury, for example, is toxic even in low concentrations. Copper and some other

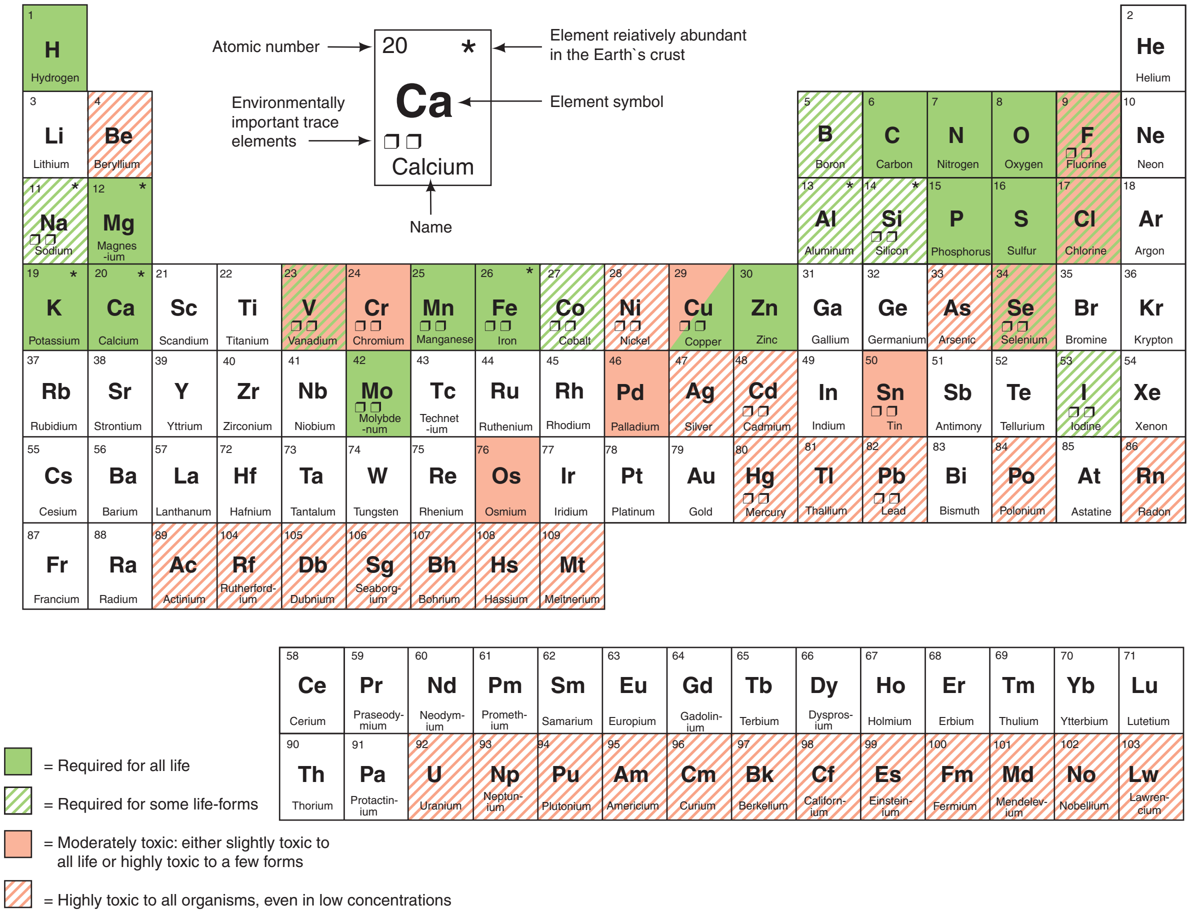


FIGURE 6.8 The Periodic Table of the Elements. The elements in green are required by all life; those in hatched green are micronutrients—required in very small amounts by all life-forms or required by only some forms of life. Those that are moderately toxic are in hatched red, and those that are highly toxic are solid red.

elements are required in low concentrations for life processes but are toxic in high concentrations.

Finally, some elements are neutral for life. Either they are chemically inert, such as the noble gases (for example, argon and neon), which do not react with other elements, or they are present on Earth in very low concentrations.

6.3 General Aspects of Biogeochemical Cycles

A **biogeochemical cycle** is the complete path a chemical takes through the four major components, or reservoirs, of Earth's system: atmosphere, hydrosphere (oceans, rivers, lakes, groundwaters, and glaciers), lithosphere (rocks and soils), and biosphere (plants and animals). A biogeochemical cycle is *chemical* because it is chemicals that are cycled, *bio-* because the cycle involves life, and *geo-* because a cycle may include atmosphere, water, rocks, and soils. Although there are as many biogeochemical cycles as there are chemicals, certain general concepts hold true for these cycles.

- Some chemical elements, such as oxygen and nitrogen, cycle quickly and are readily regenerated for biological activity. Typically, these elements have a gas phase and are present in the atmosphere and/or easily dissolved in water and carried by the hydrologic cycle (discussed later in the chapter).
- Other chemical elements are easily tied up in relatively immobile forms and are returned slowly, by geologic processes, to where they can be reused by life. Typically, they lack a gas phase and are not found in significant concentrations in the atmosphere. They also are relatively insoluble in water. Phosphorus is an example.
- Most required nutrient elements have a light atomic weight. The heaviest required micronutrient is iodine, element 53.
- Since life evolved, it has greatly altered biogeochemical cycles, and this alteration has changed our planet in many ways.
- The continuation of processes that control biogeochemical cycles is essential to the long-term maintenance of life on Earth.

Through modern technology, we have begun to transfer chemical elements among air, water, and soil, in some cases at rates comparable to natural processes. These transfers can benefit society, as when they improve crop production, but they can also pose environmental dangers, as illustrated by the opening case study. To live wisely with our environment, we must recognize the positive and negative consequences of altering biogeochemical cycles.

The simplest way to visualize a biogeochemical cycle is as a box-and-arrow diagram of a system (see the discussion of systems in Chapter 3), with the boxes representing places where a chemical is stored (*storage compartments*) and the arrows representing pathways of transfer (Figure 6.9a). In this kind of diagram, the **flow** is the amount moving from one compartment to another, whereas the **flux** is the rate of transfer—the amount per unit time—of a chemical that enters or leaves a storage compartment. The **residence time** is the average time that an atom is stored in a compartment. The donating compartment is a **source**, and the receiving compartment is a **sink**.

A biogeochemical cycle is generally drawn for a single chemical element, but sometimes it is drawn for a compound—for example, water (H_2O). Figure 6.9b shows the basic elements of a biogeochemical cycle for water, represented about as simply as it can be, as three compartments: water stored temporarily in a lake (compartment B); entering the lake from the atmosphere (compartment A) as precipitation and from the land around the lake as runoff (compartment C). It leaves the lake through evaporation to the atmosphere or as runoff via a surface stream or subsurface flows. We diagrammed the Missouri River in the opening case study of Chapter 3 in this way.

As an example, consider a salt lake with no transfer out except by evaporation. Assume that the lake contains 3,000,000 m^3 (106 million ft^3) of water and the evaporation is 3,000 m^3/day (106,000 ft^3/day). Surface runoff into the lake is also 3,000 m^3/day, so the volume of water in the lake remains constant (input = output). We can calculate the average residence time of the water in the lake as the volume of the lake divided by the evaporation rate (rate of transfer), or 3,000,000 m^3 divided by 3,000 m^3/day, which is 1,000 days (or 2.7 years).

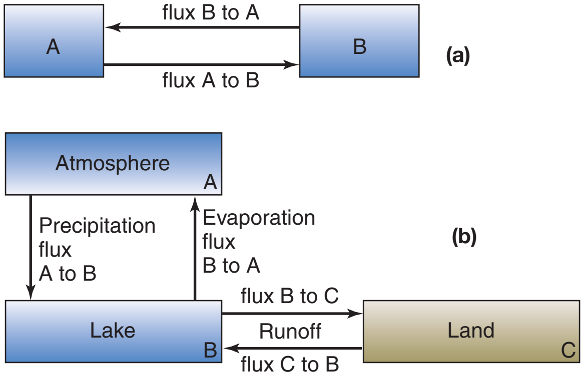


FIGURE 6.9 **(a)** A unit of a biogeochemical cycle viewed as a systems diagram; **(b)** a highly simplified systems diagram of the water cycle.

6.4 The Geologic Cycle

Throughout the 4.6 billion years of Earth's history, rocks and soils have been continuously created, maintained, changed, and destroyed by physical, chemical, and biological processes. This is another illustration that the biosphere is a dynamic system, not in steady state. Collectively, the processes responsible for formation and change of Earth materials are referred to as the **geologic cycle** (Figure 6.10). The geologic cycle is best described as a group of cycles: tectonic, hydrologic, rock, and biogeochemical. (We discuss the last cycle separately because it requires lengthier examination.)

The Tectonic Cycle

The **tectonic cycle** involves the creation and destruction of Earth's solid outer layer, the *lithosphere*. The lithosphere is about 100 km (60 mi) thick on average and is broken into several large segments called *plates*, which are moving relative to one another (Figure 6.11). The slow movement of these large segments of Earth's outermost rock shell is referred to as **plate tectonics**. The plates "float" on denser material and move at rates of 2 to 15 cm/year (0.8 to 6.9 in./year), about as fast as your fingernails grow. The tectonic cycle is driven by forces originating deep within the earth. Closer to the surface, rocks are deformed by spreading plates, which produce ocean basins, and by collisions of plates, which produce mountain ranges and island-arc volcanoes.

Plate tectonics has important environmental effects. Moving plates change the location and size of continents, altering atmospheric and ocean circulation and thereby altering climate. Plate movement has also created ecological islands by breaking up continental areas. When this happens, closely related life-forms are isolated from one another for millions of years, leading to the evolution of new species. Finally, boundaries

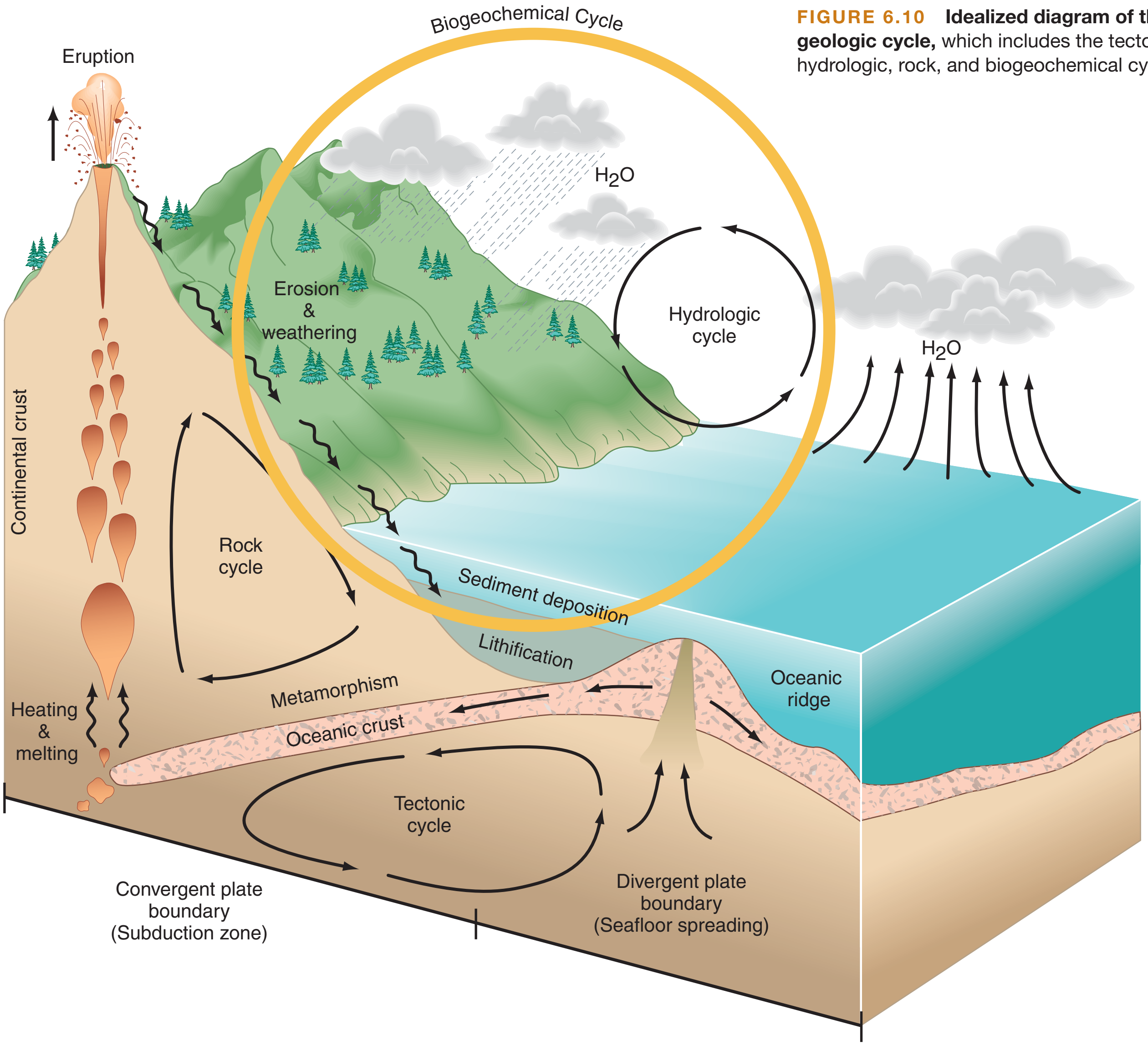


FIGURE 6.10 Idealized diagram of the geologic cycle, which includes the tectonic, hydrologic, rock, and biogeochemical cycles.

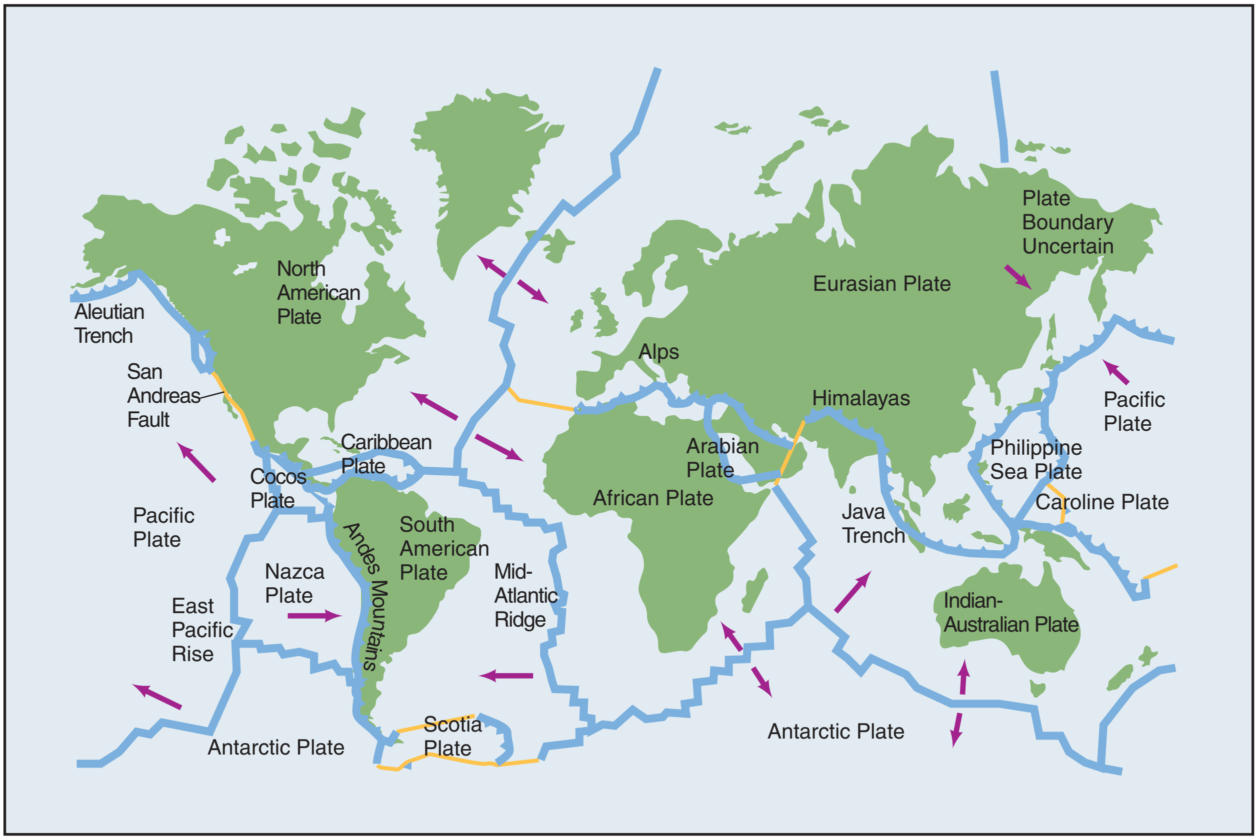


FIGURE 6.11 **Generalized map of Earth's lithospheric plates.** Divergent plate boundaries are shown as heavy lines (for example, the Mid-Atlantic Ridge). Convergent boundaries are shown as barbed lines (for example, the Aleutian trench). Transform fault boundaries are shown as yellow, thinner lines (for example, the San Andreas Fault). Arrows indicate directions of relative plate motions. (*Source*: Modified from B.C. Burchfiel, R.J. Foster, E.A. Keller, W.N. Melhorn, D.G. Brookins, L.W. Mintz, and H.V. Thurman, *Physical Geology: The Structures and Processes of the Earth* [Columbus, Ohio: Merrill, 1982].)

between plates are geologically active areas, and most volcanic activity and earthquakes occur there. Earthquakes occur when the brittle upper lithosphere fractures along faults (fractures in rock within the Earth's crust). Movement of several meters between plates can occur within a few seconds or minutes, in contrast to the slow, deeper plate movement described above.

Three types of plate boundaries occur: divergent, convergent, and transform faults.

A divergent plate boundary occurs at a spreading ocean ridge, where plates are moving away from one another and new lithosphere is produced. This process, known as *seafloor spreading*, produces ocean basins.

A convergent plate boundary occurs when plates collide. When a plate composed of relatively heavy ocean-basin rocks dives (subducts) beneath the leading edge of a plate composed of lighter continental rocks, a subduction zone is present. Such a convergence may produce linear coastal mountain ranges, such as the Andes in South America. When two plates that are both composed of lighter continental rocks collide, a continental mountain range may form, such as the Himalayas in Asia.

A transform fault boundary occurs where one plate slides past another. An example is the San Andreas Fault in California, which is the boundary between the North American and Pacific plates. The Pacific plate is moving north, relative to the North American plate, at about 5 cm/year (2 in./year). As a result, Los Angeles is moving slowly toward San Francisco, about 500 km (300 mi) north. If this continues, in about 10 million years San Francisco will be a suburb of Los Angeles.

Uplift and subsidence of rocks, along with erosion, produce Earth's varied topography. The spectacular Grand Canyon of the Colorado River in Arizona (Figure 6.12a), sculpted from mostly sedimentary rocks, is one example. Another is the beautiful tower karst in China (Figure 6.12b). These resistant blocks of limestone have survived chemical weathering and erosion that removed the surrounding rocks.

FIGURE 6.12 **Plate tectonics and landscapes. (a)** In response to slow tectonic uplift of the region, the Colorado River has eroded through the sedimentary rocks of the Colorado plateau to produce the spectacular Grand Canyon. The river in recent years has been greatly modified by dams and reservoirs above and below the canyon. Sediment once carried to the Gulf of California is now deposited in reservoirs. The dam stores sediments, and some of the water released is from the deeper and thus cooler parts of the reservoir, so water flowing out of the dam and down through the Grand Canyon is clearer and colder than it used to be. Fewer sandbars are created; this and the cooler water change which species of fish are favored. Thus this upstream dam has changed the hydrology and environment of the Colorado River in the Grand Canyon. **(b)** This landscape in the People's Republic of China features tower karst, steep hills or pinnacles composed of limestone. The rock has been slowly dissolving through chemical weathering. The pinnacles and hills are remnants of the weathering and erosion processes.

The Hydrologic Cycle

The **hydrologic cycle** (Figure 6.13) is the transfer of water from the oceans to the atmosphere to the land and back to the oceans. It includes evaporation of water from the oceans; precipitation on land; evaporation from land; transpiration of water by plants; and runoff from streams, rivers, and subsurface groundwater. Solar energy drives the hydrologic cycle by evaporating water from oceans, freshwater bodies, soils, and vegetation. Of the total 1.3 billion km^3 of water on Earth, about 97% is in oceans and about 2% is in glaciers and ice caps; 0.76% is shallow groundwater: 0.013% is in lakes and rivers; and only 0.001% is in the atmosphere. Although water on land and in the atmosphere accounts for only a small fraction of the water on Earth, this water is important in moving chemicals,

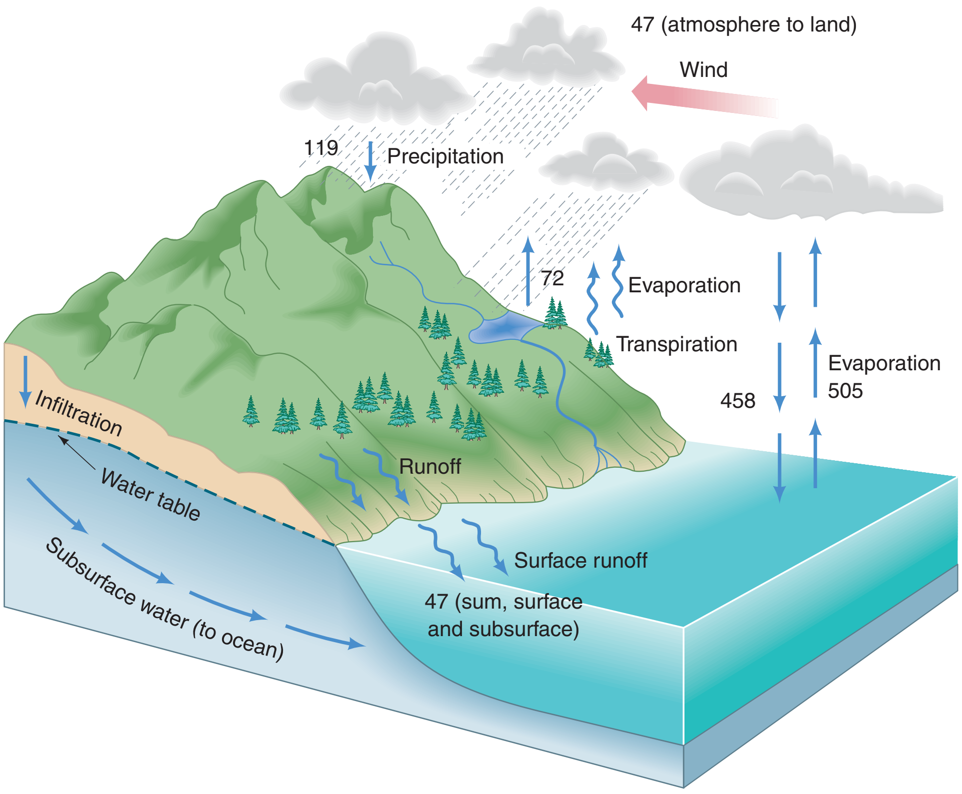


FIGURE 6.13 **The hydrologic cycle**, showing the transfer of water (thousands of km^3/yr) from the oceans to the atmosphere to the continents and back to the oceans again. (*Source*: From P.H. Gleick, *Water in Crisis* [New York: Oxford University Press, 1993].)

sculpting landscape, weathering rocks, transporting sediments, and providing our water resources.

The rates of transfer of water from land to the ocean are relatively low, and the land and oceans are somewhat independent in the water cycle because most of the water that evaporates from the ocean falls back into the ocean as precipitation, and most of the water that falls as precipitation on land comes from evaporation of water from land, as shown in Figure 6.13. Approximately 60% of precipitation on land evaporates each year back to the atmosphere, while the rest, about 40%, returns to the ocean as surface and subsurface runoff. The distribution of water is far from uniform on the land, and this has many environmental and ecological effects, which we discuss in Chapter 8 (on biological diversity), Chapters 19 and 20 (on water and climate), and Chapter 22 (urban environments).

At the regional and local levels, the fundamental hydrologic unit of the landscape is the *drainage basin* (also called a *watershed* or *catchment*). As explained in Chapter 5, a watershed is the area that contributes surface runoff to a particular stream or river. The term is used in evaluating the hydrology of an area (such as the stream flow or runoff from slopes) and in ecological research and biological conservation. Watersheds are best categorized by drainage basin area, and further by how many streams flow into the final, main channel. A first-order watershed is drained by a single small stream; a second-order watershed includes streams from first-order watersheds, and so on. Drainage basins vary greatly in size, from less than a hectare (2.5 acres) for a first-order watershed to millions of square kilometers for major rivers like the Missouri, Amazon, and Congo. A watershed is usually named for its main stream or river, such as the Mississippi River drainage basin.

The Rock Cycle

The **rock cycle** consists of numerous processes that produce rocks and soils. The rock cycle depends on the tectonic cycle for energy, and on the hydrologic cycle for water. As shown in Figure 6.14, rock is classified as igneous, sedimentary, or metamorphic. These three types of rock are involved in a worldwide recycling process. Internal heat from the tectonic cycle produces *igneous rocks* from molten material (magma) near the surface, such as lava from volcanoes. When magma crystalized deep in the earth the igneous rock granite was formed. These new rocks weather when exposed at the surface. Water in cracks of rocks expands when it freezes, breaking the rocks apart. This physical weathering makes smaller particles of rock from bigger ones, producing sediment, such as gravel, sand, and silt. Chemical weathering occurs, too, when the weak acids in water dissolve chemicals from rocks. The sediments and dissolved chemicals are then transported by water, wind, or ice (glaciers).

Weathered materials that accumulate in *depositional basins*, such as the oceans, are compacted by overlying sediments and converted to *sedimentary rocks.* The process of creating rock by compacting and cementing particles is called *lithification.* Sedimentary rocks buried at sufficient depths (usually tens to hundreds of kilometers) are altered by heat, pressure, or chemically active fluids and transformed into *metamorphic rocks.* Later, plate tectonics uplift may bring these deeply buried rocks to the surface, where they, too, are subjected to weathering, producing new sediment and starting the cycle again.

You can see in Figure 6.14 that life processes play an important role in the rock cycle by adding organic carbon to rocks. The addition of organic carbon produces rocks such as limestone, which is mostly calcium carbonate (the material of seashells and bones), as well as fossil fuels, such as coal.

Our discussion of geologic cycles has emphasized tectonic, hydrologic, and rock-forming processes. We can now begin to integrate biogeochemical processes into the picture.

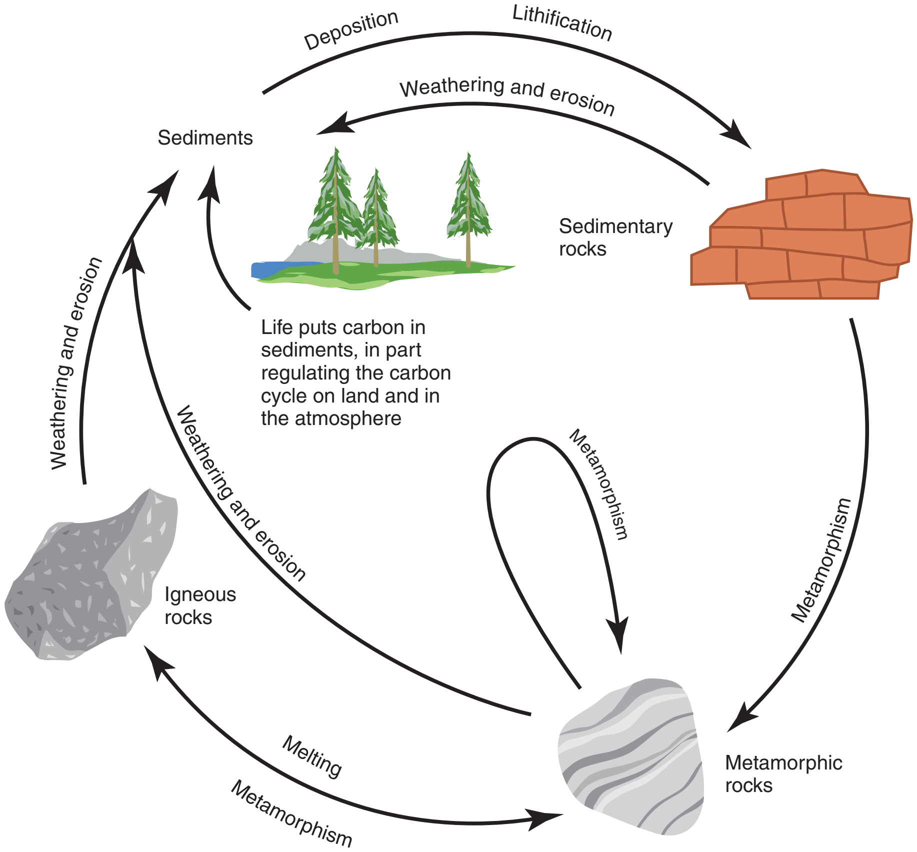


FIGURE 6.14 **The rock cycle** and major paths of material transfer as modified by life.

6.5 Some Major Global Biogeochemical Cycles

With Figure 6.14's basic diagram in mind, we can now consider complete chemical cycles, though still quite simplified. Each chemical element has its own specific cycle, but all the cycles have certain features in common (Figure 6.15).

The Carbon Cycle

Carbon is the basic building block of life and the element that anchors all organic substances, from coal and oil to DNA (deoxyribonucleic acid), the compound that carries genetic information. Although of central importance to life, carbon is not one of the most abundant elements in Earth's crust. It contributes only 0.032% of the weight of the crust, ranking far behind oxygen (45.2%), silicon (29.5%), aluminum (8.0%), iron (5.8%), calcium (5.1%), and magnesium (2.8%).[10, 11]

The major pathways and storage reservoirs of the **carbon cycle** are shown in Figure 6.16. This diagram is simplified to show the big picture of the carbon cycle. Details are much more complex. [12]

- **Oceans and land ecosystems:** In the past half-century, ocean and land ecosystems have removed about 3.1 ± 0.5 GtC/yr, which is approximately 45% of the carbon emitted from burning fossil fuels during that period.
- **Land-use change:** Deforestation and decomposition of what is cut and left, as well as burning of forests to make room for agriculture in the tropics, are the main reasons 2.2 ± 0.8 GtC/yr is added to the atmosphere. A small flux of carbon (0.2 ± 0.5 GtC/yr) from hot tropical areas is pulled from the atmosphere by growing forests. In other words, when considering land-use change, deforestation is by far the dominant process.
- **Residual land sink:** The observed net uptake of CO_2 from the atmosphere (see Figure 6.16) by land ecosystems suggests there must be a sink for carbon in land ecosystems that has not been adequately identified. The sink is large, at 2 to 3 GtC/yr, with large uncertainty (± 1.7GtC/yr). Thus, our understanding of the carbon cycle is not yet complete.

Carbon has a gaseous phase as part of its cycle, occurring in the atmosphere as carbon dioxide (CO_2) and methane (CH_4), both greenhouse gases. Carbon enters

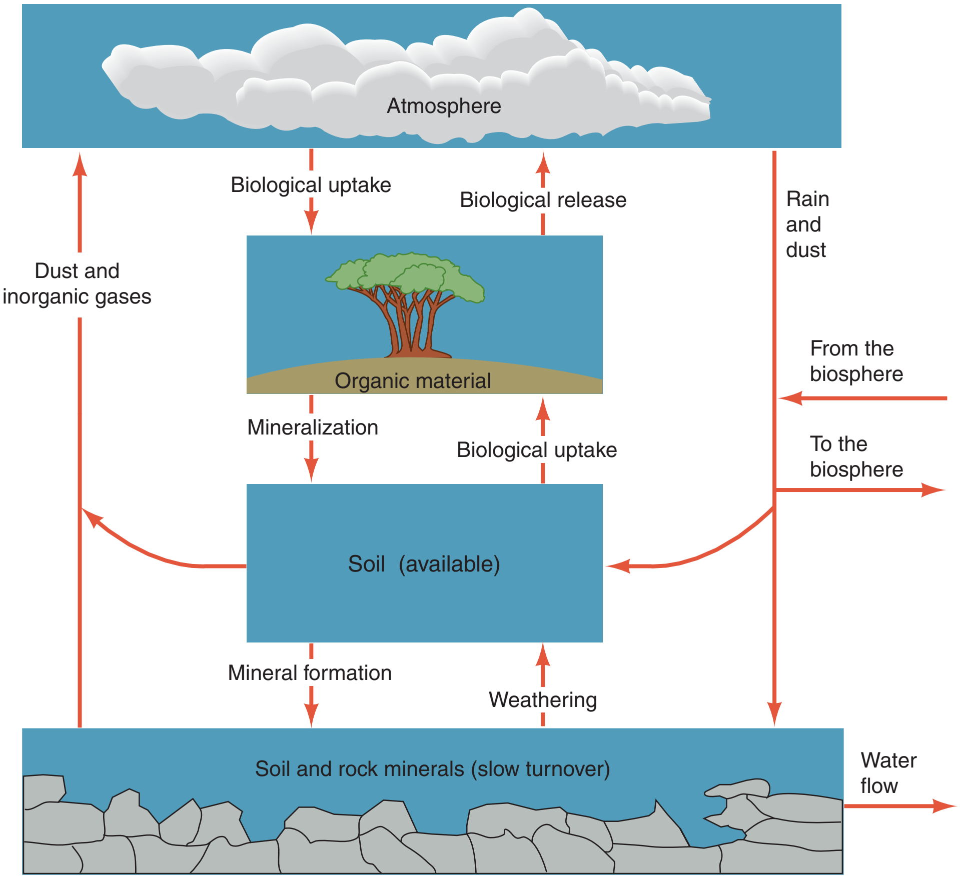
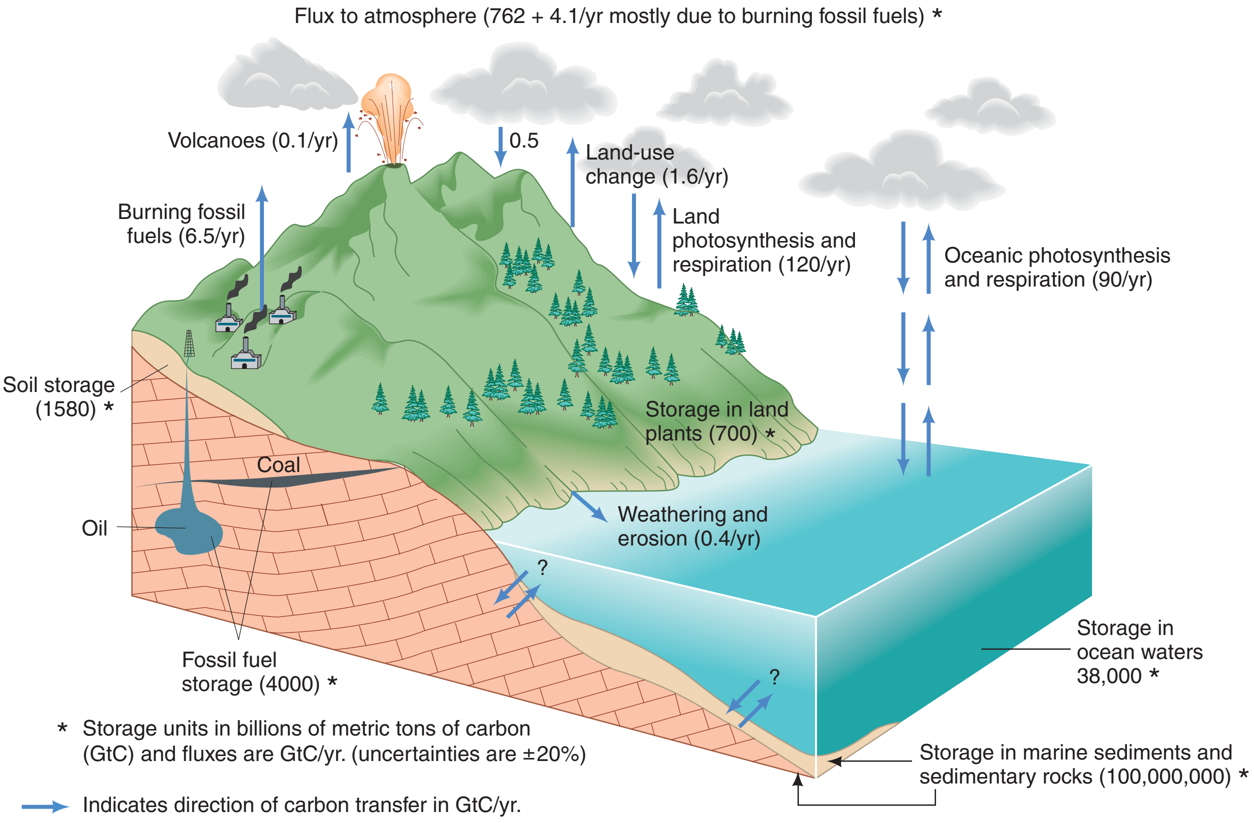


FIGURE 6.15 **Basic biogeochemical cycle.**

the atmosphere through the respiration of living things, through fires that burn organic compounds, and by diffusion from the ocean. It is removed from the atmosphere by photosynthesis of green plants, algae, and photosynthetic bacteria and enters the ocean from the atmosphere by the simple diffusion of carbon dioxide. The carbon dioxide then dissolves, some of it remaining in that state and the rest converting to carbonate ($CO_3^{=}$) and bicarbonate (HCO_3^{-}). Marine algae and photosynthetic bacteria obtain the carbon dioxide they use from the water in one of these three forms.

Carbon is transferred from the land to the ocean in rivers and streams as dissolved carbon, including organic compounds, and as organic particulates (fine particles of organic matter) and seashells and other forms of calcium carbonate ($CaCO_3$). Winds, too, transport small organic particulates from the land to the ocean. Rivers and streams transfer a relatively small fraction of the total global carbon flux to the oceans. However, on the local and regional scale, input of carbon from rivers to nearshore areas, such as deltas and salt marshes, which are often highly biologically productive, is important.

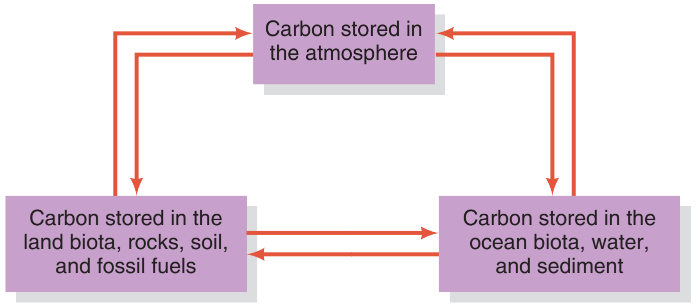
Carbon enters the **biota**—the term for all life in a region—through photosynthesis and is returned to the atmosphere or waters by respiration or by wildfire. When an organism dies, most of its organic material decomposes into inorganic compounds, including carbon dioxide. Some carbon may be buried where there is not sufficient



* Storage units in billions of metric tons of carbon (GtC) and fluxes are GtC/yr. (uncertainties are ±20%)

→ Indicates direction of carbon transfer in GtC/yr.

(a)



(b)

FIGURE 6.16 The carbon cycle. (a) Generalized global carbon cycle. **(b)** Parts of the carbon cycle simplified to illustrate the cyclic nature of the movement of carbon. (*Source*: Modified from G. Lambert, *La Recherche* 18 [1987]:782–83, with some data from R. Houghton, *Bulletin of the Ecological Society of America* 74, no. 4 [1993]: 355–356, and R. Houghton, *Tellus* 55B, no. 2 [2003]: 378–390), and IPCC, The Physical Science Basis: Working Group I. Contribution to the *Fourth Assessment Report* [New York: Cambridge University Press, 2007].)

oxygen to make this conversion possible or where the temperatures are too cold for decomposition. In these locations, organic matter is stored. Over years, decades, and centuries, storage of carbon occurs in wetlands, including parts of floodplains, lake basins, bogs, swamps, deep-sea sediments, and near-polar regions. Over longer periods (thousands to several million years), some carbon may be buried with sediments that become sedimentary rocks. This carbon is transformed into fossil fuels. Nearly all of the carbon stored in the lithosphere exists as sedimentary rocks, mostly carbonates, such as limestone, much of which has a direct biological origin.

The cycling of carbon dioxide between land organisms and the atmosphere is a large flux. Approximately 15% of the total carbon in the atmosphere is taken up by photosynthesis and released by respiration on land annually. Thus, as noted, life has a large effect on the chemistry of the atmosphere.

Because carbon forms two of the most important greenhouse gases—carbon dioxide and methane—much research has been devoted to understanding the carbon cycle, which will be discussed in Chapter 20 about the atmosphere and climate change.

The Carbon–Silicate Cycle

Carbon cycles rapidly among the atmosphere, oceans, and life. However, over geologically long periods, the cycling of carbon becomes intimately involved with the cycling of silicon. The combined carbon–silicate cycle is therefore of geologic importance to the long-term stability of the biosphere over periods that exceed half a billion years.[12]

The **carbon–silicate cycle** begins when carbon dioxide in the atmosphere dissolves in the water to form weak carbonic acid (H_2CO_3) that falls as rain (Figure 6.17). As the mildly acidic water migrates through the ground, it chemically weathers (dissolves) rocks and facilitates the erosion of Earth's abundant silicate-rich rocks. Among other products, weathering and erosion release calcium ions (Ca^{++}) and bicarbonate ions (HCO_3^-). These ions enter the groundwater and surface waters and eventually are transported to the ocean. Calcium and bicarbonate ions make up a major portion of the chemical load that rivers deliver to the oceans.

Tiny floating marine organisms use the calcium and bicarbonate to construct their shells. When these organisms die, the shells sink to the bottom of the ocean, where they accumulate as carbonate-rich sediments. Eventually, carried by moving tectonic plates, they enter a subduction zone (where the edge of one continental plate slips under the edge of another). There they are subjected to increased heat, pressure, and partial melting. The resulting magma releases carbon dioxide, which rises in volcanoes and is released into the atmosphere. This process provides a lithosphere-to-atmosphere flux of carbon.

The long-term carbon–silicate cycle (Figure 6.17) and the short-term carbon cycle (Figure 6.16) interact to affect levels of CO_2 and O_2 in the atmosphere. For example, the burial of organic material in an oxygen-poor environment amounts to a net increase of photosynthesis (which produces O_2) over respiration (which produces CO_2). Thus, if burial of organic carbon in oxygen-poor environments increases, the concentration of atmospheric

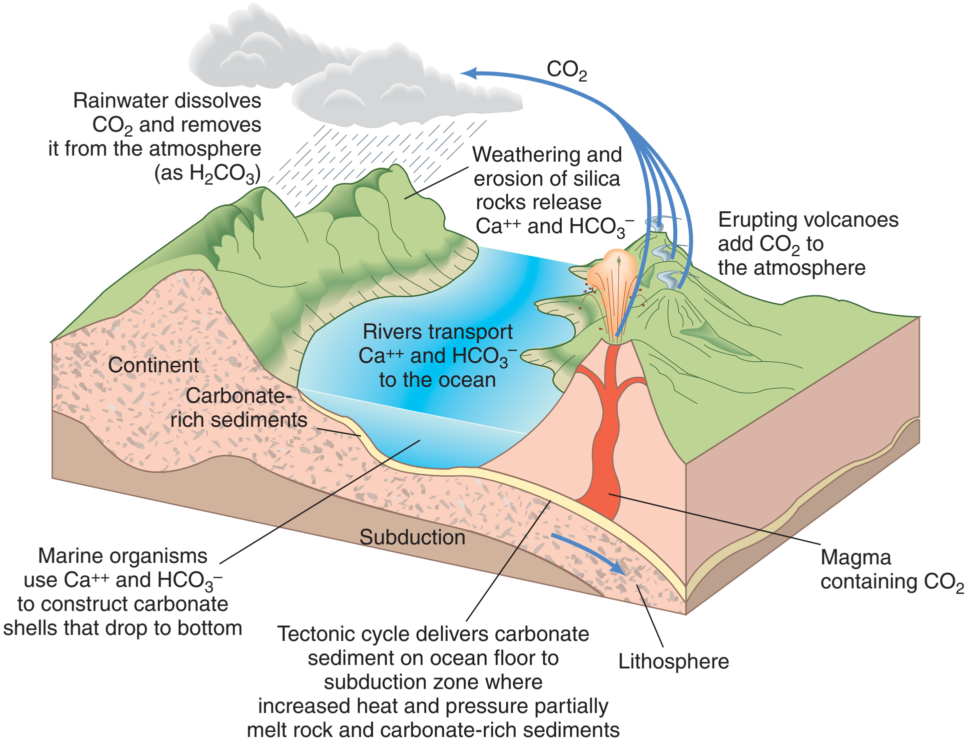


FIGURE 6.17 An idealized diagram showing the carbon–silicate cycle. (*Source*: Modified from J.E. Kasting, O.B. Toon, and J.B. Pollack, How climate evolved on the terrestrial planets, *Scientific American* 258 [1988]:2.)

oxygen will increase. Conversely, if more organic carbon escapes burial and is oxidized to produce CO_2, then the CO_2 concentration in the atmosphere will increase.[13]

The Nitrogen Cycle

Nitrogen is essential to life in proteins and DNA. As we discussed at the beginning of this chapter, free or diatonic nitrogen (N_2 uncombined with any other element) makes up approximately 78% of Earth's atmosphere. However, no organism can use molecular nitrogen directly. Some organisms, such as animals, require nitrogen in an organic compound. Others, including plants, algae, and bacteria, can take up nitrogen either as the nitrate ion (NO_3^-) or the ammonium ion (NH_4^+). Because nitrogen is a relatively unreactive element, few processes convert molecular nitrogen to one of these compounds. Lightning oxidizes nitrogen, producing nitric oxide. In nature, essentially all other conversions of molecular nitrogen to biologically useful forms are conducted by bacteria.

The **nitrogen cycle** is one of the most important and most complex of the global cycles (Figure 6.18). The process of converting inorganic, molecular nitrogen in the atmosphere to ammonia or nitrate is called **nitrogen fixation**. Once in these forms, nitrogen can be used on land by plants and in the oceans by algae. Bacteria, plants, and algae then convert these inorganic nitrogen compounds into organic ones through chemical reactions, and the nitrogen becomes available in ecological food chains. When organisms die, bacteria convert the organic compounds containing nitrogen back to ammonia, nitrate, or molecular nitrogen, which enters the atmosphere. The process of releasing fixed nitrogen back to molecular nitrogen is called **denitrification**.

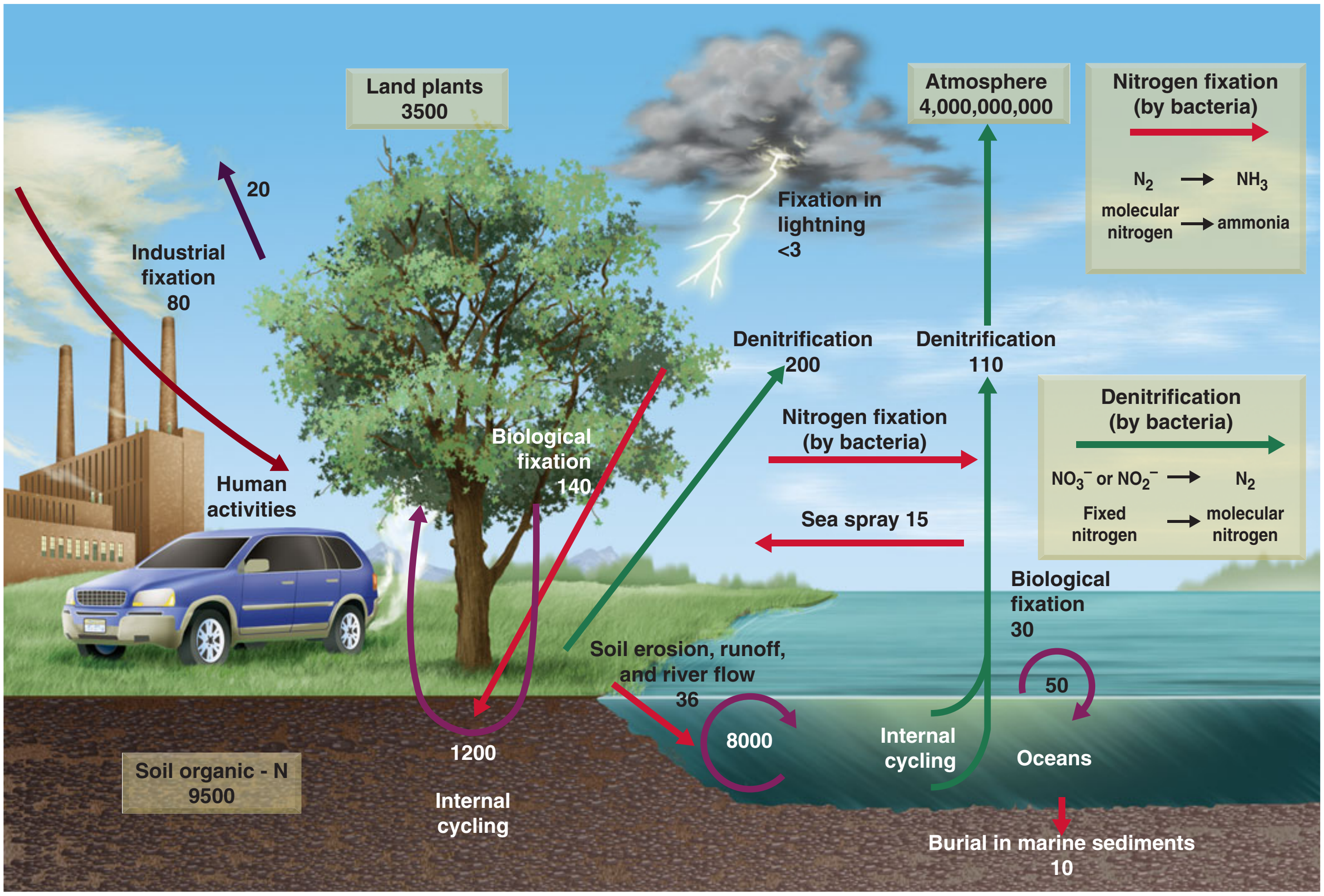


FIGURE 6.18 **The global nitrogen cycle.** Numbers in boxes indicate amounts stored, and numbers with arrows indicate annual flux, in millions of metric tons of nitrogen. Note that the industrial fixation of nitrogen is nearly equal to the global biological fixation. (*Source*: Data from R. Söderlund and T. Rosswall, in *The Handbook of Environmental Chemistry*, Vol. 1, Pt. B, O. Hutzinger, ed. [New York: Springer-Verlag, 1982]; W.H. Schlosinger, *Biogeochemistry: An Analysis of Global Change* [San Diego: Academic Press, 1997], p. 386; and Peter M. Vitousek, Chair, John Aber, Robert W. Howarth, Gene E. Likens, Pamela A. Matson, David W. Schindler, William H. Schlesinger, and G. David Tilman, Human alteration of the global nitrogen cycle: Causes and consequences, *Issues in Ecology—Human Alteration of the Global Nitrogen Cycle*, Ecological Society of America publication http://esa.sdsc.edu/tilman.htm 30/08/2000.)

Thus, all organisms depend on nitrogen-converting bacteria. Some organisms, including termites and ruminant (cud-chewing) mammals, such as cows, goats, deer, and bison, have evolved symbiotic relationships with these bacteria. For example, the roots of the pea family have nodules that provide a habitat for the bacteria. The bacteria obtain organic compounds for food from the plants, and the plants obtain usable nitrogen. Such plants can grow in otherwise nitrogen-poor environments. When these plants die, they contribute nitrogen-rich organic matter to the soil, improving the soil's fertility. Alder trees, too, have nitrogen-fixing bacteria in their roots. These trees grow along streams, and their nitrogen-rich leaves fall into the streams and increase the supply of organic nitrogen to freshwater organisms.

In terms of availability for life, nitrogen lies somewhere between carbon and phosphorus. Like carbon, nitrogen has a gaseous phase and is a major component of Earth's atmosphere. Unlike carbon, however, it is not very reactive, and its conversion depends heavily on biological activity. Thus, the nitrogen cycle is not only essential to life but also primarily driven by life.

In the early part of the 20th century, scientists invented industrial processes that could convert molecular nitrogen into compounds usable by plants. This greatly increased the availability of nitrogen in fertilizers. Today, industrial fixed nitrogen is about 60% of the amount fixed in the biosphere and is a major source of commercial nitrogen fertilizer.[14]

Although nitrogen is required for all life, and its compounds are used in many technological processes and in modern agriculture, nitrogen in agricultural runoff can pollute water, and many industrial combustion processes and automobiles that burn fossil fuels produce nitrogen oxides that pollute the air and play a significant role in urban smog (see Chapter 21).

The Phosphorus Cycle

Phosphrus, one of the "big six" elements required in large quantities by all forms of life, is often a limiting nutrient for plant and algae growth. We call it the "energy element" because it is fundamental to a cell's use of energy, and therefore to the use of energy by all living things. Phosphorus is in DNA, which carries the genetic material of life. It is an important ingredient in cell membranes.

The **phosphorus cycle** is significantly different from the carbon and nitrogen cycles. Unlike carbon and nitrogen, phosphorus does not have a gaseous phase on Earth; it is found in the atmosphere only in small particles of dust (Figure 6.19). In addition, phosphorus tends to form compounds that are relatively insoluble in water, so phosphorus is not readily weathered chemically. It does occur commonly in an oxidized state as phosphate, which combines with calcium, potassium, magnesium, or iron to form minerals. All told, however, the rate of transfer of phosphorus in Earth's system is slow compared with that of carbon or nitrogen.

Phosphorus enters the biota through uptake as phosphate by plants, algae, and photosynthetic bacteria. It is recycled locally in life on land nearly 50 times before being transported by weathering and runoff. Some phosphorus is inevitably lost to ecosystems on the land. It is transported by rivers to the oceans, either in a water-soluble form or as suspended particles. When it finally reaches the ocean, it may be recycled about 800 times before entering marine sediments to become part of the rock cycle. Over tens to hundreds of millions of years, the sediment is transformed into sedimentary rocks, after which it may eventually be returned to the land by uplift, weathering, and erosion.[15]

Ocean-feeding birds, such as the brown pelican, provide an important pathway in returning phosphrus from the ocean to the land. These birds feed on small fish, especially anchovies, which in turn feed on tiny ocean plankton. Plankton thrive where nutrients, such as phosphorus, are present. Areas of rising oceanic currents known as upwellings are such places. Upwellings occur near continents where the prevailing winds blow offshore, pushing surface waters away from the land and allowing deeper waters to rise and replace them. Upwellings carry nutrients, including phosphorus, from the depths of the oceans to the surface.

The fish-eating birds nest on offshore islands, where they are protected from predators. Over time, their nesting sites become covered with their phosphorus-laden excrement, called guano. The birds nest by the thousands, and deposits of guano accumulate over centuries. In relatively dry climates, guano hardens into a rocklike mass that may be up to 40 m (130 ft) thick. The guano results from a combination of biological and nonbiological processes. Without the plankton, fish, and birds, the phosphorus would have remained in the ocean. Without the upwellings, the phosphorus would not have been available.

Guano deposits were once major sources of phosphorus for fertilizers. In the mid-1800s, as much as 9 million metric tons per year of guano deposits were shipped to London from islands near Peru (Figure 6.20). Today, most phosphorus fertilizers come from the mining of phosphate-rich sedimentary rocks containing fossils of marine animals. The richest phosphate mine in the world is Bone Valley, 40 km east of Tampa, Florida. But 10–15 million years ago Bone Valley was the bottom of a shallow sea where marine invertebrates lived and died.[16]

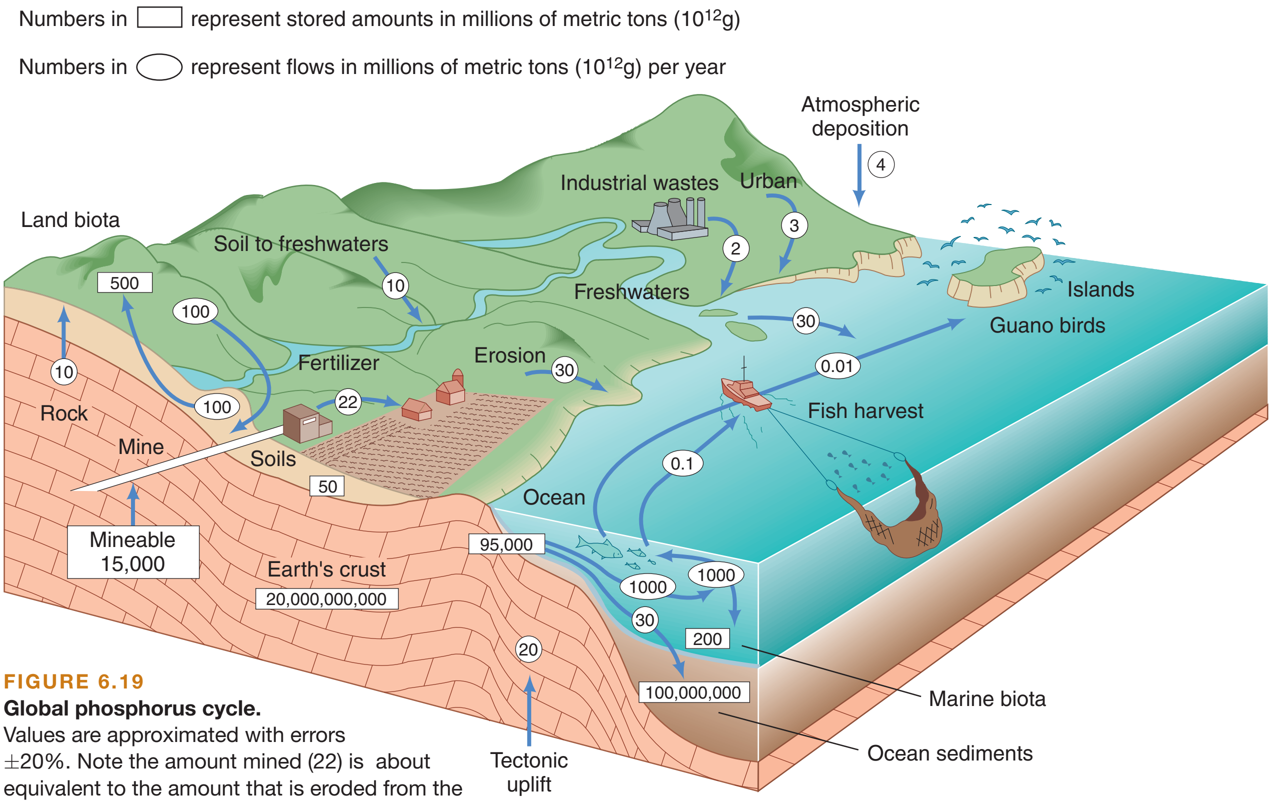


FIGURE 6.19
Global phosphorus cycle.
Values are approximated with errors ±20%. Note the amount mined (22) is about equivalent to the amount that is eroded from the land and enters the oceans by runoff (25).
(*Sources*: Data from 5 mil, 2000 *Phosphorus in the environment: Natural flows and human interference*. Annual Review of Environment and Resources 25:53–88.)

FIGURE 6.20 **Guano Island**, Peru. For centuries the principal source of phosphorus fertilizer was guano deposits from seabirds. The birds feed on fish and nest on small islands. Their guano accumulates in this dry climate over centuries, forming rocklike deposits that continue to be mined commercially for phosphate fertilizers. On the Peruvian Ballestas Islands **(a)** seabirds (in this case, Incan terns) nest, providing some of the guano, and **(b)** sea lions haul out and rest on the rocklike guano.

Through tectonic processes, the valley was slowly uplifted, and in the 1880s and 1890s phosphate ore was discovered there. Today, Bone Valley provides about 20% of the world's phosphate (Figure 6.21).

About 80% of phosphorus is produced in four countries: the United States, China, South Africa, and Morocco.[17,18] The global supply of phosphorus that can be extracted economically is about 15 billion tons (15,000 million tons). Total U.S. reserves are estimated at 1.2 billion metric tons. In 2009, in the United States, approximately 30.9 million tons of marketable phosphorus rocks valued at $3.5 billion were obtained by removing more than 120 million tons of rocks from mines. Most of the U.S. phosphorus, about 85%, came from Florida and North Carolina, the rest from Utah and Idaho.[19] All of our industrialized agriculture—most of the food produced in the United States—depends on phosphorus for fertilizers that comes from just four states!

Phosphorus may become much more difficult to obtain in the next few decades. According to the U.S. Geological Survey, in 2007 the price of phosphate rock "jumped dramatically worldwide owing to increased agricultural demand and tight supplies," and by 2009 "the average U.S. price was more than double that of 2007," reaching as much as $500 a ton in some parts of the world.[20]

One fact is clear: Without phosphorus, we cannot produce food. Thus, declining phosphorus resources will harm the global food supply and affect all of the world's economies. Extraction continues to increase as the expanding human population demands more food and as we grow more corn for biofuel. However, if the price of phosphorus rises as high-grade deposits dwindle, phosphorus from lower-grade deposits can be mined at a profit. Florida is thought to have as much as 8 billion metric tons of phosphorus that might eventually be recovered if the price is right.

Mining, of course, may have negative effects on the land and ecosystems. For example, in some phosphorus mines, huge pits and waste ponds have scarred the landscape, damaging biologic and hydrologic resources. Balancing the need for phosphorus with the adverse environmental impacts of mining is a major environmental issue. Following phosphate extraction, land disrupted by open-pit phosphate mining, shown in Figure 6.21 is reclaimed to pastureland, as mandated by law.

As with nitrogen, an overabundance of phosphorus causes environmental problems. In bodies of water, from ponds to lakes and the ocean, phosphorus can promote unwanted growth of photosynthetic bacteria. As the algae proliferate, oxygen in the water may be depleted. In oceans, dumping of organic materials high in nitrogen and phosphorus has produced several hundred "dead zones." collectively covering about 250,000 km^2. Although this is an area almost as large as Texas, it represents less than 1% of the area of the Earth's oceans (335,258,000 km^2).

What might we do to maintain our high agriculture production but reduce our need for newly mined phosphate? Among the possibilities:

- Recycle human waste in the urban environment to reclaim phosphorus and nitrogen.
- Use wastewater as a source of fertilizer, rather than letting it end up in waterways.
- Recycle phosphorus-rich animal waste and bones for use in fertilizer.
- Further reduce soil erosion from agricultural lands so that more phosphorus is retained in the fields for crops.
- Apply fertilizer more efficiently so less is immediately lost to wind and water erosion.
- Find new phosphorus sources and more efficient and less expensive ways to mine it.
- Use phosphorus to grow food crops rather than biofuel crops.

We have focused on the biogeochemical cycles of three of the macronutrients, illustrating the major kinds of biogeochemical cycles—those with and those without an atmospheric component—but obviously this is just an introduction about methods that can be applied to all elements required for life and especially in agriculture.

FIGURE 6.21 A large open-pit phosphate mine in Florida (similar to Bone Valley), with piles of waste material. The land in the upper part of the photograph has been reclaimed and is being used for pasture.

CRITICAL THINKING ISSUE

How Are Human Activities Linked to the Phosphorus and Nitrogen Cycles?

Scientists estimate that nitrogen deposition to Earth's surface will double in the next 25 years and that the use of phosphorus will also increase greatly as we attempt to feed a few billion more people in coming decades. The natural rate of nitrogen fixation is estimated to be 140 teragrams (Tg) of nitrogen a year (1 teragram = 1 million metric tons). Human activities—such as the use of fertilizers, draining of wetlands, clearing of land for agriculture, and burning of fossil fuels—are causing additional nitrogen to enter the environment. Currently, human activities are responsible for more than half of the fixed nitrogen that is deposited on land. Before the 20th century, fixed nitrogen was recycled by bacteria, with no net accumulation. Since 1900, however, the use of commercial fertilizers has increased exponentially (Figure 6.22). Nitrates and ammonia from burning fossil fuels have increased about 20% in the last decade or so. These inputs have overwhelmed the denitrifying part of the nitrogen cycle and the ability of plants to use fixed nitrogen.

Nitrate ions, in the presence of soil or water, may form nitric acid. With other acids in the soil, nitric acid can leach out chemicals important to plant growth, such as magnesium and potassium. When these chemicals are depleted, more toxic ones, such as aluminum, may be released, damaging tree roots. Acidification of soil by nitrate ions is also harmful to organisms. When toxic chemicals wash into streams, they can kill fish. Excess nitrates in rivers and along coasts can cause algae to overgrow, damaging ecosystems. High levels of nitrates in drinking water from streams or groundwater contaminated by fertilizers are a health hazard.[21, 22, 23, 24]

The nitrogen, phosphorus, and carbon cycles are linked because nitrogen is a component of chlorophyll, the molecule that plants use in photosynthesis. Phosphorus taken up by plants enters the food chain and, thus, the carbon cycle. It is an irreplaceable ingredient in life. Because nitrogen is a limiting factor on land, it has been predicted that rising levels of global nitrogen may increase plant growth. Recent studies have suggested, however, that a beneficial effect from increased nitrogen would be short-lived. As plants use additional nitrogen, some other factor, such as phosphorus, will become limiting. When that occurs, plant growth will slow, and so will the uptake of carbon dioxide. More research is needed to understand the interactions between carbon and the phosphorus and nitrogen cycles and to be able to predict the long-term effects of human activities.

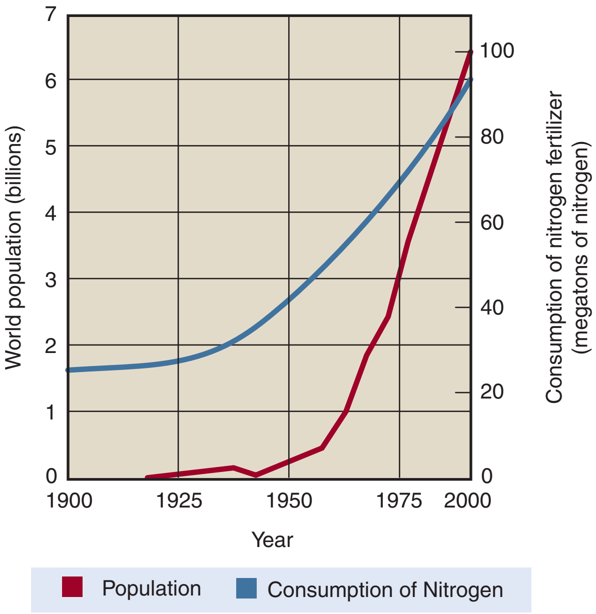


FIGURE 6.22 The use of nitrogen fertilizers has increased greatly. (*Source*: Modified from Rhodes, D. 2009. Purdue University Department of Horticulture & Landscape Architecture.)

Critical Thinking Questions

1. The supply of phosphorus from mining is a limited resource. In the U.S., extraction is decreasing, and the price is rising dramatically. Do you think phosphorus can be used sustainably? How? If not, what are the potential consequences for agriculture?
2. Do you think phosphorus use should be governed by an international body? Why? Why not?
3. Compare the rate of human contributions to nitrogen fixation with the natural rate.
4. How does the change in fertilizer use relate to the change in world population? Why?
5. Develop a diagram to illustrate the links between the phosphorus, nitrogen, and carbon cycles.
6. Make a list of ways in which we could modify our activities to reduce our contributions to the phosphorus and nitrogen cycles.
7. Should phosphorus and nitrogen be used to produce corn as a biofuel (alcohol)? Why? Why not?

SUMMARY

- Biogeochemical cycles are the major way that elements important to Earth processes and life are moved through the atmosphere, hydrosphere, lithosphere, and biosphere.
- Biogeochemical cycles can be described as a series of reservoirs, or storage compartments, and pathways, or fluxes, between reservoirs.
- In general, some chemical elements cycle quickly and are readily regenerated for biological activity. Elements whose biogeochemical cycles include a gaseous phase in the atmosphere tend to cycle more rapidly.
- Life on Earth has greatly altered biogeochemical cycles, creating a planet with an atmosphere unlike those of any others known, and especially suited to sustain life.
- Every living thing, plant or animal, requires a number of chemical elements. These chemicals must be available at the appropriate time and in the appropriate form and amount.
- Chemicals can be reused and recycled, but in any real ecosystem some elements are lost over time and must be replenished if life in the ecosystem is to persist. Change and disturbance of natural ecosystems are the norm. A steady state, in which the net storage of chemicals in an ecosystem does not change with time, cannot be maintained.
- Our modern technology has begun to alter and transfer chemical elements in biogeochemical cycles at rates comparable to those of natural processes. Some of these activities are beneficial to society, but others create problems, such as pollution by nitrogen and phosphorus
- To be better prepared to manage our environment, we must recognize both the positive and the negative consequences of activities that transfer chemical elements, and we must deal with them appropriately.
- Biogeochemical cycles tend to be complex, and Earth's biota has greatly altered the cycling of chemicals through the air, water, and soil. Continuation of these processes is essential to the long-term maintenance of life on Earth.
- There are many uncertainties in measuring either the amount of a chemical in storage or the rate of transfer between reservoirs.

REEXAMINING THEMES AND ISSUES

Human Population

Through modern technology, we are transferring some chemical elements through the air, water, soil, and biosphere at rates comparable to those of natural processes. As our population increases, so does our use of resources and so do these rates of transfer. This is a potential problem because eventually the rate of transfer for a particular chemical may become so large that pollution of the environment results.

Sustainability

If we are to sustain a high-quality environment, the major biogeochemical cycles must transfer and store the chemicals necessary to maintain healthy ecosystems. That is one reason why understanding biogeochemical cycles is so important. For example, the release of sulfur into the atmosphere is degrading air quality at local to global levels. As a result, the United States is striving to control these emissions.

Global Perspective

The major biogeochemical cycles discussed in this chapter are presented from a global perspective. Through ongoing research, scientists are trying to better understand how major biogeochemical cycles work. For example, the carbon cycle and its relationship to the burning of fossil fuels and the storage of carbon in the biosphere and oceans are being intensely investigated. Results of these studies are helping us to develop strategies for reducing carbon emissions. These strategies are implemented at the local level, at power plants, and in cars and trucks that burn fossil fuels.

Urban World

Our society has concentrated the use of resources in urban regions. As a result, the release of various chemicals into the biosphere, soil, water, and atmosphere is often greater in urban centers, resulting in biogeochemical cycles that cause pollution problems.

People and Nature

Humans, like other animals, are linked to natural processes and nature in complex ways. We change ecosystems through land-use changes and the burning of fossil fuels, both of which change biogeochemical cycles, especially the carbon cycle that anchors life and affects Earth's climate.

Science and Values

Our understanding of biogeochemical cycles is far from complete. There are large uncertainties in the measurement of fluxes of chemical elements—nitrogen, carbon, phosphorus, and others. We are studying biogeochemical cycles because understanding them will help us to solve environmental problems. Which problems we address first will reflect the values of our society.

KEY TERMS

biogeochemical cycle	**112**
biosphere	**110**
biota	**118**
carbon cycle	**117**
carbon–silicate cycle	**119**
denitrification	**120**
eukaryote	**110**
flow	**112**
flux	**112**
geologic cycle	**113**
hydrologic cycle	**115**
limiting factor	**111**
macronutrients	**111**
micronutrients	**111**
nitrogen cycle	**120**
nitrogen fixation	**120**
organelle	**110**
phosphorus cycle	**121**
plate tectonics	**113**
prokaryote	**110**
residence time	**112**
rock cycle	**116**
sink	**112**
source	**112**
tectonic cycle	**113**
thermodynamic equilibrium	**108**

STUDY QUESTIONS

1. Why is an understanding of biogeochemical cycles important in environmental science? Explain your answer, using two examples.
2. What are some of the general rules that govern biogeochemical cycles, especially the transfer of material?
3. Identify the major aspects of the carbon cycle and the environmental concerns associated with it.
4. What are the differences in the geochemical cycles for phosphorus and nitrogen, and why are the differences important in environmental science?
5. What are the major ways that people have altered biogeochemical cycles?
6. If all life ceased on Earth, how quickly would the atmosphere become like that of Venus and Mars? Explain.

FURTHER READING

Lane, Nick, ***Oxygen: The Molecule That Made the World*** (Oxford: Oxford University Press, 2009).

Lovelock, J., ***The Ages of Gaia: A Biography of the Earth*** (Oxford: Oxford University Press, 1995).

Schlesinger, W.H., ***Biogeochemistry: An Analysis of Global Change,*** **2nd ed.** (San Diego: Academic Press, 1997). This book provides a comprehensive and up-to-date overview of the chemical reactions on land, in the oceans, and in the atmosphere of Earth.