3 Ecosystems: What Are They and How Do They Work?

CORE CASE STUDY Tropical Rain Forests Are Disappearing

Tropical rain forests are found near the earth's equator and contain an incredible variety of life. These lush forests are warm year round and have high humidity and heavy rainfall almost daily. Although they cover only about 2% of the earth's land surface, studies indicate that they contain up to half of the world's known terrestrial plant and animal species. For these reasons, they make an excellent natural laboratory for the study of *ecosystems*—communities of organisms interacting with one another and with the physical environment of matter and energy in which they live.

So far, at least half of these forests have been destroyed or disturbed by humans cutting down trees, growing crops, grazing cattle, and building settlements (Figure 3-1), and the degradation of these centers of life (biodiversity) is increasing. Ecologists warn that without strong conservation measures, most of these forests will probably be gone or severely degraded within your lifetime.

Scientists project that disrupting these ecosystems will have three major harmful effects. *First,* it will reduce the earth's vital biodiversity by destroying or degrading the habitats of many of their unique plant and animal species, thereby causing their premature extinction. *Second,* it will help to accelerate climate change due to global warming by eliminating large areas of trees faster than they can grow back, thereby reducing the trees' overall uptake of the greenhouse gas carbon dioxide.

Third, it will change regional weather patterns in ways that will prevent the return of diverse tropical rain forests in cleared or degraded areas. Once this tipping point is reached, tropical rain forest in such areas will become less diverse tropical grassland.

Ecosystems recycle materials and provide humans and other organisms with essential natural services (Figure 1-3, p. 8) and natural resources such as nutrients (Figure 1-4, p. 9). In this chapter, we look more closely at how ecosystems work and how human activities, such as stripping a large area of its trees, can disrupt the cycling of nutrients within ecosystems and the flow of energy through them.

Figure 3-1 **Natural capital degradation:** satellite image of the loss of tropical rain forest, cleared for farming, cattle grazing, and settlements, near the Bolivian city of Santa Cruz between June 1975 (left) and May 2003 (right).

Key Questions and Concepts

3-1 What is ecology?

CONCEPT 3-1 Ecology is the study of how organisms interact with one another and with their physical environment of matter and energy.

3-2 What keeps us and other organisms alive?

CONCEPT 3-2 Life is sustained by the flow of energy from the sun through the biosphere, the cycling of nutrients within the biosphere, and gravity.

3-3 What are the major components of an ecosystem?

CONCEPT 3-3A Ecosystems contain living (biotic) and nonliving (abiotic) components.

CONCEPT 3-3B Some organisms produce the nutrients they need, others get their nutrients by consuming other organisms, and some recycle nutrients back to producers by decomposing the wastes and remains of organisms.

3-4 What happens to energy in an ecosystem?

CONCEPT 3-4A Energy flows through ecosystems in food chains and webs.

CONCEPT 3-4B As energy flows through ecosystems in food chains and webs, the amount of chemical energy available to organisms at each succeeding feeding level decreases.

3-5 What happens to matter in an ecosystem?

CONCEPT 3-5 Matter, in the form of nutrients, cycles within and among ecosystems and the biosphere, and human activities are altering these chemical cycles.

3-6 How do scientists study ecosystems?

CONCEPT 3-6 Scientists use field research, laboratory research, and mathematical and other models to learn about ecosystems.

Note: Supplements 2 (p. S4), 4 (p. S20), 6 (p. S39), 7 (p. S46), and 13 (p. S78) can be used with this chapter.

The earth's thin film of living matter is sustained by grand-scale cycles of chemical elements.

G. EVELYN HUTCHINSON

3-1 What Is Ecology?

CONCEPT 3-1 Ecology is the study of how organisms interact with one another and with their physical environment of matter and energy.

Cells Are the Basic Units of Life

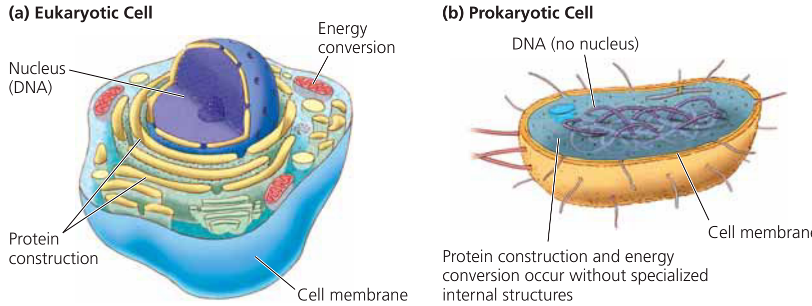
All organisms (living things) are composed of **cells:** the smallest and most fundamental structural and functional units of life. They are minute compartments covered with a thin membrane and within which the processes of life occur. The idea that all living things are composed of cells is called the **cell theory** and it is the most widely accepted scientific theory in biology. Organisms may consist of a single cell (bacteria, for instance) or huge numbers of cells, as is the case for most plants and animals.

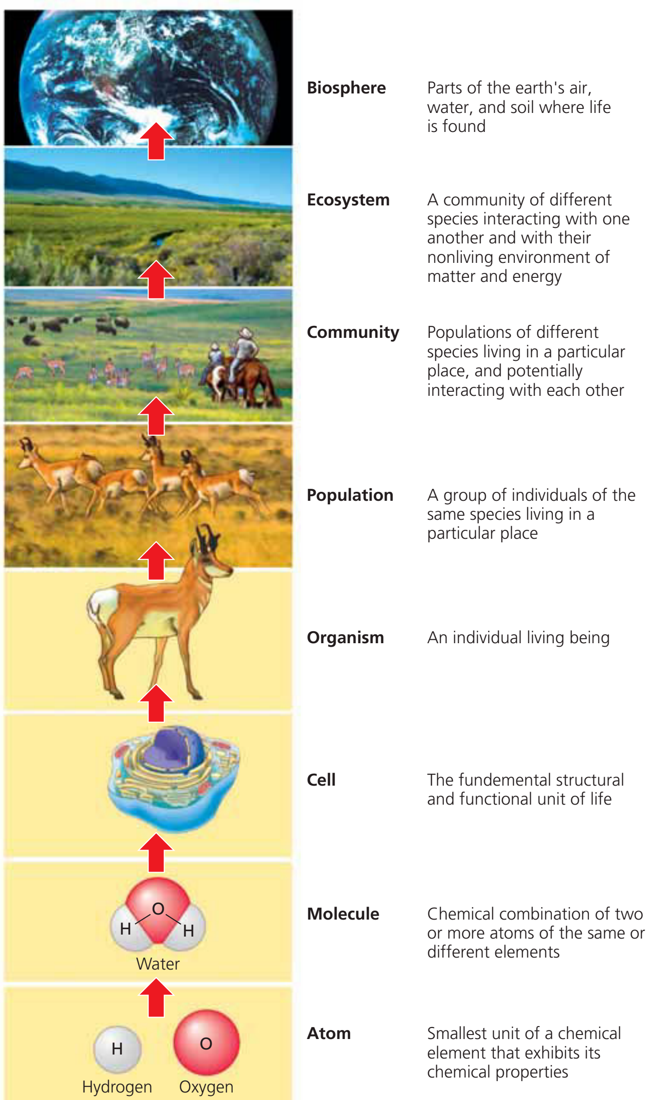
On the basis of their cell structure, organisms can be classified as either *eukaryotic* or *prokaryotic.* A **eukaryotic cell** is surrounded by a membrane and has a distinct *nucleus* (a membrane-bounded structure containing genetic material in the form of DNA) and several other internal parts called *organelles,* which are also surrounded by membranes (Figure 3-2a, p. 52). Most organisms consist of eukaryotic cells. A **prokaryotic cell** is also surrounded by a membrane, but it has no distinct nucleus and no other internal parts surrounded by membranes (Figure 3-2b, p. 52). All bacteria consist of a single prokaryotic cell. The relationships among cells and their genetic material were shown in Figure 2-5 (p. 38).

Species Make Up the Encyclopedia of Life

For a group of sexually reproducing organisms, a **species** is a set of individuals that can mate and produce fertile offspring. Every organism is a member of a certain species with certain traits. Scientists have developed a

Figure 3-2 **Natural capital:** (a) generalized structure of a *eukaryotic cell* and (b) *prokaryotic cell*. Note that a prokaryotic cell lacks a distinct nucleus and generalized structure of a *eukaryotic cell*.





CENGAGENOW™ **Active Figure 3-3** Some levels of organization of matter in nature. Ecology focuses on the top five of these levels. *See an animation based on this figure at* CengageNOW.

distinctive system for classifying and naming each species, as discussed in Supplement 7 on p. S46.

We do not know how many species are on the earth. Estimates range from 4 million to 100 million. The best guess is that there are 10–14 million species. So far biologists have identified about 1.8 million species. These and millions of species still to be classified are the entries in the encyclopedia of life found on the earth. Up to half of the world's plant and animal species live in tropical rain forests that are being cleared rapidly (**Core Case Study**). Insects make up most of the world's known species (Science Focus, p. 54). In 2007, scientists began a $100 million, 10-year project to list and describe all 1.8 million known species in a free Internet encyclopedia (**www.eol.org**).

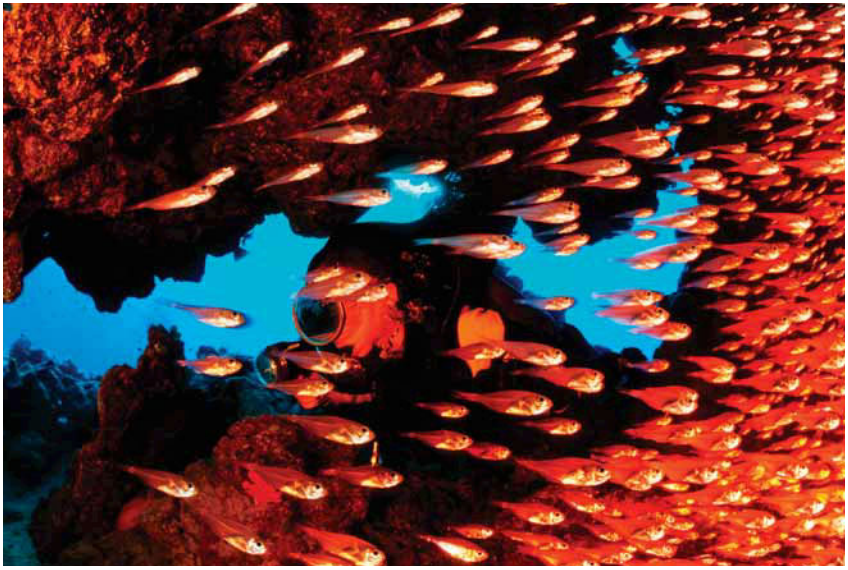
CORE CASE STUDY

Ecologists Study Connections in Nature

Ecology (from the Greek words *oikos,* meaning "house" or "place to live," and *logos,* meaning "study of") is the study of how organisms interact with their living (biotic) environment of other organisms and with their nonliving (abiotic) environment of soil, water, other forms of matter, and energy mostly from the sun (**Concept 3-1**). In effect, it is a study of *connections in nature.*

To enhance their understanding of nature, scientists classify matter into levels of organization from atoms to the biosphere (Figure 3-3). Ecologists focus on organisms, populations, communities, ecosystems, and the biosphere.

A **population** is a group of individuals of the same species that live in the same place at the same time. Examples include a school of glassfish in the Red Sea (Figure 3-4), the field mice living in a cornfield, monarch butterflies clustered in a tree, and people in a country.



Wolfgang Poelzer/Peter Arnold, Inc.

Figure 3-4 Population (school) of glassfish in a cave in the Red Sea.

In most natural populations, individuals vary slightly in their genetic makeup, which is why they do not all look or act alike. This variation in a population is called **genetic diversity** (Figure 3-5).

The place where a population or an individual organism normally lives is its **habitat.** It may be as large as an ocean or as small as the intestine of a termite. An organism's habitat can be thought of as its natural "address." Each habitat, such as a tropical rain forest (Figure 3-1, **Core Case Study**), a desert, or a pond, has certain resources, such as water, and environmental conditions, such as temperature and light, that its organisms need in order to survive.

CORE CASE STUDY

A **community,** or **biological community,** consists of all the populations of different species that live in a particular place. For example, a catfish species in a pond usually shares the pond with other fish species, and with plants, insects, ducks, and many other species that make up the community. Many of the organisms in a community interact with one another in feeding and other relationships.

An **ecosystem** is a community of different species interacting with one another and with their nonliving environment of soil, water, other forms of matter, and energy, mostly from the sun. Ecosystems can range in size from a puddle of water to an ocean, or from a patch of woods to a forest. Ecosystems can be natural or artificial (human created). Examples of artificial ecosystems are crop fields, tree farms, and reservoirs.

Ecosystems do not have clear boundaries and are not isolated from one another. Matter and energy move from one ecosystem to another. For example, soil can wash from a grassland or crop field into a nearby river or lake. Water flows from forests into nearby rivers and crop fields. Birds and various other species migrate from one ecosystem to another. And winds can blow pollen from a forest into a grassland.

The **biosphere** consists of the parts of the earth's air, water, and soil where life is found. In effect, it is the global ecosystem in which all organisms exist and can interact with one another.

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Figure 3-5 *Genetic diversity* among individuals in a population of a species of Caribbean snail is reflected in the variations in shell color and banding patterns. Genetic diversity can also include other variations such as slight differences in chemical makeup, sensitivity to various chemicals, and behavior.

SCIENCE FOCUS

Have You Thanked the Insects Today?

Insects are an important part of the earth's natural capital, although they generally have a bad reputation. We classify many insect species as *pests* because they compete with us for food, spread human diseases such as malaria, bite or sting us, and invade our lawns, gardens, and houses. Some people fear insects and think the only good bug is a dead bug. They fail to recognize the vital roles insects play in helping to sustain life on earth.

For example, pollination is a natural service that allows plants to reproduce sexually when pollen grains are transferred from one plant to a receptive part of another plant. Some plants are pollinated by species such as hummingbirds and bats, and by pollen being transmitted by wind or flowing water. But many of the earth's plant species depend on insects to pollinate their flowers (Figure 3-A, left).

Insects that eat other insects—such as the praying mantis (Figure 3-A, right)—help control the populations of at least half the species of insects we call pests. This free pest control service is an important part of the earth's natural capital. Some insects also play a key role in loosening and renewing the soil that supports terrestrial plant life. In 2006, scientists John Losey and Mace Vaughan estimated that the value of the ecological services provided by insects in the United States is at least $57 billion a year.

John Henry Williams/Bruce Coleman USA

Peter J. Bryant/Biological Photo Service

Figure 3-A *Importance of insects:* The monarch butterfly, which feeds on pollen in a flower (left), and other insects pollinate flowering plants that serve as food for many plant eaters. The praying mantis, which is eating a house cricket (right), and many other insect species help to control the populations of most of the insect species we classify as pests.

Insects have been around for at least 400 million years—about 4,000 times longer than the latest version of the human species that we belong to. They are phenomenally successful forms of life. Some reproduce at an astounding rate and can rapidly develop new genetic traits, such as resistance to pesticides. They also have an exceptional ability to evolve into new species when faced with new environmental conditions, and they are very resistant to extinction. This is fortunate because, according to ant specialist and biodiversity expert E. O. Wilson, if all insects disappeared, parts of the life support systems for us and other species would be greatly disrupted.

The environmental lesson: although insects do not need newcomer species such as us, we and most other land organisms need them.

Critical Thinking

Identify three insect species not discussed above that benefit your life.

3-2 What Keeps Us and Other Organisms Alive?

▶ **CONCEPT 3-2 Life is sustained by the flow of energy from the sun through the biosphere, the cycling of nutrients within the biosphere, and gravity.**

The Earth's Life-Support System Has Four Major Components

Scientific studies reveal that the earth's life-support system consists of four main spherical systems that interact with one another—the atmosphere (air), the hydrosphere (water), the geosphere (rock, soil, sediment), and the biosphere (living things) (Figure 3-6).

The **atmosphere** is a thin spherical envelope of gases surrounding the earth's surface. Its inner layer, the **troposphere,** extends only about 17 kilometers (11 miles) above sea level at the tropics and about 7 kilometers (4 miles) above the earth's north and south poles. It contains the majority of the air that we breathe, consisting mostly of nitrogen (78% of the total volume) and oxygen (21%). The remaining 1% of the air includes water vapor, carbon dioxide, and methane, all of which are called **greenhouse gases,** because they trap heat and thus warm the lower atmosphere. Almost all of the earth's weather occurs in this layer.

The next layer, stretching 17–50 kilometers (11–31 miles) above the earth's surface, is the **stratosphere.** Its lower portion contains enough ozone (O_3) gas to filter out most of the sun's harmful ultraviolet radiation. This global sunscreen allows life to exist on land and in the surface layers of bodies of water.

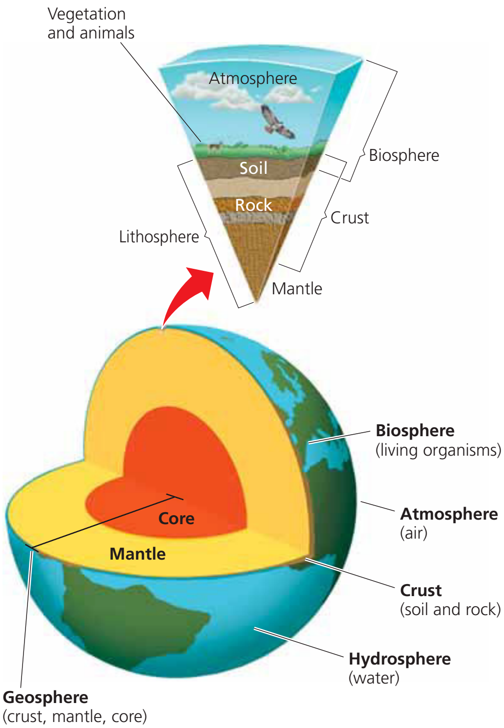


Figure 3-6 **Natural capital:** general structure of the earth showing that it consists of a land sphere, air sphere, water sphere, and life sphere.

The **hydrosphere** consists of all of the water on or near the earth's surface. It is found as *liquid water* (on the surface and underground), *ice* (polar ice, icebergs, and ice in frozen soil layers called *permafrost*), and *water vapor* in the atmosphere. Most of this water is in the oceans, which cover about 71% of the globe.

The **geosphere** consists of the earth's intensely hot *core,* a thick *mantle* composed mostly of rock, and a thin outer *crust.* Most of the geosphere is located in the earth's interior. Its upper portion contains nonrenewable fossil fuels and minerals that we use, as well as renewable soil chemicals that organisms need in order to live, grow, and reproduce.

The *biosphere* occupies those parts of the atmosphere, hydrosphere, and geosphere where life exists. This thin layer of the earth extends from about 9 kilometers (6 miles) above the earth's surface down to the bottom of the ocean, and it includes the lower part of the atmosphere, most of the hydrosphere, and the uppermost part of the geosphere. If the earth were an apple, the biosphere would be no thicker than the apple's skin. *The goal of ecology is to understand the interactions in this thin layer of air, water, soil, and organisms.*

Life Exists on Land and in Water

Biologists have classified the terrestrial (land) portion of the biosphere into **biomes**—large regions such as forests, deserts, and grasslands, with distinct climates and certain species (especially vegetation) adapted to them. Figure 3-7 shows different major biomes along the 39th parallel spanning the United States (see Figure 5 on p. S27 in Supplement 4 for a map of the major biomes

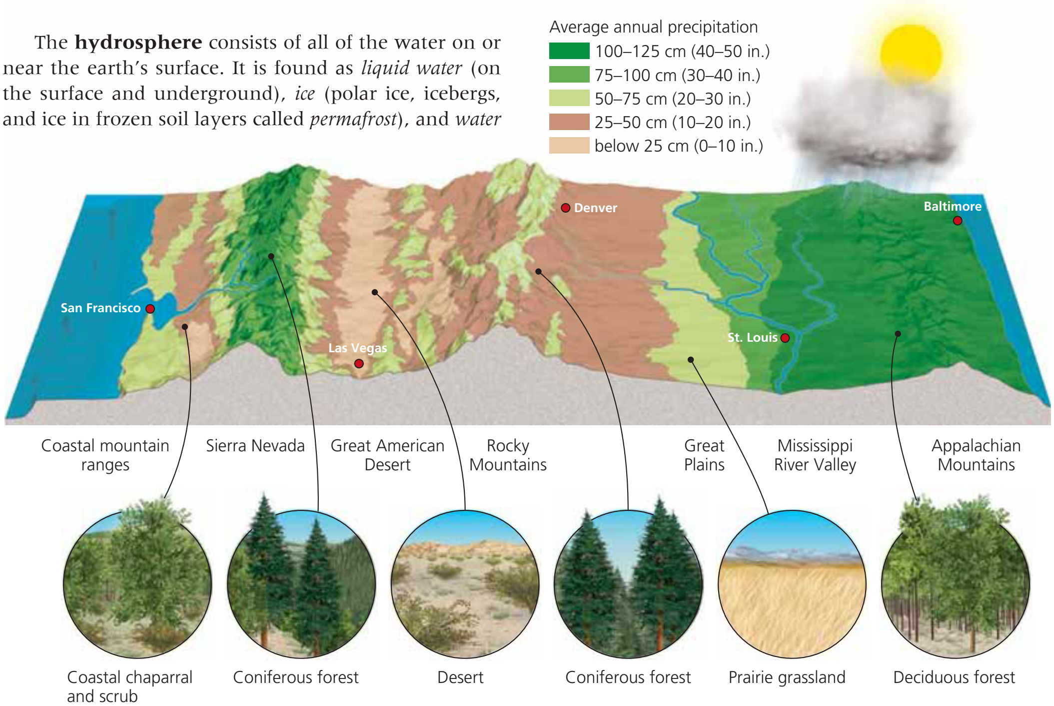


Figure 3-7 Major biomes found along the 39th parallel across the United States. The differences reflect changes in climate, mainly differences in average annual precipitation and temperature.

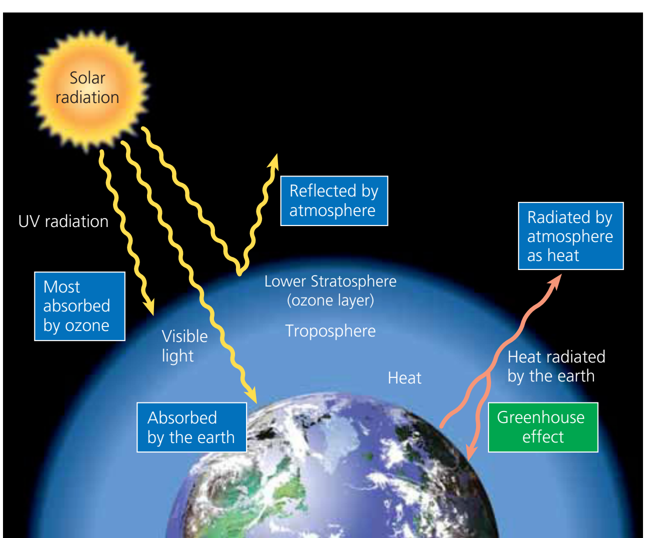
of North America). We discuss biomes in more detail in Chapter 7.

Scientists divide the watery parts of the biosphere into **aquatic life zones,** each containing numerous ecosystems. There are *freshwater life zones* (such as lakes and streams) and *ocean* or *marine life zones* (such as coral reefs and coastal estuaries). The earth is mostly a water planet with saltwater covering about 71% of its surface and freshwater covering just 2%.

Three Factors Sustain Life on Earth

Life on the earth depends on three interconnected factors (**Concept 3-2**):

- The *one-way flow of high-quality energy* from the sun, through living things in their feeding interactions, into the environment as low-quality energy (mostly heat dispersed into air or water at a low temperature), and eventually back into space as heat. No round-trips are allowed because high-quality energy cannot be recycled. The first and second laws of thermodynamics (**Concepts 2-4A** and **2-4B**, p. 40) govern this energy flow. CONCEPT LINKS
- The *cycling of matter* or *nutrients* (the atoms, ions, and compounds needed for survival by living organisms) through parts of the biosphere. Because the earth is closed to significant inputs of matter from space, its essentially fixed supply of nutrients must be continually recycled to support life (Figure 1-4, p. 9). Nutrient movements in ecosystems and in the biosphere are round-trips, which can take from seconds to centuries to complete. The law of conservation of matter (**Concept 2-3**, p. 39) governs this nutrient cycling process. CONCEPT LINK
- *Gravity,* which allows the planet to hold onto its atmosphere and helps to enable the movement and cycling of chemicals through the air, water, soil, and organisms.



CENGAGENOW™ **Active Figure 3-8** *Solar capital:* flow of energy to and from the earth. *See an animation based on this figure at* CengageNOW.

THINKING ABOUT
Energy Flow and the First and Second Laws of Thermodynamics

Explain the relationship between energy flow through the biosphere and the first and second laws of thermodynamics (pp. 42–43).

What Happens to Solar Energy Reaching the Earth?

Millions of kilometers from the earth, in the immense nuclear fusion reactor that is the sun, nuclei of hydrogen fuse together to form larger helium nuclei (Figure 2-7, bottom, p. 41), releasing tremendous amounts of energy into space. Only a very small amount of this output of energy reaches the earth—a tiny sphere in the vastness of space. This energy reaches the earth in the form of electromagnetic waves, mostly as visible light, ultraviolet (UV) radiation, and heat (infrared radiation) (Figure 2-8, p. 42). Much of this energy is absorbed or reflected back into space by the earth's atmosphere, clouds, and surface (Figure 3-8). Ozone gas (O_3) in the lower stratosphere absorbs about 95% of the sun's harmful incoming UV radiation. Without this ozone layer, life as we know it on the land and in the upper layer of water would not exist.

The UV, visible, and infrared energy that reaches the atmosphere lights the earth during daytime, warms the air, and evaporates and cycles water through the biosphere. Approximately 1% of this incoming energy generates winds. Green plants, algae, and some types of bacteria use less than 0.1% of it to produce the nutrients they need through photosynthesis and in turn to feed animals that eat plants and flesh.

Of the total solar radiation intercepted by the earth, about 1% reaches the earth's surface, and most of it is then reflected as longer-wavelength infrared radiation. As this infrared radiation travels back up through the lower atmosphere toward space, it encounters greenhouse gases such as water vapor, carbon dioxide, methane, nitrous oxide, and ozone. It causes these gaseous molecules to vibrate and release infrared radiation with even longer wavelengths. The vibrating gaseous molecules then have higher kinetic energy, which helps to warm the lower atmosphere and the earth's surface. Without this **natural greenhouse effect,** the earth would be too cold to support the forms of life we find here today. (See *The Habitable Planet,* Video 2, **www.learner.org/resources/series209.html**.)

Human activities add greenhouse gases to the atmosphere. For example, burning carbon-containing fuels releases huge amounts of carbon dioxide (CO_2) into the atmosphere. Growing crops and raising livestock release large amounts of methane (CH_4) and nitrous oxide (N_2O). Clearing CO_2-absorbing tropical rain forests (**Core Case Study**) faster than they can grow back also increases the amount of CO_2 in the atmosphere. There is considerable and growing evidence that these activities are increasing the natural greenhouse effect and warming the earth's atmosphere (Science Focus, p. 33). This in turn is changing the earth's climate as we discuss at length in Chapter 19.

CORE CASE STUDY

CENGAGENOW™ Learn more about the flow of energy—from sun to earth and within the earth's systems—at CengageNOW.

3-3 What Are the Major Components of an Ecosystem?

▶ **CONCEPT 3-3A Ecosystems contain living (biotic) and nonliving (abiotic) components.**

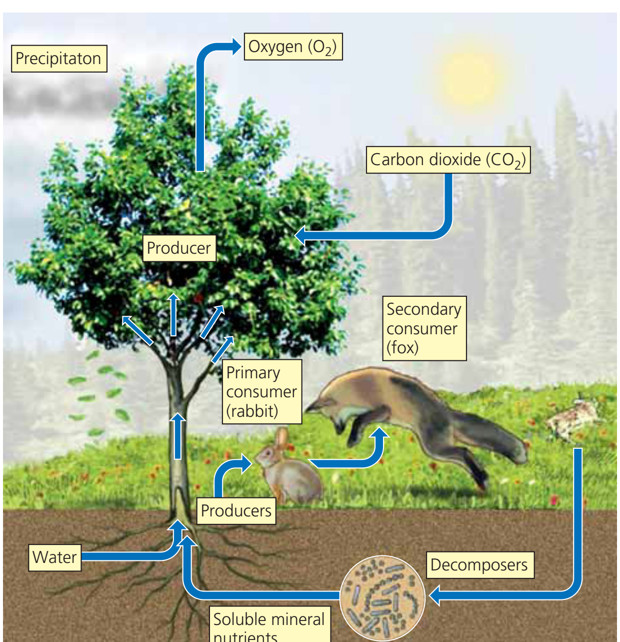
▶ **CONCEPT 3-3B Some organisms produce the nutrients they need, others get their nutrients by consuming other organisms, and some recycle nutrients back to producers by decomposing the wastes and remains of organisms.**

Ecosystems Have Living and Nonliving Components

Two types of components make up the biosphere and its ecosystems: One type, called **abiotic,** consists of nonliving components such as water, air, nutrients, rocks, heat, and solar energy. The other type, called **biotic,** consists of living and once living biological components—plants, animals, and microbes (**Concept 3-3A**). Biotic factors also include dead organisms, dead parts of organisms, and the waste products of organisms. Figure 3-9 is a greatly simplified diagram of some of the biotic and abiotic components of a terrestrial ecosystem.

Different species and their populations thrive under different physical and chemical conditions. Some need bright sunlight; others flourish in shade. Some need a hot environment; others prefer a cool or cold one. Some do best under wet conditions; others thrive under dry conditions.

Each population in an ecosystem has a **range of tolerance** to variations in its physical and chemical environment, as shown in Figure 3-10 (p. 58). Individuals within a population may also have slightly different tolerance ranges for temperature or other factors because of small differences in genetic makeup, health, and age. For example, a trout population may do best within



CENGAGENOW™ **Active Figure 3-9** Major living (biotic) and nonliving (abiotic) components of an ecosystem in a field. *See an animation based on this figure at* CengageNOW.

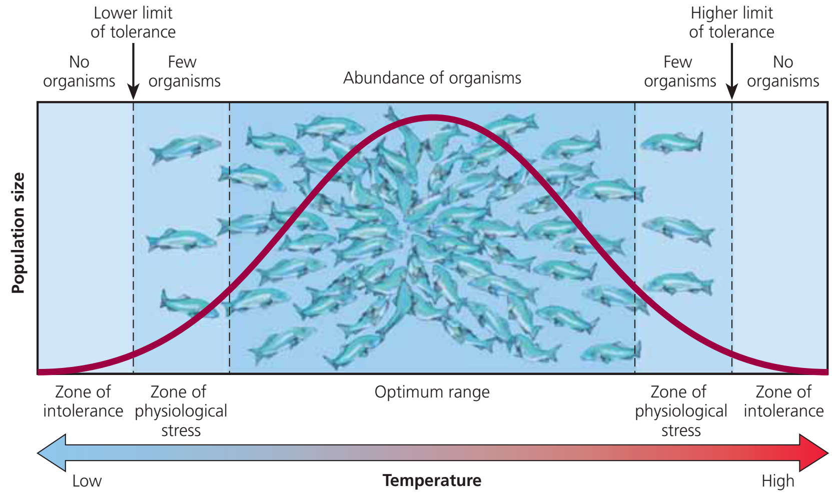


Figure 3-10 Range of tolerance for a population of organisms, such as fish, to an abiotic environmental factor—in this case, temperature. These restrictions keep particular species from taking over an ecosystem by keeping their population size in check. **Question:** Which **scientific principle of sustainability** (see back cover) is related to the range of tolerance concept?

a narrow band of temperatures (*optimum level* or *range*), but a few individuals can survive above and below that band. Of course, if the water becomes much too hot or too cold, none of the trout can survive.

Several Abiotic Factors Can Limit Population Growth

A variety of abiotic factors can affect the number of organisms in a population. Sometimes one or more factors, known as **limiting factors,** are more important in regulating population growth than other factors are. This ecological principle is called the **limiting factor principle:** *Too much or too little of any abiotic factor can limit or prevent growth of a population, even if all other factors are at or near the optimal range of tolerance.* This principle describes one way in which population control—a **scientific principle of sustainability** (see back cover)—is achieved.

On land, precipitation often is the limiting abiotic factor. Lack of water in a desert limits plant growth. Soil nutrients also can act as a limiting factor on land. Suppose a farmer plants corn in phosphorus-poor soil. Even if water, nitrogen, potassium, and other nutrients are at optimal levels, the corn will stop growing when it uses up the available phosphorus. Too much of an abiotic factor can also be limiting. For example, too much water or fertilizer can kill plants. Temperature can also be a limiting factor. Both high and low temperatures can limit the survival and population sizes of various terrestrial species, especially plants.

Important limiting abiotic factors in aquatic life zones include temperature, sunlight, nutrient availability, and the low solubility of oxygen gas in water (*dissolved oxygen content*). Another such factor is *salinity*—the amounts of various inorganic minerals or salts dissolved in a given volume of water.

Producers and Consumers Are the Living Components of Ecosystems

Ecologists assign every organism in an ecosystem to a *feeding level,* or **trophic level,** depending on its source of food or nutrients. The organisms that transfer energy and nutrients from one trophic level to another in an ecosystem can be broadly classified as producers and consumers.

Producers, sometimes called **autotrophs** (self-feeders), make the nutrients they need from compounds and energy obtained from their environment. On land, most producers are green plants, which generally capture about 1% of the solar energy that falls on their leaves and convert it to chemical energy stored in organic molecules such as carbohydrates. In freshwater and marine ecosystems, algae and aquatic plants are the major producers near shorelines. In open water, the dominant producers are *phytoplankton*—mostly microscopic organisms that float or drift in the water.

Most producers capture sunlight to produce energy-rich carbohydrates (such as glucose, $C_6H_{12}O_6$) by **photosynthesis,** which is the way energy enters most ecosystems. Although hundreds of chemical changes take place during photosynthesis, the overall reaction can be summarized as follows:

$$\text{carbon dioxide} + \text{water} + \text{solar energy} \longrightarrow \text{glucose} + \text{oxygen}$$

$$6\ CO_2 + 6\ H_2O + \text{solar energy} \longrightarrow C_6H_{12}O_6 + 6\ O_2$$

(See p. S44 in Supplement 6 for information on how to balance chemical equations such as this one and p. S44 in Supplement 6 for more details on photosynthesis.)

A few producers, mostly specialized bacteria, can convert simple inorganic compounds from their environment into more complex nutrient compounds without using sunlight, through a process called **chemosynthesis.** In 1977, scientists discovered a community of bacteria living in the extremely hot water around *hydrothermal vents* on the deep ocean floor. These bacteria serve as producers for their ecosystems without the use of sunlight. They draw energy and produce carbohydrates from hydrogen sulfide (H_2S) gas escaping through fissures in the ocean floor. Most of the earth's organisms get their energy indirectly from the sun. But chemosynthetic organisms in these dark and deep-sea habitats survive indirectly on *geothermal energy* from the earth's interior and represent an exception to the first **scientific principle of sustainability**.

All other organisms in an ecosystem are **consumers,** or **heterotrophs** ("other-feeders"), that cannot produce the nutrients they need through photosynthesis or other processes and must obtain their nutrients by feeding on other organisms (producers or other consumers) or their remains. In other words, all consumers (including humans) are directly or indirectly dependent on producers for their food or nutrients.

There are several types of consumers:

- **Primary consumers,** or **herbivores** (plant eaters), are animals such as rabbits, grasshoppers, deer, and zooplankton that eat producers, mostly by feeding on green plants.
- **Secondary consumers,** or **carnivores** (meat eaters), are animals such as spiders, hyenas, birds, frogs, and some zooplankton-eating fish, all of which feed on the flesh of herbivores.
- **Third-** and **higher-level consumers** are carnivores such as tigers, wolves, mice-eating snakes, hawks, and killer whales (orcas) that feed on the flesh of other carnivores. Some of these relationships are shown in Figure 3-9.
- **Omnivores** such as pigs, foxes, cockroaches, and humans, play dual roles by feeding on both plants and animals.
- **Decomposers,** primarily certain types of bacteria and fungi, are consumers that release nutrients from the dead bodies of plants and animals and return them to the soil, water, and air for reuse by producers. They feed by secreting enzymes that speed up the break down of bodies of dead organisms into nutrient compounds such as water, carbon dioxide, minerals, and simpler organic compounds.
- **Detritus feeders,** or **detritivores,** feed on the wastes or dead bodies of other organisms, called **detritus** ("di-TRI-tus," meaning debris). Examples include small organisms such as mites and earthworms, some insects, catfish, and larger scavenger organisms such as vultures.

Hordes of decomposers and detritus feeders can transform a fallen tree trunk into a powder and finally into simple inorganic molecules that plants can absorb as nutrients (Figure 3-11, p. 60). In summary, some organisms produce the nutrients they need, others get their nutrients by consuming other organisms, and still others recycle the nutrients in the wastes and remains of organisms so that producers can use them again (**Concept 3-3B**).

THINKING ABOUT
What You Eat

When you had your most recent meal, were you an herbivore, a carnivore, or an omnivore?

Producers, consumers, and decomposers use the chemical energy stored in glucose and other organic compounds to fuel their life processes. In most cells this energy is released by **aerobic respiration,** which uses oxygen to convert glucose (or other organic nutrient molecules) back into carbon dioxide and water. The net effect of the hundreds of steps in this complex process is represented by the following reaction:

$$\text{glucose} + \text{oxygen} \longrightarrow \text{carbon dioxide} + \text{water} + \text{energy}$$

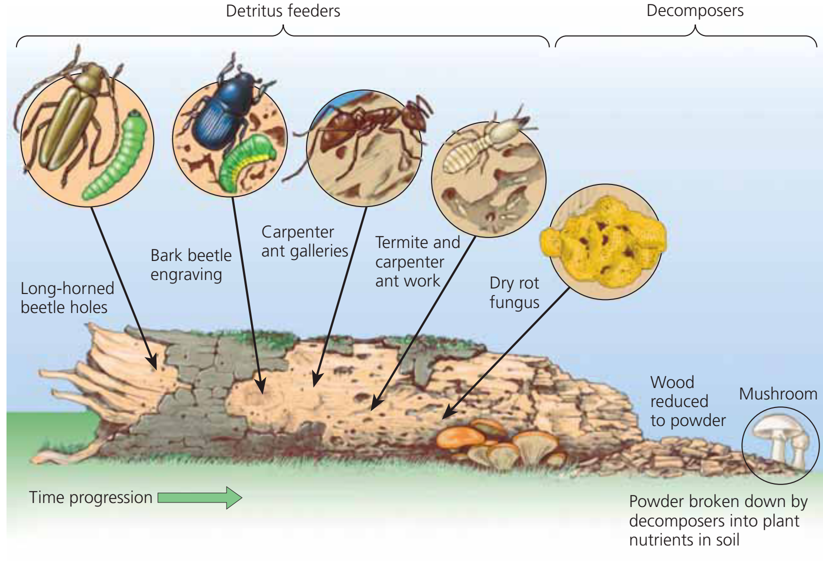
$$C_6H_{12}O_6 + 6\ O_2 \longrightarrow 6\ CO_2 + 6\ H_2O + \text{energy}$$

Although the detailed steps differ, the net chemical change for aerobic respiration is the opposite of that for photosynthesis.

Some decomposers get the energy they need by breaking down glucose (or other organic compounds) in the *absence* of oxygen. This form of cellular respiration is called **anaerobic respiration,** or **fermentation.** Instead of carbon dioxide and water, the end products of this process are compounds such as methane gas (CH_4, the main component of natural gas), ethyl alcohol (C_2H_6O), acetic acid ($C_2H_4O_2$, the key component of vinegar), and hydrogen sulfide (H_2S, when sulfur compounds are broken down). Note that all organisms get their energy from aerobic or anaerobic respiration but only plants carry out photosynthesis.

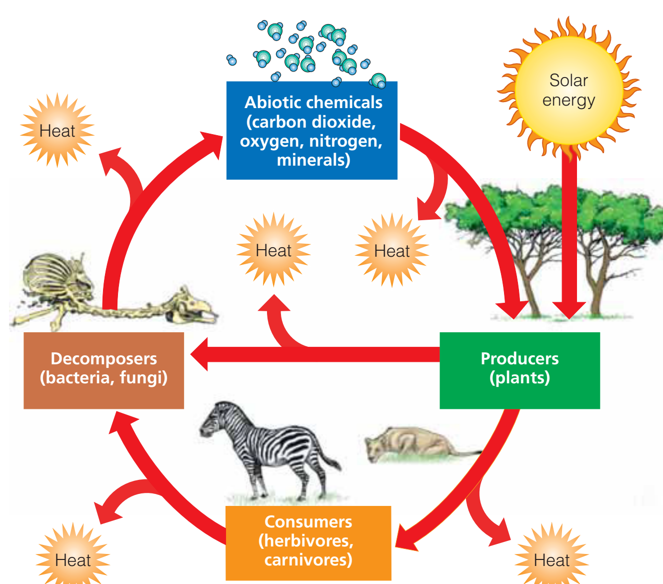
CENGAGENOW™ Explore the components of ecosystems, how they interact, the roles of bugs and plants, and what a fox will eat at CengageNOW.

Figure 3-11 Various detritivores and decomposers (mostly fungi and bacteria) can "feed on" or digest parts of a log and eventually convert its complex organic chemicals into simpler inorganic nutrients that can be taken up by producers.



Energy Flow and Nutrient Cycling Sustain Ecosystems and the Biosphere

Ecosystems and the biosphere are sustained through a combination of *one-way energy flow* from the sun through these systems and *nutrient cycling* of key materials within them—two important natural services that are components of the earth's natural capital. These two **scientific principles of sustainability** arise from the structure and function of natural ecosystems (Figure 3-12), the law of conservation of matter (**Concept 2-3**, p. 39), and the two laws of thermodynamics (**Concepts 2-4A** and **2-4B**, p. 40).



CENGAGENOW™ **Active Figure 3-12** **Natural capital:** the main structural components of an ecosystem (energy, chemicals, and organisms). Nutrient cycling and the flow of energy—first from the sun, then through organisms, and finally into the environment as low-quality heat—link these components. *See an animation based on this figure at* CengageNOW.

SCIENCE FOCUS

Many of the World's Most Important Species Are Invisible to Us

They are everywhere. Billions of them can be found inside your body, on your body, in a handful of soil, and in a cup of ocean water.

These mostly invisible rulers of the earth are *microbes,* or *microorganisms,* catchall terms for many thousands of species of bacteria, protozoa, fungi, and floating phytoplankton—most too small to be seen with the naked eye.

Microbes do not get the respect they deserve. Most of us view them primarily as threats to our health in the form of infectious bacteria or "germs," fungi that cause athlete's foot and other skin diseases, and protozoa that cause diseases such as malaria. But these harmful microbes are in the minority.

We are alive because of multitudes of microbes toiling away mostly out of sight. Bacteria in our intestinal tracts help to break down the food we eat and microbes in our noses help to prevent harmful bacteria from reaching our lungs.

Bacteria and other microbes help to purify the water we drink by breaking down wastes. Bacteria also help to produce foods such as bread, cheese, yogurt, soy sauce, beer, and wine. Bacteria and fungi in the soil decompose organic wastes into nutrients that can be taken up by plants that we and most other animals eat. Without these tiny creatures, we would go hungry and be up to our necks in waste matter.

Microbes, particularly phytoplankton in the ocean, provide much of the planet's oxygen, and help slow global warming by removing some of the carbon dioxide produced when we burn coal, natural gas, and gasoline. (See *The Habitable Planet,* Video 3, **www.learner.org/resources/series209.html**.) Scientists are working on using microbes to develop new medicines and fuels. Genetic engineers are inserting genetic material into existing microbes to convert them to microbes that can help clean up polluted water and soils.

Some microbes help control diseases that affect plants and populations of insect species that attack our food crops. Relying more on these microbes for pest control could reduce the use of potentially harmful chemical pesticides. In other words, microbes are a vital part of the earth's natural capital.

Critical Thinking

What are three advantages that microbes have over us for thriving in the world?

Decomposers and detritus feeders, many of which are microscopic organisms, (Science Focus, above) are the key to nutrient cycling because they break down organic matter into simpler nutrients that can be reused by producers. Without decomposers and detritus feeders, there would be little, if any, nutrient cycling and the planet would be overwhelmed with plant litter, dead animal bodies, animal wastes, and garbage. In addition, most life as we know it could not exist because the nutrients stored in such wastes and dead bodies would be locked up and unavailable for use by other organisms.

THINKING ABOUT
Chemical Cycling and the Law of Conservation of Matter

CONCEPT LINK

Explain the relationship between chemical cycling in ecosystems and in the biosphere and the law of conservation of matter (**Concept 2-3**, p. 39).

3-4 What Happens to Energy in an Ecosystem?

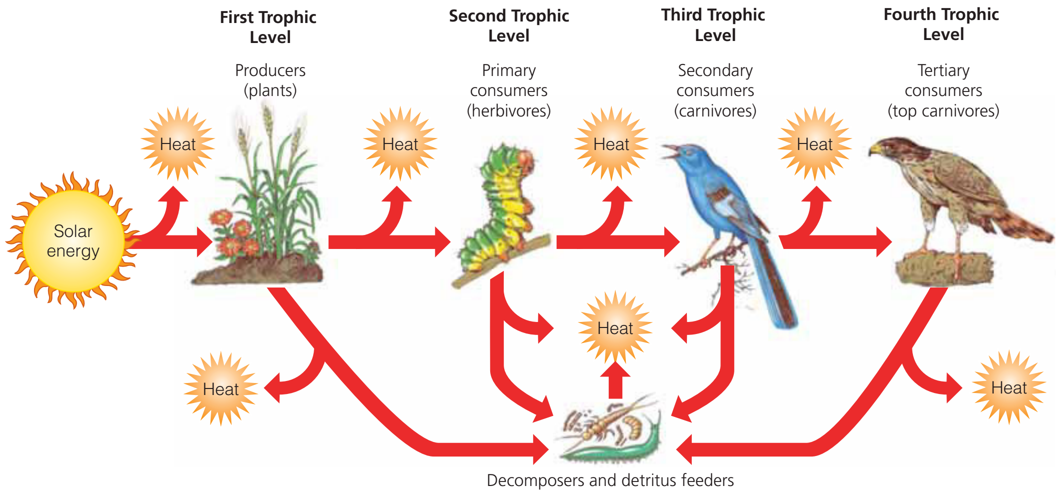
▶ **CONCEPT 3-4A Energy flows through ecosystems in food chains and webs.**

▶ **CONCEPT 3-4B As energy flows through ecosystems in food chains and webs, the amount of chemical energy available to organisms at each succeeding feeding level decreases.**

Energy Flows through Ecosystems in Food Chains and Food Webs

The chemical energy stored as nutrients in the bodies and wastes of organisms flows through ecosystems from one trophic (feeding) level to another. For example, a plant uses solar energy to store chemical energy in a leaf. A caterpillar eats the leaf, a robin eats the caterpillar, and a hawk eats the robin. Decomposers and detritus feeders consume the leaf, caterpillar, robin, and hawk after they die and return their nutrients to the soil for reuse by producers.

A sequence of organisms, each of which serves as a source of food or energy for the next, is called a **food chain.** It determines how chemical energy and nutrients move from one organism to another through the trophic levels in an ecosystem—primarily through photosynthesis, feeding, and decomposition—as shown



CENGAGENOW™ **Active Figure 3-13** A *food chain.* The arrows show how chemical energy in nutrients flows through various *trophic levels* in energy transfers; most of the energy is degraded to heat, in accordance with the second law of thermodynamics. *See an animation based on this figure at* CengageNOW. **Question:** Think about what you ate for breakfast. At what level or levels on a food chain were you eating?

in Figure 3-13. Every use and transfer of energy by organisms involves a loss of some useful energy to the environment as heat. Thus, eventually an ecosystem and the biosphere would run out of energy if they were not powered by a continuous inflow of energy from an outside source, ultimately the sun.

In natural ecosystems, most consumers feed on more than one type of organism, and most organisms are eaten or decomposed by more than one type of consumer. Because of this, organisms in most ecosystems form a complex network of interconnected food chains called a **food web** (Figure 3-14). Trophic levels can be assigned in food webs just as in food chains. Food chains and webs show how producers, consumers, and decomposers are connected to one another as energy flows through trophic levels in an ecosystem.

THINKING ABOUT
Energy Flow and Tropical Rain forests CORE CASE STUDY

What happens to the flow of energy through tropical rain forest ecosystems when such forests are degraded (**Core Case Study**)?

Usable Energy Decreases with Each Link in a Food Chain or Web

Each trophic level in a food chain or web contains a certain amount of **biomass,** the dry weight of all organic matter contained in its organisms. In a food chain or web, chemical energy stored in biomass is transferred from one trophic level to another.

Energy transfer through food chains and food webs is not very efficient because, with each transfer, some usable chemical energy is degraded and lost to the environment as low-quality heat, as a result of the second law of thermodynamics. In other words, as energy flows through ecosystems in food chains and webs, there is a decrease in the amount of chemical energy available to organisms at each succeeding feeding level (**Concept 3-4B**).

The percentage of usable chemical energy transferred as biomass from one trophic level to the next is called **ecological efficiency.** It ranges from 2% to 40% (that is, a loss of 60–98%) depending on what types of species and ecosystems are involved, but 10% is typical.

Assuming 10% ecological efficiency (90% loss of usable energy) at each trophic transfer, if green plants in an area manage to capture 10,000 units of energy from the sun, then only about 1,000 units of chemical energy will be available to support herbivores, and only about 100 units will be available to support carnivores.

The more trophic levels there are in a food chain or web, the greater is the cumulative loss of usable chemical energy as it flows through the trophic levels. The **pyramid of energy flow** in Figure 3-15 illustrates this energy loss for a simple food chain, assuming a 90% energy loss with each transfer.

THINKING ABOUT
Energy Flow and the Second Law of Thermodynamics CONCEPT LINK

Explain the relationship between the second law of thermodynamics (**Concept 2-4B**, p. 40) and the flow of energy through a food chain or web.

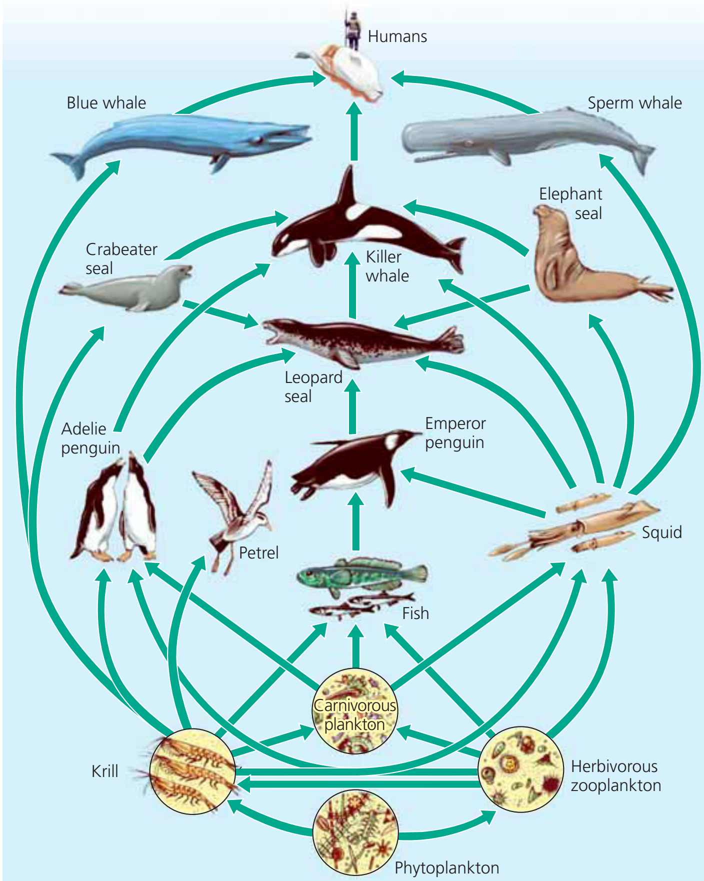


Figure 3-14 *Greatly simplified food web* in the Antarctic. Many more participants in the web, including an array of decomposer and detritus feeder organisms, are not depicted here. **Question:** Can you imagine a food web of which you are a part? Try drawing a simple diagram of it.

Energy flow pyramids explain why the earth can support more people if they eat at lower trophic levels by consuming grains, vegetables, and fruits directly, rather than passing such crops through another trophic level and eating grain eaters or herbivores such as cattle. About two-thirds of the world's people survive primarily by eating wheat, rice, and corn at the first trophic level, mostly because they cannot afford meat.

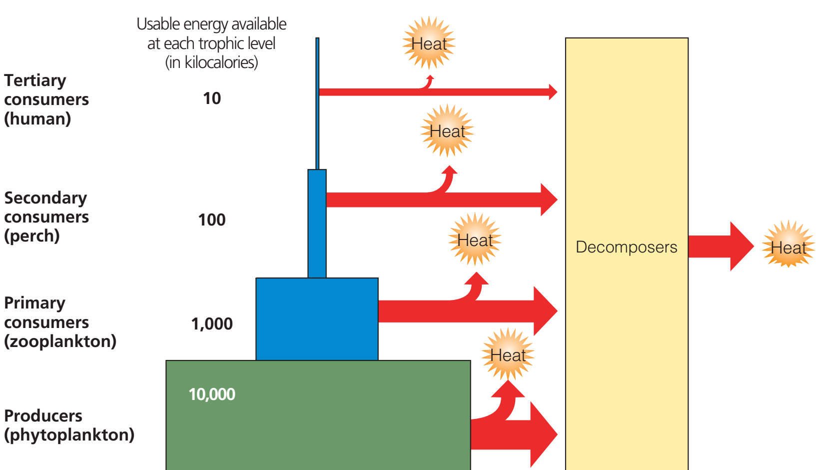


Figure 3-15 Generalized *pyramid of energy flow* showing the decrease in usable chemical energy available at each succeeding trophic level in a food chain or web. In nature, ecological efficiency varies from 2% to 40%, with 10% efficiency being common. This model assumes a 10% ecological efficiency (90% loss of usable energy to the environment, in the form of low-quality heat) with each transfer from one trophic level to another. **Question:** Why is a vegetarian diet more energy efficient than a meat-based diet?

The large loss in chemical energy between successive trophic levels also explains why food chains and webs rarely have more than four or five trophic levels. In most cases, too little chemical energy is left after four or five transfers to support organisms feeding at these high trophic levels.

THINKING ABOUT
Food Webs, Tigers, and Insects

Use Figure 3-15 to help explain **(a)** why there are not many tigers in the world and why they are vulnerable to premature extinction because of human activities, and **(b)** why there are so many insects (Science Focus, p. 54) in the world.

CENGAGENOW™ Examine how energy flows among organisms at different trophic levels and through food webs in tropical rain forests, prairies, and other ecosystems at CengageNOW.

Some Ecosystems Produce Plant Matter Faster Than Others Do

The amount, or mass, of living organic material (biomass) that a particular ecosystem can support is determined by the amount of energy captured and stored as chemical energy by the producers of that ecosystem and by how rapidly they can produce and store such chemical energy. **Gross primary productivity (GPP)** is the *rate* at which an ecosystem's producers (usually plants) convert solar energy into chemical energy as biomass found in their tissues. It is usually measured in terms of energy production per unit area over a given time span, such as kilocalories per square meter per year (kcal/m^2/yr).

To stay alive, grow, and reproduce, producers must use some of the chemical energy stored in the biomass they make for their own respiration. **Net primary productivity (NPP)** is the *rate* at which producers use photosynthesis to produce and store chemical energy *minus* the *rate* at which they use some of this stored chemical energy through aerobic respiration. In other words, NPP = GPP − R, where R is energy used in respiration. NPP measures how fast producers can provide the chemical energy stored in their tissue that is potentially available to other organisms (consumers) in an ecosystem.

Ecosystems and life zones differ in their NPP as illustrated in Figure 3-16. On land, NPP generally decreases from the equator toward the poles because the amount of solar radiation available to terrestrial plant producers is highest at the equator and lowest at the poles.

In the ocean, the highest NPP is found in estuaries where high inputs of plant nutrients flow from nutrient-laden rivers, which also stir up nutrients in bottom sediments. Because of the lack of nutrients, the open ocean has a low NPP, except at occasional areas where an *upwelling* (water moving up from the depths toward the surface) brings nutrients in bottom sediments to the surface. Despite its low NPP, the open

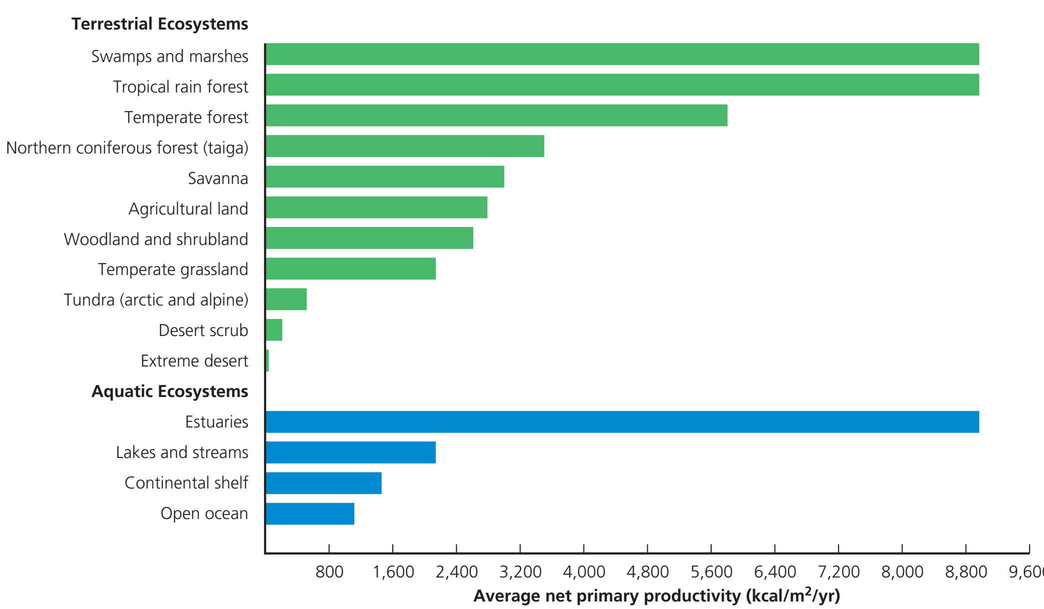


Figure 3-16 Estimated annual average *net primary productivity* in major life zones and ecosystems, expressed as kilocalories of energy produced per square meter per year (kcal/m^2/yr). **Question:** What are nature's three most productive and three least productive systems? (Data from R. H. Whittaker, *Communities and Ecosystems,* 2nd ed., New York: Macmillan, 1975)

ocean produces more of the earth's biomass per year than any other ecosystem or life zone, simply because there is so much open ocean.

As we have seen, producers are the source of all nutrients or chemical energy in an ecosystem for themselves and for the animals and decomposers that feed on them. Only the biomass represented by NPP is available as nutrients for consumers, and they use only a portion of this amount. Thus, *the planet's NPP ultimately limits the number of consumers (including humans) that can survive on the earth*. This is an important lesson from nature.

Peter Vitousek, Stuart Rojstaczer, and other ecologists estimate that humans now use, waste, or destroy about 20–32% of the earth's total potential NPP. This is a remarkably high value, considering that the human population makes up less than 1% of the total biomass of all of the earth's consumers that depend on producers for their nutrients.

3-5 What Happens to Matter in an Ecosystem?

CONCEPT 3-5 Matter, in the form of nutrients, cycles within and among ecosystems and the biosphere, and human activities are altering these chemical cycles.

Nutrients Cycle in the Biosphere

The elements and compounds that make up nutrients move continually through air, water, soil, rock, and living organisms in ecosystems and in the biosphere in cycles called **biogeochemical cycles** (literally, life-earth-chemical cycles) or **nutrient cycles**—prime examples of one of the four **scientific principles of sustainability** (see back cover). These cycles, driven directly or indirectly by incoming solar energy and gravity, include the hydrologic (water), carbon, nitrogen, phosphorus, and sulfur cycles. These cycles are an important component of the earth's natural capital (Figure 1-3, p. 8), and human activities are altering them (**Concept 3-5**).

As nutrients move through the biogeochemical cycles, they may accumulate in one portion of the cycle and remain there for different lengths of time. These temporary storage sites such as the atmosphere, the oceans and other waters, and underground deposits are called *reservoirs.*

Nutrient cycles connect past, present, and future forms of life. Some of the carbon atoms in your skin may once have been part of an oak leaf, a dinosaur's skin, or a layer of limestone rock. Your grandmother, Attila the Hun, or a hunter–gatherer who lived 25,000 years ago may have inhaled some of the oxygen molecules you just inhaled.

Water Cycles through the Biosphere

The **hydrologic cycle,** or **water cycle,** collects, purifies, and distributes the earth's fixed supply of water, as shown in Figure 3-17 (p. 66). The water cycle is a global cycle because there is a large reservoir of water in the atmosphere as well as in the hydrosphere, especially the oceans. Water is an amazing substance (Science Focus, p. 67), which makes the water cycle critical to life on earth.

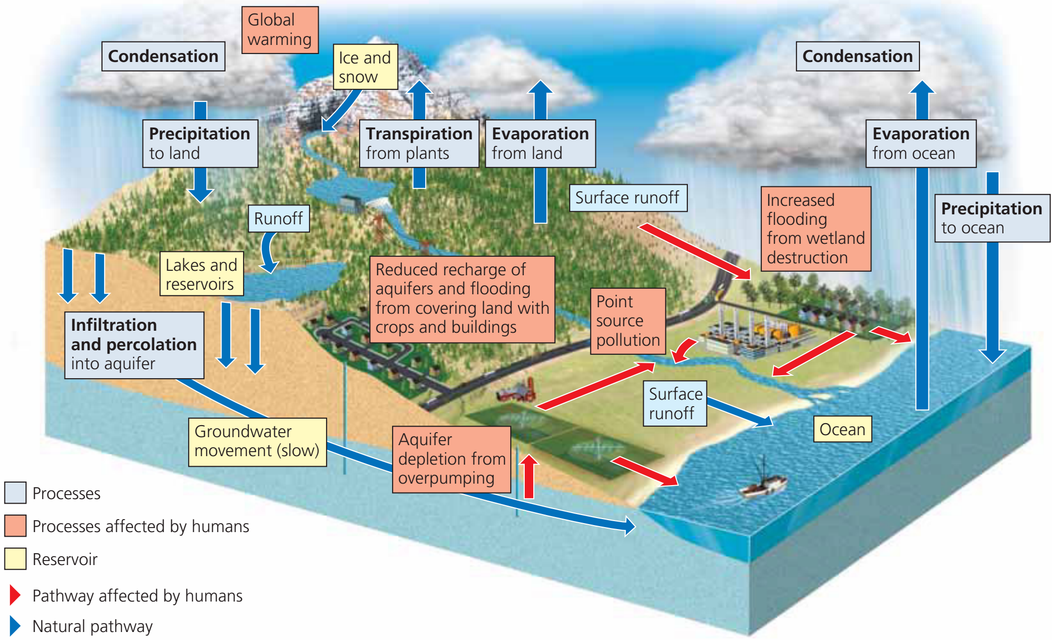
The water cycle is powered by energy from the sun and involves three major processes—evaporation, precipitation, and transpiration. Incoming solar energy causes *evaporation* of water from the oceans, lakes, rivers, and soil. Evaporation changes liquid water into water vapor in the atmosphere, and gravity draws the water back to the earth's surface as *precipitation* (rain, snow, sleet, and dew). About 84% of water vapor in the atmosphere comes from the oceans, which cover almost three-fourths of the earth's surface; the rest comes from land. Over land, about 90% of the water that reaches the atmosphere evaporates from the surfaces of plants through a process called **transpiration.**

Water returning to the earth's surface as precipitation takes various paths. Most precipitation falling on terrestrial ecosystems becomes *surface runoff.* This water flows into streams and lakes, which eventually carry water back to the oceans, from which it can evaporate to repeat the cycle. Some surface water also seeps into the upper layer of soils and some evaporates from soil, lakes, and streams back into the atmosphere.

Some precipitation is converted to ice that is stored in *glaciers,* usually for long periods of time. Some precipitation sinks through soil and permeable rock formations to underground layers of rock, sand, and gravel called *aquifers,* where it is stored as *groundwater.*

A small amount of the earth's water ends up in the living components of ecosystems. Roots of plants absorb some of this water, most of which evaporates from plant leaves back into the atmosphere. Some combines with carbon dioxide during photosynthesis to produce high-energy organic compounds such as carbohydrates. Eventually these compounds are broken down in plant cells, which release water back into the environment. Consumers get their water from their food or by drinking it.

Surface runoff replenishes streams and lakes, but also causes soil erosion, which moves soil and rock fragments from one place to another. Water is the primary sculptor of the earth's landscape. Because water



CENGAGENOW™ **Active Figure 3-17** **Natural capital:** simplified model of the *hydrologic cycle* with major harmful impacts of human activities shown in red. *See an animation based on this figure at* CengageNOW. **Question:** What are three ways in which your lifestyle directly or indirectly affects the hydrologic cycle?

dissolves many nutrient compounds, it is a major medium for transporting nutrients within and between ecosystems.

Throughout the hydrologic cycle, many natural processes purify water. Evaporation and subsequent precipitation act as a natural distillation process that removes impurities dissolved in water. Water flowing above ground through streams and lakes and below ground in aquifers is naturally filtered and partially purified by chemical and biological processes—mostly by the actions of decomposer bacteria—as long as these natural processes are not overloaded. Thus, *the hydrologic cycle can be viewed as a cycle of natural renewal of water quality.*

Only about 0.024% of the earth's vast water supply is available to us as liquid freshwater in accessible groundwater deposits and in lakes, rivers, and streams. The rest is too salty for us to use, is stored as ice, or is too deep underground to extract at affordable prices using current technology.

We alter the water cycle in three major ways (see red arrows and boxes in Figure 3-17). *First,* we withdraw large quantities of freshwater from streams, lakes, and underground sources, sometimes at rates faster than nature can replace it.

Second, we clear vegetation from land for agriculture, mining, road building, and other activities, and cover much of the land with buildings, concrete, and asphalt. This increases runoff, reduces infiltration that would normally recharge groundwater supplies, increases the risk of flooding, and accelerates soil erosion and landslides.

Clearing vegetation can also alter weather patterns by reducing transpiration. This is especially important in dense tropical rain forests (**Core Case Study** and Figure 3-1). Because so many plants in a tropical rain forest transpire water into the atmosphere, vegetation is the primary source of local rainfall. In other words, as part of the water cycle, these plants create their own rain.

CORE CASE STUDY

Cutting down the forest raises ground temperatures (because it reduces shade) and can reduce local rainfall so much that the forest cannot grow back. When such a tipping point is reached, these biologically diverse forests are converted into much less diverse tropical grasslands, as a 2005 study showed in parts of Brazil's huge Amazon basin. Models project that if current burning and deforestation rates continue, 20–30% of the Amazon rain forests will turn into tropical grassland in the next 50 years.

The *third* way in which we alter the water cycle is by increasing flooding. This happens when we drain wetlands for farming and other purposes. Left undisturbed, wetlands provide the natural service of flood control, acting like sponges to absorb and hold overflows of water from drenching rains or rapidly melting snow. We also cover much of the land with roads, parking lots, and buildings, eliminating the land's ability to absorb water and dramatically increasing runoff and flooding.

SCIENCE FOCUS

Water's Unique Properties

Water is a remarkable substance with a unique combination of properties:

- *Forces of attraction,* called *hydrogen bonds* (see Figure 7 on p. S42 in Supplement 6), *hold water molecules together*—the major factor determining water's distinctive properties.
- *Water exists as a liquid over a wide temperature range because of the hydrogen bonds.* Without water's high boiling point the oceans would have evaporated long ago.
- *Liquid water changes temperature slowly because it can store a large amount of heat without a large change in temperature.* This high heat storage capacity helps protect living organisms from temperature changes, moderates the earth's climate, and makes water an excellent coolant for car engines and power plants.
- *It takes a large amount of energy to evaporate water because of the hydrogen bonds.* Water absorbs large amounts of heat as it changes into water vapor and releases this heat as the vapor condenses back to liquid water. This helps to distribute heat throughout the world and to determine regional and local climates. It also makes evaporation a cooling process—explaining why you feel cooler when perspiration evaporates from your skin.
- *Liquid water can dissolve a variety of compounds* (see Figure 3, p. S40, in Supplement 6). It carries dissolved nutrients into the tissues of living organisms, flushes waste products out of those tissues, serves as an all-purpose cleanser, and helps remove and dilute the water-soluble wastes of civilization. This property also means that water-soluble wastes can easily pollute water.
- *Water filters out some of the sun's ultraviolet radiation* (Figure 2-8, p. 42) *that would harm some aquatic organisms.* However, up to a certain depth it is transparent to visible light needed for photosynthesis.
- *Hydrogen bonds allow water to adhere to a solid surface.* This enables narrow columns of water to rise through a plant from its roots to its leaves (a process called capillary action).
- *Unlike most liquids, water expands when it freezes.* This means that ice floats on water because it has a lower density (mass per unit of volume) than liquid water. Otherwise, lakes and streams in cold climates would freeze solid, losing most of their aquatic life. Because water expands upon freezing, it can break pipes, crack a car's engine block (if it doesn't contain antifreeze), break up street pavements, and fracture rocks.

Critical Thinking

Water is a bent molecule (see Figure 4 on p. S40 in Supplement 6) and this allows it to form hydrogen bonds (Figure 7, p. S42, in Supplement 6) between its molecules. What are three ways in which your life would be different if water were a linear or straight molecule?

Carbon Cycles through the Biosphere and Depends on Photosynthesis and Respiration

Carbon is the basic building block of the carbohydrates, fats, proteins, DNA, and other organic compounds necessary for life. It circulates through the biosphere, the atmosphere, and parts of the hydrosphere, in the **carbon cycle** shown in Figure 3-18 (p. 68). It depends on photosynthesis and aerobic respiration by the earth's living organisms.

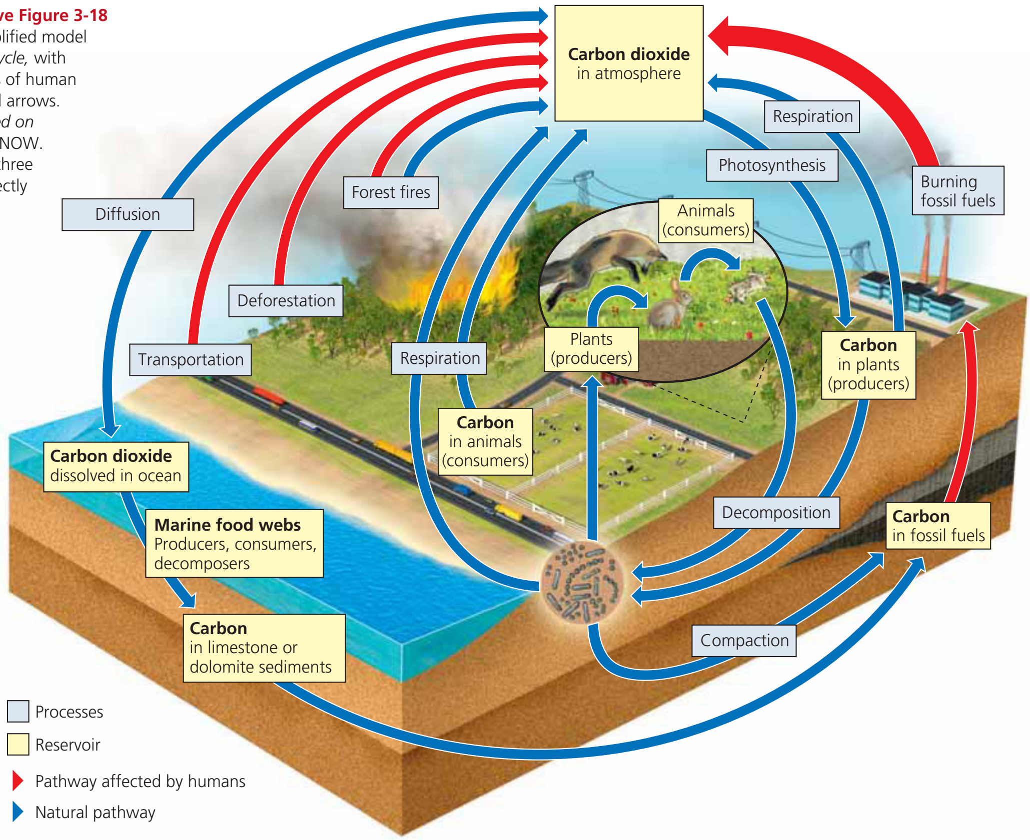
The carbon cycle is based on carbon dioxide (CO_2) gas, which makes up 0.038% of the volume of the atmosphere and is also dissolved in water. Carbon dioxide is a key component of nature's thermostat. If the carbon cycle removes too much CO_2 from the atmosphere, the atmosphere will cool, and if it generates too much CO_2, the atmosphere will get warmer. Thus, even slight changes in this cycle caused by natural or human factors can affect climate and ultimately help determine the types of life that can exist in various places.

Terrestrial producers remove CO_2 from the atmosphere and aquatic producers remove it from the water. (See *The Habitable Planet,* Video 3, **www.learner.org/resources/series209.html**.) These producers then use photosynthesis to convert CO_2 into complex carbohydrates such as glucose ($C_6H_{12}O_6$).

The cells in oxygen-consuming producers, consumers, and decomposers then carry out aerobic respiration. This process breaks down glucose and other complex organic compounds and converts the carbon back to CO_2 in the atmosphere or water for reuse by producers. This linkage between *photosynthesis* in producers and *aerobic respiration* in producers, consumers, and decomposers circulates carbon in the biosphere. Oxygen and hydrogen—the other elements in carbohydrates—cycle almost in step with carbon.

Some carbon atoms take a long time to recycle. Decomposers release the carbon stored in the bodies of dead organisms on land back into the air as CO_2. However, in water, decomposers can release carbon that is stored as insoluble carbonates in bottom sediment. Indeed, marine sediments are the earth's largest store of carbon. Over millions of years, buried deposits of dead plant matter and bacteria are compressed between layers of sediment, where high pressure and heat convert them to carbon-containing *fossil fuels* such as coal, oil, and natural gas (Figure 3-18). This carbon is not released to the atmosphere as CO_2 for recycling until these fuels are extracted and burned, or until long-term geological processes expose these deposits to air. In only a few hundred years, we have extracted and burned large quantities of fossil fuels that took millions of years to form. This is why, on a human time scale, fossil fuels are nonrenewable resources.

CENGAGENOW™ **Active Figure 3-18**
Natural capital: simplified model of the global *carbon cycle,* with major harmful impacts of human activities shown by red arrows. *See an animation based on this figure at* CengageNOW. **Question:** What are three ways in which you directly or indirectly affect the carbon cycle?



Since 1800, and especially since 1950, we have been intervening in the earth's carbon cycle by adding carbon dioxide to the atmosphere in two ways (shown by red arrows in Figure 3-18). *First,* in some areas, especially in tropical forests, we clear trees and other plants, which absorb CO_2 through photosynthesis, faster than they can grow back (**Core Case Study**). *Second,* we add large amounts of CO_2 to the atmosphere by burning carbon-containing fossil fuels and wood.

CORE CASE STUDY

THINKING ABOUT
The Carbon Cycle, Tropical Deforestation, and Global Warming

CORE CASE STUDY

Use Figure 3-18 and Figure 3-8 to explain why clearing tropical rain forests faster than they can grow back (**Core Case Study**) can warm the earth's atmosphere. What are two ways in which this could affect the survival of remaining tropical forests? What are two ways in which it could affect your lifestyle?

Computer models of the earth's climate systems indicate that increased concentrations of atmospheric CO_2 and other gases are very likely (90–99% probability) to enhance the planet's natural greenhouse effect, which will cause global warming and change the earth's climate (see Science Focus, p. 33).

Nitrogen Cycles through the Biosphere: Bacteria in Action

The major reservoir for nitrogen is the atmosphere. Chemically unreactive nitrogen gas (N_2) makes up 78% of the volume of the atmosphere. Nitrogen is a crucial component of proteins, many vitamins, and nucleic acids such as DNA. However, N_2 cannot be absorbed and used directly as a nutrient by multicellular plants or animals.

Fortunately, two natural processes convert or *fix* N_2 into compounds useful as nutrients for plants and animals. One is electrical discharges, or lightning, taking place in the atmosphere. The other takes place in aquatic systems, soil, and the roots of some plants, where specialized bacteria, called *nitrogen-fixing bacteria,* complete this conversion as part of the **nitrogen cycle,** which is depicted in Figure 3-19.

The nitrogen cycle consists of several major steps. In *nitrogen fixation,* specialized bacteria in soil and blue-green algae (cyanobacteria) in aquatic environments combine gaseous N_2 with hydrogen to make ammonia (NH_3). The bacteria use some of the ammonia they produce as a nutrient and excrete the rest to the soil or water. Some of the ammonia is converted to ammonium ions (NH_4^+) that can be used as a nutrient by plants.

Ammonia not taken up by plants may undergo *nitrification.* In this two-step process, specialized soil bacteria convert most of the NH_3 and NH_4^+ in soil to *nitrate ions* (NO_3^-), which are easily taken up by the roots of plants. The plants then use these forms of nitrogen to produce various amino acids, proteins, nucleic acids, and vitamins (see Supplement 6, p. S39). Animals that eat plants eventually consume these nitrogen-containing compounds, as do detritus feeders, or decomposers.

Plants and animals return nitrogen-rich organic compounds to the environment as wastes, cast-off particles, and through their bodies when they die and are decomposed or eaten by detritus feeders. In *ammonification,* vast armies of specialized decomposer bacteria convert this detritus into simpler nitrogen-containing inorganic compounds such as ammonia (NH_3) and water-soluble salts containing ammonium ions (NH_4^+).

In *denitrification,* specialized bacteria in waterlogged soil and in the bottom sediments of lakes, oceans, swamps, and bogs convert NH_3 and NH_4^+ back into nitrite and nitrate ions, and then into nitrogen gas (N_2) and nitrous oxide gas (N_2O). These gases are released to the atmosphere to begin the nitrogen cycle again.

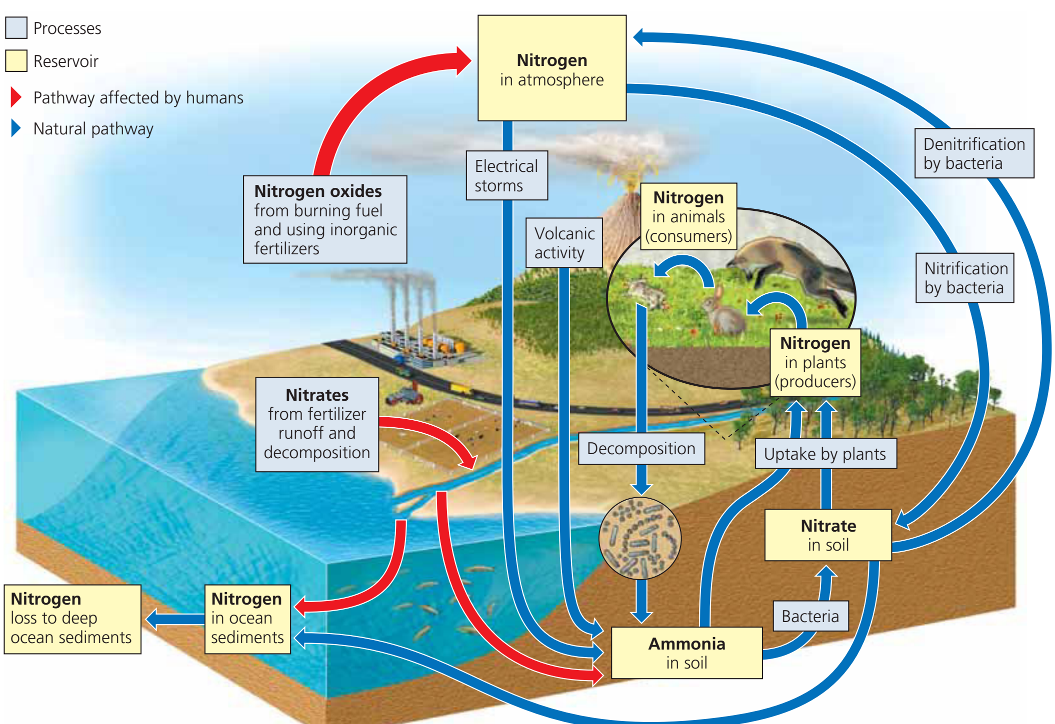
We intervene in the nitrogen cycle in several ways (as shown by red arrows in Figure 3-19). *First,* we add large amounts of nitric oxide (NO) into the atmosphere when N_2 and O_2 combine as we burn any fuel at high temperatures, such as in car, truck, and jet engines. In the atmosphere, this gas can be converted to nitrogen dioxide gas (NO_2) and nitric acid vapor (HNO_3), which can return to the earth's surface as damaging *acid deposition,* commonly called *acid rain.*

Second, we add nitrous oxide (N_2O) to the atmosphere through the action of anaerobic bacteria on livestock wastes and commercial inorganic fertilizers applied to the soil. This greenhouse gas can warm the atmosphere and deplete stratospheric ozone, which keeps most of the sun's harmful ultraviolet radiation from reaching the earth's surface.

Third, we release large quantities of nitrogen stored in soils and plants as gaseous compounds into the atmosphere through destruction of forests, grasslands, and wetlands.

Fourth, we upset the nitrogen cycle in aquatic ecosystems by adding excess nitrates to bodies of water through agricultural runoff and discharges from municipal sewage systems.

Fifth, we remove nitrogen from topsoil when we harvest nitrogen-rich crops, irrigate crops (washing nitrates out of the soil), and burn or clear grasslands and forests before planting crops.



CENGAGENOW™
Figure 3-19 **Natural capital:** simplified model of the *nitrogen cycle* with major harmful human impacts shown by red arrows. *See an animation based on this figure at* CengageNOW. **Question:** What are three ways in which you directly or indirectly affect the nitrogen cycle?

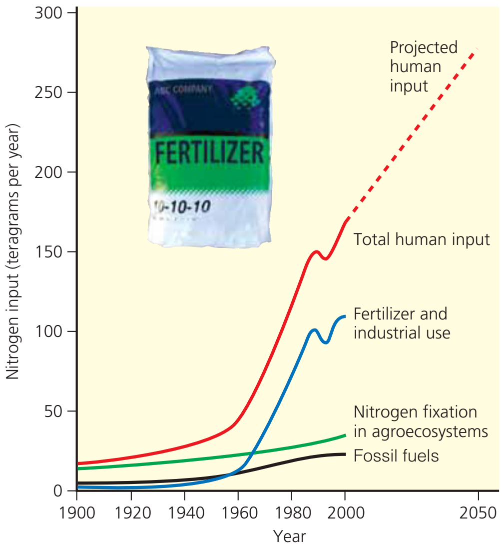


Figure 3-20 Global trends in the annual inputs of nitrogen into the environment from human activities, with projections to 2050. (Data from 2005 Millennium Ecosystem Assessment)

According to the 2005 Millennium Ecosystem Assessment, since 1950, human activities have more than doubled the annual release of nitrogen from the land into the rest of the environment. Most of this is from the greatly increased use of inorganic fertilizer to grow crops, and the amount released is projected to double again by 2050 (Figure 3-20). This excessive input of nitrogen into the air and water contributes to pollution, acid deposition, and other problems to be discussed in later chapters.

Nitrogen overload is a serious and growing local, regional, and global environmental problem that has attracted little attention. Princeton University physicist Robert Socolow calls for countries around the world to work out some type of nitrogen management agreement to help prevent this problem from reaching crisis levels.

THINKING ABOUT

The Nitrogen Cycle and Tropical Deforestation

What effects might the clearing and degrading of tropical rain forests (**Core Case Study**) have on the nitrogen cycle in such ecosystems and on any nearby water systems (see Figure 2-1, p. 28, and Figure 2-4, p. 37).

Phosphorus Cycles through the Biosphere

Phosphorus circulates through water, the earth's crust, and living organisms in the **phosphorus cycle,** depicted in Figure 3-21. In contrast to the cycles of water, carbon, and nitrogen, the phosphorus cycle does not include the atmosphere. The major reservoir for phosphorous is phosphate salts containing phosphate ions (PO_4^{3-}) in terrestrial rock formations and ocean bottom sediments. The phosphorus cycle is slow compared to the water, carbon, and nitrogen cycles.

As water runs over exposed phosphorus-containing rocks, it slowly erodes away inorganic compounds that contain phosphate ions (PO_4^{3-}). The dissolved phosphate can be absorbed by the roots of plants and by other producers. Phosphorous is transferred by food webs from such producers to consumers, eventually including detritus feeders and decomposers. In both producers and consumers, phosphorous is a component of biologically important molecules such as nucleic acids (Figure 10, p. S43, in Supplement 6) and energy transfer molecules such as ADP and ATP (Figure 14, p. S44, in Supplement 6). It is also a major component of vertebrate bones and teeth.

Phosphate can be lost from the cycle for long periods when it washes from the land into streams and rivers and is carried to the ocean. There it can be deposited as marine sediment and remain trapped for millions of years. Someday, geological processes may uplift and expose these seafloor deposits, from which phosphate can be eroded to start the cycle again.

Because most soils contain little phosphate, it is often the *limiting factor* for plant growth on land unless phosphorus (as phosphate salts mined from the earth) is applied to the soil as an inorganic fertilizer. Phosphorus also limits the growth of producer populations in many freshwater streams and lakes because phosphate salts are only slightly soluble in water.

Human activities are affecting the phosphorous cycle (as shown by red arrows in Figure 3-21). This includes removing large amounts of phosphate from the earth to make fertilizer and reducing phosphorus in tropical soils by clearing forests (**Core Case Study**). Soil that is eroded from fertilized crop fields carries large quantities of phosphates into streams, lakes, and the ocean, where it stimulates the growth of producers. Phosphorous-rich runoff from the land can produce huge populations of algae, which can upset chemical cycling and other processes in lakes.

Sulfur Cycles through the Biosphere

Sulfur circulates through the biosphere in the **sulfur cycle,** shown in Figure 3-22 (p. 72). Much of the earth's sulfur is stored underground in rocks and minerals, including sulfate (SO_4^{2-}) salts buried deep under ocean sediments.

Sulfur also enters the atmosphere from several natural sources. Hydrogen sulfide (H_2S)—a colorless, highly poisonous gas with a rotten-egg smell—is released from active volcanoes and from organic matter broken down

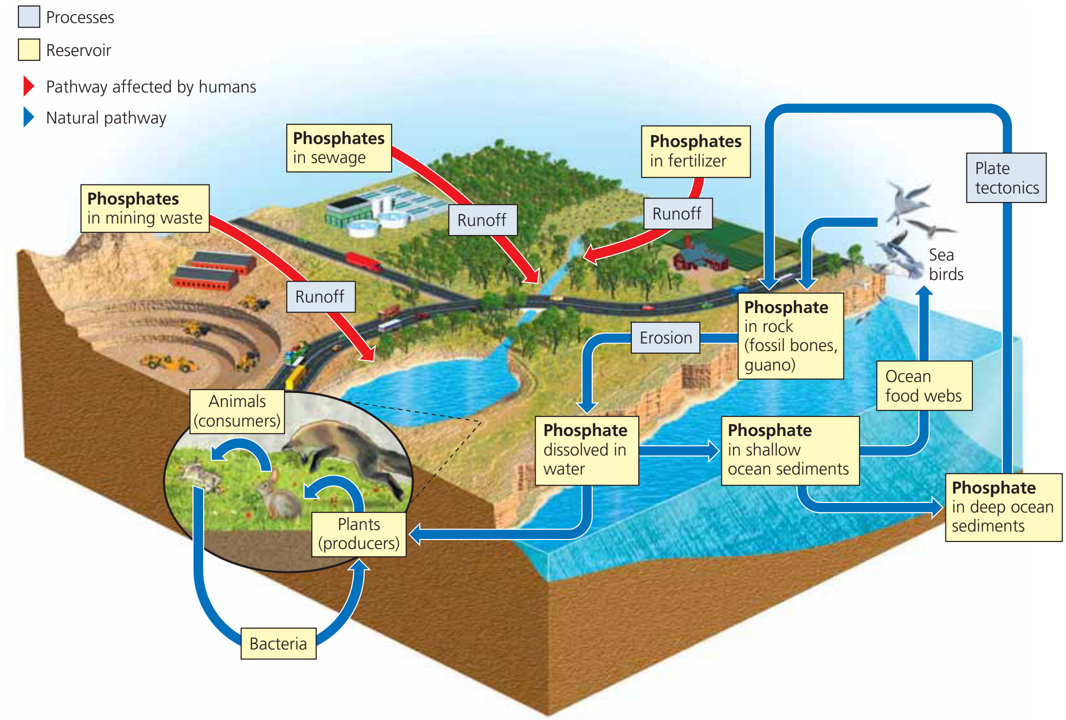


Figure 3-21 **Natural capital:** simplified model of the *phosphorus cycle,* with major harmful human impacts shown by red arrows. **Question:** What are three ways in which you directly or indirectly affect the phosphorus cycle?

by anaerobic decomposers in flooded swamps, bogs, and tidal flats. Sulfur dioxide (SO_2), a colorless and suffocating gas, also comes from volcanoes.

Particles of sulfate (SO_4^{2-}) salts, such as ammonium sulfate, enter the atmosphere from sea spray, dust storms, and forest fires. Plant roots absorb sulfate ions and incorporate the sulfur as an essential component of many proteins.

Certain marine algae produce large amounts of volatile dimethyl sulfide, or DMS (CH_3SCH_3). Tiny droplets of DMS serve as nuclei for the condensation of water into droplets found in clouds. In this way, changes in DMS emissions can affect cloud cover and climate.

In the atmosphere, DMS is converted to sulfur dioxide, some of which in turn is converted to sulfur trioxide gas (SO_3) and to tiny droplets of sulfuric acid (H_2SO_4). DMS also reacts with other atmospheric chemicals such as ammonia to produce tiny particles of sulfate salts. These droplets and particles fall to the earth as components of *acid deposition,* which along with other air pollutants can harm trees and aquatic life.

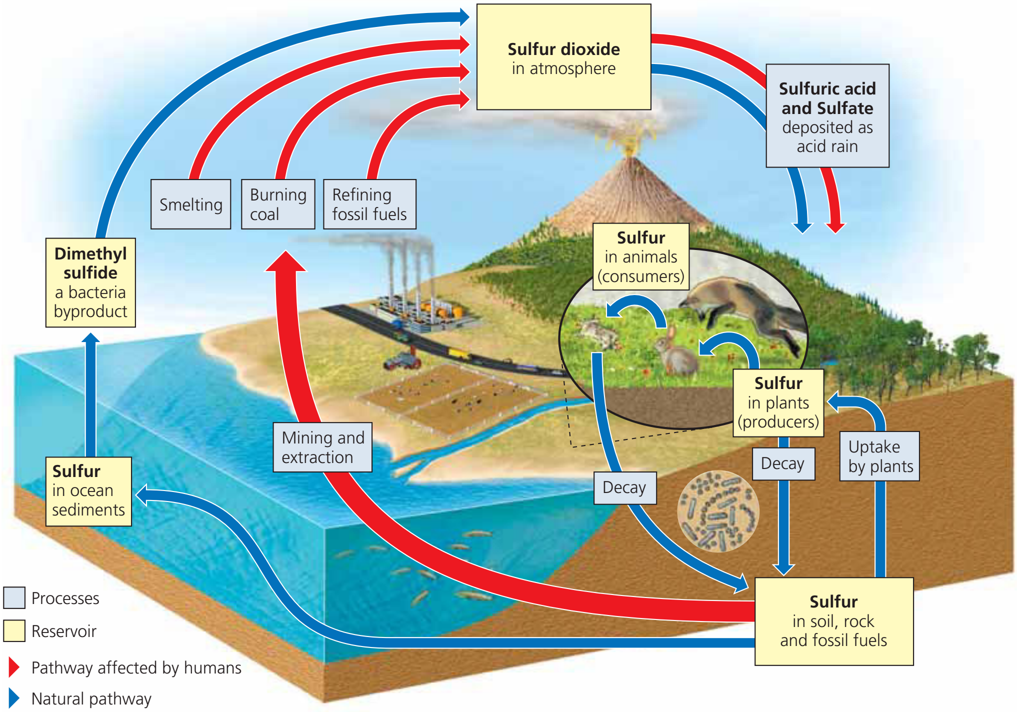
In the oxygen-deficient environments of flooded soils, freshwater wetlands, and tidal flats, specialized bacteria convert sulfate ions to sulfide ions (S^{2-}). The sulfide ions can then react with metal ions to form insoluble metallic sulfides, which are deposited as rock, and the cycle continues.

Human activities have affected the sulfur cycle primarily by releasing large amounts of sulfur dioxide (SO_2) into the atmosphere (as shown by red arrows in Figure 3-22). We add sulfur dioxide to the atmosphere in three ways. *First,* we burn sulfur-containing coal and oil to produce electric power. *Second,* we refine sulfur-containing petroleum to make gasoline, heating oil, and other useful products. *Third,* we convert sulfur-containing metallic mineral ores into free metals such as copper, lead, and zinc. Once in the atmosphere, SO_2 is converted to droplets of sulfuric acid (H_2SO_4) and particles of sulfate (SO_4^{2-}) salts, which return to the earth as acid deposition.

RESEARCH FRONTIER

The effects of human activities on the major nutrient cycles and how we can reduce these effects. See **academic .cengage.com/biology/miller**.

CENGAGENOW™ Learn more about the water, carbon, nitrogen, phosphorus, and sulfur cycles using interactive animations at CengageNOW.



CENGAGENOW™ **Active Figure 3-22** **Natural capital:** simplified model of the *sulfur cycle*, with major harmful impacts of human activities shown by red arrows. *See an animation based on this figure at* CengageNOW. **Question:** What are three ways in which your lifestyle directly or indirectly affects the sulfur cycle?

3-6 How Do Scientists Study Ecosystems?

CONCEPT 3-6 Scientists use field research, laboratory research, and mathematical and other models to learn about ecosystems.

Some Scientists Study Nature Directly

Scientists use field research, laboratory research, and mathematical and other models to learn about ecosystems (**Concept 3-6**). *Field research,* sometimes called "muddy-boots biology," involves observing and measuring the structure of natural ecosystems and what happens in them. Most of what we know about structure and functioning of ecosystems has come from such research. **GREEN CAREER:** Ecologist. See **academic .cengage.com/biology/miller** for details on various green careers.

Ecologists trek through forests, deserts, and grasslands and wade or boat through wetlands, lakes, streams, and oceans collecting and observing species. Sometimes they carry out controlled experiments by isolating and changing a variable in part of an area and comparing the results with nearby unchanged areas (Chapter 2 Core Case Study, p. 28, and see *The Habitable Planet,* Videos 4 and 9, **www.learner.org/resources/series209.html**). Tropical ecologists have erected tall construction cranes over the canopies of tropical forests from which they observe the rich diversity of species living or feeding in these treetop habitats.

Increasingly, new technologies are being used to collect ecological data. Scientists use aircraft and satellites equipped with sophisticated cameras and other *remote sensing* devices to scan and collect data on the earth's surface. Then they use *geographic information system* (GIS) software to capture, store, analyze, and display such geographically or spatially based information.

In a GIS, geographic and ecological data can be stored electronically as numbers or as images in computer databases. For example, a GIS can convert digital satellite images generated through remote sensing into global, regional, and local maps showing variations in vegetation (Figure 1, pp. S20–S21, and Figure 2, pp. S22–S23, in Supplement 4), gross primary productivity (Figure 6, p. S27, in Supplement 4), temperature patterns, air pollution emissions, and other variables.

Scientists also use GIS programs and digital satellite images to produce two- or three-dimensional maps combining information about a variable such as land use with other data. Separate layers within such maps, each showing how a certain factor varies over an area, can be combined to show a composite effect (Figure 3-23). Such composites of information can lead to a better understanding of environmental problems and to better decision making about how to deal with such problems.

In 2005, scientists launched the Global Earth Observation System of Systems (GEOSS)—a 10-year program to integrate data from sensors, gauges, buoys, and satellites that monitor the earth's surface, atmosphere, and oceans. **GREEN CAREERS:** GIS analyst; remote sensing analyst

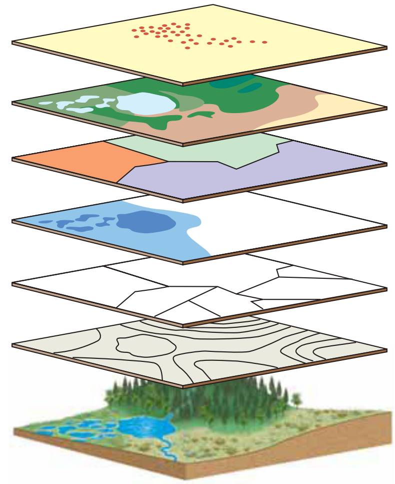


Figure 3-23 *Geographic information systems* (*GIS*) provide the computer technology for storing, organizing, and analyzing complex data collected over broad geographic areas. They enable scientists to produce maps of various geographic data sets and then to overlay and compare the layers of data (such as soils, topography, distribution of endangered populations, and land protection status).

Some Scientists Study Ecosystems in the Laboratory

During the past 50 years, ecologists have increasingly supplemented field research by using *laboratory research* to set up, observe, and make measurements of model ecosystems and populations under laboratory conditions. Such simplified systems have been created in containers such as culture tubes, bottles, aquaria tanks, and greenhouses, and in indoor and outdoor chambers where temperature, light, CO_2, humidity, and other variables can be controlled.

Such systems make it easier for scientists to carry out controlled experiments. In addition, laboratory experiments often are quicker and less costly than similar experiments in the field.

THINKING ABOUT
Greenhouse Experiments and Tropical Rain Forests

CORE CASE STUDY

How would you design an experiment, including an experimental group and a control group, that uses a greenhouse to determine the effect of clearing a patch of tropical rain forest vegetation (**Core Case Study**) on the temperature above the cleared patch?

But there is a catch. Scientists must consider how well their scientific observations and measurements in a simplified, controlled system under laboratory conditions reflect what takes place under the more complex and dynamic conditions found in nature. Thus, the results of laboratory research must be coupled with and supported by field research. (See *The Habitable Planet,* Videos, 2, 3, and 12, **www.learner.org/resources/series209.html**.)

Some Scientists Use Models to Simulate Ecosystems

Since the late 1960s, ecologists have developed mathematical and other models that simulate ecosystems. Computer simulations can help scientists understand large and very complex systems that cannot be adequately studied and modeled in field and laboratory research. Examples include rivers, lakes, oceans, forests, grasslands, cities, and the earth's climate system. Scientists are learning a lot about how the earth works by feeding data into increasingly sophisticated models of the earth's systems and running them on supercomputers.

Researchers can change values of the variables in their computer models to project possible changes in environmental conditions, to help them anticipate environmental surprises, and to analyze the effectiveness of various alternative solutions to environmental problems. **GREEN CAREER:** Ecosystem modeler

Of course, simulations and projections made with ecosystem models are no better than the data and assumptions used to develop the models. Ecologists must do careful field and laboratory research to get *baseline data,* or beginning measurements, of variables being studied. They also must determine the relationships among key variables that they will use to develop and test ecosystem models.

RESEARCH FRONTIER

Improved computer modeling for understanding complex environmental systems. See **academic.cengage.com/biology/miller**.

We Need to Learn More about the Health of the World's Ecosystems

We need baseline data on the condition of the world's ecosystems to see how they are changing and to develop effective strategies for preventing or slowing their degradation.

By analogy, your doctor needs baseline data on your blood pressure, weight, and functioning of your organs and other systems, as revealed through basic tests. If your health declines in some way, the doctor can run new tests and compare the results with the baseline data to identify changes and come up with a treatment.

According to a 2002 ecological study published by the Heinz Foundation and the 2005 Millennium Ecosystem Assessment, scientists have less than half of the basic ecological data they need to evaluate the status of ecosystems in the United States. Even fewer data are available for most other parts of the world. Ecologists call for a massive program to develop baseline data for the world's ecosystems.

RESEARCH FRONTIER

A crash program to gather and evaluate baseline data for all of the world's major terrestrial and aquatic systems. See **academic.cengage.com/biology/miller**.

REVISITING Tropical Rain Forests and Sustainability

CONCEPT LINKS CORE CASE STUDY SUSTAINABILITY

This chapter applied two of the **scientific principles of sustainability** (see back cover and **Concept 1-6**, p. 23) by which the biosphere and the ecosystems it contains have been sustained over the long term. *First,* the biosphere and almost all of its ecosystems use *solar energy* as their energy source, and this energy flows through the biosphere. *Second,* they *recycle the chemical nutrients* that their organisms need for survival, growth, and reproduction.

These two principles arise from the structure and function of natural ecosystems (Figure 3-12), the law of conservation of matter (**Concept 2-3**, p. 39), and the two laws of thermodynamics (**Concepts 2-4A** and **2-4B**, p. 40). Nature's required adherence to these principles is enhanced by *biodiversity,* another sustainability principle, which also helps to *regulate population levels* of interacting species in the world's ecosystems—yet another of the sustainability principles.

This chapter started with a discussion of the importance of incredibly diverse tropical rain forests (**Core Case Study**), which showcase the functioning of the four **scientific principles of sustainability**. Producers within rain forests rely on solar energy to produce a vast amount of biomass through photosynthesis. Species living in the forests take part in, and depend on cycling of nutrients in the biosphere and the flow of energy through the biosphere. Tropical forests contain a huge and vital part of the earth's biodiversity, and interactions among species living in these forests help to control the populations of the species living there.

All things come from earth,
and to earth they all return.

MENANDER (342–290 B.C.)

REVIEW

1. Review the Key Questions and Concepts for this chapter on p. 51. What are three harmful effects resulting from the clearing and degradation of tropical rain forests?
2. What is a **cell?** What is the **cell theory?** Distinguish between a **eukaryotic cell** and a **prokaryotic cell.** What is a **species?** Explain the importance of insects. Define **ecology.** What is **genetic diversity?** Distinguish among a **species, population, community (biological community), habitat, ecosystem,** and the **biosphere.**
3. Distinguish among the **atmosphere, troposphere, stratosphere, greenhouse gases, hydrosphere,** and

geosphere. Distinguish between **biomes** and **aquatic life zones** and give an example of each. What three interconnected factors sustain life on earth?

4. Describe what happens to solar energy as it flows to and from the earth. What is the **natural greenhouse effect** and why is it important for life on earth?

5. Distinguish between the **abiotic** and **biotic components** in ecosystems and give two examples of each. What is the **range of tolerance** for an abiotic factor? Define and give an example of a **limiting factor.** What is the **limiting factor principle?**

6. What is a **trophic level?** Distinguish among **producers (autotrophs), consumers (heterotrophs),** and **decomposers** and give an example of each in an ecosystem. Distinguish among **primary consumers (herbivores), secondary consumers (carnivores), high-level (third-level) consumers, omnivores, decomposers,** and **detritus feeders (detritivores),** and give an example of each.

7. Distinguish among **photosynthesis, chemosynthesis, aerobic respiration,** and **anaerobic respiration (fermentation).** What two processes sustain ecosystems and the biosphere and how are they linked? Explain the importance of microbes.

8. Explain what happens to energy as it flows through the food chains and food webs of an ecosystem. Distinguish between a **food chain** and a **food web.** What is **biomass?** What is **ecological efficiency?** What is the **pyramid of energy flow?** Discuss the difference between **gross primary productivity (GPP)** and **net primary productivity (NPP)** and explain their importance.

9. What happens to matter in an ecosystem? What is a **biogeochemical cycle (nutrient cycle)?** Describe the unique properties of water. What is **transpiration?** Describe the **hydrologic (water), carbon, nitrogen, phosphorus,** and **sulfur cycles** and describe how human activities are affecting each cycle.

10. Describe three ways in which scientists study ecosystems. Explain why we need much more basic data about the structure and condition of the world's ecosystems. How are the four scientific principles of sustainability showcased in tropical rain forests (Core Case Study)?

SUSTAINABILITY

CORE CASE STUDY

Note: Key Terms are in **bold** type.

CRITICAL THINKING

1. List three ways in which you could apply Concept 3-4B and Concept 3-5 to making your lifestyle more environmentally sustainable.

2. How would you explain the importance of tropical rain forests (Core Case Study) to people who think that such forests have no connection to their lives?

CORE CASE STUDY

3. Explain why **(a)** the flow of energy through the biosphere (Concept 3-2) depends on the cycling of nutrients, and **(b)** the cycling of nutrients depends on gravity.

4. Explain why microbes are so important. List two beneficial and two harmful effects of microbes on your health and lifestyle.

5. Make a list of the food you ate for lunch or dinner today. Trace each type of food back to a particular producer species.

6. Use the second law of thermodynamics (Concept 2-5B, p. 44) to explain why many poor people in developing countries live on a mostly vegetarian diet.

CONCEPT LINK

7. Why do farmers not need to apply carbon to grow their crops but often need to add fertilizer containing nitrogen and phosphorus?

8. What changes might take place in the hydrologic cycle if the earth's climate becomes **(a)** hotter or **(b)** cooler? In each case, what are two ways in which these changes might affect your lifestyle?

9. What would happen to an ecosystem if **(a)** all its decomposers and detritus feeders were eliminated, **(b)** all its producers were eliminated, or **(c)** all of its insects were eliminated? Could a balanced ecosystem exist with only producers and decomposers and no consumers such as humans and other animals? Explain.

10. List two questions that you would like to have answered as a result of reading this chapter.

Note: See Supplement 13 (p. S78) for a list of Projects related to this chapter.

ECOLOGICAL FOOTPRINT ANALYSIS

Based on the following carbon dioxide emissions data and 2007 population data, answer the questions below.

Country	Total Carbon Footprint—Carbon Dioxide Emissions (in metric gigatons per year*)	Population (in billions, 2007)	Per Capita Carbon Footprint—Per Capita Carbon Dioxide Emissions Per Year
China	5.0 (5.5)	1.3	
India	1.3 (1.4)	1.1	
Japan	1.3 (1.4)	0.13	
Russia	1.5 (1.6)	1.14	
United States	6.0 (6.6)	0.30	
WORLD	29 (32)	6.6	

Souce: Data from World Resources Institute and International Energy Agency

*The prefix *giga* stands for "1 billion."

1. Calculate the per capita carbon footprint for each country and the world and complete the table.
2. It has been suggested that a sustainable average worldwide carbon footprint per person should be no more than 2.0 metric tons per person per year (2.2 tons per person per year). How many times larger is the U.S. carbon footprint per person than are **(a)** the sustainable level, and **(b)** the world average?
3. By what percentage will China, Japan, Russia, the United States, and the world each have to reduce their carbon footprints per person to achieve the estimated maximum sustainable carbon footprint per person of 2.0 metric tons (2.2 tons) per person per year?

LEARNING ONLINE

Log on to the Student Companion Site for this book at **academic.cengage.com/biology/miller**, and choose Chapter 3 for many study aids and ideas for further reading and research. These include flash cards, practice quizzing, Weblinks, information on Green Careers, and InfoTrac® College Edition articles.