chapter

3 Ecosystem Ecology

Reversing the Deforestation of Haiti

Even before the devastating earthquake of 2010, life in Haiti was hard. On the streets of the capital city, Port-au-Prince, people would line up to buy charcoal to cook their meals. According to the United Nations, 76 percent of Haitians lived on less than $2.00 a day. Because other forms of cooking fuel, including oil and propane, were too expensive, people turned to the forests, cutting trees to make charcoal from firewood.

Relying on charcoal for fuel has had a serious impact on the forests of Haiti. In 1923, 60 percent of this mountainous country was covered in forest. However, as the population grew and demand for charcoal increased, the amount of forest shrunk. By 2012, with more than 9 million people living in this small nation, less than 2 percent of its land remained forested. Today, most trees in Haiti are cut before they grow to more than a few centimeters in diameter. This rate of deforestation is not sustainable for the people or for the forest.

Deforestation disrupts the ecosystem services that living trees provide. In Chapter 1 we saw how events on Easter Island demonstrated some of the consequences of subjecting land to massive deforestation. When Haitian forests are clear-cut, the land becomes much more susceptible to erosion. When trees are cut, their roots die and can no longer stabilize the soil. Without roots to anchor it, the soil is eroded away by the heavy rains of tropical storms and hurricanes. Unimpeded by vegetation, the rainwater runs quickly down the mountainsides, dislodging the topsoil that is so important for forest growth. In addition, this oversaturation of the soil causes massive mudslides that can destroy entire villages.

By 2012, with more than 9 million people living in this small nation, less than 2 percent of its land remained forested.

But the news from Haiti is not all bad. Since the 1980s, the U.S. Agency for International Development, in cooperation with other groups, has provided funds to plant 60 million trees in Haiti. Unfortunately, simply planting trees is not enough; the local people can't afford to let trees grow when they are in desperate need of firewood and charcoal. One solution has been to plant mango trees (*Mangifera indica*).

Because a mature mango tree can provide $70 to $150 worth of mangoes annually, this value provides an economic incentive to let the trees grow to maturity. The deforestation problem is also being addressed through efforts to develop alternative fuel sources, such as discarded paper that is processed into dried cakes that can be burned. In 2013, the president of Haiti announced a new program to plant 50 million trees every year, with the goal of moving the country from the current 2 percent forest cover to 29 percent forest cover 50 years from now.

Extensive forest removal is a problem in many developing nations. Widespread removal of trees on mountains causes rapid soil erosion and substantial disruptions of the natural cycles of water and soil nutrients. This leads to long-term degradation of the environment. The results not only illustrate the connectedness of ecological systems, but also show how forest ecosystems, like all ecosystems, can be influenced by human decisions.

Sources:
"Haitians seek remedies for environmental ruin," National Public Radio, July 15, 2009, http://www.npr.org/templates/story/story.php?storyId=104684950; "Haiti to plant millions of trees to boost forests and help tackle poverty," *The Guardian*, March 28, 2013, http://www.theguardian.com/world/2013/mar/28/haiti-plant-millions-trees-deforestation.

The story of deforestation in Haiti reminds us that all the components of an ecosystem are interrelated. As we noted in Chapter 1, an ecosystem is a particular location on Earth distinguished by its particular mix of interacting biotic and abiotic components. A forest, for example, contains many interacting biotic components, such as trees, wildflowers, birds, mammals, insects, fungi, and bacteria, that are quite distinct from those found in a grassland. Ecosystems also have abiotic components such as sunlight, temperature, soil, water, pH, and nutrients. The abiotic components of the ecosystem help determine which organisms can live there. In this chapter, we will see that ecosystems control the movement of the energy, water, and nutrients organisms must have to grow and reproduce. Understanding the processes that determine these movements is the goal of ecosystem ecology.

module 6

The Movement of Energy

To understand how an ecosystem functions and the relationship of its biotic and abiotic components, we must first study how energy moves through the ecosystem. In this module we will examine how we delineate ecosystems so that we can examine the movement of energy. We will then consider how photosynthesis and respiration capture and release energy. Finally, we will look at how energy moves through the different components of the ecosystem.

Learning Objectives

After reading this module you should be able to

- explain the concept of ecosystem boundaries.
- describe the processes of photosynthesis and respiration.
- distinguish among the trophic levels that exist in food chains and food webs.
- quantify ecosystem productivity.
- explain energy transfer efficiency and trophic pyramids.

Ecosystem boundaries are not clearly defined

The characteristics of any given ecosystem are highly dependent on the climate that exists in that location on Earth. For example, ecosystems in the dry desert of Death Valley, California, where temperatures may reach 50°C (120°F), are very different from those on the continent of Antarctica, where temperatures may drop as low as −85°C (−120°F). Similarly, water can range from being immeasurable in deserts to being the defining feature of the ecosystem in lakes and oceans. On less extreme scales, small differences in precipitation and the ability of the soil to retain water can favor different terrestrial ecosystem types. Regions with greater quantities of water in the soil can support trees, whereas regions with less water in the soil can support only grasses.

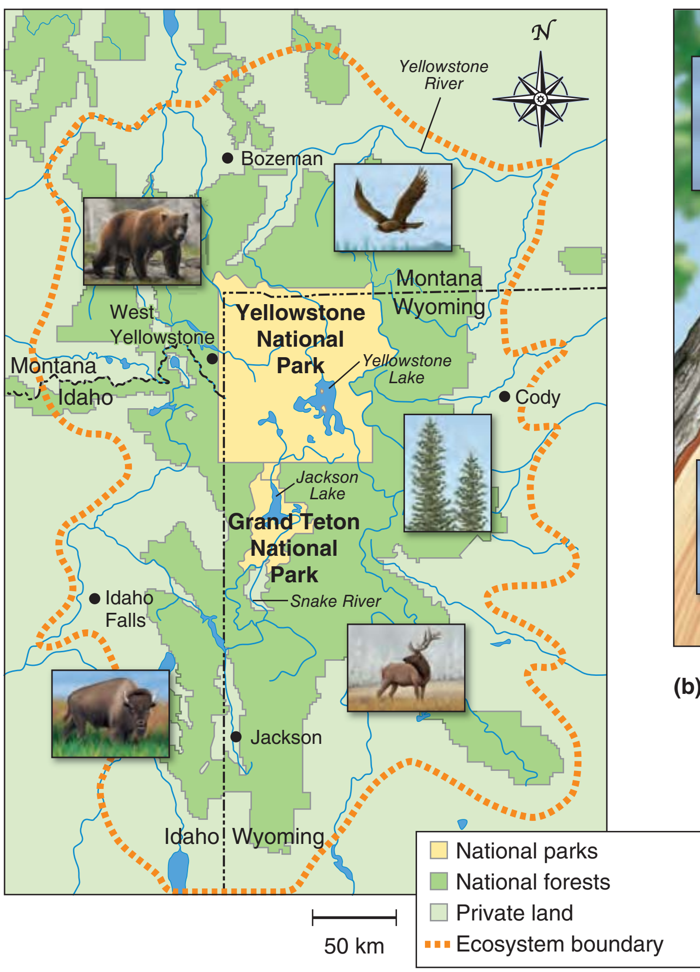
The biotic and abiotic components of an ecosystem provide the boundaries that distinguish one ecosystem from another. Some ecosystems have well-defined boundaries, whereas others do not. A cave, for example, is a well-defined ecosystem (FIGURE 6.1). It contains identifiable biotic components, such as animals

FIGURE 6.1 A cave ecosystem. Cave ecosystems, such as this one in Kenya with emerging bats, typically have distinct boundaries and are home to highly adapted species. *(Ivan Kuzmin/age fotostock)*

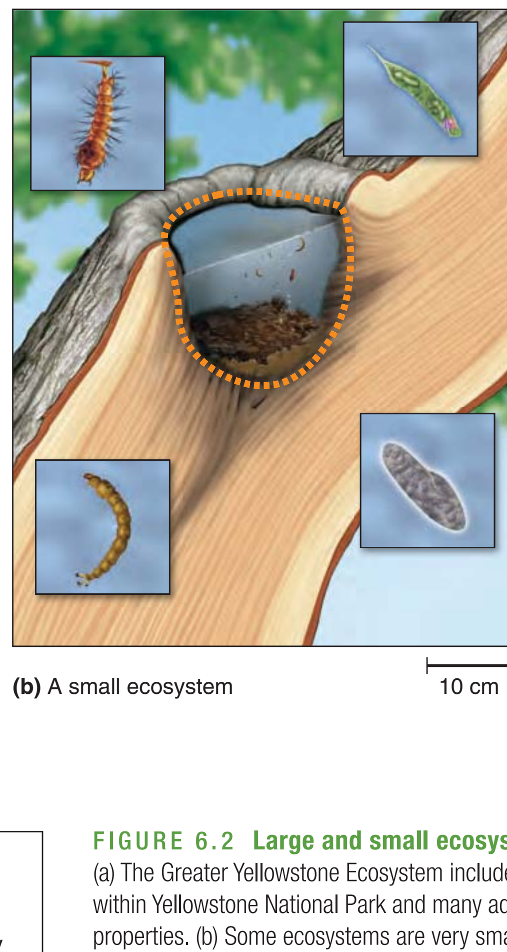
and microorganisms that are specifically adapted to live in a cave environment, as well as distinctive abiotic components, including temperature, salinity, and water that flows through the cave as an underground stream. Roosting bats fly out of the cave each night and consume insects. When the bats return to the cave and defecate, their feces provide energy that passes through the relatively few animal species that live in the cave. In many caves, for example, small invertebrate animals consume bat feces and are in turn consumed by cave salamanders.

The cave ecosystem is relatively easy to study because its boundaries are clear. With the exception of the bats feeding outside the cave, the cave ecosystem is easily defined as everything from the point where the stream enters the cave to the point where it exits. Likewise, many aquatic ecosystems, such as lakes, ponds, and streams, are relatively easy to define because the ecosystem's boundaries correspond to the boundaries between land and water. Knowing the boundaries of an ecosystem makes it easier to identify the system's biotic and abiotic components and to trace the cycling of energy and matter through the system.

In most cases, however, determining where one ecosystem ends and another begins is difficult. For this reason, ecosystem boundaries are often subjective. Environmental scientists might define a terrestrial ecosystem as the range of a particular species of interest, such as the area where wolves roam, or they might define it by using topographic features, such as two mountain ranges enclosing a valley. The boundaries of some managed ecosystems, such as national parks, are set according to administrative rather than scientific criteria. Yellowstone National Park, for example, was once managed as its own ecosystem until scientists began to realize that many species of conservation interest, such as grizzly bears (*Ursus arctos horribilis*), spent time both inside and outside the park, despite the park's massive area of 898,000 ha (2.2 million acres). To manage these species effectively, scientists had to think much more broadly; they had to include nearly 20 million ha (50 million acres) of public and private land outside the park. This larger region, shown in **FIGURE 6.2a**, was named the Greater Yellowstone Ecosystem. As the name suggests, the actual ecosystem extends well beyond the administrative boundaries of the park.



(a) The Greater Yellowstone Ecosystem



(b) A small ecosystem

FIGURE 6.2 Large and small ecosystems. (a) The Greater Yellowstone Ecosystem includes the land within Yellowstone National Park and many adjacent properties. (b) Some ecosystems are very small, such as a rain-filled tree hole that houses a diversity of microbes and aquatic insects.

FIGURE 6.3 The flow of energy in the Serengeti ecosystem of Africa. The Serengeti ecosystem has more plants than herbivores, and more herbivores than carnivores. *(Michel & Christine Denis-Huot/Science Source)*

As we saw in Chapter 2, not all ecosystems are as vast as the Greater Yellowstone Ecosystem. Some can be quite small, such as a water-filled hole in a fallen tree trunk or an abandoned car tire that fills with rainwater (Figure 6.2b). Such tiny ecosystems include all the physical and chemical components necessary to support a diverse set of species, such as microbes, mosquito larvae, and other insects.

Although it is helpful to divide locations on Earth into distinct ecosystems, it is important to remember that each ecosystem interacts with surrounding ecosystems through the exchange of energy and matter. Organisms such as bats—which fly in and out of caves—move across ecosystem boundaries, as do chemical elements, such as carbon or nitrogen dissolved in water. As a result, changes in any one ecosystem can ultimately have far-reaching effects on the global environment.

The combination of all ecosystems on Earth forms the **biosphere,** which is the region of our planet where life resides. It forms a 20-km (12-mile) thick layer around Earth between the deepest ocean bottom and the highest mountain peak.

Photosynthesis captures energy and respiration releases energy

To understand how ecosystems function and how best to protect and manage them, ecosystem ecologists also study the processes that move energy and matter within an ecosystem. To understand energy relationships, we need to look at the way energy flows across an ecosystem.

Consider the Serengeti Plain in East Africa (**FIGURE 6.3**). Plants, such as grasses and acacia trees, absorb energy directly from the Sun. That energy spreads throughout an ecosystem as plants are eaten by animals, such as gazelles, and the animals are subsequently eaten by predators, such as cheetahs. There are millions of herbivores, such as zebras and wildebeests, in the Serengeti ecosystem, but far fewer carnivores, such as lions (*Panthera leo*) and cheetahs (*Acinonyx jubatus*), that feed on herbivores. In accordance with the second law of thermodynamics, when one organism consumes another, not all of the energy in the consumed organism is transferred to the consumer. Some of that energy is lost as heat. Therefore, all the carnivores in an area contain less energy than all the herbivores in the same area because all the energy going to the carnivores must come from the animals they eat. Let's trace this energy flow in more detail by looking at the processes of *photosynthesis* and *cellular respiration*.

Photosynthesis

Nearly all of the energy that powers ecosystems comes from the Sun as solar energy, which is a form of kinetic energy. Plants, algae, and some bacteria that use the Sun's energy to produce usable forms of energy are called **producers,** or **autotrophs.** As you can see

Biosphere The region of our planet where life resides, the combination of all ecosystems on Earth.

Producer An organism that uses the energy of the Sun to produce usable forms of energy. *Also known as* **Autotroph**.

in the top half of FIGURE 6.4, these producers use **photosynthesis,** which means they use solar energy to convert carbon dioxide (CO_2) and water (H_2O) into glucose ($C_6H_{12}O_6$). Glucose is a form of potential energy that can be used by a wide range of organisms. The photosynthesis process also produces oxygen (O_2) as a waste product. That is why plants and other producers are beneficial to our atmosphere; they produce the oxygen we need to breathe.

Cellular Respiration

Producers use the glucose they produce by photosynthesis to store energy and to build structures such as leaves, stems, and roots. Other organisms, such as the herbivores on the Serengeti Plain, eat the tissues of producers and gain energy from the chemical energy contained in those tissues. They do this through **cellular respiration,** a process by which cells unlock the energy of chemical compounds. **Aerobic respiration,** which is shown in the bottom half of Figure 6.4, is the opposite of photosynthesis; cells convert glucose and oxygen into energy, carbon dioxide, and water. In essence, organisms conducting aerobic respiration run photosynthesis backward to recover the solar energy stored in glucose. Some organisms, such as bacteria that live in the mud underlying a swamp where oxygen is not available, conduct **anaerobic respiration,** a process by which cells convert glucose into energy in the absence of oxygen. Anaerobic respiration does not provide as much energy as aerobic respiration.

Many organisms—including producers—carry out aerobic respiration to fuel their own metabolism and growth. Thus producers both produce and consume oxygen. When the Sun is shining and photosynthesis occurs, producers generate more oxygen through photosynthesis than they consume through respiration. At night, when producers only respire, they consume oxygen without generating it. Overall, producers photosynthesize more than they respire. The net effect is an excess of oxygen released into the air and an excess of carbon stored in the tissues of producers.

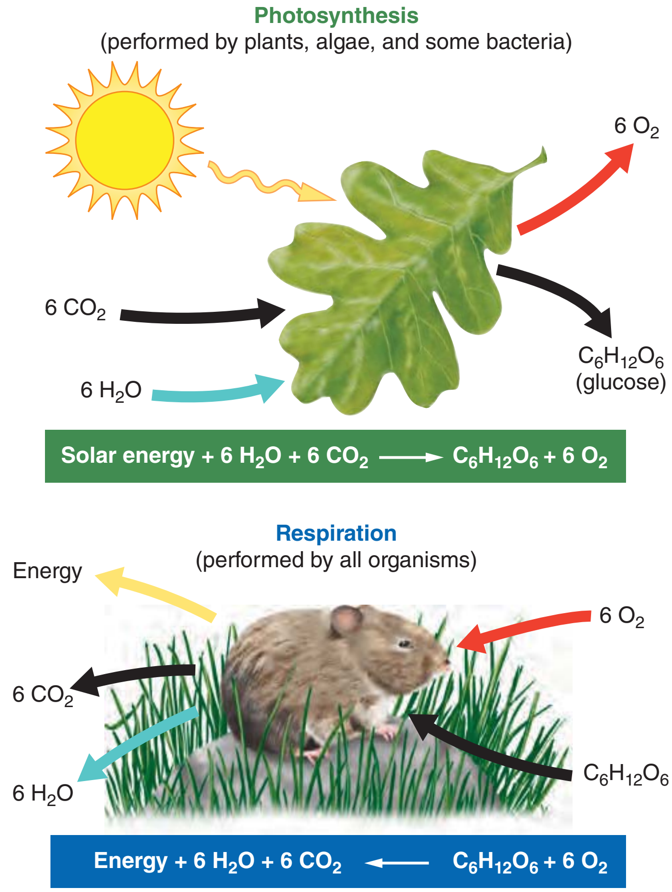


FIGURE 6.4 Photosynthesis and respiration. Photosynthesis is the process by which producers use solar energy to convert carbon dioxide and water into glucose and oxygen. Respiration is the process by which organisms convert glucose and oxygen into water and carbon dioxide, releasing the energy needed to live, grow, and reproduce. All organisms, including producers, perform respiration.

Energy captured by producers moves through many trophic levels

We have seen that producers make their own food. However, **consumers,** or **heterotrophs,** are incapable of photosynthesis and must obtain their energy by consuming other organisms. In FIGURE 6.5, we can see that consumers in both terrestrial and aquatic ecosystems fall into different categories. Consumers that eat producers are called **herbivores** or **primary consumers.** Primary consumers include a variety of familiar plant- and

Photosynthesis The process by which producers use solar energy to convert carbon dioxide and water into glucose.

Cellular respiration The process by which cells unlock the energy of chemical compounds.

Aerobic respiration The process by which cells convert glucose and oxygen into energy, carbon dioxide, and water.

Anaerobic respiration The process by which cells convert glucose into energy in the absence of oxygen.

Consumer An organism that is incapable of photosynthesis and must obtain its energy by consuming other organisms. *Also known as* **Heterotroph**.

Herbivore A consumer that eats producers. *Also known as* **Primary consumer**.

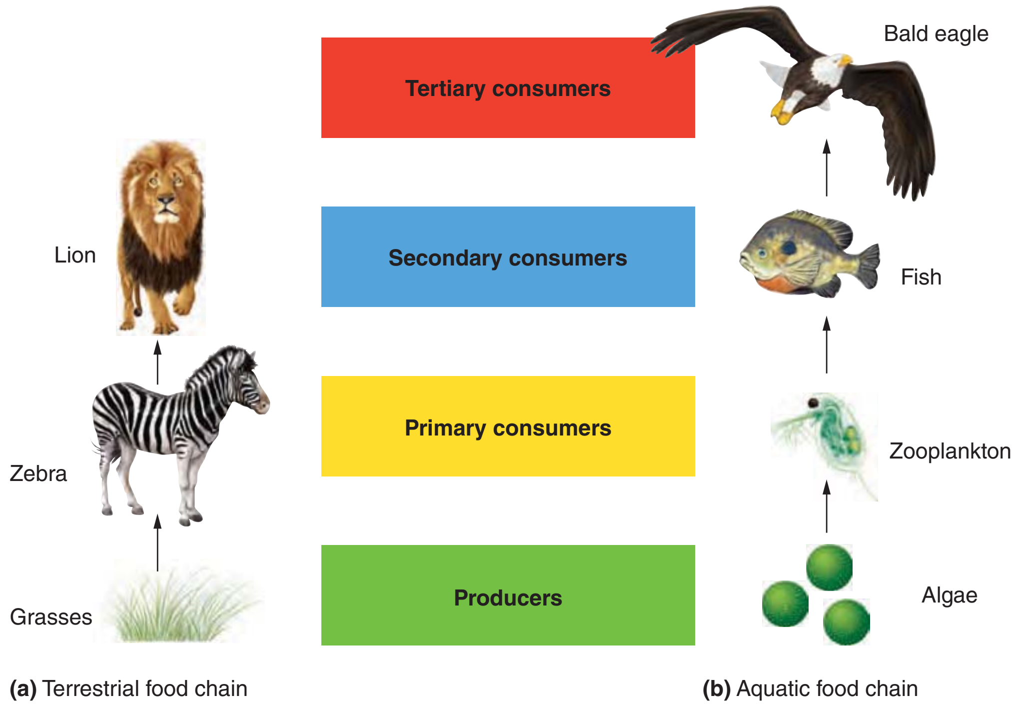


FIGURE 6.5 **Simple food chains.** A simple food chain that links producers and consumers in a linear fashion illustrates how energy and matter move through the trophic levels of an ecosystem. (a) An example of a terrestrial food chain. (b) An example of an aquatic food chain.

alga-eating animals, such as zebras, grasshoppers, tadpoles, and zooplankton. Consumers that eat other consumers are called **carnivores.** Carnivores that eat primary consumers are called **secondary consumers.** Secondary consumers include creatures such as lions, hawks, and rattlesnakes. Carnivores that eat secondary consumers are called **tertiary consumers.** As you can see on the right side of Figure 6.5, animals such as bald eagles can be tertiary consumers. In this food chain, the algae (producers) living in lakes convert sunlight into glucose, zooplankton (primary consumers) eat the algae, fish (secondary consumers) eat the zooplankton, and eagles (tertiary consumers) eat the fish.

The successive levels of organisms consuming one another are known as **trophic levels** (from the Greek word *trophe,* which means "nourishment"). The sequence of consumption from producers through tertiary consumers is known as a **food chain,** where energy moves from one trophic level to the next. A food chain helps us visualize how energy and matter move between trophic levels.

Species in natural ecosystems are rarely connected in such a simple, linear fashion. A more realistic type of model, shown in FIGURE 6.6, is known as a *food web.* A **food web** is a complex model of how energy and matter move through trophic levels. Food webs illustrate one of the most important concepts of ecology: All species in an ecosystem are connected to one another.

Not all organisms fit neatly into a single trophic level. Some organisms, called *omnivores,* operate at several trophic levels. Omnivores include grizzly bears, which eat berries and fish, and the Venus flytrap (*Dionaea muscipula*), which can photosynthesize as well as digest insects that become trapped in its leaves.

Each trophic level eventually produces dead individuals and waste products. Three groups of organisms feed on this dead organic matter: *scavengers, detritivores,* and *decomposers.* **Scavengers** are organisms,

Carnivore A consumer that eats other consumers.

Secondary consumer A carnivore that eats primary consumers.

Tertiary consumer A carnivore that eats secondary consumers.

Trophic levels The successive levels of organisms consuming one another.

Food chain The sequence of consumption from producers through tertiary consumers.

Food web A complex model of how energy and matter move between trophic levels.

Scavenger An organism that consumes dead animals.

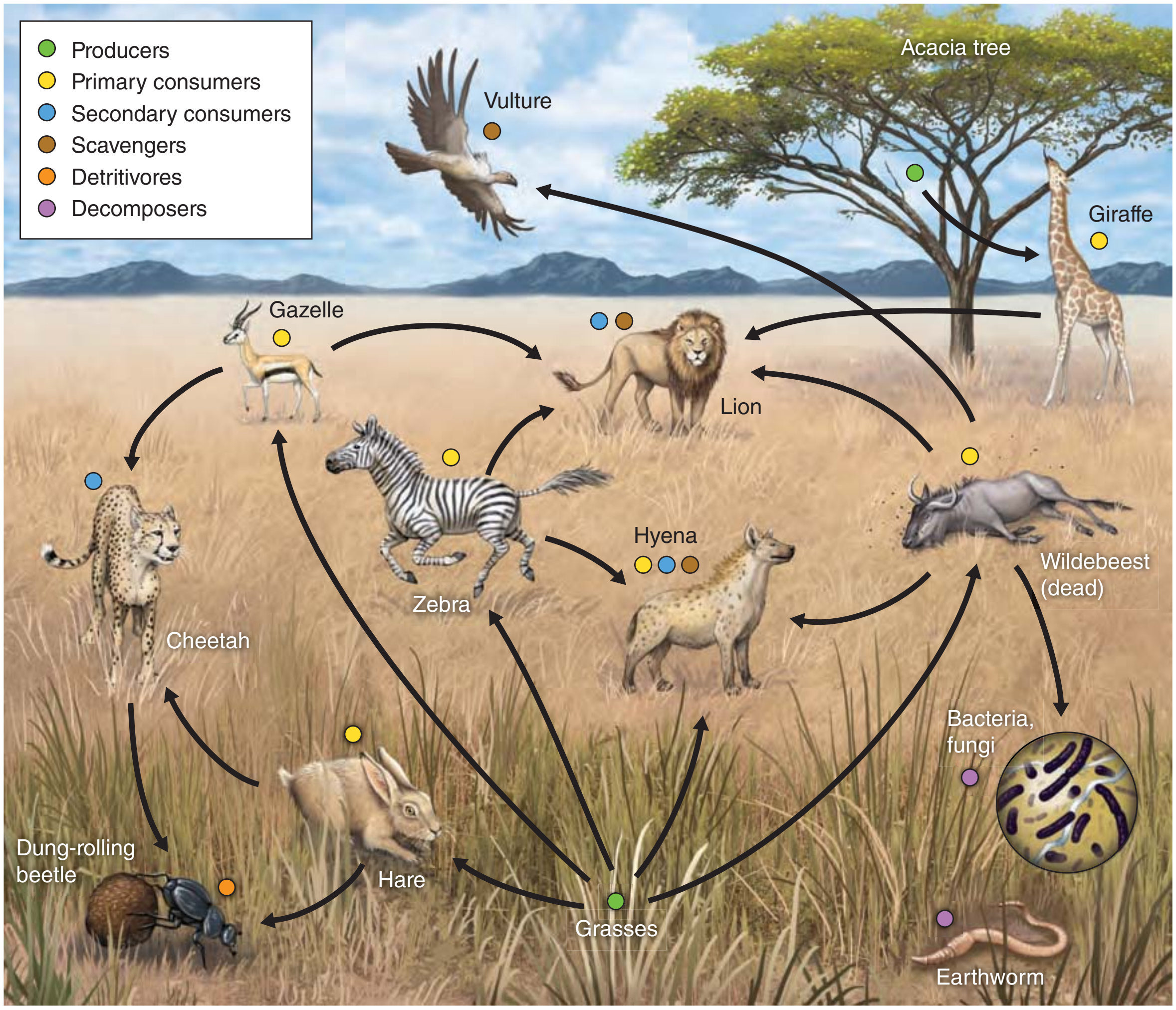


FIGURE 6.6 A simplified food web. Food webs are more realistic representations of trophic relationships than simple food chains. They include scavengers, detritivores, and decomposers, and they recognize that some species feed at multiple trophic levels. Arrows indicate the direction of energy movement. This is a real but somewhat simplified food web; in an actual ecosystem, many more organisms are present. In addition, there are many more energy movements.

such as vultures, that consume dead animals. **Detritivores** are organisms, such as dung beetles, that specialize in breaking down dead tissues and waste products (referred to as detritus) into smaller particles. These particles can then be further processed by **decomposers,** which are the fungi and bacteria that complete the breakdown process by converting organic matter into small elements and molecules that can be recycled back into the ecosystem. Without scavengers, detritivores, and decomposers, there would be no way of recycling organic matter and energy, and the world would rapidly fill up with dead plants and animals.

Detritivore An organism that specializes in breaking down dead tissues and waste products into smaller particles.

Decomposers Fungi and bacteria that convert organic matter into small elements and molecules that can be recycled back into the ecosystem.

Some ecosystems are more productive than others

The amount of energy available in an ecosystem determines how much life the ecosystem can support. For example, the amount of sunlight that reaches a lake surface determines how much algae can live in the lake. In turn, the amount of algae determines the number of zooplankton the lake can support, and the size of the zooplankton population determines the number of fish the lake can support.

To understand where the energy in an ecosystem comes from and how it is transferred through food webs, environmental scientists measure the ecosystem's productivity. The **gross primary productivity (GPP)** of the ecosystem is a measure of the total amount of solar energy that the producers in the system capture via photosynthesis over a given amount of time. Note that the term *gross,* as used here, indicates the total amount of energy captured by producers. In other words, GPP does not subtract the energy lost when the producers respire. The energy captured minus the energy respired by producers is the ecosystem's **net primary productivity (NPP)**:

$$\text{net primary productivity} = \text{gross primary productivity} - \text{respiration by producers}$$

You can think of GPP and NPP in terms of a paycheck: GPP is the total amount your employer pays you while NPP is the actual amount you take home after taxes are deducted.

GPP is essentially a measure of how much photosynthesis is occurring over some amount of time. Determining GPP is a challenge for scientists because a plant rarely photosynthesizes without simultaneously respiring. However, if we can determine the rate of photosynthesis and the rate of respiration, we can use this information to calculate GPP.

We can determine the rate of photosynthesis by measuring the compounds that participate in the reaction. So, for example, we can measure the rate at which CO_2 is taken up during photosynthesis and the rate at which CO_2 is produced during respiration. A common approach to measuring GPP is to first measure the production of CO_2 in the dark. Because no photosynthesis occurs in the dark, this measure eliminates CO_2 uptake by photosynthesis. Next, we measure the uptake of CO_2 in sunlight. This measure gives us the net movement of CO_2 when respiration and photosynthesis are both occurring. By adding the amount of CO_2 produced in the dark to the amount of CO_2 taken up in the sunlight, we can determine the gross amount of CO_2 that is taken up during photosynthesis:

$$CO_2 \text{ taken up during photosynthesis} = CO_2 \text{ taken up in sunlight} + CO_2 \text{ produced in the dark}$$

In this way, we can derive the GPP of an ecosystem per day within a given area. We can give our answer in units of kilograms of carbon taken up per square meter per day (kg C/m^2/day).

Converting sunlight into chemical energy is not an efficient process. As **FIGURE 6.7** shows, only about 1 percent of the total amount of solar energy that reaches the producers in an ecosystem—the sunlight on a pond surface, for example—is converted into chemical energy via photosynthesis. Most of that solar energy is lost from the ecosystem as heat that returns to the atmosphere. Some of the lost energy consists of wavelengths of light that producers cannot absorb.

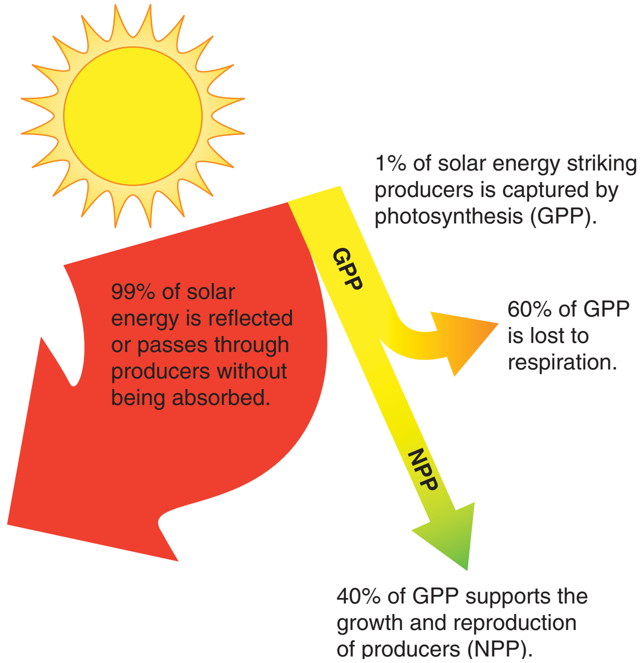


FIGURE 6.7 Gross and net primary productivity. Producers typically capture only about 1 percent of available solar energy via photosynthesis. This is known as gross primary productivity, or GPP. About 60 percent of GPP is typically used for respiration. The remaining 40 percent of GPP is used for the growth and reproduction of the producers. This is known as net primary productivity, or NPP.

Those wavelengths are either reflected from the surfaces of producers or pass through their tissues.

The NPP of ecosystems ranges from 25 to 50 percent of GPP, or as little as 0.25 percent of the solar energy striking the plant. Clearly, it takes a lot of energy to conduct photosynthesis. Let's look at the math. Recall from Figure 6.7 that on average, of the 1 percent of the Sun's energy that is captured by a producer, about 60 percent is used to fuel the producer's respiration. The remaining 40 percent can be used to support the producer's growth and reproduction. A forest in North America, for example, might have a GPP of 2.5 kg C/m^2/year and lose 1.5 kg C/m^2/year to respiration by plants. Because NPP = GPP − respiration, the NPP of the forest is 1 kg C/m^2/year (1.8 pounds $C/yard^2$/year). This means that the plants living in 1 m^2 of forest will add 1 kg of carbon to their tissues every year by means of growth and reproduction. So, in this example, NPP is 40 percent of GPP.

Gross primary productivity (GPP) The total amount of solar energy that producers in an ecosystem capture via photosynthesis over a given amount of time.

Net primary productivity (NPP) The energy captured by producers in an ecosystem minus the energy producers respire.

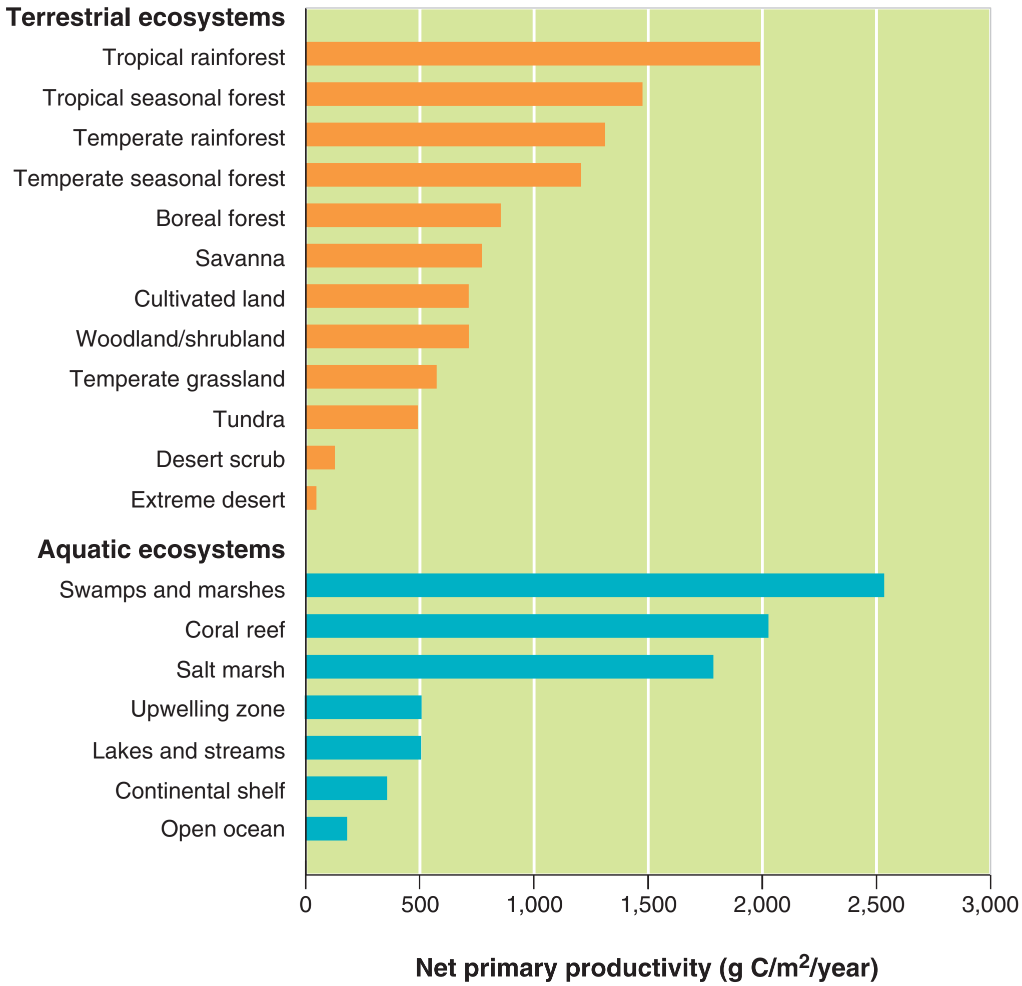


FIGURE 6.8 Net primary productivity. Net primary productivity varies among ecosystems. Productivity is highest where temperatures are warm and water and solar energy are abundant. As a result, NPP varies tremendously among different areas of the world. (Data from R. H. Whittaker and G. E. Likens, Primary production: The biosphere and man, *Human Ecology* 1 (1973): 357–369.)

Measurement of NPP allows us to compare the productivity of different ecosystems, as shown in FIGURE 6.8. As you can see, producers grow best in ecosystems where they have plenty of sunlight, lots of available water and nutrients, and warm temperatures, such as tropical rainforests and salt marshes, which are the most productive ecosystems on Earth. Conversely, producers grow poorly in the cold regions of the Arctic, dry deserts, and the dark regions of the deep sea. In general, the greater the productivity of an ecosystem, the more primary consumers can be supported.

Measuring NPP is also a useful way to measure change in an ecosystem. For example, after a drastic change alters an ecosystem, the amount of stored energy (NPP) tells us whether the new system is more or less productive than the previous system.

Biomass The total mass of all living matter in a specific area.

Standing crop The amount of biomass present in an ecosystem at a particular time.

The efficiency of energy transfer affects the energy present in each trophic level

The net primary productivity of an ecosystem establishes the rate at which **biomass**—the total mass of all living matter in a specific area—is produced over a given amount of time. The amount of biomass present in an ecosystem at a particular time is its **standing crop.** It is important to differentiate standing crop, which measures the amount of energy in a system at a given time, from productivity, which measures the rate of energy production over a span of time. For example, slow-growing forests have low productivity; the trees add only a small amount of biomass through growth and reproduction each year. However, the standing crop of long-lived trees—the biomass of trees that has accumulated over hundreds of years—is quite high. In contrast, the high growth rates of algae living in the ocean make them extremely productive. But because primary consumers eat these algae so rapidly, the standing crop of algae at any particular time is relatively low.

Not all of the energy contained in a particular trophic level is in a usable form. Some parts of plants are not digestible and are excreted by primary consumers. Secondary consumers such as owls consume the muscles and organs of their prey, but they cannot digest bones and hair. Of the food that is digestible, some fraction of the energy it contains is used to power the consumer's day-to-day activities, including moving, eating, and (for birds and mammals) maintaining a constant body temperature. That energy is ultimately lost as heat. Any energy left over may be converted into consumer biomass for growth and reproduction and thus becomes available for consumption by organisms at the next higher trophic level. The proportion of consumed energy that can be passed from one trophic level to another is referred to as **ecological efficiency.**

Ecological efficiencies are fairly low; they range from 5 to 20 percent and average about 10 percent across all ecosystems. In other words, of the total biomass available at a given trophic level, only about 10 percent can be converted into energy at the next higher trophic level. We can represent the distribution of biomass among trophic levels using a **trophic pyramid,** like the one for the Serengeti ecosystem shown in FIGURE 6.9. Trophic pyramids tend to look similar across ecosystems. Most of the energy and biomass are found at the producer level, and they commonly decrease as we move up the pyramid.

The Serengeti ecosystem offers a good example of a trophic pyramid. The biomass of producers (such as grasses and shrubs) is much greater than the biomass of primary consumers (such as gazelles, wildebeests, and zebras) for which the producers serve as food. Likewise, the biomass of primary consumers is much greater than the biomass of secondary consumers (such as lions and cheetahs). The flow of energy between trophic levels helps to determine the population sizes of the various species within each trophic level. As we saw earlier in this chapter, the number of primary consumers in an area is generally higher than that of the carnivores they sustain.

The principle of ecological efficiency also has implications for the human diet. For example, if all humans were to act only as primary consumers—that is, become vegetarians—we would harvest much more energy from any given area of land or water. How would this work?

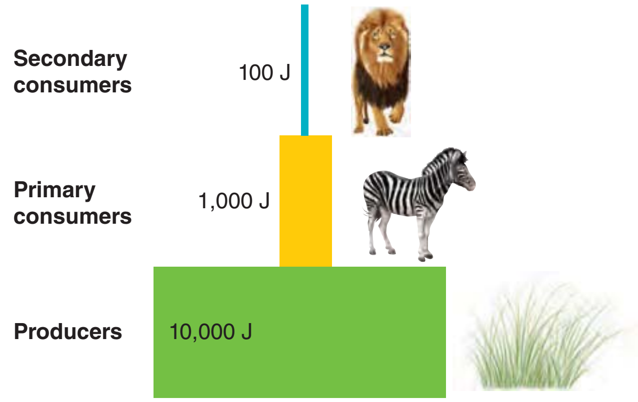


FIGURE 6.9 Trophic pyramid for the Serengeti ecosystem. This trophic pyramid represents the amount of energy that is present at each trophic level, measured in joules (J). While this pyramid assumes 10 percent ecological efficiency, actual ecological efficiencies range from 5 to 20 percent across different ecosystems. For most ecosystems, graphing the numbers of individuals or biomass within each trophic level would produce a similar pyramid.

Suppose a hectare of cropland could produce 1,000 kg of soybeans. This food could feed humans directly. Or, if we assume 10 percent ecological efficiency, it could be fed to cattle to produce approximately 100 kg of meat. In terms of biomass, there would be 10 times more food available for humans acting as primary consumers by eating soybeans than for humans acting as secondary consumers by eating beef. However, 1 kg of soybeans actually contains about 2.5 times as many calories as 1 kg of beef. Therefore, 1 ha of land would produce 25 times more calories when used for soybeans than when used for beef. In general, when we act as secondary consumers, the animals we eat require land to support the producers they consume. When we act as primary consumers, we require only the land necessary to support the producers we eat.

Ecological efficiency The proportion of consumed energy that can be passed from one trophic level to another.

Trophic pyramid A representation of the distribution of biomass, numbers, or energy among trophic levels.

module

6

REVIEW

In this module, we have learned that ecosystems can range widely in size and have boundaries that are either natural or defined by humans. Energy from the Sun is captured by producers during the process of photosynthesis and released during the process of respiration. The energy captured by producers helps to determine the productivity of different ecosystems around the world. This energy moves from producers through the many trophic levels. The efficiency of such energy transfers determines the biomass found in different trophic levels. In the next module we will apply this understanding of how energy moves through an ecosystem to consider how matter cycles around an ecosystem.

Module 6 AP® Review Questions

1. Autotrophs
   (a) use photosynthesis.
   (b) are able to survive without oxygen.
   (c) are primary consumers.
   (d) are at the top of the food chain.
   (e) cannot assimilate carbon.

2. A zebra is an example of
   (a) a secondary consumer.
   (b) a producer.
   (c) a detritivore.
   (d) a primary consumer.
   (e) a scavenger.

3. If gross primary productivity in a wetland is 3 kg C/m^2/year and respiration is 1.5 kg C/m^2/year, what is the net primary productivity of the wetland?
   (a) 1.5 kg C/m^2/year
   (b) 2 kg C/m^2/year
   (c) 3 kg C/m^2/year
   (d) 4.5 kg C/m^2/year
   (e) Impossible to determine from the given information

4. The average efficiency of energy transfer between trophic levels is approximately
   (a) 1 percent.
   (b) 4 percent.
   (c) 10 percent.
   (d) 40 percent.
   (e) 50 percent.

5. The gross primary productivity of an ecosystem is
   (a) the total amount of biomass.
   (b) the total energy captured by photosynthesis.
   (c) the energy captured after accounting for respiration.
   (d) the energy available to primary consumers.
   (e) the biomass of the producers.

6. Ecosystem boundaries are
   (a) based primarily on topographic features.
   (b) boundaries to nutrient flows.
   (c) never based on human created features.
   (d) are only used for ecosystems smaller than a few square hectares.
   (e) depend on many subjective factors.

module

7

The Movement of Matter

As we saw in Chapter 2, Earth is an open system with respect to energy, but a closed system with respect to matter. In the previous module, we examined how energy flows through the biosphere; it enters as energy from the Sun, moves among the living and nonliving components of ecosystems, and is ultimately emitted back into space. In contrast, matter—such as water, carbon, nitrogen, and phosphorus—does not enter or leave the biosphere, but cycles within the biosphere in a variety of forms. In this module, we will explore the cycling of matter with a focus on the major biotic and abiotic processes that cause this cycling.

The specific chemical forms that elements take determine how they cycle within the biosphere. We will look at the elements that are the most important to the productivity of photosynthetic organisms. We will begin with the hydrologic cycle—the movement of water. Then we will explore the cycles of carbon, nitrogen, and phosphorus. Finally, we will take a brief look at the cycles of calcium, magnesium, potassium, and sulfur.

Learning Objectives

After reading this module you should be able to

- describe how water cycles within ecosystems.
- explain how carbon cycles within ecosystems.
- describe how nitrogen cycles within ecosystems.
- explain how phosphorus cycles within ecosystems.
- discuss the movement of calcium, magnesium, potassium, and sulfur within ecosystems.

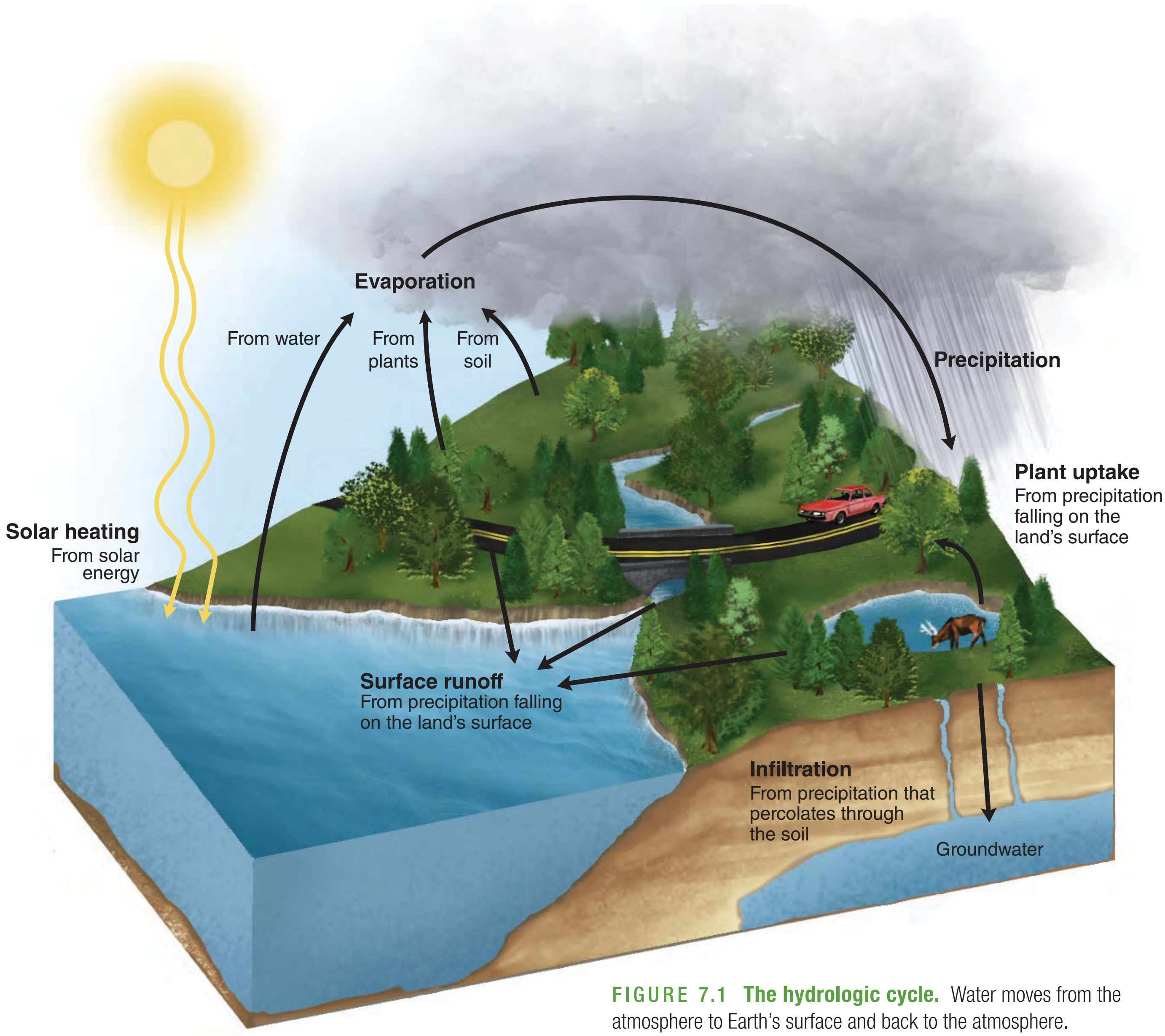


FIGURE 7.1 The hydrologic cycle. Water moves from the atmosphere to Earth's surface and back to the atmosphere.

The hydrologic cycle moves water through the biosphere

Because the movement of matter within and between ecosystems involves cycles of biological, geological, and chemical processes, these cycles are known as **biogeochemical cycles.** To keep track of the movement of matter in biogeochemical cycles, we refer to the components that contain the matter—including air, water, and organisms—as "pools." Processes that move matter between pools are known as "flows." We will begin our study of biogeochemical cycles with water.

Biogeochemical cycle The movements of matter within and between ecosystems.

Hydrologic cycle The movement of water through the biosphere.

Water is essential to life. It makes up over one-half of a typical mammal's body weight, and no organism can survive without it. Water allows essential molecules to move within and between cells, draws nutrients into the leaves of trees, dissolves and removes toxic materials, and performs many other critical biological functions. On a larger scale, water is the primary agent responsible for dissolving and transporting the chemical elements necessary for living organisms. The movement of water through the biosphere is known as the **hydrologic cycle.**

The Hydrologic Cycle

FIGURE 7.1 shows how the hydrologic cycle works. Heat from the Sun causes water to evaporate from oceans, lakes, and soils. Solar energy also provides the energy for photosynthesis, during which plants release water from their leaves into the atmosphere—a process

do the math

Raising Mangoes

As we saw at the beginning of this chapter, farmers in Haiti are being encouraged to plant mango trees to help reduce runoff and increase the uptake of water by the soil and the trees. Consider a group of Haitian farmers that decides to plant mango trees. Mango saplings cost $10 each. Once the trees become mature, each tree will produce $75 worth of fruit per year. A village of 225 people decides to pool its resources and set up a community mango plantation. Their goal is to generate a per capita income of $300 per year for everyone in the village.

1. How many mature trees will the village need to meet the goal?
   Total annual income desired:

   $$\$300/\text{person} \times 225 \text{ persons} = \$67{,}500$$

   Number of trees needed to produce $67,500 in annual income:

   $$\$67{,}500 \div \$75/\text{tree} = 900 \text{ trees}$$

2. Each tree requires 25 m^2 of space. How many hectares must the village set aside for the plantation?

   $$900 \text{ trees} \times 25 \text{ m}^2 = 22{,}500 \text{ m}^2 = 2.25 \text{ ha}$$

Your Turn

Each tree requires 20 L of water per day during the 6 hot months of the year (180 days). The water must be pumped to the plantation from a nearby stream. How many liters of water are needed each year to water the plantation of 900 trees?

known as **transpiration.** The water vapor that enters the atmosphere eventually cools and forms clouds, which, in turn, produce precipitation in the form of rain, snow, and hail. Some precipitation falls back into the ocean and some falls on land.

When water falls on land, it may take one of three distinct routes. First, it may return to the atmosphere by evaporation or, after being taken up by plant roots, by transpiration. The combined amount of evaporation and transpiration, called **evapotranspiration,** is often used by scientists as a measure of the water moving through an ecosystem. Alternatively, water can be absorbed by the soil and percolate down into the groundwater. Finally, water can move as **runoff** across the land surface and into streams and rivers, eventually reaching the ocean, which is the ultimate pool of water on Earth. As water in the ocean evaporates, the cycle begins again.

The hydrologic cycle is instrumental in the cycling of elements. Many elements are carried to the ocean or taken up by organisms in dissolved form. As you read about biogeochemical cycles, notice the role that water plays in these processes.

Human Activities and the Hydrologic Cycle

Because Earth is a closed system with respect to matter, water never leaves it. Nevertheless, human activities can alter the hydrologic cycle in a number of ways. For example, harvesting trees from a forest can reduce evapotranspiration by reducing plant biomass. If evapotranspiration decreases, then runoff or percolation will increase. On a moderate or steep slope, most water will leave the land surface as runoff. That is why, as we saw at the opening of this chapter, clear-cutting a mountain slope can lead to erosion and flooding. Similarly, paving over land surfaces to build roads, businesses, and homes reduces the amount of percolation that can take place in a given area, increasing runoff and evaporation. Humans can also alter the hydrologic cycle by diverting water from one area to another to provide water for drinking, irrigation, and industrial uses. In "Do the Math: Raising Mangoes" you can see how citizens in Haiti are working to reforest the country and reduce the impacts of humans on the hydrologic cycle.

Transpiration The release of water from leaves during photosynthesis.

Evapotranspiration The combined amount of evaporation and transpiration.

Runoff Water that moves across the land surface and into streams and rivers.

The carbon cycle moves carbon between air, water, and land

Carbon is the most important element in living organisms; it makes up about 20 percent of their total body weight. Carbon is the basis of the long chains of organic molecules that form the membranes and walls of cells, constitute the backbones of proteins, and store energy for later use. Other than water, few molecules in the bodies of organisms do not contain carbon. To understand the **carbon cycle,** which is the movement of carbon around the biosphere, we need to examine the flows that move carbon and the major pools that contain carbon.

The Carbon Cycle

FIGURE 7.2 illustrates the seven processes that drive the carbon cycle: *photosynthesis, respiration, exchange, sedimentation, burial, extraction,* and *combustion*. These processes can be categorized as either fast or slow. The fast part of the cycle involves processes that are associated with living organisms. The slow part of the cycle involves carbon that is held in rocks, in soils, or as petroleum hydrocarbons (the materials we use as fossil fuels). Carbon may be stored in these forms for millions of years.

Photosynthesis and Respiration

Let's take a closer look at Figure 7.2, which depicts the carbon cycle. When producers photosynthesize, whether on land or in the water, they take in CO_2 and incorporate the carbon into their tissues. Some of this carbon is returned as CO_2 when organisms respire. It is also returned after organisms die. When organisms die, carbon that was part of the live biomass pool becomes part of the dead biomass pool. Decomposers break down the dead material, which returns CO_2 to the water or air via respiration and continues the cycle.

Exchange, Sedimentation, and Burial

As you can see on the left side of Figure 7.2, carbon is exchanged between the atmosphere and the ocean. The amount of carbon released from the ocean into the atmosphere roughly equals the amount of atmospheric CO_2 that diffuses into ocean water. Some of the CO_2 dissolved in the ocean enters the food web via photosynthesis by algae.

Another portion of the CO_2 dissolved in the ocean combines with calcium ions in the water to form calcium carbonate ($CaCO_3$), a compound that can precipitate out of the water and form limestone and dolomite rock via sedimentation and burial. Although sedimentation is a very slow process, the small amounts of calcium carbonate sediment formed each year have accumulated over millions of years to produce the largest carbon pool in the slow part of the carbon cycle.

A small fraction of the organic carbon in the dead biomass pool is buried and incorporated into ocean sediments before it can decompose into its constituent elements. This organic matter becomes fossilized and, over millions of years, some of it may be transformed into fossil fuels. The amount of carbon removed from the food web by this slow process is roughly equivalent to the amount of carbon returned to the atmosphere by weathering of rocks containing carbon (such as limestone) and by volcanic eruptions, so the slow part of the carbon cycle is in steady state.

Carbon cycle The movement of carbon around the biosphere.

Extraction and Combustion

The final processes in the carbon cycle are extraction and combustion, as are shown in the middle of Figure 7.2. The extraction of fossil fuels by humans is a relatively recent phenomenon that began when human society started to rely on coal, oil, and natural gas as energy sources. Extraction by itself does not alter the carbon cycle; it is the subsequent step of combustion that makes the difference. Combustion of fossil fuels by humans and the natural combustion of carbon by fires or volcanoes release carbon into the atmosphere as CO_2 or into the soil as ash.

As you can see, combustion, respiration, and decomposition operate in very similar ways: All three processes cause organic molecules to be broken down to produce CO_2, water, and energy. However, respiration and decomposition are biotic processes, whereas combustion is an abiotic process.

Human Impacts on the Carbon Cycle

In the absence of human disturbance, the exchange of carbon between Earth's surface and atmosphere is in steady state. Carbon taken up by photosynthesis eventually ends up in the soil. Decomposers in the soil gradually release that carbon at roughly the same rate it is added. Similarly, the gradual movement of carbon into the buried or fossil fuel pools is offset by the slow processes that release it. Before the Industrial Revolution, the atmospheric concentration of carbon dioxide had changed very little for 10,000 years (see Figure 2.5 on page 12). So, until recently, carbon entering any of these pools was balanced by carbon leaving these pools.

Since the Industrial Revolution, however, human activities have had a major influence on carbon cycling.

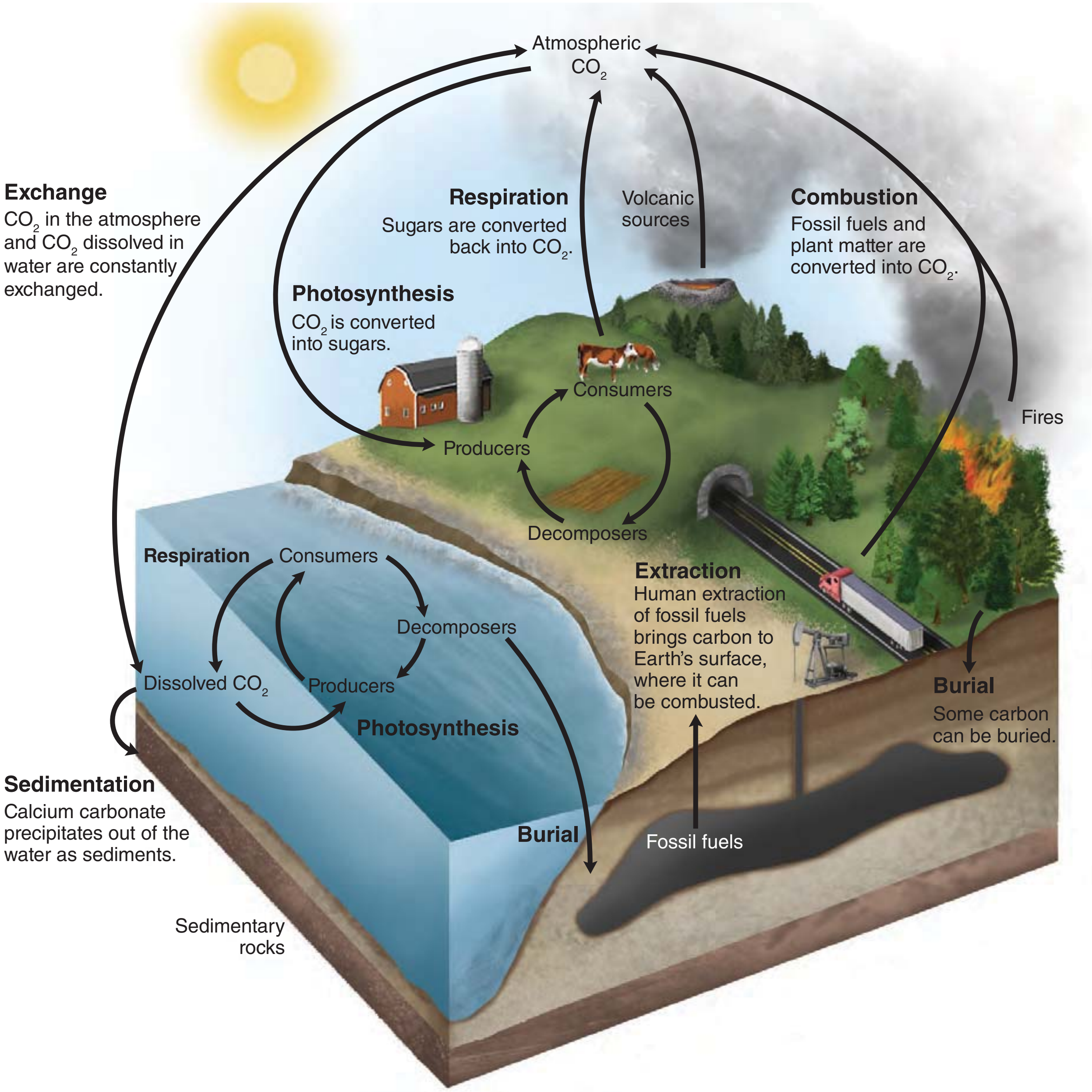


FIGURE 7.2 The carbon cycle. Producers take up carbon from the atmosphere via photosynthesis and pass it on to consumers and decomposers. Some inorganic carbon sediments out of the water to form sedimentary rock while some organic carbon may be buried and become fossil fuels. Respiration by organisms returns carbon to the atmosphere and water. Combustion of fossil fuels and other organic matter returns carbon to the atmosphere.

The best-known and most significant human alteration of the carbon cycle is the combustion of fossil fuels. This process releases fossilized carbon into the atmosphere, which increases atmospheric carbon concentrations and upsets the balance between Earth's carbon pools and the atmosphere. The excess CO_2 in the atmosphere acts to increase the retention of heat energy in the biosphere. The result, global warming, is a major concern among environmental scientists and policy makers.

Tree harvesting is another human activity that can affect the carbon cycle. Trees store a large amount of carbon in their wood, both above and below ground. The destruction of forests by cutting and burning increases the amount of CO_2 in the atmosphere. Unless enough new trees are planted to recapture the carbon, the destruction of forests will upset the balance of CO_2. To date, large areas of forest, including tropical forests as well as North American and European temperate forests, have been converted into pastures, grasslands, and croplands. In addition to destroying a great deal of biodiversity, this destruction of forests has added large amounts of carbon to the atmosphere. The increases in

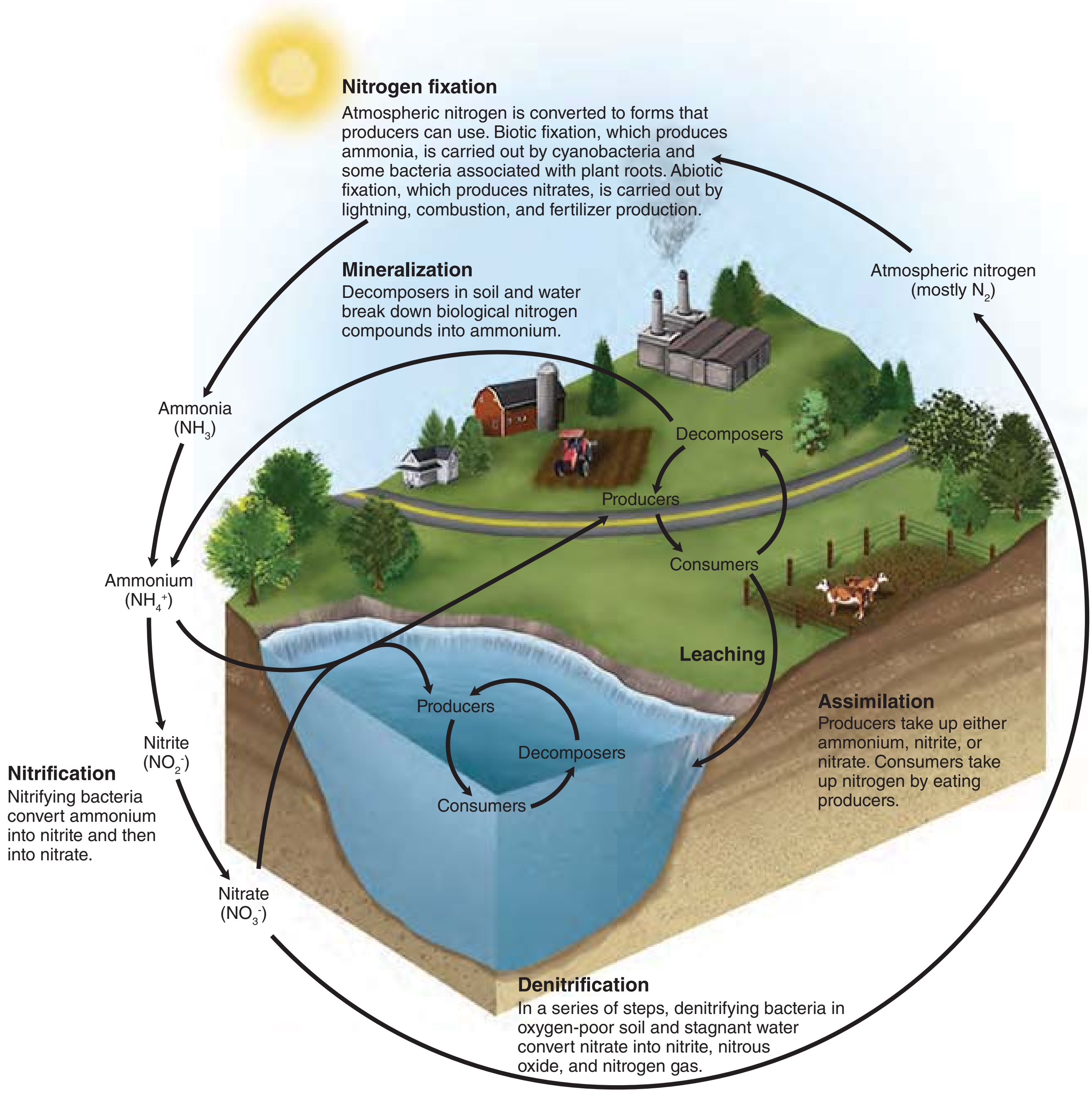


FIGURE 7.3 **The nitrogen cycle.** The nitrogen cycle moves nitrogen from the atmosphere and into soils through several fixation pathways, including the production of fertilizers by humans. In the soil, nitrogen can exist in several forms. Denitrifying bacteria release nitrogen gas back into the atmosphere.

atmospheric carbon due to human activities have been partly offset by an increase in carbon absorption by the ocean. Still, the loss of forest remains a concern.

Macronutrient One of six key elements that organisms need in relatively large amounts: nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur.

The nitrogen cycle includes many chemical transformations

There are six key elements, known as **macronutrients,** that are needed by organisms in relatively large amounts: nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur.

Nitrogen is an element that organisms need in relatively high amounts. Nitrogen is used to form amino acids, the building blocks of proteins, and nucleic acids, the building blocks of DNA and RNA. Because so much of it is required, nitrogen is often a *limiting nutrient* for producers. A **limiting nutrient** is a nutrient required for the growth of an organism but available in a lower quantity than other nutrients. Therefore, a lack of nitrogen constrains the growth of the organism. Adding other nutrients, such as water or phosphorus, will not improve plant growth in nitrogen-poor soil.

The Nitrogen Cycle

The **nitrogen cycle** is the movement of nitrogen around the biosphere. As nitrogen moves through an ecosystem, it experiences many chemical transformations. As shown in FIGURE 7.3, there are five major transformations in the nitrogen cycle: *nitrogen fixation, nitrification, assimilation, mineralization,* and *denitrification*.

Nitrogen Fixation

Although Earth's atmosphere is 78 percent nitrogen by volume, the vast majority of that nitrogen is in a gas form that most producers cannot use. **Nitrogen fixation** is the process that converts nitrogen gas in the atmosphere (N_2) into forms of nitrogen that producers can use. As you can see in Figure 7.3, nitrogen fixation can occur through biotic or abiotic processes. In the biotic process, a few species of bacteria can convert N_2 gas directly into ammonia (NH_3), which is rapidly converted to ammonium (NH_4^+), a form that is readily used by producers. Nitrogen-fixing organisms include cyanobacteria (also known as blue-green algae) and certain bacteria that live within the roots of legumes, which include plants such as peas, beans, and a few species of trees. Nitrogen-fixing organisms use the fixed nitrogen to synthesize their own tissues, then excrete any excess. Cyanobacteria, which are primarily aquatic organisms, excrete excess ammonium ions into the water, where they can be taken up by aquatic producers. Nitrogen-fixing bacteria that live within plant roots excrete excess ammonium ions into the plant's root system; the plant, in turn, supplies the bacteria with sugars it produces via photosynthesis.

Nitrogen fixation can also occur through two abiotic pathways. N_2 can be fixed in the atmosphere by lightning or during combustion processes such as fires and the burning of fossil fuels. These processes convert N_2 into nitrate (NO_3^-), which is usable by plants. The nitrate is carried to Earth's surface in precipitation. Humans have developed techniques for nitrogen fixation into ammonia or nitrate to be used in plant fertilizers. Although these processes require a great deal of energy, humans now fix more nitrogen than is fixed in nature. The development of synthetic nitrogen fertilizers has led to large increases in crop yields, particularly for crops such as corn that require large amounts of nitrogen.

Nitrification

Another step in the nitrogen cycle is **nitrification,** which is the conversion of ammonium (NH_4^+) into nitrite (NO_2^-) and then into nitrate (NO_3^-). These conversions are conducted by specialized species of bacteria. Although nitrite is not used by most producers, nitrate is readily used.

Assimilation

Once producers take up nitrogen in the form of ammonia, ammonium, nitrite, or nitrate, they incorporate the element into their tissues in a process called **assimilation.** When primary consumers feed on the producers, some of the producer's nitrogen is assimilated into the tissues of the consumers while the rest is eliminated as waste products.

Mineralization

Eventually, organisms die and their tissues decompose. In a process called **mineralization,** fungal and bacterial decomposers break down the organic matter found in dead bodies and waste products and convert organic compounds back into inorganic compounds. In the nitrogen cycle, the process of mineralization is sometime called **ammonification** because organic nitrogen compounds are converted into the inorganic ammonium (NH_4^+). The ammonium produced by this process can either be taken up by producers in the ecosystem or be converted into nitrite (NO_2^-) and nitrate (NO_3^-) through the process of nitrification.

Limiting nutrient A nutrient required for the growth of an organism but available in a lower quantity than other nutrients.

Nitrogen cycle The movement of nitrogen around the biosphere.

Nitrogen fixation A process by which some organisms can convert nitrogen gas molecules directly into ammonia.

Nitrification The conversion of ammonia (NH_4^+) into nitrite (NO_2^-) and then into nitrate (NO_3^-).

Assimilation The process by which producers incorporate elements into their tissues.

Mineralization The process by which fungal and bacterial decomposers break down the organic matter found in dead bodies and waste products and convert it into inorganic compounds.

Ammonification The process by which fungal and bacterial decomposers break down the organic nitrogen found in dead bodies and waste products and convert it into inorganic ammonium (NH_4^+).

Denitrification

The final step that completes the nitrogen cycle is **denitrification,** which is the conversion of nitrate (NO_3^-) in a series of steps into the gases nitrous oxide (N_2O) and, eventually, nitrogen gas (N_2), which is emitted into the atmosphere. Denitrification is conducted by specialized bacteria that live under anaerobic conditions, such as waterlogged soils or the bottom sediments of oceans, lakes, and swamps.

Human Impacts on the Nitrogen Cycle

Nitrogen is a limiting nutrient in most terrestrial ecosystems, so excess inputs of nitrogen can have consequences in these ecosystems. For example, nitrate is readily transported through the soil with water through **leaching,** a process in which dissolved molecules are transported through the soil via groundwater. In addition, adding nitrogen to soils in fertilizers ultimately increases atmospheric concentrations of nitrogen in regions where the fertilizer is applied. This nitrogen can be transported through the atmosphere and deposited by rainfall in natural ecosystems that have adapted over time to a particular level of nitrogen availability. The added nitrogen can alter the distribution or abundance of species in those ecosystems.

In one study of nine different terrestrial ecosystems across the United States, scientists added nitrogen fertilizer to some plots and left other plots unfertilized as controls. They found that adding nitrogen reduced the number of species in a plot by up to 48 percent because some species that could survive under low-nitrogen conditions could no longer compete against larger plants that thrived under high-nitrogen conditions. Other studies have documented cases in which plant communities that have grown on low-nitrogen soils for millennia are now experiencing changes in their species composition. An influx of nitrogen due to human activities has favored colonization by new species that are better adapted to soils with higher fertility.

The observation that nutrients can have unintended effects on ecosystems highlights an important principle of environmental science: In ecosystems containing species that have adapted to their environments over thousands of years or longer, changes in conditions are likely to cause changes in biodiversity as well as in the movement of energy through, and the cycling of matter within, those ecosystems.

Denitrification The conversion of nitrate (NO_3^-) in a series of steps into the gases nitrous oxide (N_2O) and, eventually, nitrogen gas (N_2), which is emitted into the atmosphere.

Leaching The transportation of dissolved molecules through the soil via groundwater.

Phosphorus cycle The movement of phosphorus around the biosphere.

The phosphorus cycle moves between land and water

Organisms need phosphorus for many biological processes. Phosphorus is a major component of DNA and RNA as well as ATP (adenosine triphosphate), the molecule cells use for energy transfer. Required by both producers and consumers, phosphorus is a limiting nutrient second only to nitrogen in its importance for successful agricultural yields. Thus phosphorus, like nitrogen, is commonly added to soils in the form of fertilizer.

The Phosphorus Cycle

The **phosphorus cycle** is the movement of phosphorus around the biosphere. As shown in FIGURE 7.4, it primarily operates between land and water. There is no gas phase, although phosphorus does enter the atmosphere in very small amounts when dust is dissolved in rainwater or sea spray. Unlike nitrogen, phosphorus rarely changes form; it is typically found in the form of phosphate (PO_4^{3-}).

Assimilation and Mineralization

The biotic processes that affect the phosphorus cycle are not complex. Producers on land and in the water take up inorganic phosphate and assimilate the phosphorus into their tissues as organic phosphorus. The waste products and eventual dead bodies of these organisms are decomposed by fungi and bacteria, which causes the mineralization of organic phosphorus back to inorganic phosphate.

Sedimentation, Geologic Uplift, and Weathering

The abiotic processes of the phosphorus cycle involve movements between the water and the land. In water, phosphorus is not very soluble, so much of it precipitates out of solution in the form of phosphate-laden sediments in the ocean. You can see this process in the left corner of Figure 7.4. Over time, geologic forces can lift these ocean layers up and they become mountains. The phosphate rocks in the mountains are slowly weathered by natural forces including rainfall and this weathering brings phosphorus to terrestrial and aquatic habitats. Phosphorus is tightly held by soils, so it is not easily leached from soils and into water bodies. Because so little phosphorus leaches into water bodies and because much of what enters water precipitates out of solution, very little dissolved phosphorus is naturally available in streams, rivers, and lakes. As a result, phosphorus is a limiting nutrient in many aquatic systems.

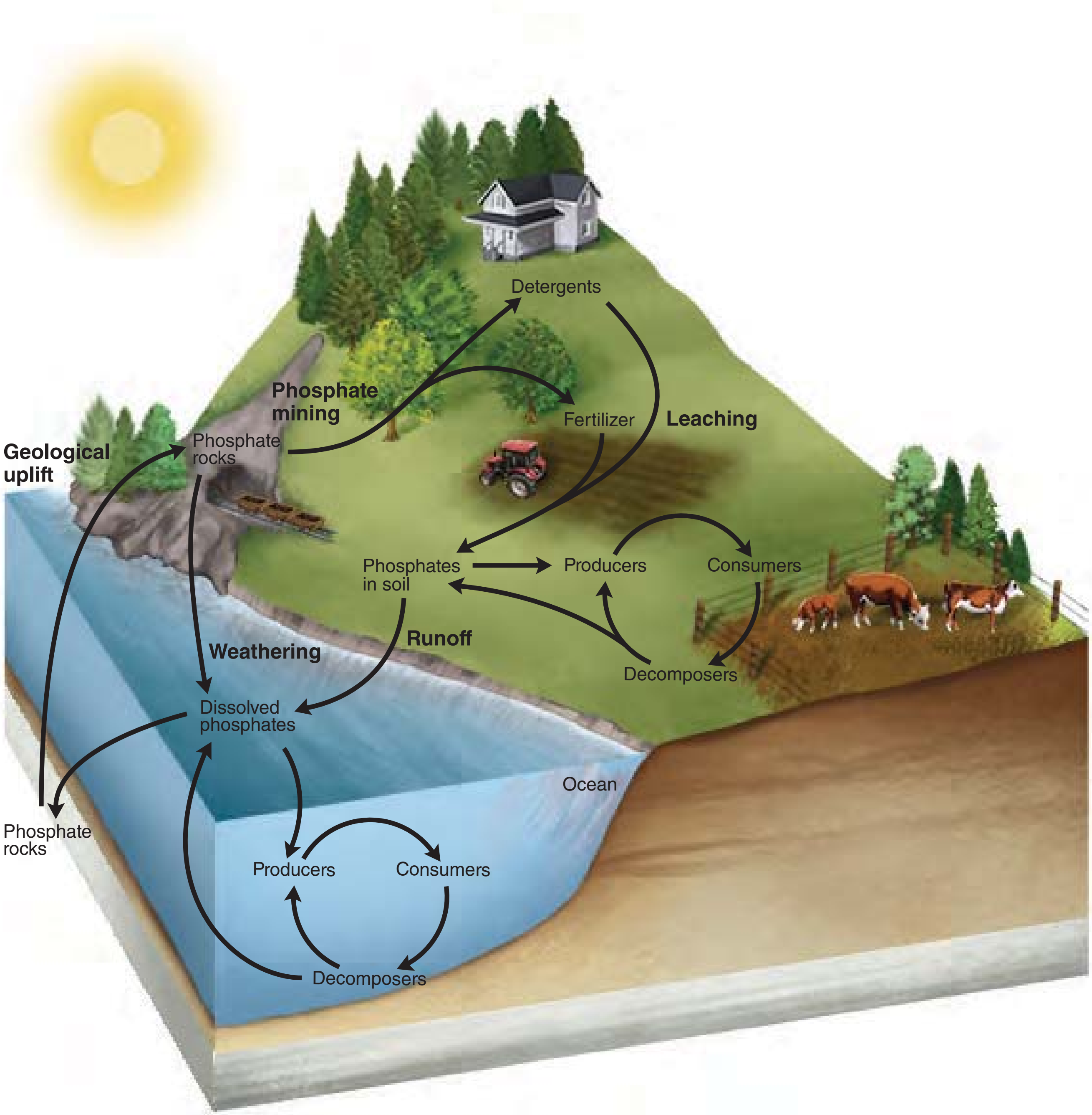


FIGURE 7.4 The phosphorus cycle. The phosphorus cycle begins with the weathering or mining of phosphate rocks and use of phosphate fertilizer, which releases phosphorus into the soil and water. This phosphorus can be used by producers and subsequently moves through the food web. In water, phosphorus can precipitate out of solution and form sediments, which over time are transformed into new phosphate rocks.

Human Impacts on the Phosphorus Cycle

Humans have had a dramatic effect on the phosphorus cycle. For example, humans mine the phosphate sediments from mountains to produce fertilizer. When these fertilizers are applied to lawns, gardens, and agricultural fields, excess phosphorus can leach into water bodies. Because aquatic systems are commonly limited by a low availability of phosphorus, even small inputs of leached phosphorus into these systems can greatly increase the growth of producers. Phosphorus inputs can cause a rapid increase in the algal population of a waterway, known as an **algal bloom,** that can quickly increase the biomass of

Algal bloom A rapid increase in the algal population of a waterway.

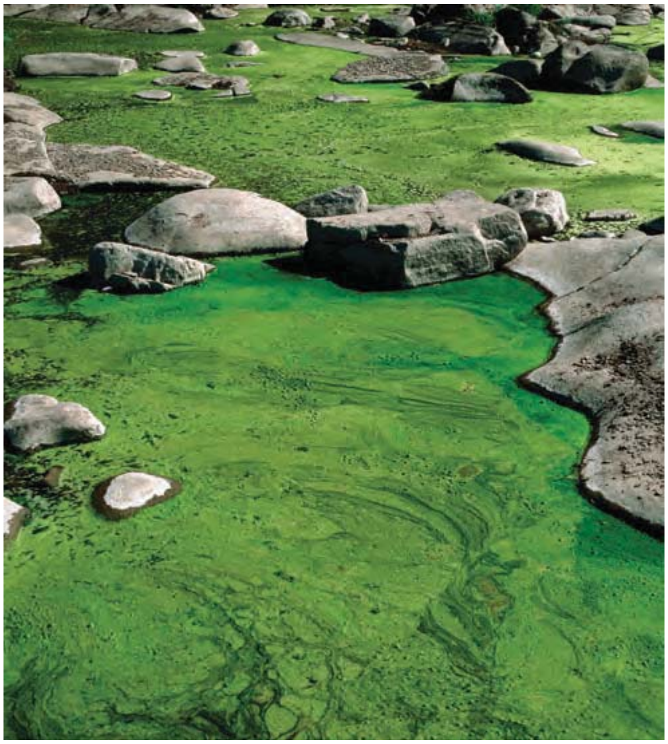


FIGURE 7.5 **Algal bloom.** When excess phosphorus enters waterways, it can stimulate a sudden and rapid growth of algae that turns the water bright green, like this area along the Susquehanna River in Pennsylvania. The algae eventually die, and the resulting increase in decomposition can reduce dissolved oxygen to levels that are lethal to fish and shellfish. *(Michael P. Gadomski/Science Source)*

algae in the ecosystem (FIGURE 7.5). As the algae die, decomposition consumes large amounts of oxygen. As a result, the water becomes low in oxygen, or **hypoxic.** Hypoxic conditions kill fish and other aquatic animals. Hypoxic dead zones occur around the world, including where the Mississippi River empties into the Gulf of Mexico.

A second major source of phosphorus in waterways is from the use of household detergents. From the 1940s through the 1990s, laundry detergents in the United States contained phosphates to make clothes cleaner. The water discharged from washing machines inadvertently fertilized streams, rivers, and lakes. Because ecological dead zones caused by excess phosphorus represent substantial environmental and economic damage, manufacturers stopped adding phosphates to laundry detergents in 1994 and 16 states banned phosphates in dishwashing detergents in 2010. In 2013, 2 more states imposed a similar ban. In Europe, the European Union recently passed a ban on phosphates in laundry detergents starting in 2013 and a ban on phosphates in dishwashing detergents starting in 2017.

Hypoxic Low in oxygen.

Sulfur cycle The movement of sulfur around the biosphere.

In addition to causing algal blooms, increases in phosphorus concentrations can alter plant communities. We have already seen one example in Chapter 2, where we discussed the deterioration of the environment in the Florida Everglades. Because of agricultural expansion in southern Florida, the water that flows through the Everglades has experienced elevated phosphorus concentrations. This change in nutrient cycling has altered the ecosystem of the Everglades. For example, over time, cattails have become more common and sawgrass has declined. Animals that depend on sawgrass are now experiencing reduced food and habitat from this plant.

Calcium, magnesium, potassium, and sulfur also cycle in ecosystems

Calcium, magnesium, and potassium play important roles in regulating cellular processes and in transmitting signals between cells. Like phosphorus, these macronutrients are derived primarily from rocks and decomposed vegetation. All three can be dissolved in water as positively charged ions: Ca^{2+}, Mg^{2+}, and K^{+}. None is present in a gaseous phase, but all can be deposited from the air in small amounts as dust.

Because of their positive charges, calcium, magnesium, and potassium ions are attracted to the negative charges present on the surfaces of most soil particles. Calcium and magnesium occur in high concentrations in limestone and marble. Because Ca^{2+} and Mg^{2+} are strongly attracted to soil particles, they are abundant in many soils overlying these types of rock. In contrast, K^{+} is only weakly attracted to soil particles and is therefore more susceptible to being leached away by water moving through the soil. Leaching of potassium can lead to potassium-deficient soils that constrain the growth of plants and animals.

The final macronutrient, sulfur, is a component of proteins and plays an important role in allowing organisms to use oxygen. The **sulfur cycle,** which is the movement of sulfur around the biosphere, is shown in FIGURE 7.6. Most sulfur exists in rocks and is released into soils and water as the rocks weather over time. Producers absorb sulfur through their roots in the form of sulfate ions (SO_4^{2-}), and the sulfur then cycles through the food web. The sulfur cycle also has a gaseous component. Volcanic eruptions are a natural source of atmospheric sulfur in the form of sulfur dioxide (SO_2). Human activities also add sulfur

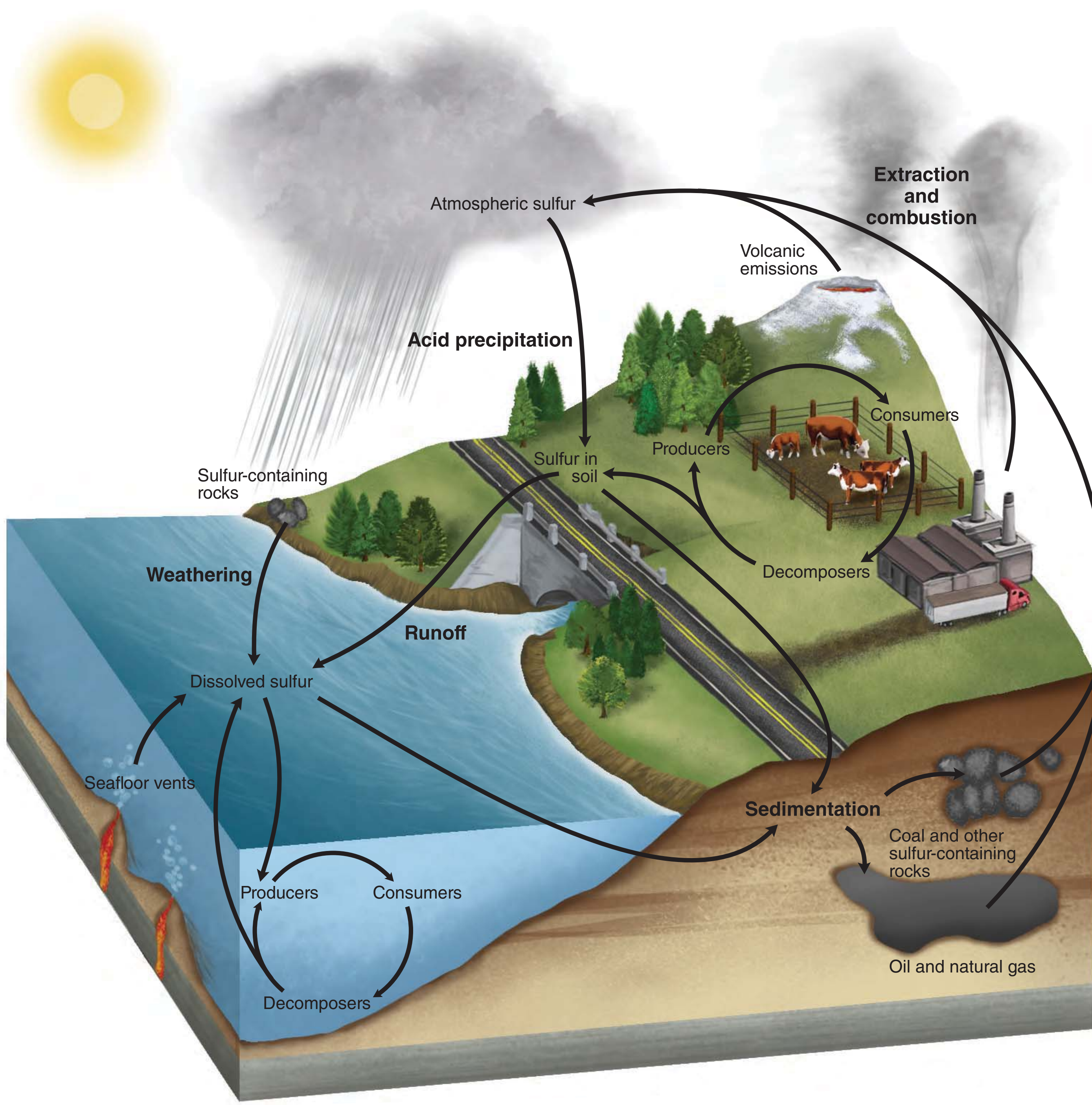


FIGURE 7.6 The sulfur cycle. Most sulfur exists as rocks. As these rocks are weathered over time, they release sulfate ions (SO_4^{2-}) that producers can take up and assimilate. This assimilated sulfur then passes through the food web. Volcanoes, the burning of fossil fuels, and the mining of copper put sulfur dioxide (SO_2) into the atmosphere. In the atmosphere, sulfur dioxide combines with water to form sulfuric acid (H_2SO_4). This sulfuric acid is carried back to Earth when it rains or snows.

dioxide to the atmosphere, especially the burning of fossil fuels and the mining of metals such as copper. In the atmosphere, SO_2 is converted into sulfuric acid (H_2SO_4) when it mixes with water. The sulfuric acid can then be carried back to Earth when it rains or snows. As humans add more sulfur dioxide to the atmosphere, we cause more acid precipitation, which can negatively affect terrestrial and aquatic ecosystems. Although anthropogenic deposition of sulfur remains an environmental concern, clean air regulations in the United States have significantly lowered these deposits since 1995.

module

7

REVIEW

In this module, we have learned that water, carbon, and the six macronutrients cycle around ecosystems. These elements become available to organisms in different ways, but once they are obtained by producers from the atmosphere or as ions dissolved in water, the elements cycle through trophic levels in similar ways. Consumers then obtain these elements by eating producers. Finally, decomposers absorb these elements from dead producers and consumers and their waste products. Through the process of decomposition, they convert the elements into forms that are once again available to producers. In the next module, we will explore how ecosystems respond to disturbances in these cycles.

Module 7 AP® Review Questions

1. Which one of the following is fixed from the atmosphere by bacteria?
   (a) Magnesium
   (b) Phosphorus
   (c) Sulfur
   (d) Nitrogen
   (e) Potassium

2. Human construction of buildings and pavement affect the hydrological cycle by
   I. increasing runoff.
   I. increasing evaporation.
   III. increasing percolation.

   (a) I only
   (b) I and II only
   (c) I and III only
   (d) II and III only
   (e) III only

3. The largest carbon pool is found in
   (a) oceans.
   (b) the atmosphere.
   (c) sedimentary rock.
   (d) living organisms.
   (e) fossil fuels.

4. Phosphorus
   (a) is a limiting nutrient in many aquatic systems.
   (b) has an important gaseous phase.
   (c) is easily lost from soils due to leaching.
   (d) is often produced by volcanic eruptions.
   (e) changes chemical form often during its biogeochemical cycle.

5. Acid rain is associated with which geochemical cycle?
   (a) Potassium
   (b) Calcium
   (c) Carbon
   (d) Phosphorus
   (e) Sulfur

6. Which of the following processes is also known as ammonification?
   (a) Nitrogen fixation
   (b) Nitrification
   (c) Assimilation
   (d) Mineralization
   (e) Denitrification

7. Haitian farmers are buying mango tree saplings for \$10 each, and the full-grown trees produce \$75 of fruit each year. If a farmer wishes to earn \$1,500 per year when the trees are grown, how much will the farmer have to spend on saplings?
   (a) \$100
   (b) \$150
   (c) \$200
   (d) \$750
   (e) \$1,000

module

8

Responses to Disturbances

As we have seen in the previous modules, flows of energy and matter in ecosystems are essential to the species that live in them. However, sometimes ecosystems experience major disturbances that alter how they operate. Disturbances can occur over both short and long time scales, and ecosystem ecologists are often interested in how disturbances affect the flow of energy and matter through an ecosystem. More specifically, they are interested in whether an ecosystem can resist the impact of a disturbance and whether a disturbed ecosystem can recover its original condition. In this module, we will look at how scientists study disturbances, how ecosystems are affected by disturbances, and how quickly these ecosystems can bounce back to their pre-disturbance condition. Finally, we will apply our knowledge to an important theory about how systems respond to disturbances.

Learning Objectives

After reading this module you should be able to

- distinguish between ecosystem resistance and ecosystem resilience.
- explain the insights gained from watershed studies.
- explain the intermediate disturbance hypothesis.

Ecosystems are affected differently by disturbance and in how well they bounce back after the disturbance

In 2012, a major hurricane came to shore in New York and New Jersey and caused a tremendous amount of damage to local ecosystems, not to mention local homes and businesses (FIGURE 8.1). Hurricanes, ice storms, tsunamis,tornadoes, volcanic eruptions, and forest fires can all be classified as a

FIGURE 8.1 **Ecosystem disturbance.** Large disturbances can have major effects on ecosystems, such as this area of New Jersey where Hurricane Sandy devastated shorelines and the residences along these shorelines. *(The Star-Ledger/Andy Mills/The Image Works)*

(a) (b)

FIGURE 8.2 Wetland restoration. (a) Once a forested wetland, this property in Maryland was cleared and drained for agricultural use in the 1970s. (b) Beginning in 2003, efforts began to plug the drainage ditches, remove undesirable trees, and plant wetland plants to restore the property to a wetland habitat. *(Rich Mason, USFWS)*

disturbance because they are events caused by physical, chemical, or biological agents that results in changes in population size or community composition in ecosystems. Disturbances also can be due to anthropogenic causes, such as human settlements, agriculture, air pollution, forest clear-cutting, and the removal of entire mountaintops for coal mining.

Not every ecosystem disturbance is a disaster. For example, a low-intensity fire might kill some plant species, but at the same time it might benefit fire-adapted species that can use the additional nutrients released from the dead plants. So, although the population of a particular producer species might be diminished or even eliminated, the net primary productivity of all the producers in the ecosystem might remain the same. When this is the case, we say that the productivity of the system is *resistant*. The **resistance** of an ecosystem is a measure of how much a disturbance can affect the flows of energy and matter. When a disturbance influences populations and communities, but has no effect on the overall flows of energy and matter, we say that the ecosystem has high resistance.

Disturbance An event, caused by physical, chemical, or biological agents, resulting in changes in population size or community composition.

Watershed All land in a given landscape that drains into a particular stream, river, lake, or wetland.

Resistance A measure of how much a disturbance can affect flows of energy and matter in an ecosystem.

Resilience The rate at which an ecosystem returns to its original state after a disturbance.

Restoration ecology The study and implementation of restoring damaged ecosystems.

When the flows of energy and matter of an ecosystem are affected by a disturbance, environmental scientists often ask how quickly and how completely the ecosystem can recover its original condition. The rate at which an ecosystem returns to its original state after a disturbance is termed **resilience.** A highly resilient ecosystem returns to its original state relatively rapidly; a less resilient ecosystem does so more slowly. For example, imagine that a severe drought has eliminated half the species in an area. In a highly resilient ecosystem, the flows of energy and matter might return to normal in the following year. In a less resilient ecosystem, the flows of energy and matter might not return to their pre-drought conditions for many years.

An ecosystem's resilience often depends on specific interactions of the biogeochemical and hydrologic cycles. For example, as human activity has led to an increase in global atmospheric CO_2 concentrations, terrestrial and aquatic ecosystems have increased the amount of carbon they absorb. In this way the carbon cycle as a whole has offset some of the changes that we might expect from increases in atmospheric CO_2 concentrations, including global climate change. Conversely, when a drought occurs, the soil may dry out and harden so much that when it eventually does rain, the soil cannot absorb as much water as it did before the drought. The soil changes in response to the drought, which leads to further drying and intensifies the drought damage. In this case, the hydrologic cycle does not relieve the effects of the drought; instead, a positive feedback in the system makes the situation worse.

Many anthropogenic disturbances—for example, housing developments, clear-cutting, or draining of wetlands—are so large that they eliminate an entire ecosystem. In some cases, however, scientists can work to reverse these effects and restore much of the original function of the ecosystem (**FIGURE 8.2**). Growing interest in restoring damaged ecosystems has led to the creation of a new scientific discipline called **restoration ecology.** Restoration ecologists are currently working on two high-profile ecosystem restoration projects, in the Florida Everglades and in the Chesapeake Bay, to restore water flows and nutrient inputs that are closer to historic levels so that the functions of these ecosystems can be restored.

Watershed studies help us understand how disturbances affect ecosystem processes

Understanding the natural rates and patterns of biogeochemical cycling in an ecosystem provides a basis for determining how a disturbance has changed the system. Because it is difficult to study biogeochemical cycles on a global scale, most of this research takes place on a smaller scale where scientists can measure all of the ecosystem processes. Scientists commonly conduct such studies in a *watershed*. As shown in FIGURE 8.3, a **watershed** is all of the land in a given landscape that drains into a particular stream, river, lake, or wetland.

One of the most thorough studies of disturbance at the watershed scale has been ongoing for more than 50 years in the Hubbard Brook ecosystem of New Hampshire. Since 1962, investigators have monitored the hydrological and biogeochemical cycles of six watersheds at Hubbard Brook, ranging in area from 12 to 43 ha (30 to 106 acres). The soil in each watershed is underlain by impenetrable bedrock, so there is no deep percolation of water; all precipitation that falls on the watershed leaves it either by evapotranspiration or by runoff. Scientists measure precipitation throughout each watershed, and a stream gauge at the bottom of the main stream that drains a given watershed allows them to measure the amounts of water and nutrients leaving the system.

Researchers at Hubbard Brook investigated the effects of clear-cutting and subsequent suppression of plant regrowth. The researchers cut down the forest in one watershed and used herbicides to suppress the regrowth of vegetation for several years. A nearby watershed that was not clear-cut served as a control (FIGURE 8.4). The concentrations of nitrate in stream

FIGURE 8.3 Watershed. A watershed is the area of land that drains into a particular body of water.

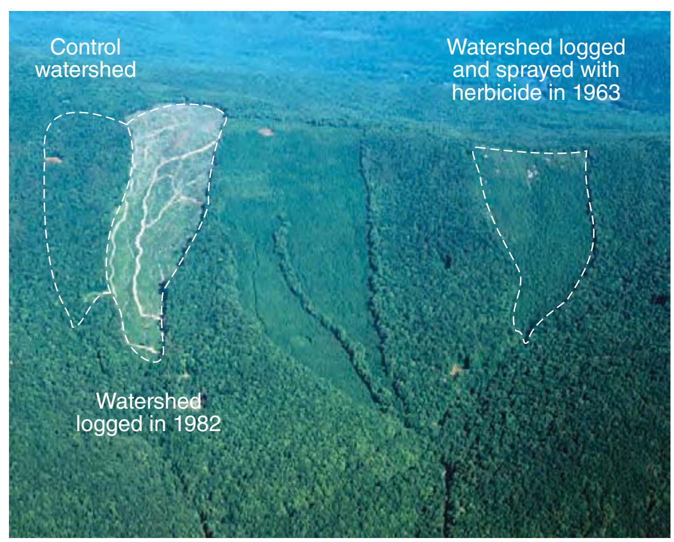


FIGURE 8.4 Studying disturbance at the watershed scale. In the Hubbard Brook ecosystem, researchers clear-cut one watershed to determine the importance of trees in retaining soil nutrients. They compared nutrient runoff in the clear-cut watershed with that in a control watershed that was not clear-cut. (The two other watersheds shown in the photo received other experimental treatments). *(U.S. Forest Service, Northern Research Station)*

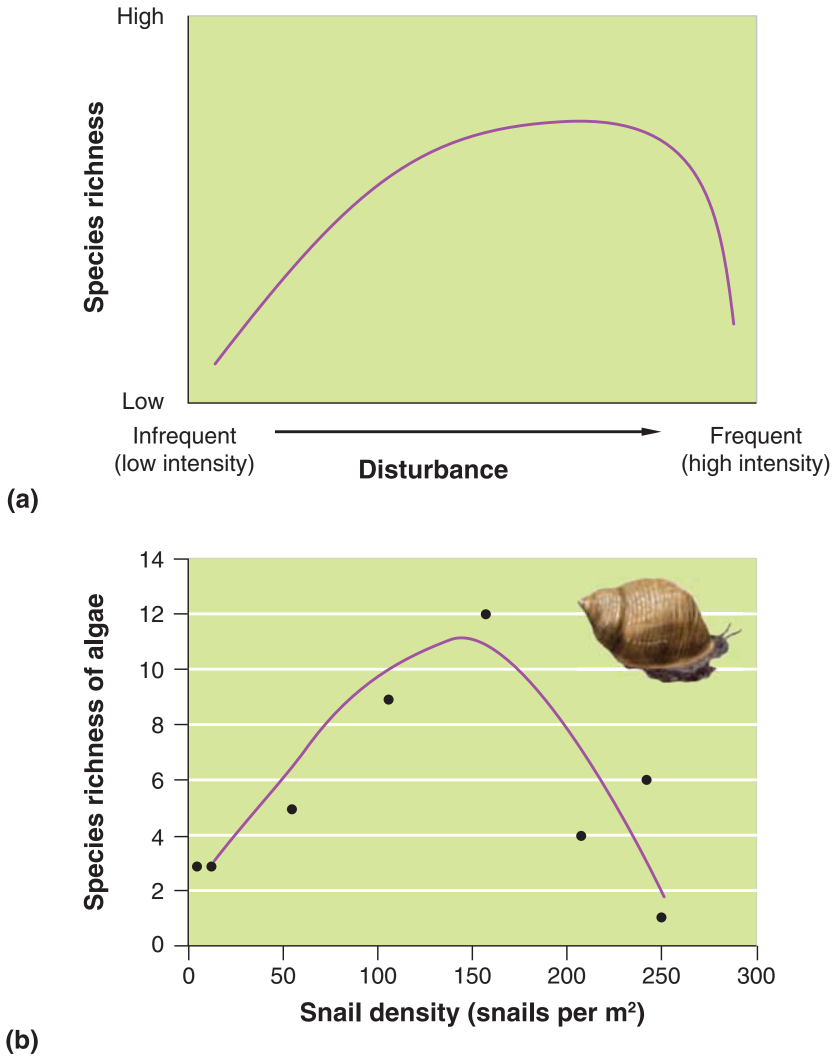


FIGURE 8.5 Intermediate disturbance hypothesis. (a) In general, we expect to see the highest species diversity at intermediate levels of disturbance. Rare disturbances favor the best competitors, which outcompete other species. Frequent disturbances eliminate most species except those that have evolved to live under such conditions. At intermediate levels of disturbance, species from both extremes can persist. (b) An example of the intermediate disturbance in the number of algal species observed in response to different amounts of herbivory by marine snails. When few or many snails are present, there is a low diversity of algal species, but when an intermediate density of snails are consuming algae, the snails cause an intermediate amount of disturbance and a higher diversity of algal species can persist in the ecosystem.

water were similar in the two watersheds before the clear-cutting. Within 6 months after the cutting, the clear-cut watershed showed significant increases in stream nitrate concentrations. With this information, the researchers were able to determine that when trees are no longer present to take up nitrate from the soil, nitrate leaches out of the soil and ends up in the stream that drains the watershed. This study and subsequent research have demonstrated the importance of plants in regulating the cycling of nutrients, as well as the consequences of not allowing new vegetation to grow when a forest is cut.

Studies such as the one done at Hubbard Brook allow investigators to learn a great deal about biogeochemical cycles. We now understand that as forests and grasslands grow, large amounts of nutrients accumulate in the vegetation and in the soil. The growth of forests allows the terrestrial landscape to accumulate nutrients that would otherwise cycle through the system and end up in the ocean. Forests, grasslands, and other terrestrial ecosystems increase the retention of nutrients on land. This is an important way in which ecosystems directly influence their own growing conditions.

Intermediate disturbance hypothesis The hypothesis that ecosystems experiencing intermediate levels of disturbance are more diverse than those with high or low disturbance levels.

Intermediate levels of disturbance favor high species diversity

We have seen that not all disturbance is bad. In fact, some level of ecosystem disturbance is natural, and may even be necessary to maintain species diversity. The **intermediate disturbance hypothesis** states that ecosystems experiencing intermediate levels of disturbance will favor a higher diversity of species than those with high or low disturbance levels. The graph in FIGURE 8.5a illustrates this relationship between ecosystem disturbance and species diversity. Ecosystems in which disturbances are rare experience intense competition among species. Because of this, populations of only a few highly competitive species eventually dominate the ecosystem. In places where disturbances are frequent, population growth rates must be high enough to counter the effects of frequent disturbance and prevent species extinction.

An example of the intermediate disturbance hypothesis can be found in marine algae that spend their lives attached to rocks along the rocky coast of New England. In areas containing low densities of common periwinkle snails (*Littorina littorea*), which cause a low disturbance through low amounts of herbivory, just a few algal species dominate the community, as shown in Figure 8.5b. In areas containing high densities of sails, the disturbance from their high amount of herbivory caused only the most herbivore-resistant algal species to persist. However, when snails were present at an intermediate density, which represents an intermediate disturbance, the populations of best competitors never reach a size at which they can dominate, and populations of other species are never driven too close to zero. As a result, we see the highest diversity of species in ecosystems that experience an intermediate frequency of disturbance.

module 8

REVIEW

In this module, we learned that disturbances are events that can alter population sizes and community compositions of ecosystems. Watershed studies help scientists investigate how disturbances affect ecosystems; by manipulating watersheds, they can observe how the cycling of water and elements is altered. When a disturbance occurs, some ecosystems exhibit high resistance to the disturbance. Other ecosystems show high resilience, which allows them to bounce back quickly to pre-disturbance conditions. Finally, an ecosystem disturbance of intermediate magnitude favors a high diversity of species.

Module 8 AP® Review Questions

1. Which is NOT true about disturbances?
   (a) They are caused by natural events such as hurricanes.
   (b) They occur only on short time scales.
   (c) They can cause complete destruction of an ecosystem.
   (d) Many result in no change in ecosystem productivity.
   (e) Some are due to anthropogenic causes.

2. An ecosystem that rapidly returns to its original state after a disturbance is
   (a) resistant.
   (b) vigorous.
   (c) resilient.
   (d) stable.
   (e) adaptable.

3. The intermediate disturbance hypothesis states that intermediate levels of disturbance will
   (a) increase runoff.
   (b) increase ecosystem nutrient cycling.
   (c) decrease primary productivity.
   (d) increase species diversity.
   (e) decrease biomass.

4. The Hubbard Brook experiment showed that
   (a) the intermediate disturbance hypothesis is plausible.
   (b) freshwater aquatic ecosystems are often very resilient.
   (c) river restoration can take many years to complete.
   (d) evapotranspiration increases with more vegetation cover.
   (e) deforestation increases nutrient runoff.

5. Which is a measure of how much a disturbance can affect the flows of energy and matter in an ecosystem?
   (a) Diversity
   (b) Intensity
   (c) Resistance
   (d) Resilience
   (e) Homeostasis

Can We Make Golf Greens Greener?

Though golf is played outdoors on open green courses designed around the contours of the natural landscape, golf courses have a poor environmental reputation. Golf courses are highly managed ecosystems that cover over 3 million ha (7.5 million acres) worldwide—an area about the size of Belgium. About two-thirds of this area consists of closely mowed turfgrass. Closely mowed grass has short leaves that cannot gain enough energy from photosynthesis to grow deep roots. This causes the grass to dry out easily and makes it difficult to obtain soil nutrients. As a result, the grass is susceptible to challenges from weeds, grubs that feed on grass roots, and fungal diseases that can weaken or kill the grass.

To combat these challenges, golf courses use disproportionate amounts of water, fertilizer, and pesticides. Because humans expect to see green, well-manicured golf courses no matter where in the world they are located, golf courses collectively use 9.5 billion liters (2.5 billion gallons) of water annually to keep their grasses green. Much of this water is used in regions where water is scarce. In addition, providing the grass with sufficient nutrients requires a large amount of fertilizer. For example, the putting greens that surround each of the 18 holes in a golf course require as much nitrogen per hectare as corn, the heaviest nitrogen user of all major food crops. If the course requires irrigation soon after the application of fertilizer, or if it rains, up to 60 percent of the fertilizer can be leached into nearby waterways. To maintain a uniform texture on the greens, golf courses use about six times the amount of agricultural pesticides per hectare as do conventional farms. These chemicals include herbicides to remove weeds, insecticides to kill soil-dwelling grubs, and fungicides to control disease.

Since 1991, the Audubon Cooperative Sanctuary Program (ACSP), a partnership between Audubon International and the U.S. Golf Association, has been working to improve the environmental management of golf courses. The ACSP encourages golf course managers to develop courses that perform more like natural ecosystems, with nutrient and water recycling to reduce waste and biodiversity to increase ecosystem resilience. It also educates golf course managers about low-impact pest management, water conservation, and water quality management.

The golf course of the Palisades Country Club in North Carolina was constructed with natural ecosystem processes in mind. To prevent the runoff of nutrients and lawn-care chemicals into nearby waters, the course directs all runoff water through a treatment system. The course was designed to reduce the amount of closely mowed turfgrass. Deep-rooted native grasses surrounding the greens and fairways soak up nutrients and help to direct water underground. As a result, maintenance costs, chemical applications, and the time spent using machinery have all declined. Smaller areas of turfgrass also leave space for more native vegetation of various heights, providing better habitats for birds and predatory insects. These consumers keep pest populations low, which reduces the need for pesticides. When pesticides are used, they are chosen to protect nontarget wildlife and applied on wind-free days to keep them from spreading beyond where they are needed.

By 2012, more than 2,400 golf courses worldwide were participating in the ACSP. Audubon International found that over 80 percent of the courses in the program reduced the amounts and toxicity of pesticides applied, improved nutrient retention within the course, and used less water for irrigation. The average course in the program saved about 7 million liters (1.9 million gallons) of water per year, and the amount of land area devoted to providing wildlife habitat increased by about 50 percent, from 18 to 27 ha (45 to 67 acres) per 60-ha (150-acre) golf course. Moreover, 99 percent of managers reported that playing quality and golfer satisfaction were maintained or improved.

Even with these changes, golf courses still require large amounts of water, nutrients, fossil fuel energy, and upkeep. Highly managed ecosystems cannot be made input free. However, within these limits, a growing number of courses are attempting to reduce their ecological footprint and make their greens greener.

Making golf more sustainable. The Palisades Country Club in North Carolina is making its golf course more environmentally friendly by considering the important roles of natural ecosystem processes. *(Courtesy The Palisades Country Club)*

Critical Thinking Questions

1. In addition to helping the environment, what factors do you think help motivate the golf course operators to join the Audubon Cooperative Sanctuary Program?
2. Is the high use of water, fertilizers, and pesticides on golf courses justified by the fact that it brings people outside to enjoy and appreciate nature?

References

Audubon Cooperative Sanctuary Program. http://www.auduboninternational.org/acspgolf.

Beecham, Tara. 2007. How green is your tee? *Stormwater Features*. http://www.stormh2o.com/september-2007/audubon-program-golf.aspx.

chapter 3 REVIEW

In this chapter, we have learned how ecosystems function by looking at how energy moves through an ecosystem and how matter cycles around an ecosystem. This energy and matter form the basis of the trophic groups that exist in ecosystems and they are responsible for the abundance of each group in nature. The typical movement of energy and matter can be altered by ecosystem disturbances, although the magnitude of the impact depends on the resistance of a particular ecosystem and its resilience after the disturbance.

Key Terms

Biosphere
Producer
Autotroph
Photosynthesis
Cellular respiration
Aerobic respiration
Anaerobic respiration
Consumer
Heterotroph
Herbivore
Primary consumer
Carnivore
Secondary consumer
Tertiary consumer
Trophic levels
Food chain
Food web
Scavenger
Detritivore
Decomposers
Gross primary productivity (GPP)
Net primary productivity (NPP)
Biomass
Standing crop
Ecological efficiency
Trophic pyramid
Biogeochemical cycle
Hydrologic cycle
Transpiration
Evapotranspiration
Runoff
Carbon cycle
Limiting nutrient
Macronutrient
Nitrogen cycle
Nitrogen fixation
Nitrification
Assimilation
Mineralization
Ammonification
Denitrification
Leaching
Phosphorus cycle
Algal bloom
Hypoxic
Sulfur cycle
Disturbance
Resistance
Resilience
Watershed
Restoration ecology
Intermediate disturbance hypothesis

Learning Objectives Revisited

Module 6 The Movement of Energy

- **Explain the concept of ecosystem boundaries.**
  Ecosystem boundaries distinguish one ecosystem from another. Although boundaries can be well-defined, often they are not. Boundaries are commonly defined either by topographic features, such as mountain ranges, or are subjectively set by administrative criteria rather than biological criteria.

- **Describe the processes of photosynthesis and respiration.**

  Photosynthesis captures the energy of the Sun to convert CO_2 and water into carbohydrates. Respiration, whether aerobic or anaerobic, unlocks the chemical energy stored in the cells of organisms.

- **Distinguish among the trophic levels that exist in food chains and food webs.**

  The trophic levels consist of producers that convert solar energy into producer biomass through photosynthesis, primary consumers that eat the producers, secondary consumers that eat the primary consumers, and tertiary consumers that eat the secondary consumers. Omnivores eat individuals from more than one trophic group. Trophic groups that eat waste products and dead organisms are scavengers, detritivores, and decomposers.

- **Quantify ecosystem productivity.**

  Ecosystem productivity can be quantified by measuring the total amount of solar energy that producers capture, which is gross primary productivity, or by measuring the total amount of solar energy captured minus the amount of energy used for respiration, which is net primary productivity.

- **Explain energy transfer efficiency and trophic pyramids.**

  The energy present in one trophic level can be transferred to a higher trophic level and the efficiency of this transfer is generally about 10 percent. Because of this low energy transfer efficiency, the amount of energy present in each trophic level declines as we move to higher trophic levels. We can represent the energy in each trophic level as a rectangular block in a pyramid, with a size that is proportional to the energy found in the trophic level. Low ecological efficiency results in a large biomass of producers, but a much lower biomass of primary consumers and an even lower biomass of secondary consumers.

Module 7 The Movement of Matter

- **Describe how water cycles within ecosystems.**

  In the water cycle, water evaporates from water bodies and transpires from plants. The resulting water vapor cools and forms clouds, which ultimately drop water back to Earth in the form of precipitation. When the water falls onto the land, it can evaporate, be taken up by plants and transpired, percolate into the groundwater, or run off along the soil surface and ultimately return to lakes and oceans.

- **Explain how carbon cycles within ecosystems.**

  In the carbon cycle, producers take up CO_2 for photosynthesis and transfer the carbon to consumers and decomposers. Some of this carbon is converted back into CO_2 by respiration, while the rest is lost to sedimentation and burial. The extraction and combustion of fossil fuels, as well as the destruction of forests, returns CO_2 to the atmosphere.

- **Describe how nitrogen cycles within ecosystems.**

  In the nitrogen cycle, nitrogen fixation by organisms, lightning, or human activities converts nitrogen gas into ammonium (NH_4^+) or nitrate (NO_3^-). Nitrification is a process that converts ammonium into nitrite (NO_2^-) and then into nitrate (NO_3^-). Once producers take up nitrogen as ammonia, ammonium, nitrite, or nitrate, they incorporate it into their tissues in a process called assimilation. Eventually, organisms die and their tissues decompose and are converted to ammonium in a process called mineralization. Finally, denitrification returns nitrogen to the atmosphere.

- **Explain how phosphorus cycles within ecosystems.**

  The phosphorus cycle involves a large pool of phosphorus in rock that is formed by the precipitation of phosphate onto the ocean floor. Geologic forces can lift these sediments and form mountains. The phosphorus in the mountains can be made available to producers either by weathering or by mining. Producers assimilate phosphorus from the soil or water and consumers assimilate it when they eat producers. The waste products and dead bodies of organisms experience mineralization, which returns phosphorus to the environment where it can be ultimately transferred back to the ocean.

- **Discuss the movement of calcium, magnesium, potassium, and sulfur within ecosystems.**

  Calcium, magnesium, and potassium are derived from rock and can be held by soils. Producers can assimilate these elements, and mineralization of waste products and dead organisms returns the elements back to the environment. Most sulfur exists in the form of rocks and is released through the process of weathering, which makes it available for plant assimilation. Some sulfur exists as a gas in the form of sulfur dioxide (SO_2), which can be produced by volcanic eruptions and the burning of fossil fuels. In the atmosphere, SO_2 is converted into sulfuric acid (H_2SO_4) when it mixes with water. The sulfuric acid can then be carried back to the ground when it rains or snows.

Module 8 Responses to Disturbances

- **Distinguish between ecosystem resistance and ecosystem resilience.**

  The resistance of an ecosystem is a measure of how much a disturbance can affect its flows of energy and matter. In contrast, the resilience of an ecosystem is the rate at which an ecosystem returns to its original state after a disturbance has occurred.

- **Explain the insights gained from watershed studies.**
  Because watersheds contain all of the land in a given landscape that drains into a particular water body, experimental manipulations such as logging allow scientists to determine how a disturbance to an ecosystem alters the flow of energy and matter.

- **Explain the intermediate disturbance hypothesis.**
  The intermediate disturbance hypothesis states that ecosystems experiencing intermediate levels of disturbance are more diverse than those with high or low disturbance levels.

Chapter 3 AP® Environmental Science Practice Exam

Section 1: Multiple-Choice Questions

Choose the best answer for questions 1–18.

1. Which of the following is NOT an example of an abiotic component of an ecosystem?
   (a) Water
   (b) Minerals
   (c) Sunlight
   (d) Fungi
   (e) Air

2. Which of the following is NOT characteristic of most ecosystems?
   (a) Biotic components
   (b) Abiotic components
   (c) Recycling of matter
   (d) Distinct boundaries
   (e) A wide range of sizes

3. The waste product in photosynthesis is
   (a) carbon dioxide.
   (b) oxygen.
   (c) glucose.
   (d) water.
   (e) energy.

4. Which of the following could be a cause of decreased evapotranspiration?
   (a) Increased precipitation
   (b) Decreased runoff
   (c) Increased percolation
   (d) Increased vegetation
   (e) Increased sunlight

For questions 5, 6, and 7, select from the following choices:
   (a) Producers
   (b) Decomposers
   (c) Primary consumers
   (d) Secondary consumers
   (e) Tertiary consumers

5. At which trophic level are eagles that consume fish that eat algae?

6. At which trophic level do organisms use a process that produces oxygen as a waste product?

7. At which trophic level are dragonflies that consume mosquitoes that feed on herbivorous mammals?

8. Beginning at the lowest trophic level, arrange the following food chain found on the Serengeti Plain of Africa in the correct sequence.
   (a) Shrubs–gazelles–cheetahs–decomposers
   (b) Shrubs–decomposers–gazelles–cheetahs
   (c) Shrubs–decomposers–cheetahs–gazelles
   (d) Gazelles–decomposers–cheetahs–shrubs
   (e) Decomposers–cheetahs–shrubs–gazelles

9. Which macronutrient is required by humans in the largest amounts?
   (a) Calcium
   (b) Nitrogen
   (c) Sulfur
   (d) Potassium
   (e) Magnesium

10. Roughly what percentage of incoming solar energy is converted into chemical energy by producers?
   (a) 99
   (b) 80
   (c) 50
   (d) Between 5 and 20
   (e) 1

11. The net primary productivity of an ecosystem is 1 kg C/m^2/year, and the energy needed by the producers for their own respiration is 1.5 kg C/m^2/year. The gross primary productivity of such an ecosystem would be
   (a) 0.5 kg C/m^2/year.
   (b) 1.0 kg C/m^2/year.
   (c) 1.5 kg C/m^2/year.
   (d) 2.0 kg C/m^2/year.
   (e) 2.5 kg C/m^2/year.

12. An ecosystem has an ecological efficiency of 10 percent. If the producer level contains 10,000 kilocalories of energy, how much energy does the tertiary consumer level contain?
    (a) 1 kcal
    (b) 10 kcal
    (c) 100 kcal
    (d) 1,000 kcal
    (e) 10,000 kcal

13. Which biogeochemical cycle(s) does NOT have a gaseous component?
    I. Potassium
    II. Sulfur
    III. Phosphorus
    (a) II only
    (b) I and II only
    (c) III only
    (d) II and III only
    (e) I and III only

14. Which of the following statements about the carbon cycle is true?
    (a) Carbon transfer from photosynthesis is in steady state with respiration and death.
    (b) The majority of dead biomass is accumulated in sedimentation.
    (c) Combustion of carbon is equivalent in mass to sedimentation.
    (d) Most of the carbon entering the oceans is from terrestrial ecosystems.
    (e) Carbon exchange between the atmosphere and terrestrial ecosystems is primarily an abiotic process.

15. Human interaction with the nitrogen cycle is primarily due to
    (a) the leaching of nitrates into terrestrial ecosystems.
    (b) the breakdown of ammonium into ammonia for industrial uses.
    (c) the interruption of the mineralization process in urban areas.
    (d) the acceleration of the nitrification process in aquatic ecosystems.
    (e) the decreased assimilation of ammonium and nitrates.

16. Research at Hubbard Brook showed that stream nitrate concentrations in two watersheds were ________ before clear-cutting, and that after one watershed was clear-cut, its stream nitrate concentration was _______.
    (a) similar/decreased
    (b) similar/increased
    (c) similar/the same
    (d) different/increased
    (e) different/decreased

17. Small inputs of this substance, commonly a limiting factor in aquatic ecosystems, can result in algal blooms and dead zones.
    (a) Dissolved carbon dioxide
    (b) Sulfur
    (c) Dissolved oxygen
    (d) Potassium
    (e) Phosphorus

18. After a severe drought, the productivity in an ecosystem took many years to return to pre-drought conditions. This observation indicates that the ecosystem has
    (a) high resilience.
    (b) low resilience.
    (c) high resistance.
    (d) low resistance.
    (e) equal resilience and resistance.

Section 2: Free-Response Questions

Write your answer to each part clearly. Support your answers with relevant information and examples. Where calculations are required, show your work.

1. Nitrogen is crucial for sustaining life in both terrestrial and aquatic ecosystems.
   - (a) Draw a fully labeled diagram of the nitrogen cycle. (4 points)
   - (b) Describe the following steps in the nitrogen cycle:
     - (i) Nitrogen fixation (1 point)
     - (ii) Ammonification (1 point)
     - (iii) Nitrification (1 point)
     - (iv) Denitrification (1 point)
   - (c) Describe one reason why nitrogen is crucial for sustaining life on Earth. (1 point)
   - (d) Describe one way that the nitrogen cycle can be disrupted by human activities. (1 point)

2. Read the following article written for a local newspaper and answer the questions below.

Neighbors Voice Opposition to Proposed Clear-Cut

A heated discussion took place last night at the monthly meeting of the Fremont Zoning Board. Local landowner Julia Taylor has filed a request that her 150-acre woodland area be rezoned from residential to multiuse in order to allow her to remove all of the timber from the site.

"This is my land, and I should be able to use it as I see fit," explained Ms. Taylor. "In due course, all of the trees will return and everything will go back to the same as it is now. The birds and the squirrels will still be there in the future. I have to sell the timber because I need the extra revenue to supplement my retirement as I am on a fixed income. I don't see what all the fuss is about," she commented.

A group of owners of adjacent properties see things very differently. Their spokesperson, Ethan Jared, argued against granting a change in the current zoning. "Ms. Taylor has allowed the community to use these woods for many years, and we thank her for that. But I hope that the local children will be able to hike and explore the woods with their children as I have done with mine. Removing the trees in a clear-cut will damage our community in many ways, and it could lead to contamination of the groundwater and streams and affect many animal and plant species. Like the rest of us property owners, Ms. Taylor gets her drinking water from a well, and I do not think she has really looked at all the ramifications should her plan go through. We strongly oppose the rezoning of this land—it has a right to be left untouched."

After more than 2 hours of debate between Ms. Taylor and many of the local residents, the chair of the Zoning Board decided to research the points raised by the neighbors and report on his findings at next month's meeting.

   - (a) Name and describe the ecosystem value(s) that are being expressed by Ms. Taylor in her proposal to clear-cut the wooded area. (2 points)
   - (b) Name and describe the ecosystem value(s) that Mr. Jared is placing on the wooded area. (2 points)
   - (c) Provide three realistic suggestions for Ms. Taylor that could provide her with revenue from the property but leave the woods intact. (3 points)
   - (d) Identify and then discuss the validity of the environmental concerns that were raised by Mr. Jared. (3 points)

Grapes used for fine wines grow best in only a few regions of the world that have a similar climate. *(swetta/Getty Images)*