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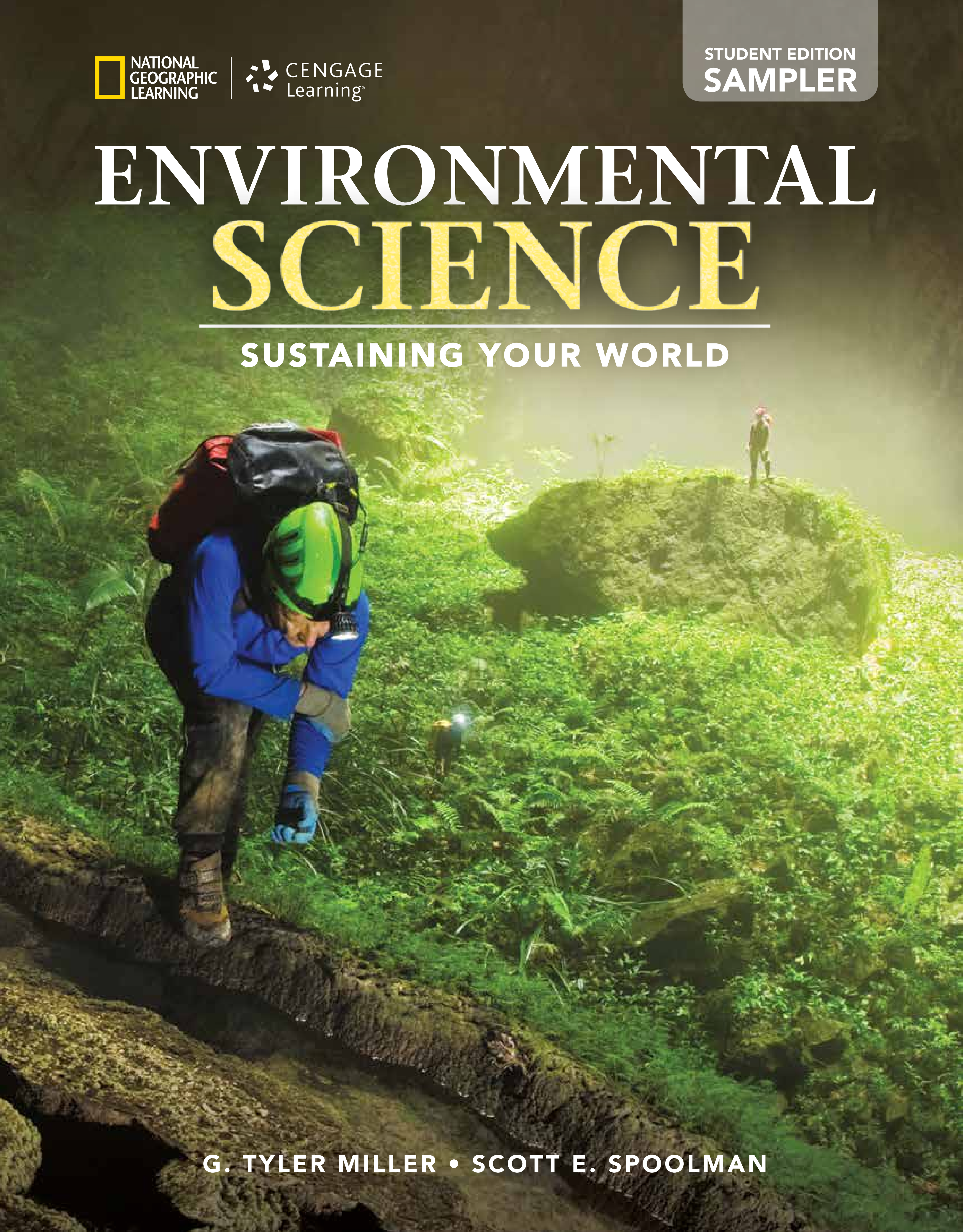

G. TYLER MILLER • SCOTT E. SPOOLMAN

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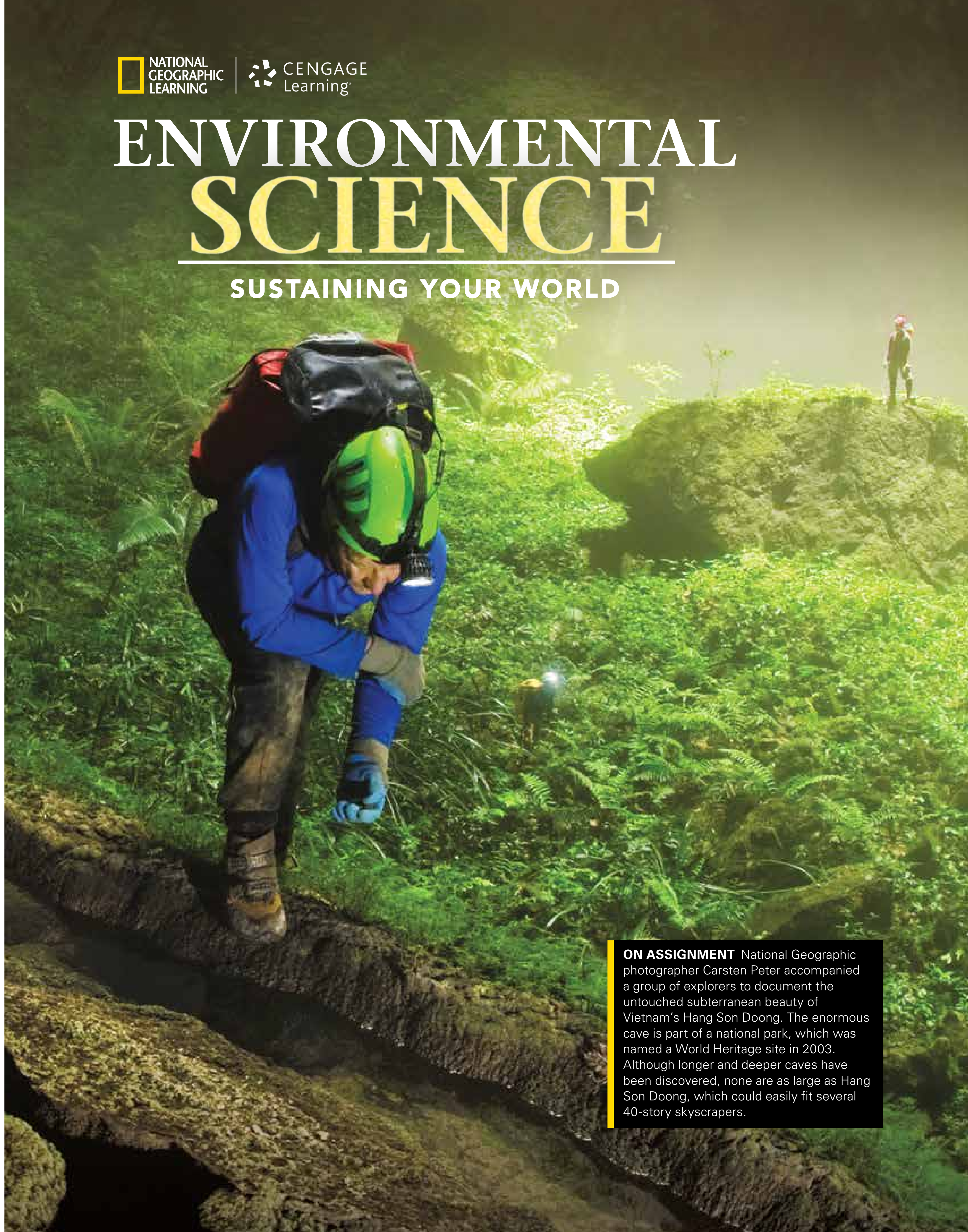

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G. TYLER MILLER

G. Tyler Miller has written 62 textbooks for introductory courses in environmental science, basic ecology, energy, and environmental chemistry. Since 1975, Miller's books have been the most widely used textbooks for environmental science in the United States and throughout the world. They have been used by almost 3 million students and have been translated into eight languages.

Miller has a professional background in chemistry, physics, and ecology. He has a PhD from the University of Virginia and has received two honorary doctoral degrees for his contributions to environmental education. He taught college for 20 years, and developed one of the nation's first environmental studies programs, before deciding to write environmental science textbooks full-time in 1975.

He describes his hopes for the future as follows.

"If I had to pick a time to be alive, it would be the next 75 years. Why? First, there is overwhelming scientific evidence that we are in the process of seriously degrading our own life-support system. In other words, we are living unsustainably. Second, within your lifetime we have the opportunity to learn how to live more sustainably by working with the rest of nature, as described in this book.

"I am fortunate to have three smart, talented, and wonderful sons—Greg, David, and Bill. I am especially privileged to have Kathleen as my wife, best friend, and research associate. It is inspiring to have a brilliant, beautiful (inside and out), and strong woman who cares deeply about nature as a lifemate. She is my hero. I dedicate this book to her and to the earth."

SCOTT E. SPOOLMAN

Scott Spoolman has more than 30 years of experience in educational publishing. He has worked with Tyler Miller first as a contributing editor and then as coauthor of *Living in the Environment*, *Environmental Science*, and *Sustaining the Earth*. With Norman Myers, he coauthored *Environmental Issues and Solutions: A Modular Approach*.

Spoolman holds a master's degree in science journalism from the University of Minnesota. He has authored numerous articles in the fields of science, environmental engineering, politics, and business. He has also worked as a consulting editor in the development of over 70 college and high school textbooks in fields of the natural and social sciences.

In his free time, he enjoys exploring the forests and waters of his native Wisconsin along with his family—his wife, environmental educator Gail Martinelli, and his children, Will and Katie.

Spoolman has the following to say about his collaboration with Tyler Miller.

"I am honored to be working with Tyler Miller as a coauthor to continue the Miller tradition of thorough, clear, and engaging writing about the vast and complex field of environmental science. I share Tyler Miller's passion for ensuring that these textbooks and their multimedia supplements will be valuable tools for students and instructors. To that end, we strive to introduce this interdisciplinary field in ways that will be informative and sobering, but also tantalizing and motivational.

"If the flip side of any problem is indeed an opportunity, then this truly is one of the most exciting times in history for students to start an environmental career. Environmental problems are numerous, serious, and daunting, but their possible solutions generate exciting new career opportunities. We place high priorities on inspiring students with these possibilities, challenging them to maintain a scientific focus, pointing them toward rewarding and fulfilling careers, and in doing so, working to help sustain life on the earth."

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CHAPTER 3

ECOSYSTEM DYNAMICS

AMAZONIA, a region loosely defined as the Amazon River Basin, covers an area of land about the size of the 48 contiguous United States. A tenth of Earth's species are thought to live in Amazonia, which includes half of the planet's tropical rain forests. People have lived in this region for at least 13,000 years. In the past 50 years, however, human activity has destroyed close to 20% of Amazonia's rain forest.

KEY QUESTIONS

3.1 What are Earth's major spheres, and how do they support life?

3.2 What are the major ecosystem components?

3.3 What happens to energy in an ecosystem?

3.4 What happens to matter in an ecosystem?

3.5 How do scientists study ecosystems?

The Nanay River in Peru is one of the Amazon River's many tributaries.

PROTOTYPE PAGES

Eco-Paradise at Serra Bonita

with National Geographic Explorer Vitor Becker

Vitor Becker takes a few moments each day to do something that hardly anyone else in the world can do: He feeds a buzzing flock of tiny hummingbirds from the palm of his hand. As you might imagine, this isn't something that happens in a suburban backyard, but at Serra Bonita, a nearly-2,225 hectare (5,000 acre) nature reserve named for the Serra Bonita Mountain in the Atlantic Forest of Brazil.

About the Atlantic Forest: There's good news and bad news. It's one of the most diverse biomes in the world. It is also one of the most destroyed in Brazil—only 8% of its original forests remain. Still, the region continues to have very high species diversity. In fact, protected areas like Serra Bonita are a refuge for thousands of species not found anywhere else in the world. This lush rain forest and the species it nurtures lead Becker to call Serra Bonita an "eco-paradise."

Dr. Becker studied forestry and trained as an entomologist, which is a scientist who studies insects. He, his wife, and their daughter—with help from National Geographic and many others—all work to maintain the reserve. Think about these numbers: More than 350 bird species, roughly 1,200 vascular plant species, and more than 70 frog species have been identified at Serra Bonita. Protecting them is no small task. The Brazilian rain forest is often a difficult place for conservationists to work because of illegal logging operations and other threats.

Despite that, the family plans to expand the reserve—and is committed to education too. The research center at Serra Bonita holds laboratories, collection rooms, and a library, and supports many research projects that yield new information nearly every day.

Hummingbirds aren't Becker's only concern—there are also the thousands of moth species he has identified at Serra Bonita. Check out online videos on Serra Bonita, and you'll find howler monkeys sitting on his shoulders. And, though you won't see them in the videos, Becker knows puma prowl through the reserve, now free from threat by hunters.

The Serra Bonita website offers ideas for how to get involved in this great project, but there are many ways to take up the causes of ecosystem conservation and species preservation. You could start by asking questions about your own region. What plants and animals live there, and are they thriving—or just barely surviving? Consider starting a citizen science project to identify species in the area. Look for ways you can help and then set out to do it.

Thinking Critically

Draw Conclusions Even though only 8% of the original forests remain, the Atlantic Forest is still considered one of the most diverse regions on Earth. Can you conclude from these facts that the loss of forests has had little effect so far on the number of species found there? Why or why not?

Vitor Becker researches hummingbirds and insects at Serra Bonita, a nature reserve in the Atlantic Forest. Today only 8% of the Atlantic Forest remains—another reason why protecting places like Serra Bonita is so important.

CASE STUDY
Disappearing Tropical Rain Forests

Tropical rain forests support an incredible variety of life. They cover only about 7% of Earth's land surface but contain half of the plant and animal species found on land. These lush forests are warm and humid year-round because of their daily rainfall and nearness to the Equator. The biodiversity of tropical rain forests makes them an excellent natural laboratory for the study of ecosystems. An ecosystem is one or more communities of organisms that interact with one another and their nonliving environment.

To date, human activities have destroyed or disturbed more than half of Earth's tropical rain forests. People continue clearing the forests to grow more crops, graze more cattle, and build more settlements. Ecologists warn that without protection, most of the forests will be gone or severely damaged by the end of this century. The preservation efforts of individuals like National Geographic Explorer Vitor Becker help combat the degradation of ecosystems.

Removing tropical rain forests reduces Earth's vital biodiversity, or the planet's variety of species and the habitats where they live. (See Chapter 4 for more about biodiversity.) Destroying the habitats of plant and animal species often results in their extinction. When the forest loses a key species, it can have a ripple effect that leads to the loss of other species.

Destroying tropical rain forests also accelerates global warming. Without tropical rain forests, the atmosphere warms, leading to climate change. Why? Eliminating large areas of trees means there are fewer plants to remove carbon dioxide (CO_2) during photosynthesis. Carbon dioxide is a gas that contributes to atmospheric warming. (See Chapter 16 for more about climate change.)

Large-scale loss of tropical rain forests can also change regional weather patterns in ways that prevent the forest from returning. When this irreversible tipping point is reached, rain forests become dryer, less diverse tropical grasslands. The presence of grasslands decreases rainfall in nearby forests, which further weakens them.

In this chapter, you will examine the living and nonliving components of ecosystems and how they function. You will learn how ecosystems support life, how ecologists study the interactions within and among different ecosystems, and the importance of maintaining ecosystem integrity. Healthy tropical rain forests like the one preserved at Serra Bonita are examples of sustainably functioning ecosystems.

As You Read Think about an ecosystem where you live. Consider what makes it unique, as well as what it might have in common with a rain forest ecosystem. Which part of the ecosystem is most damaged or threatened? How might this affect the other parts of the ecosystem and its long-term sustainability?

FIGURE 3-1
Satellite images of the same area show the loss of tropical rain forest near the Bolivian city of Santa Cruz de la Sierra. The forest was cleared for farming, cattle grazing, and settlements between June 1975 (left) and July 2013 (right).

3.1 What Are Earth's Major Spheres, and How Do They Support Life?

CORE IDEAS AND SKILLS

- Describe the four major spheres that support life on Earth.
- Understand how nutrients cycle and energy flows through ecosystems.

KEY TERMS

geosphere
atmosphere
troposphere
stratosphere
hydrosphere
biosphere
greenhouse effect

Earth's Spheres Function As a Life-Support System

Earth's "life-support system" is based on the interaction among four planetary systems, or spheres: the atmosphere, hydrosphere, geosphere, and biosphere (Figure 3-2). The natural capital (resources and ecosystem services) on which life depends is the product of Earth's spheres and energy from the sun.

The Geosphere The **geosphere** consists of Earth's core, mantle, and thin outer crust—all the material above and below the surface that forms the planet's mass. Without its large mass, Earth would not have the gravitational force needed to keep the atmosphere from escaping into space. The geosphere's upper crust contains nutrients organisms need to live, grow, and reproduce (Science Focus 3.1). The crust also includes nonrenewable fossil fuels—coal, oil, and natural gas—and mineral resources.

The Atmosphere Held to Earth by gravity, the **atmosphere** is an envelope of gases surrounding the planet (Figure 3-4). If Earth were the size of a basketball, the atmosphere would be about the thickness of a sheet of paper. This thin blanket of gases shields the planet from meteors and blocks most of the sun's harmful ultraviolet (UV) radiation. It also helps regulate Earth's climates, allowing surface temperatures to be suitable for life to exist in the **troposphere**, the lowest layer of the atmosphere.

The troposphere is the layer in which weather occurs. It is also the only layer in which terrestrial organisms can survive. Thickest at the Equator, the troposphere extends up to 19 kilometers (12 miles) above sea level. At the Poles, the troposphere extends up to 6 kilometers (4 miles). Life in the atmosphere has evolved to tolerate the temperature ranges and composition of gases only within the troposphere.

The **stratosphere** is the atmospheric layer above the troposphere. Although nothing lives in the stratosphere, this layer has a direct impact on life at the surface. The lower stratosphere contains a relatively high concentration of ozone (O_3), which is called the ozone layer. The ozone layer absorbs more than 95% of the sun's harmful UV radiation. It acts as a global sunscreen that allows life to exist on Earth's surface.

Three more atmospheric layers extend for hundreds of kilometers beyond the stratosphere: the mesosphere, the thermosphere, and the exosphere. Together, these five layers of the atmosphere protect Earth from the extremes of space.

FIGURE 3-2
Earth's Spheres Earth consists of a land sphere (geosphere), an air sphere (atmosphere), a water sphere (hydrosphere), and a life sphere (biosphere).

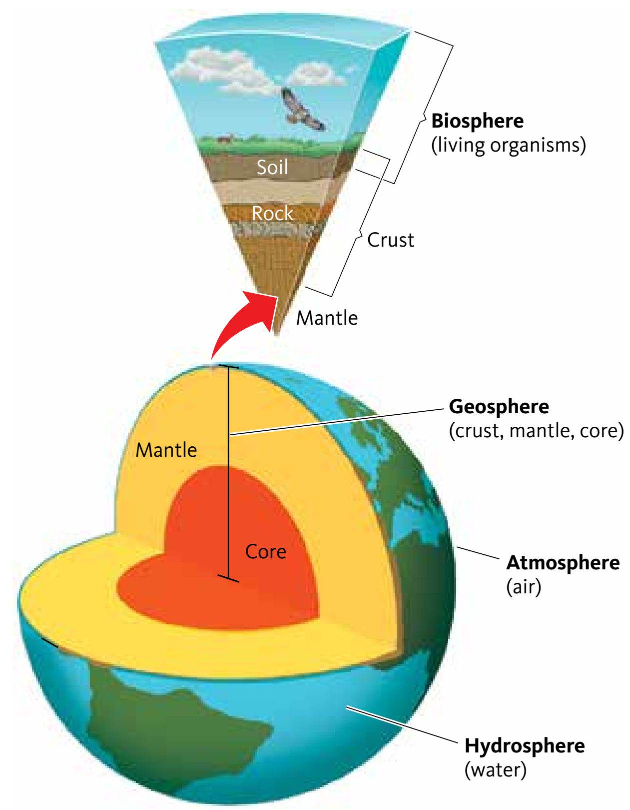


FIGURE 3-3
Hundreds of macaws make up for the lack of sodium in their diet by eating small amounts of salty clay at this avian salt lick in Manu National Park, Peru. Sodium is an essential mineral nutrient.

SCIENCE FOCUS 3.1

NUTRIENT CYCLING

Life on Earth depends on two processes: the one-way flow of energy from the sun and the cycling of matter through the biosphere. This is in keeping with the solar energy and nutrient cycling factors of sustainability described in Chapter 1.

The life-sustaining energy of nearly every ecosystem originates with sunlight, converted to chemical energy by plants and other producers. As you will learn in Lesson 3.3, without the continual input of energy from the sun, nearly every ecosystem would quickly run out of the energy needed for life.

As energy flows through ecosystems, it fuels the building up and breaking down of chemical compounds (Lesson 3.4). The resulting atoms, ions, and molecules form the planet's living organisms and the nutrients they need to survive.

Earth does not get significant inputs of matter from space, so the fixed supply of nutrients must be recycled to sustain generation after generation of organisms.

Carbon, oxygen, nitrogen, and phosphorus are examples of elemental nutrients that are continually recycled through the living (biosphere) and nonliving (atmosphere, hydrosphere, geosphere) parts of ecosystems. Water helps cycle these important nutrients and is itself an essential nutrient.

What makes something a nutrient? A *nutrient* is any matter that an organism needs to survive and function. Feeding is the means by which organisms obtain most of their nutrients.

Macronutrients are nutrients that organisms need in large amounts. They form the bulk of the foods you eat. Proteins, fats, and carbohydrates are examples of macronutrients. *Micronutrients*—vitamins and minerals—are nutrients that organisms need in very small amounts.

Vitamins are considered "organic" compounds because they contain carbon. Minerals, which do not contain carbon, are "inorganic" compounds. Some important mineral nutrients include calcium, zinc, potassium, and iron.

Thinking Critically
Infer How would nutrient cycling be affected if all of Earth's producers died off?

FIGURE 3-4
The Atmosphere On average, the troposphere layer is 78% nitrogen and 21% oxygen. The remaining 1% is mostly argon, water vapor, carbon dioxide, and other gases. The amount of water vapor may increase to more than 4% depending on altitude and air temperature.

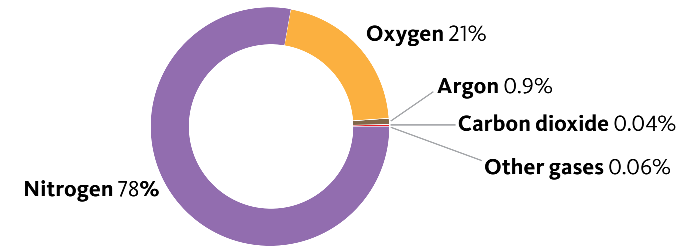
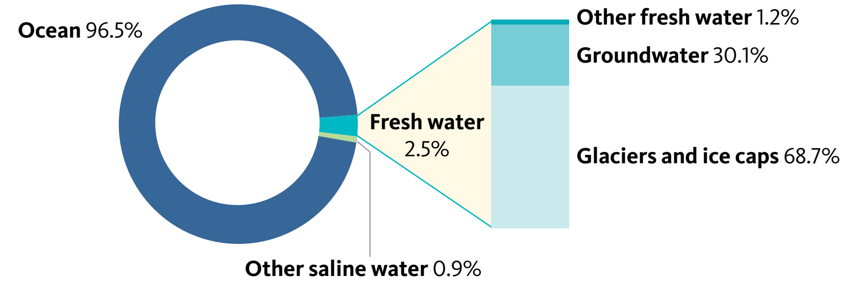


FIGURE 3-5
The Hydrosphere At any given time, approximately 96.5% of Earth's water molecules exist in the ocean. What percentage of the hydrosphere consists of glaciers and ice caps? (Hint: The answer is not 68.7%.)



The Hydrosphere Glaciers, lakes, rivers, aquifers, water vapor, clouds, and the ocean are all part of the hydrosphere (Figure 3-5). The **hydrosphere** includes all of the gaseous, liquid, and solid water on or near Earth's surface. The distribution of water is dominated by the ocean, which contains about 96.5% of Earth's total supply of water and covers about 71% of its surface. Less than 3% of Earth's water is available as fresh water, and most of that is frozen in polar ice caps and glaciers.

The Biosphere If Earth were an apple, the biosphere would be no thicker than the apple's skin. The **biosphere** consists of the parts of the atmosphere, hydrosphere, and geosphere where life exists. It is the living part of every ecosystem. An important goal of environmental science is to understand the key interactions that occur within this thin layer of air, water, soil, and organisms, and how human activities affect the biosphere.

checkpoint **In which layer of the atmosphere do you live?**

Earth's Spheres Interact

Through a process known as the **greenhouse effect**, solar energy warms the troposphere as it reflects from Earth's surface (geosphere) and interacts with carbon dioxide (CO_2), methane (CH_4), water vapor (from the hydrosphere and biosphere), and other greenhouse gases (atmosphere). These interactions are part of Earth's life-support system. Without the greenhouse effect, Earth would be too cold to support life as we know it.

Interactions among the spheres clean Earth's water and air. As plants absorb water and water transpires, or evaporates from their leaves, pollutants are absorbed. Animals such as clams and mussels filter impurities from bodies of water, and microorganisms in water and soil can break down many contaminants. As water evaporates from Earth's surface into the atmosphere, particles that make the water impure are left behind.

Forests play an important role in purifying air. Trees can absorb air-polluting gases near the surface. A single tree can produce enough oxygen for two people to breathe for a year. The same tree might absorb about 4.5 kilograms (10 pounds) of pollutants in a year.

checkpoint **What are some of the gases that help produce the greenhouse effect?**

3.1 Assessment

1. **Recall** What are Earth's four major spheres that support life?
2. **Explain** What is the greenhouse effect and why is it important to life on Earth?
3. **Generalize** What is Earth's "life-support system"?

CROSSCUTTING CONCEPTS

4. **Systems and System Models** Use one or more examples from everyday life to explain how Earth's four major spheres interact.

3.2 What Are the Major Ecosystem Components?

CORE IDEAS AND SKILLS

- Describe trophic levels and how they can be represented in a conceptual model.
- Explain the roles of producers, consumers, and decomposers in an ecosystem.
- Identify the different ways in which energy and matter are transformed in an ecosystem.
- Summarize the processes of photosynthesis and cellular respiration.

KEY TERMS

trophic level
producer
photosynthesis
consumer
primary consumer
herbivore
secondary consumer
tertiary consumer
carnivore
omnivore
decomposer
detritivore
aerobic respiration
anaerobic respiration

Ecosystems Have Several Important Components

Ecology is the branch of biology that focuses on how organisms interact with one another and their physical environment (Lesson 1.1). Scientists classify matter into levels of organization ranging from atoms to galaxies. Ecologists study interactions within and among several of these levels—from molecules to the biosphere. See Figure 3-6 for a definition of each level.

The biosphere and its ecosystems are made up of living (biotic) and nonliving (abiotic) components. Examples of nonliving components are water, air, rocks, nutrients, thermal energy (heat), and sunlight. Living components include plants, animals, microbes, and all other organisms. Figure 3-7 is a simplified model of some of the living and non-living components of a terrestrial ecosystem.

Ecologists assign each organism in an ecosystem to a feeding level called a **trophic level**. An organism's trophic level depends on (a) whether it makes food or finds food, and (b) if it finds food, what its feeding behavior is. Organisms are classified as producers or consumers by whether they make (produce) or find (consume) food.

Producers such as plants make the food they need from compounds in soil, carbon dioxide in air, and water—using the energy of sunlight. In the process known as **photosynthesis**, producers change radiant energy (sunlight) into chemical energy stored primarily in glucose. By harnessing the energy of light, producers can convert inorganic molecules of carbon dioxide and water into organic molecules such as glucose. Glucose ($C_6H_{12}O_6$) is an important building block of many energy-rich carbohydrates that are necessary for life. The chemical equation for photosynthesis is:

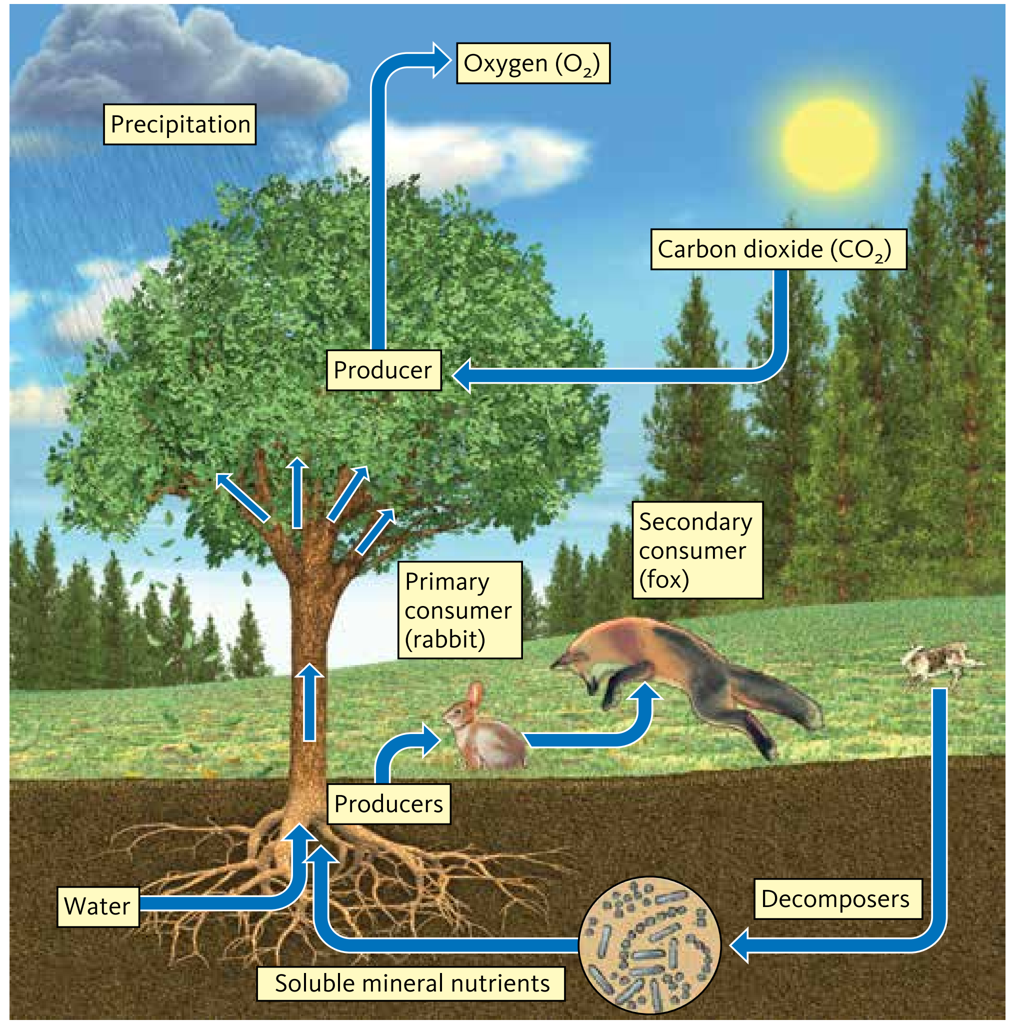
carbon dioxide + water + light energy → glucose + oxygen

$$6\,CO_2 + 6\,H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6\,O_2$$

FIGURE 3-6
Ladder of Matter Ecology includes all of these levels of the organization of matter.

Biosphere	Parts of Earth's air, water, and soil where life is found
Ecosystem	A community of different species interacting with one another and with their nonliving environment
Community	Populations of different species living in a particular place and potentially interacting with each other
Population	A group of individuals of the same species living in a particular place
Organism	An individual living entity such as a bacterium or plant
Cell	The fundamental structural and functional unit of life
Molecule	A chemical combination of two or more atoms of the same or different elements
Atom	The smallest unit of a chemical element that exhibits its chemical properties

FIGURE 3-7
Matter on the Move Arrows in this simplified ecosystem trace the movement of matter through key living (biotic) and nonliving (abiotic) components.



On land, most producers are green plants such as trees and grasses. In freshwater and ocean ecosystems, algae and aquatic plants growing near shorelines are the major producers. In open water, the dominant producers are phytoplankton—mostly microscopic organisms that float or drift in the water.

The other organisms in an ecosystem that are not producers are consumers. **Consumers** are organisms that cannot produce their own food. They get the food and energy they need by feeding on producers or other consumers, or on the wastes and remains of producers and consumers.

Primary consumers, or **herbivores**, are organisms that eat mostly green plants or algae. Examples of herbivores are caterpillars, giraffes, and zooplankton, which are tiny sea animals that feed on phytoplankton. **Secondary consumers** are animals that feed on primary consumers. **Tertiary** (or higher-order) **consumers** feed on both primary and secondary consumers.

Among the secondary and tertiary groups are carnivores and omnivores. **Carnivores** feed mostly on other animals. Some carnivores, including spiders, lions, and most small fishes, are secondary consumers. Others, such as tigers, hawks, and killer whales (orcas), are tertiary consumers.

Omnivores, such as pigs, rats, and humans, eat both plants and animals. Like carnivores, omnivores may be secondary or tertiary consumers.

FIGURE 3-8
ON ASSIGNMENT National Geographic photographer Frans Lanting snapped this image of deforestation while flying above the edge of a lush rain forest in Brazil's Iguacu National Park. The stark agricultural landscape reveals the park's boundary—and the loss of biodiversity when crops replace trees.

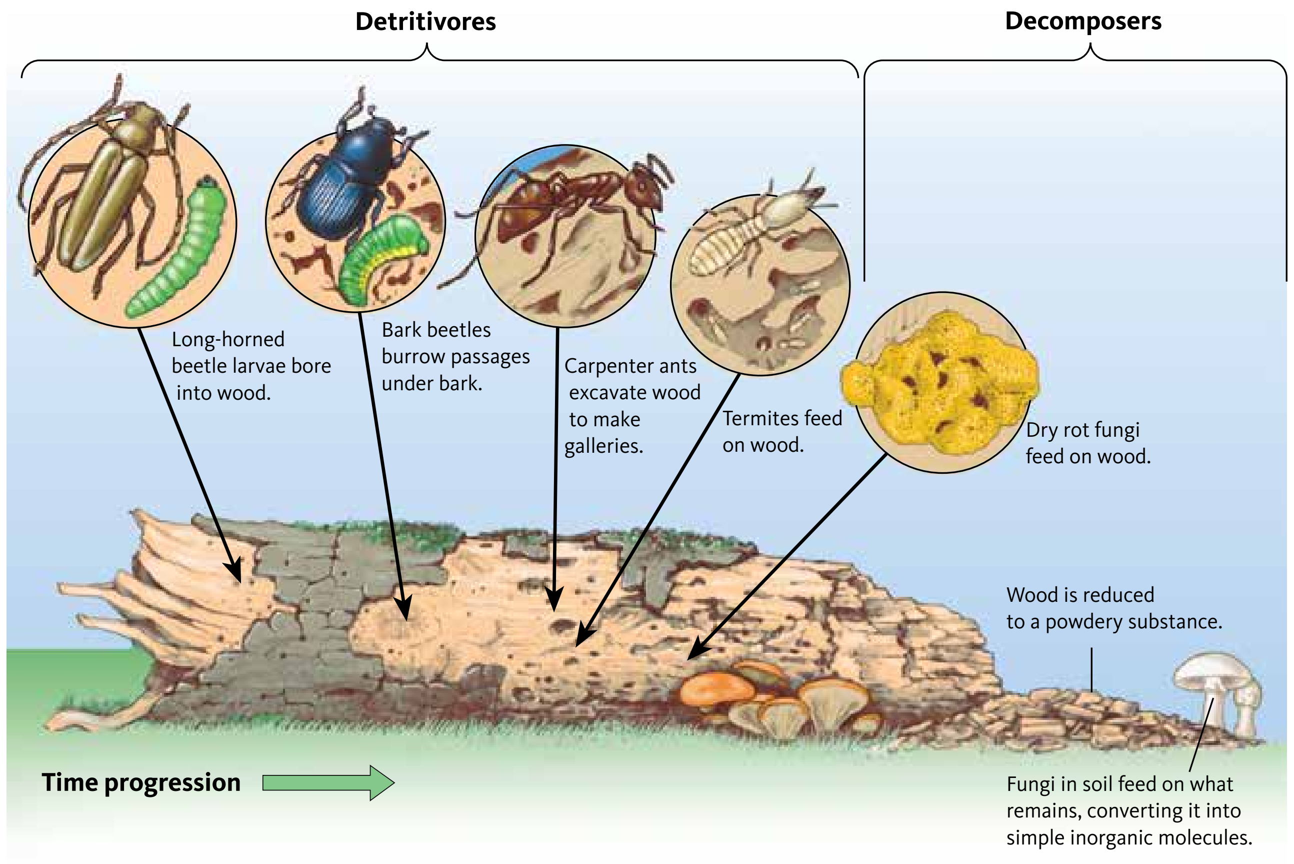
Decomposers are consumers that get their nutrients by breaking down (decomposing) nonliving organic matter such as leaf litter, fallen trees, and dead animals. In the process of obtaining their own food, decomposers release nutrients from the wastes or remains of plants and animals. The process of decomposition returns nutrients to soil and water, making them available to the ecosystem. Most decomposers are bacteria and fungi. **Detritivores**, or detritus feeders, get their nourishment by consuming detritus, or freshly dead organisms, before they are fully decomposed. Detritus feeders include earthworms, some insects, hyenas, and vultures.

In natural ecosystems, decomposers and detritivores eliminate the build up of plant litter, animal wastes, and dead plants and animals. In doing so, they are the key to nutrient cycling. For example, decomposers and detritivores can transform a fallen tree into wood particles and, finally, simple inorganic molecules that producers absorb as nutrients (Figure 3-9). In this way, many of the nutrients that make life possible are continually recycled.

checkpoint **What does an organism's trophic level indicate about that organism?**

FIGURE 3-9

Detritivores and Decomposers Various detritivores and decomposers (mostly fungi and bacteria) "feed on" or digest parts of a log. They eventually convert its complex organic chemicals into simpler inorganic nutrients that can be used by producers.



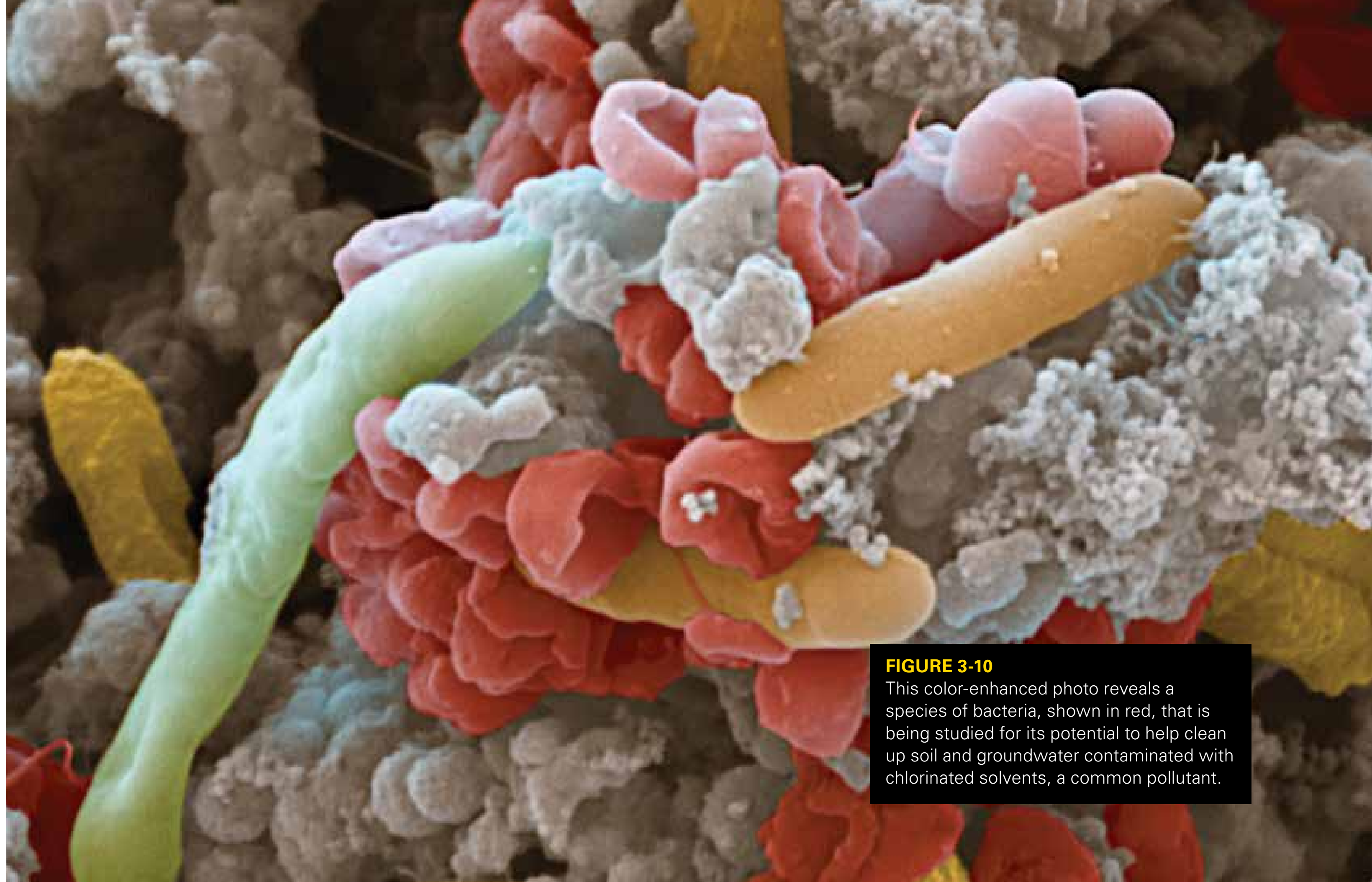


FIGURE 3-10
This color-enhanced photo reveals a species of bacteria, shown in red, that is being studied for its potential to help clean up soil and groundwater contaminated with chlorinated solvents, a common pollutant.

ENGINEERING FOCUS 3.2

NATURE'S CLEANUP CREW

The word *microbe*, or *microorganism*, is a catchall term for thousands of species of bacteria, protozoa, fungi, and floating phytoplankton. Microbes play key roles as decomposers throughout the entire biosphere.

Bacteria and fungi in the soil and oceans decompose organic wastes into inorganic nutrients such as nitrogen and phosphorus. The nutrients are then taken up by plants that are then eaten by consumers. Within your own intestinal ecosystem, trillions of bacteria are busily breaking down the food you eat.

Scientists and engineers have learned how to use microbes to break down pollutants in oil spills and toxic waste leaks. *Bioremediation* is the use of microbes or other decomposers to clean up polluted sites.

But using microbes for environmental cleanup doesn't always work as planned. Toxins can be hard to digest. Some microbes have the genes to survive in an environment, but not to clean it, while others have the genes to clean it, but wouldn't be able to survive in the environment.

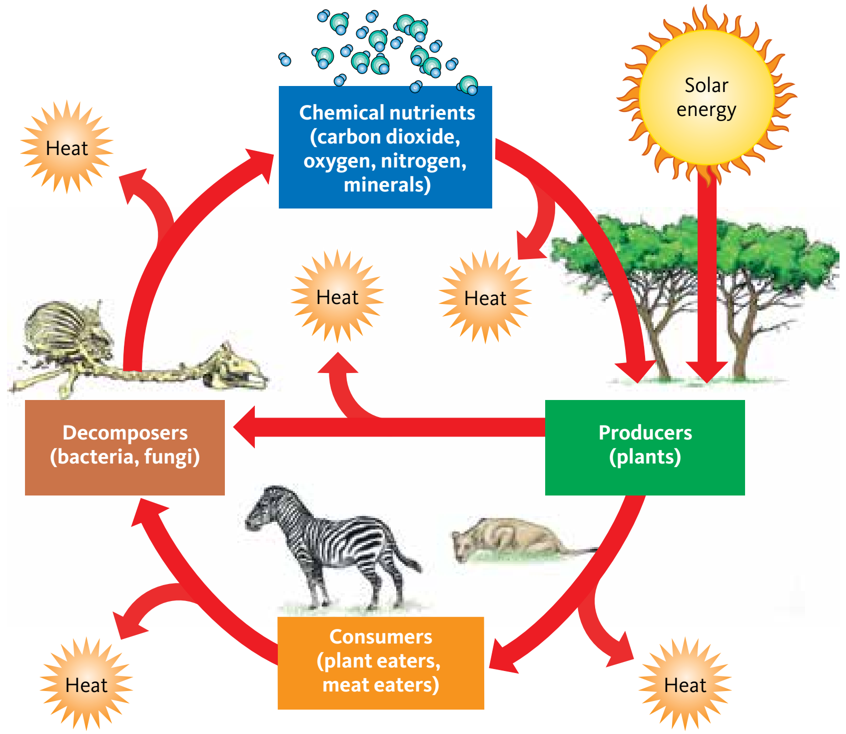
Environmental engineers are solving this problem by creating custom-made bacteria with the genes needed for a specific job. Bioengineers have learned how to transfer the desired genes from one species of bacteria to another—usually a local species that lives naturally in the sort of environmental conditions that are found at the cleanup site. As you can imagine, the resulting combination of traits—an appetite for oil or other pollutant at a contamination site, and the ability to flourish under the natural conditions found there—makes for much more resilient bacteria.

Thinking Critically

Evaluate What are some possible risks of introducing genetically engineered bacteria into the environment?

FIGURE 3-11

Component Interactions The main components of an ecosystem are energy, matter, and organisms. Nutrient cycling and the flow of energy—first from the sun, then through organisms and into the environment as heat—link these components.



Cellular Respiration

Organisms 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 and glucose to produce energy. Carbon dioxide and water are the by-products of this reaction. The chemical equation for aerobic respiration is:

glucose + oxygen → carbon dioxide + water + energy

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

Although the detailed steps differ, the net chemical change for aerobic respiration is the opposite of that for photosynthesis. As cells respire, the reaction also produces some thermal energy, which is eventually lost to the environment as heat.

Decomposers such as yeast and some bacteria get the energy they need by breaking down glucose and 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 by-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, a highly poisonous gas that smells like rotten eggs).

Anaerobic respiration also occurs temporarily in oxygen-starved muscle cells, a by-product of which is lactic acid ($C_3H_6O_3$). All organisms—including producers—get their energy from aerobic or anaerobic respiration. Only producers, however, carry out photosynthesis.

To summarize, ecosystems and the biosphere are sustained by the one-way energy flow from the sun through these systems and the nutrient cycling of key materials within them (Figure 3-11).

checkpoint **What is the difference between aerobic and anaerobic respiration?**

3.2 Assessment

1. **Contrast** How are photosynthesis and cellular respiration different?
2. **Infer** Could an ecosystem function without decomposers? Why or why not?

SCIENCE AND ENGINEERING PRACTICES

3. **Use Models** How would you revise Figure 3-7 to account for tertiary consumers, photosynthesis, aerobic respiration, and anaerobic respiration?

CROSSCUTTING CONCEPTS

4. **Energy and Matter** Explain why a natural ecosystem is both an open system and a closed system.

3.3 What Happens to Energy in an Ecosystem?

CORE IDEAS AND SKILLS

- Identify the role of food chains and food webs in an ecosystem.
- Describe the flow of energy through an ecosystem.
- Explain the difference between gross primary productivity and net primary productivity.

KEY TERMS

food chain
food web
gross primary productivity (GPP)
net primary productivity (NPP)

Food Chains and Food Webs

Food chains and food webs describe how energy flows through ecosystems. A sequence of organisms that serves as a source of nutrients or energy for the next level of organisms is called a **food chain**. Figure 3-13 illustrates a simplified food chain.

Organisms at each trophic level obtain high-quality chemical energy from their food. However, about 90% of the chemical energy is lost at each link in the food chain, as required by the second law of thermodynamics (Lesson 2.2). So where does the energy go? As organisms live and grow and their cells respire, the chemical energy obtained through food is converted to other forms of energy. When energy transforms from one form to another in a food chain, there is an automatic loss of energy "quality," with most of it flowing into the environment as low-quality thermal energy (heat). Thus, there is less high-quality energy left to support large numbers of top predators such as tigers or hawks (Figure 3-12).

Food webs offer another way to describe the flow of energy through ecosystems. A food web is a complex network of interconnected food chains. Food webs are useful in studies at the ecosystem level. For example, scientists studying the effect of decreasing killer whale populations on marine ecosystem health may refer to food webs similar to the one illustrated in Figure 3-15. Food chains and food webs show how producers, consumers, and decomposers are connected to one another as energy flows through trophic levels in an ecosystem.

checkpoint **What is the difference between a food chain and a food web?**

Primary Productivity

Scientists measure the rates at which ecosystems produce chemical energy to compare ecosystems and understand how they interact. **Gross primary productivity (GPP)** is the rate at which an ecosystem's producers convert radiant energy into chemical energy. This energy is stored in compounds in their bodies. To stay alive, grow, and reproduce, producers must use some of their stored chemical energy for cellular respiration.

Net primary productivity (NPP) is the rate at which producers use photosynthesis to produce and

FIGURE 3-12
Only a small fraction of energy produced at the lowest trophic level is available to top predators such as this black-collared hawk.

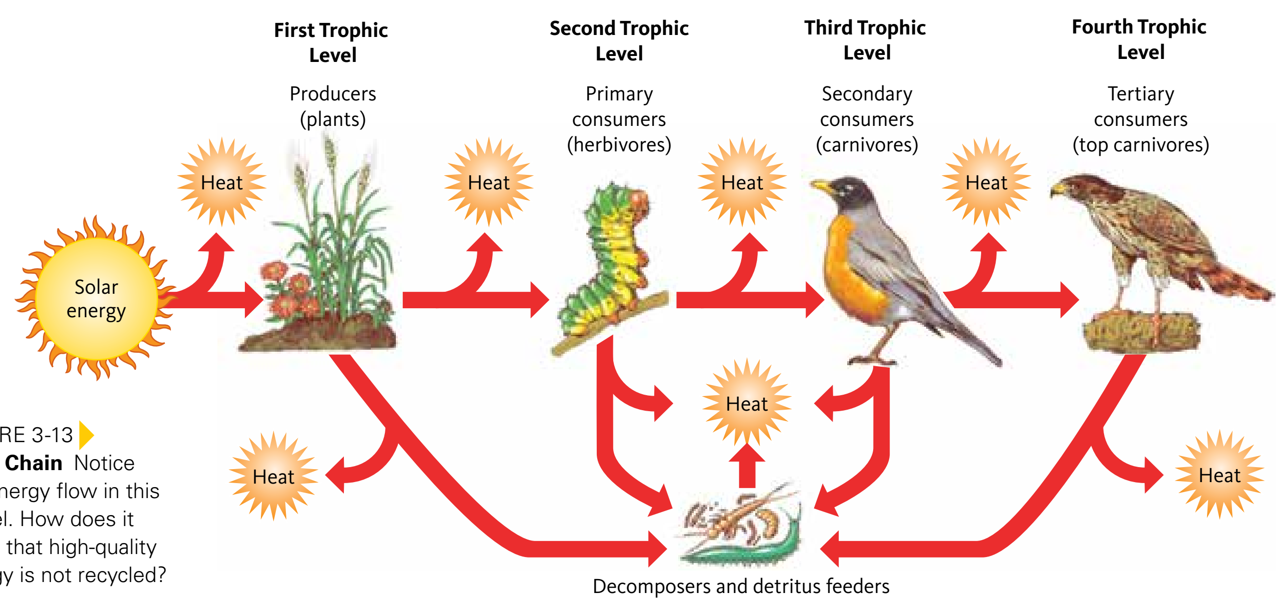


FIGURE 3-13 **Food Chain** Notice the energy flow in this model. How does it show that high-quality energy is not recycled?

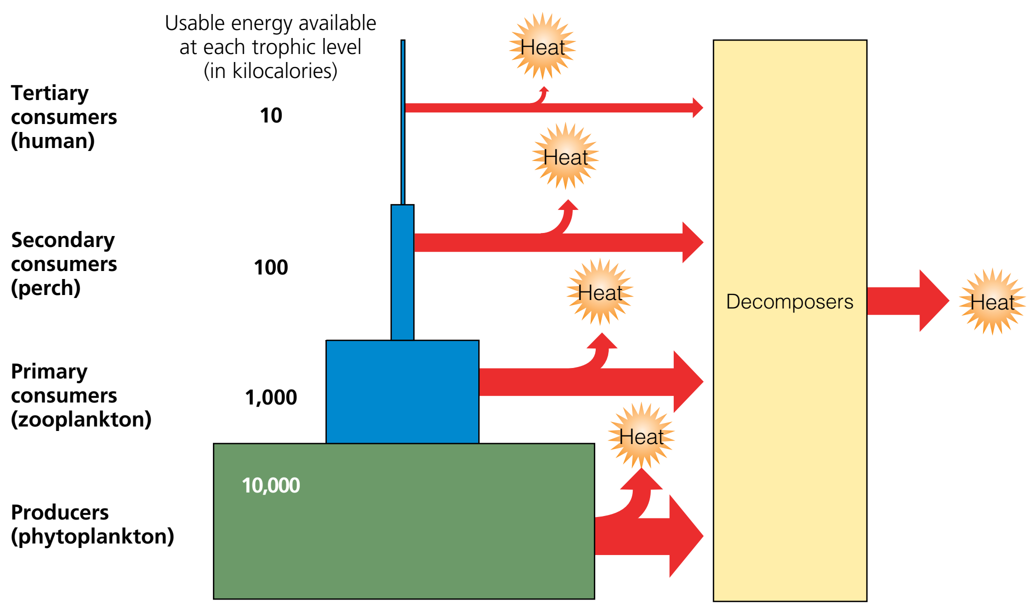


FIGURE 3-14 **Energy Pyramid** Energy pyramids model the general loss of available energy at each trophic level. Energy pyramids are not drawn to scale. Similar diagrams, called biomass pyramids, show the decrease in dry weight of organic matter at each level.

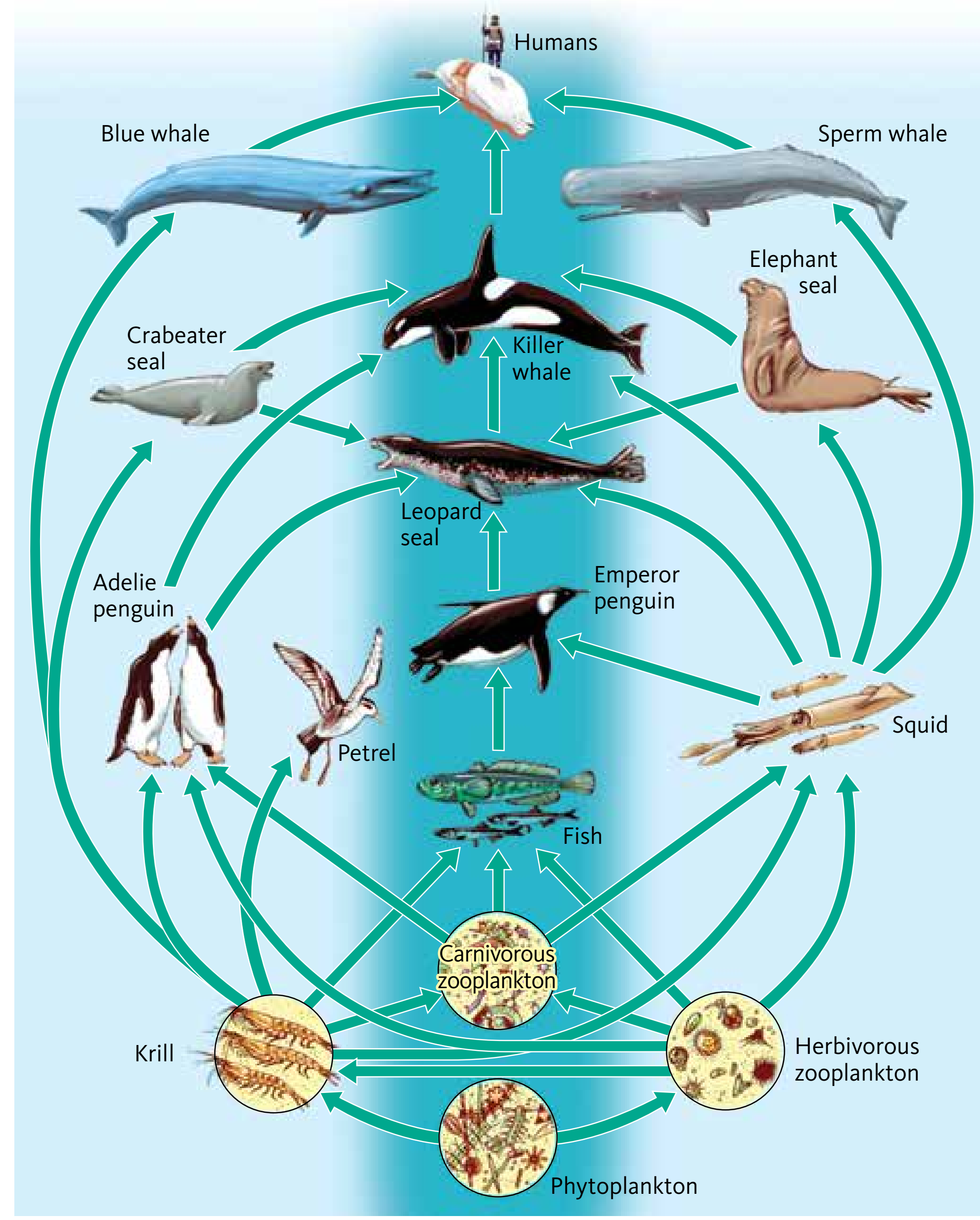
store chemical energy, minus the rate at which they use some of this stored chemical energy through cellular respiration (Figure 3-14). In other words, NPP is the difference between gross primary productivity and cellular respiration. NPP is a measure of the rate at which producers make chemical energy potentially available to the consumers in an ecosystem.

Ecosystems vary in their NPP. For example, tropical rain forests have a high NPP and collectively are large contributors to Earth's overall NPP. They have a great abundance and variety of plants to support a large biomass of consumers. By contrast, the open ocean has a low NPP but is more productive annually than any other ecosystem or life zone. This happens because of the enormous volume of the ocean and its huge numbers of phytoplankton and other producers.

Only the plant matter represented by NPP is available as nutrients for consumers. Thus, *the planet's NPP ultimately limits the number of consumers (including humans) that can survive*. This is one of nature's important lessons. When the most highly productive ecosystems suffer destruction from human activities, Earth's total productivity is reduced—and so is the total number of consumers the planet can support.

checkpoint **What happens to energy as it flows through food chains and food webs?**

FIGURE 3-15 **Food Web** A simplified food web shows some of the feeding relationships among marine organisms in the Southern Hemisphere. The shaded middle area is a food chain within the more complex food web. Many more species, including an array of decomposer and detritus feeder organisms, are not shown in this model.



3.3 Assessment

1. **Identify Main Ideas** What is the ecological role of food chains and food webs?
2. **Summarize** What is the difference between gross primary productivity (GPP) and net primary productivity (NPP)?
3. **Synthesize** The plants in a red-tailed hawk's food chain produce 3 million kcal of chemical energy per day. How much energy is available to the hawk's trophic level, assuming 90% loss at each level? (Hint: Refer to Figure 3-13.)

SCIENCE AND ENGINEERING PRACTICES

4. **Developing and Using Models** Create a simplified model of a food chain in your region. Include the names of the organisms and their relationship to each other. Indicate the flow of energy, starting with the sun and including producers, consumers, and decomposers.

SCIENCE AND ENGINEERING PRACTICES

5. **Constructing Explanations** Explain how diagrams can be useful for studying smaller-scale mechanisms within the larger ecosystem. Discuss the limitations of such models.

3.4 What Happens to Matter in an Ecosystem?

CORE IDEAS AND SKILLS

- Describe the hydrologic cycle.
- Describe nutrient cycles within and among ecosystems and the biosphere.
- Explain how human activities impact nutrient cycles in ecosystems.

KEY TERMS

nutrient cycle	groundwater	nitrogen cycle
hydrologic cycle	aquifer	phosphorus cycle
surface runoff	carbon cycle	

Nutrients Cycle Within and Among Ecosystems

The elements and compounds that make up nutrients move continually through air, water, soil, rock, and living organisms within ecosystems. Within the biosphere, this movement of matter occurs in **nutrient cycles**, or biogeochemical cycles (life-earth-chemical cycles). Nutrient cycles are driven directly or indirectly by energy from the sun and by Earth's gravity. These cycles include the hydrologic (water), carbon, nitrogen, and phosphorus cycles. They are important parts of Earth's natural capital. Yet, human activities are disrupting these cycles.

As a nutrient moves through a biogeochemical cycle, it may accumulate in a certain stage of the cycle and remain there for varying periods. Such temporary reservoirs include the atmosphere, the ocean and other bodies of water, underground deposits, and living organisms.

Throughout your study of environmental science, you may want to refer to the diagrams on these pages again and again because they relate to many key lessons of the book. For example, when studying forms of pollution or overuse of natural resources, these cycles will help you understand the impact human actions can have on Earth's life support system and possible solutions for maintaining sustainability on Earth.

checkpoint **Why do you think it is important to understand biogeochemical cycles?**

The Hydrologic Cycle

Water (H_2O) is essential to life on Earth. The **hydrologic cycle**, also called the water cycle, collects, purifies, and distributes Earth's fixed supply of water (Figure 3-16). The water cycle facilitates all of the important nutrient cycles discussed later in this chapter.

The sun provides the energy needed to power the water cycle. In the water cycle, incoming solar energy causes evaporation. *Evaporation* is the conversion of liquid water to water vapor. Most water vapor rises in the atmosphere, where it condenses into droplets in clouds. Gravity then draws the water back to Earth's surface as *precipitation*, such as rain, snow, or sleet. Above land about 90% of the water vapor in the atmosphere evaporated from soil and plants. Evaporation from plant surfaces is called *transpiration*. Plants draw enormous amounts of water from the ground through their roots. Transpiration is the process by which plants use evaporation to release excess water through tiny pores in their leaves.

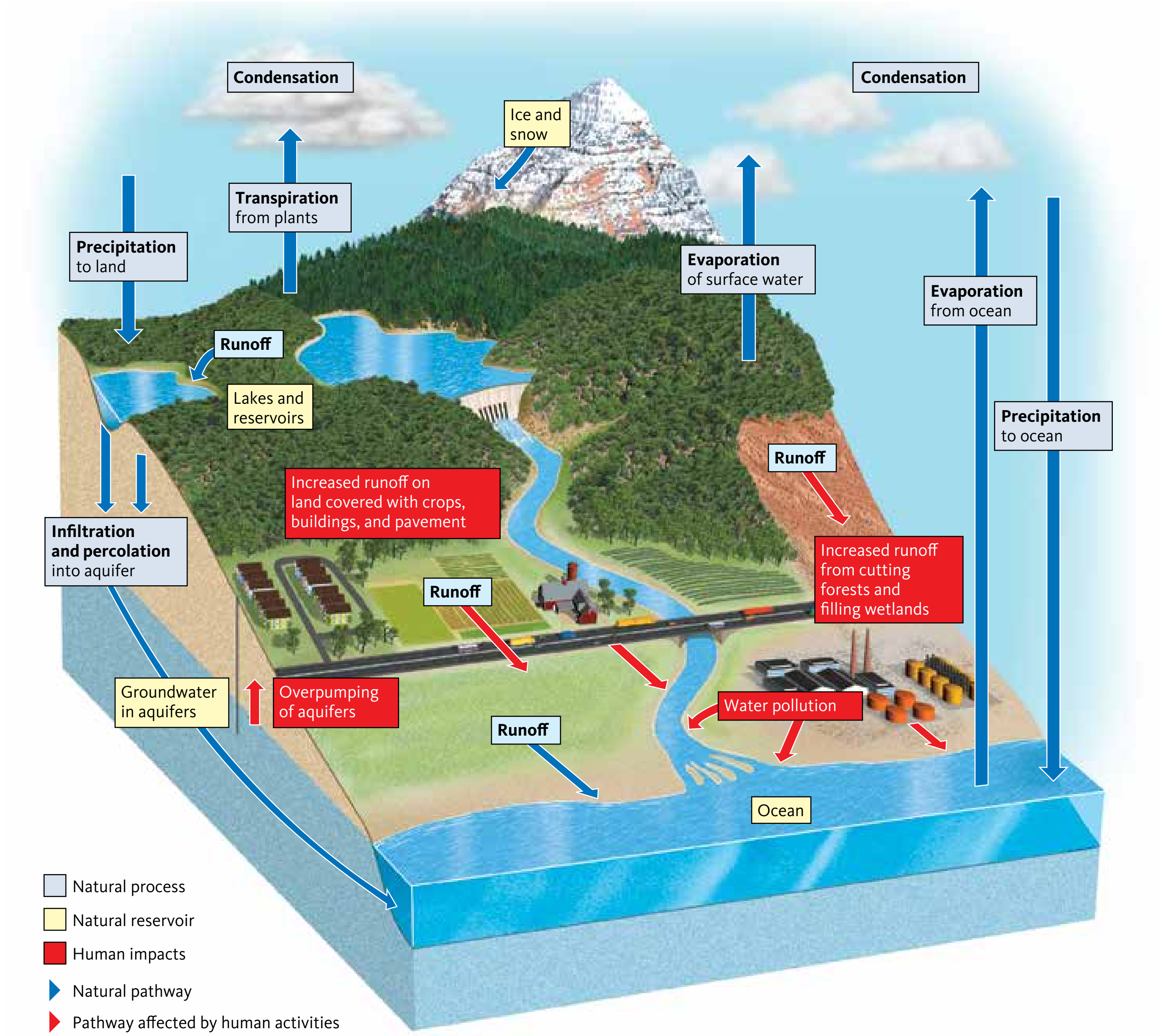
When precipitation returns to Earth's surface, it takes various paths. Most precipitation falling on land ecosystems becomes **surface runoff**. Surface runoff flows over land surfaces into streams, rivers, lakes, wetlands, and the ocean, where it can evaporate and repeat the cycle.

Some precipitation seeps into the soil. This water may evaporate back into the atmosphere or be consumed by plants and other organisms. Water that seeps deeper through soil is known as **groundwater**. Groundwater collects in **aquifers**, which are underground layers of sand, gravel, and water-bearing rock.

Water easily dissolves many compounds, which means it can be polluted easily. Throughout the hydrologic cycle, several natural processes purify water by drawing out pollutants. For example, when water evaporates, dissolved solids, including pollutants, are left behind. The hydrologic cycle can be viewed as a natural cycle of water quality renewal—an important and free ecosystem service. Without the hydrologic cycle's purification processes, humans and other species would rapidly run out of drinkable water.

FIGURE 3-16

Hydrologic Cycle This illustration shows a simplified model of the hydrologic, or water, cycle. Water circulates in various physical forms within the atmosphere, geosphere, hydrosphere, and biosphere. The red arrows and boxes identify major effects of human activities on this cycle.



Only about 0.024% of Earth's vast water supply is available to humans and other species as liquid fresh water. This small fraction is further reduced when human activities pollute freshwater sources. Fresh water is found in accessible groundwater deposits and in surface water from lakes, rivers, and streams. Some groundwater deposits are too deep to extract affordably. The rest of the planet's water is too salty to drink or is permanently frozen in glaciers.

Human Impacts Humans alter the water cycle in three primary ways. (See the red arrows and boxes in Figure 3-16.)

First, people drain and fill wetlands for farming and urban development. Left undisturbed, wetlands provide the ecosystem service of flood control. Wetlands act like sponges to absorb and hold overflows of water from drenching rains or rapidly melting snow.

PROTOTYPE PAGES

FIGURE 3-17
ON ASSIGNMENT National Geographic photographer Peter McBride documents this canoeist's struggle through a shallow pool of garbage and muddy froth at the end of the Colorado River, just inside Mexico.

SCIENCE FOCUS 3.3

WATER

Without water, Earth would be a lifeless planet. Water's unique properties make it one of nature's most extraordinary compounds. Here are a few of the reasons why water is so wondrous.

Water exists as a liquid over a wide range of temperatures. At first glance, this may not seem important. But what if liquid water had a narrower temperature range between freezing and boiling like so many other liquids? The ocean would have frozen solid or boiled away long ago.

Liquid water has a high heat capacity. In other words, water can store a large amount of thermal energy. It takes a lot more energy to raise the temperature of water than it does to raise the temperature of most other liquids. This property of water helps organisms regulate body temperature and plays a critical role in moderating Earth's climate.

Liquid water dissolves more substances than any other liquid. For this reason, water is often called the "universal solvent." In nutrient cycling, water is like the vehicle in which nutrients travel. Water carries dissolved nutrients into the tissues of living organisms and flushes waste products from those tissues. (More than half of your body mass is water.) It helps remove and dilute the water-soluble wastes of civilization. Unfortunately, this property also makes water susceptible to pollution.

Water expands when it freezes. Ice floats on water because it has a lower density (mass per unit of volume) than its liquid form. Otherwise, lakes and streams in cold climates would freeze solid, killing virtually all of the aquatic life. This special property fractures rocks in a phenomenon called ice wedging. Thus, water plays a major role in shaping landscapes and forming soil.

Thinking Critically
Infer The expansion of water when it freezes plays a major role in shaping landscapes and forming soil. Which other property described above also plays a major role in altering landscapes?

Second, people withdraw fresh water from rivers, lakes, and aquifers, often at rates faster than natural processes can replace it. As a result, some aquifers are being depleted and several rivers no longer flow to the ocean.

Third, people clear vegetation from land for agriculture, mining, road building, and other activities, and then cover much of the land with buildings, concrete, and asphalt. This increases runoff and reduces infiltration that normally recharges groundwater supplies.

checkpoint How does energy from the sun drive the hydrologic cycle?

The Carbon Cycle

Carbon is the basic building block of the carbohydrates, fats, proteins, DNA, and all other organic compounds required for life. Carbon is found in every cell of your body. It is part of the carbohydrate molecules produced through photosynthesis and eaten or decomposed by consumers. In the **carbon cycle** (Figure 3-18), different compounds of carbon circulate through the biosphere, atmosphere, and parts of the geosphere and hydrosphere.

A key component of the carbon cycle is carbon dioxide (CO_2) gas. Carbon dioxide makes up only about 0.04% of the volume of the atmosphere and is also dissolved in water. The amount of carbon dioxide (along with water vapor) has a big effect on global temperatures because of the greenhouse effect (Lesson 3.1).

On land, photosynthesis by producers moves carbon from the atmosphere to the biosphere. In marine environments, producers remove carbon from water. Meanwhile, the cells of oxygen-consuming producers, consumers, and decomposers (both terrestrial and aquatic) carry out aerobic respiration. As you learned in Lesson 3.3, the by-product of aerobic respiration is water and CO_2. Together, the processes of photosynthesis and aerobic respiration circulate carbon through the biosphere.

FIGURE 3-18

Carbon Cycle This simplified model shows the circulation of various chemical forms of carbon in the global carbon cycle.

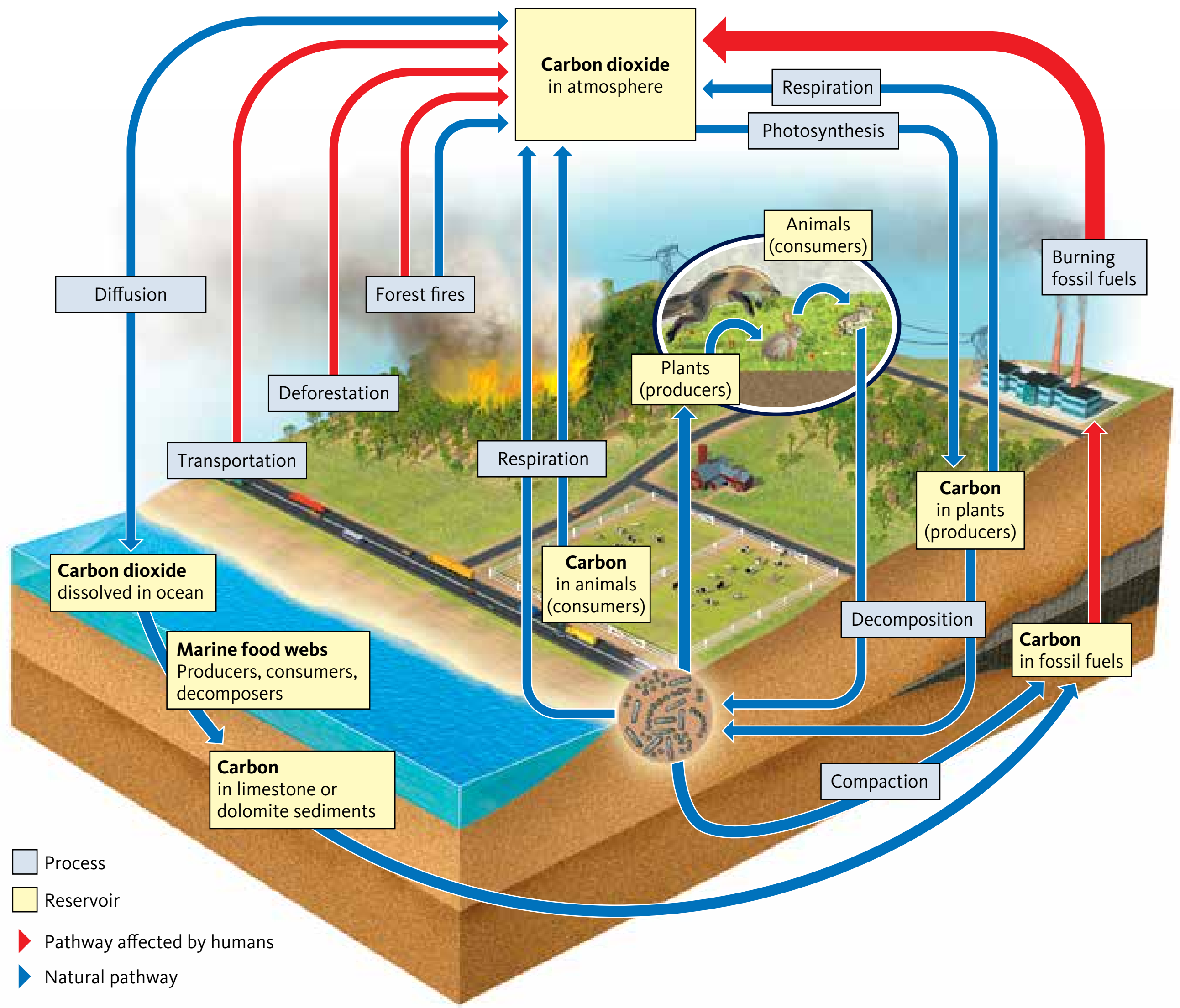
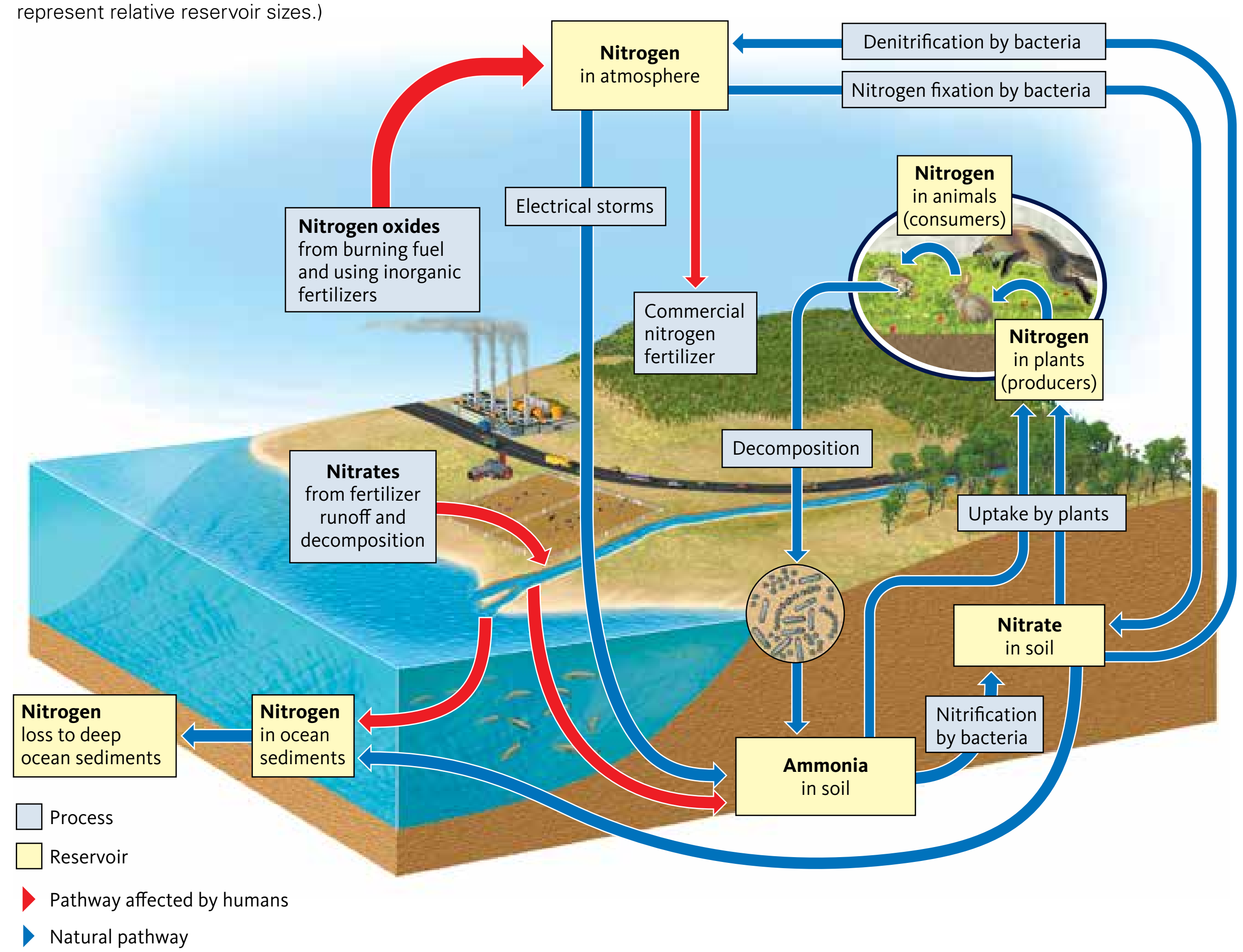


FIGURE 3-19

Nitrogen Cycle Various chemical forms of nitrogen circulate in this simplified model of the nitrogen cycle. Red arrows indicate the major harmful human impacts. (Yellow box sizes do not represent relative reservoir sizes.)



On land, decomposers release some of the carbon stored in the bodies of dead organisms back into the air as CO_2. Carbon dioxide can remain in the atmosphere for 100 years or longer. In water, decomposers release carbon that can be stored as insoluble minerals in bottom sediment for much longer periods. In fact, marine sediments are Earth's largest store of carbon.

Over millions of years, the carbon in deeply buried marine deposits of dead plant matter and algae were converted into carbon-containing fossil fuels. The high pressure from the weight of overlying sediments and heat released during the decomposition of dead matter formed coal, oil, and natural gas (fossil fuels).

Human Impacts Humans are altering the carbon cycle mostly by adding large amounts of carbon dioxide to the atmosphere. (See the red arrows and boxes in Figure 3-18.) In the past few hundred years, humans have extracted and burned huge quantities of fossil fuels that took millions of years to form, releasing tremendous quantities of CO_2 into the atmosphere. Humans also alter the cycle by clearing carbon-absorbing vegetation from forests, especially tropical forests, faster than it can grow back (Case Study). These alterations contribute to environmental problems that affect the atmosphere and ocean.

checkpoint **Why is carbon essential to your survival?**

The Nitrogen Cycle

Nitrogen gas (N_2) makes up 78% of the volume of the atmosphere. Nitrogen is a crucial component of proteins, many vitamins, and DNA. Despite its abundance and importance to life, nitrogen cannot be absorbed and used directly as a nutrient by plants or other organisms. It becomes usable by producers only in the form of compounds such as ammonia (NH_3) and ammonium ions (NH_4^+).

These compounds are created within the **nitrogen cycle** (Figure 3-19) by reactions involving either lightning or specialized bacteria found in topsoil and aquatic ecosystems. Other bacteria convert most of the NH_3 and NH_4^+ in the topsoil to nitrate ions (NO_3^-), which the roots of plants take up. Plants use these forms of nitrogen to produce the proteins, nucleic acids, and vitamins necessary for their own survival and that of other organisms. Animals that eat plants absorb these nitrogen-containing compounds, as do detritivores and decomposers.

Organisms return nitrogen-rich organic compounds to the environment in their wastes and cast-off particles of matter such as leaves, skin, or hair. When organisms die, their bodies are decomposed or eaten by detritus feeders. In both instances, specialized bacteria break down the remains into simpler chemicals such as nitrate ions (NO_3), ammonia (NH_3) and ammonium ions (NH_4^+). Bacteria then convert such chemicals to N_2 gas, which returns to the atmosphere to begin the nitrogen cycle again.

Human Impacts Human activities impact the nitrogen cycle in several ways. (See the red arrows and boxes in Figure 3-19.) Nitric oxide (NO) is added to the atmosphere as a product of combustion when humans burn gasoline and other fuels. In the atmosphere, NO can be converted to nitrogen dioxide gas (NO_2) and nitric acid vapor (HNO_3), which return to Earth's surface as acid rain. Acid rain damages stone buildings and statues. It can also kill forests and other plant ecosystems, and wipe out life in ponds and lakes.

Humans remove nitrogen (N_2) from the atmosphere to make ammonia (NH_3) and ammonium ions (NH_4^+) for fertilizers. In addition, humans alter the nitrogen cycle in aquatic ecosystems by adding excess nitrates (NO_3^-). These nitrates contaminate bodies of water through agricultural runoff of fertilizers, animal manure, and discharges from municipal sewage treatment systems. This can cause excessive growth of algae that deplete oxygen levels and cause stress or death of aquatic organisms.

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 comes from the increased use of inorganic fertilizers to grow crops. The amount released is projected to double again by 2050, which would seriously alter the nitrogen cycle.

CONSIDER THIS

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 deep in the ocean. Your great-grandmother, George Washington, or a hunter-gatherer who lived 25,000 years ago may have breathed some of the nitrogen molecules you just inhaled. The hydrogen and oxygen atoms that formed the water you drank today may have flowed in the Nile River in Egypt thousands of years ago or floated in a cloud over the Pacific Ocean only two months ago.

checkpoint **How can the release of excess nitrates into bodies of water affect aquatic organisms?**

The Phosphorus Cycle

Phosphorus (P) is an element that is essential for living things. It is contained in ATP, a compound that provides energy for life processes. It is necessary for the production of DNA and cell membranes, and is important for the formation of bones and teeth.

The cyclic movement of phosphorus through water, Earth's crust, and living organisms is called the **phosphorus cycle** (Figure 3-20). Most of the phosphorus compounds contain phosphate ions (PO_4^{3-}), which serve as an important plant nutrient.

As water runs over exposed rocks, it slowly erodes inorganic compounds that contain phosphate ions. Water carries these ions into the soil, where plants and other producers absorb them. Phosphate compounds are then transferred through food webs from producers to consumers. Unlike water, carbon, and nitrogen, phosphorus does not cycle through the atmosphere.

The phosphorus cycle is slow compared to the water, carbon, and nitrogen cycles. As phosphate is eroded from exposed rocks, much of it is carried in rivers and streams to the ocean. When it reaches the ocean, phosphate can be deposited as marine sediments and remain trapped for millions of years. Over time, geological processes uplift and expose some of these seafloor deposits. The exposed rocks are then eroded, freeing up the phosphorus to re-enter the cycle.

Most soils contain little phosphate, which limits plant growth on land. For this reason, people often fertilize soil by adding phosphorus (as phosphate compounds mined from the ground). Under natural conditions, low levels of phosphorus also limit the growth of producer populations in many freshwater environments. Phosphate compounds are only slightly soluble in water, so they release fewer phosphate ions to aquatic producers that need them as nutrients.

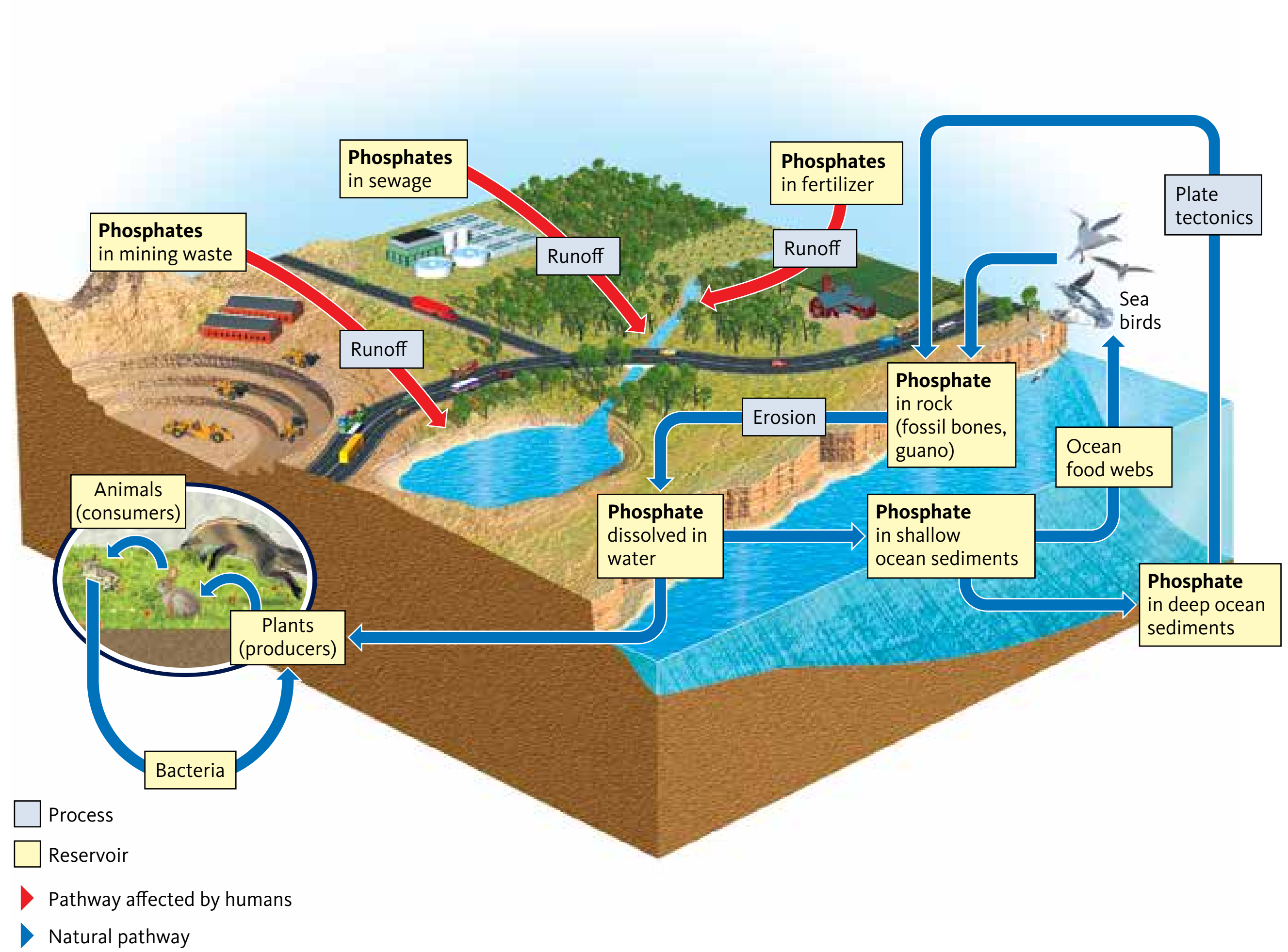
Human Impacts Human activities, including the mining of large amounts of phosphate to make fertilizer, disrupt the phosphorus cycle. (See the red arrows in Figure 3-20.) By clearing tropical forests, humans expose the topsoil to greater erosion, which reduces phosphate levels in the soil.

Phosphate fertilizer is then added to make up for the lost phosphate. Eroded topsoil and fertilizer washed from fertilized crop fields, lawns, and golf courses carry large quantities of phosphate ions into streams, lakes, and oceans. Phosphates stimulate the growth of producers such as algae. Similar to nitrogen-rich runoff, phosphate-rich runoff from the land often causes huge increases in algae populations. As the algae die and decompose, oxygen in the water is depleted, wiping out populations of aquatic organisms.

checkpoint **How is the phosphorus cycle different from the water, carbon, and nitrogen cycles?**

FIGURE 3-20

Phosphorus Cycle Different chemical forms of phosphorus (mostly phosphates) circulate among land, water, and organisms in this simplified model of the phosphorus cycle. (Yellow box sizes do not represent relative reservoir sizes.)



PROTOTYPE PAGES

3.4 Assessment

1. **Identify Main Ideas** What is the role of the hydrologic cycle in relation to the carbon, nitrogen, and phosphorus cycles?
2. **Summarize** Describe at least one way humans impact each of the following cycles: hydrologic, carbon, nitrogen, and phosphorus.

SCIENCE AND ENGINEERING PRACTICES

3. **Using Mathematics** There are about 11,200,000 billion metric tons of O_2 in the atmosphere. Based on an estimated photosynthesis rate of 600 billion metric tons per year, how many years might it have taken to reach current O_2 levels? (Note: Assume for this exercise that the rate of O_2 production is constant even though it has changed over time.)

SCIENCE AND ENGINEERING PRACTICES

4. **Developing Models** Create a simplified model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon. Include how carbon cycles through the biosphere, atmosphere, hydrosphere, and geosphere.

CROSSCUTTING CONCEPTS

5. **Energy and Matter** How is matter conserved in the nutrient cycles?

3.5 How Do Scientists Study Ecosystems?

CORE IDEAS AND SKILLS

- Compare and contrast the advantages and disadvantages between field research and laboratory research.
- Explain why mathematical models are an important tool for studying natural systems.
- Describe how a better scientific understanding of planetary boundaries can help measure the health of ecosystems.

KEY TERMS

Holocene Anthropocene

Ecologists Study Ecosystems Directly

Scientists such as ecologists use several approaches to increasing the scientific understanding of ecosystems. Field research involves going into a natural setting to study one or more features of an ecosystem. Ecologists have numerous methods of field research, including taking water or soil samples, identifying the species in an area, doing population counts, observing feeding behaviors, and using GPS to track animals' movements. In this lesson you will read about the pioneering field research of one scientist, National Geographic Explorer Thomas E. Lovejoy. Much of what people know about ecosystems comes from data obtained through field work.

Scientists who study tropical rain forests, for example, use a variety of methods to study those ecosystems. Most animals in a tropical forest live in the canopy, which can be as high as 28 meters (92 feet) above the ground. Scientists often use ropes and pulleys to access a canopy (Figure 3-21). They may also install rope walkways, spiral staircases, and temporary platforms. Some long-term scientific projects have built construction cranes that tower over the surrounding trees. These "canopy cranes" can bring researchers and heavy equipment to many different points within the canopy. All of these methods help researchers identify and observe the rich diversity of species living or feeding in treetop habitats.

Ecologists may carry out controlled experiments in the field by isolating and changing a variable within a defined area. They then compare the results with unchanged areas nearby. You learned about a classic example of this in the Case Study in Chapter 2.

Advances in technology allow ecologists to obtain data in new ways. Satellites and aircraft equipped with sophisticated cameras can scan and collect data about Earth's surface. Scientists use geographic information system (GIS) software to capture, store, analyze, and display this data. For example, a GIS can convert digital satellite images into global, regional, and local maps. The maps can show variations in vegetation, gross primary productivity, air pollution emissions, and other variables. More recently, scientists have used drones to photograph, document, and monitor rates of deforestation.

Some researchers attach small radio transmitters to animals and use global positioning systems (GPS) to track where and how far the animals travel. This technology is an important tool for studying endangered species, which you will learn about in Chapter 7.

checkpoint **What are some of the methods ecologists use in field research?**

FIGURE 3-21
National Geographic Explorer and tropical ecologist Greg Goldsmith pauses to take notes a mere 30 meters (98 feet) above the ground. Some of Greg's fieldwork involves hanging out with wildlife in the upper canopy of this montane cloud forest in Costa Rica.

PROTOTYPE PAGES

Ecologists Study Ecosystems Indirectly

Most ecologists supplement their field research by conducting research in laboratories. In a lab, scientists can set up, observe, and make measurements of model ecosystems and populations. They can create simplified systems in culture tubes, bottles, aquariums, and greenhouses, and in indoor and outdoor chambers.

By isolating biological systems, scientists can control variables such as temperature, light, CO_2, and humidity. Scientists must consider how well their observations and measurements in laboratory conditions reflect what actually takes place in the more complex and often changing conditions found in nature. Although they provide only part of the picture, controlled experiments (in the field or a lab) offer the best means by which to identify cause-and-effect relationships.

Scientific knowledge advances when multiple lines of evidence support the same explanation, so ecologists often use a combination of indirect and direct observation.

Ecologists also use mathematical modeling. Mathematical models can simulate large and complex systems with many variables and large data sets. The models usually require so many variables and so much data that they can only be run on a high-speed supercomputer. Whole systems such as lakes, oceans, forests, and Earth's climate cannot be observed in their entirety or modeled physically. The scope of these systems is too large, and the timescales may be too long, for direct study. Mathematical modeling, however, is ideally suited to these large-scale natural systems.

checkpoint **What are some of the methods ecologists use in laboratory research?**

NATIONAL GEOGRAPHIC | EXPLORERS AT WORK

Thomas E. Lovejoy Tropical and Conservation Biologist

Meet conservation biologist and National Geographic Explorer Thomas E. Lovejoy, the person who coined the term *biological diversity*. For decades, Dr. Lovejoy has played a major role in educating people about the need to protect biodiversity. His conclusions about biodiversity are supported by data he and others have collected over many years of field research.

Lovejoy has been carrying out field research in the Amazon forests of Brazil since 1965. He helped start the world's largest and longest-running study of habitat fragmentation, the Biological Dynamics of Forest Fragments Project (BDFFP). Since 1979, the project has measured the impacts of fragmentation across a 1,000 square-kilometer (386 square-mile) area of the central Amazon.

A goal of the BDFFP is to define the minimum amount of land area necessary for sustaining biodiversity in a tropical forest. As forests become increasingly fragmented, a better understanding of how fragmentation affects biodiversity is more important than ever before.

Threats to tropical forest ecosystems—such as deforestation, poaching, and pollution—are a matter of public interest today largely through Lovejoy's efforts at raising public awareness.

Lovejoy founded the popular and widely-acclaimed public television series *Nature*. He has also written numerous articles and books on issues related to the conservation of biodiversity.

In addition to teaching environmental science and policy at George Mason University, he has held several important posts, including director of the World Wildlife Fund's conservation program, president of the Society for Conservation Biology, and executive director of the UN Environment Programme (UNEP). In 2012, he was awarded the Blue Planet Prize for his efforts to understand and sustain Earth's biodiversity.

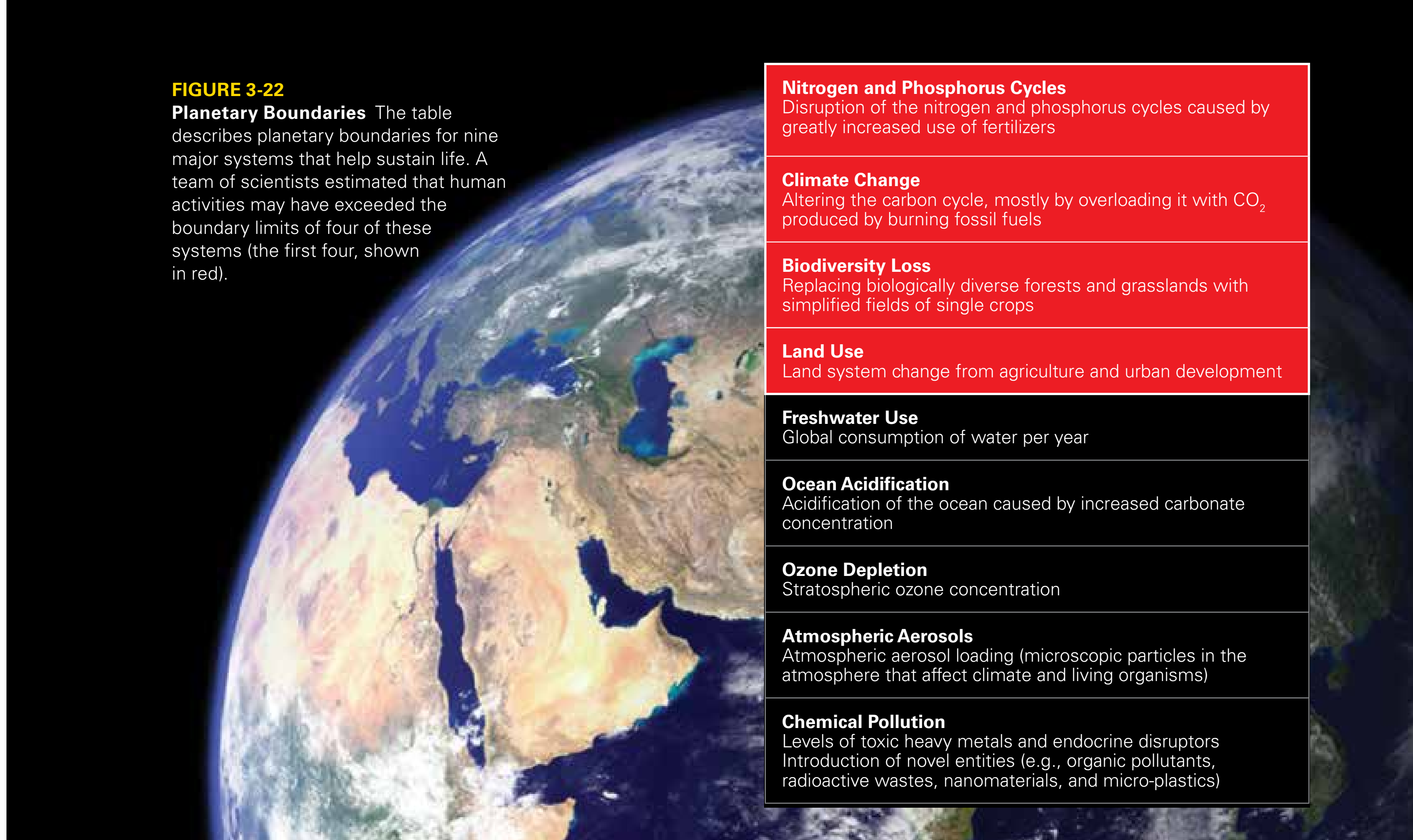


FIGURE 3-22
Planetary Boundaries The table describes planetary boundaries for nine major systems that help sustain life. A team of scientists estimated that human activities may have exceeded the boundary limits of four of these systems (the first four, shown in red).

Nitrogen and Phosphorus Cycles	Disruption of the nitrogen and phosphorus cycles caused by greatly increased use of fertilizers
Climate Change	Altering the carbon cycle, mostly by overloading it with CO_2 produced by burning fossil fuels
Biodiversity Loss	Replacing biologically diverse forests and grasslands with simplified fields of single crops
Land Use	Land system change from agriculture and urban development
Freshwater Use	Global consumption of water per year
Ocean Acidification	Acidification of the ocean caused by increased carbonate concentration
Ozone Depletion	Stratospheric ozone concentration
Atmospheric Aerosols	Atmospheric aerosol loading (microscopic particles in the atmosphere that affect climate and living organisms)
Chemical Pollution	Levels of toxic heavy metals and endocrine disruptors Introduction of novel entities (e.g., organic pollutants, radioactive wastes, nanomaterials, and micro-plastics)

SCIENCE FOCUS 3.4

TESTING PLANETARY BOUNDARIES

For most of the past 10,000 years, humans have lived in an era called the **Holocene**—a period of relatively stable climate and other environmental conditions. This general stability has allowed humans to develop agriculture and expand the human population around the world.

Although most geologists argue that we are still living in the Holocene, a growing number of other scientists think we are living in a new era, which they call the **Anthropocene**. According to their argument, the Anthropocene began around 1750 with the Industrial Revolution. Since that time, people have been consuming a much greater share of Earth's resources and have become the dominant cause of changes to the planet's major systems that sustain life.

In 2015, an international group of 28 scientists, led by Will Steffen and Johan Rockström of the Stockholm Resilience Centre, identified the boundaries, or ecological tipping points, of nine major planetary systems that play a key role in supporting life. (Recall that an ecological tipping point is like a system's "point of no return," resulting in severe degradation or collapse.) The team's research indicates that, apparently, we have exceeded four of these boundaries (Figure 3-22).

According to the Stockholm group, if humans exceed too many boundaries, we could trigger abrupt and long-lasting environmental changes that will degrade the planet's ability to support life. They argue that there is an urgent need for more research to better define the boundary limits of these planetary systems, which are still not exact. They also say we need to learn more about what exceeding the boundaries will do to the health of humans and other species.

If this is the Anthropocene, how will it end for humans and other species? What will Earth's next era look like?

Thinking Critically

Infer Which boundaries are most affected by urban development? Which ones are most affected by agriculture?

3.5 Assessment

1. **Compare and Contrast** Compare and contrast the advantages and disadvantages between field research and laboratory research.
2. **Summarize** Why are mathematical models an important tool for studying complex natural systems?
3. **Draw Conclusions** How can a better scientific understanding of planetary boundaries help scientists determine the health of ecosystems?

CROSSCUTTING CONCEPTS

4. **Stability and Change** Use the text and your own research to argue for or against the view that we are living in a new era called the Anthropocene.

TYING IT ALL TOGETHER

The Energy Cost of Cutting Rain Forests

The Case Study at the beginning of this chapter discusses the importance of the world's incredibly diverse tropical rain forests. Producers in rain forests rely on solar energy to produce a vast amount of biomass through photosynthesis. A huge variety of forest species take part in and depend on the flow of the sun's energy and cycling of nutrients through the ecosystem. In other words, rain forests are highly complex and highly productive.

Recall that net primary productivity (NPP) is the rate at which producers can make the chemical energy that is potentially available to the rest of the organisms in an ecosystem. Figure 3-23 provides an estimated annual average NPP for Earth's major types of ecosystems.

Look through the table in light of all you have learned about how energy moves through ecosystems. What meaning can be drawn from these numbers? In this exercise, you will analyze these data and synthesize ideas from this chapter with your own thinking.

Use the table to help you answer the questions that follow.

1. Highly complex ecosystems are relatively resilient, meaning they are likely to recover over time from "small" changes, such as the loss of a species. Explain this in terms of food webs.
2. Even highly complex ecosystems cannot recover from extreme changes. Give an example of a change from which a rain forest would likely not recover.
3. Look at the units for NPP in Figure 3-23. Kilocalorie (kcal) is a unit of energy. Develop a formula to determine the impact of clear-cutting one square meter per year on the energy produced by an ecosystem.
4. An estimated 5,000 m^2 of Amazon rain forest is cleared annually. Use your formula to calculate the impact on NPP.
5. Compare your answer from item 4 to the impact of clear-cutting an equal area of desert scrub.
6. Work with a partner. Use your answers from items 1–4 to help you evaluate the statement below. Revise the statement and add 1–2 paragraphs that explain your reasoning. Support your argument with data.

"Damage to rain forests results in less harm to Earth's life support system than damage to simpler ecosystems because complex ecosystems are more resilient to change."

FIGURE 3-23

Ecosystem/Life Zone	Average Net Primary Productivity (kcal/m²/year)
Terrestrial Ecosystems	
Swamp and marsh	9,000
Tropical rain forest	9,000
Temperate forest	5,800
Taiga	3,400
Savanna	3,000
Woodland and shrubland	2,600
Temperate grassland	2,200
Tundra	600
Desert scrub	200
Aquatic Ecosystems	
Estuary	9,000
Lake and stream	2,200
Continental shelf	1,500
Open ocean	1,100

CHAPTER 3 SUMMARY

3.1 What are Earth's major spheres, and how do they support life?

- Earth's capacity to support life depends on the proper functioning of, and interaction among, four major planetary spheres. The major planetary spheres are the atmosphere (air), hydrosphere (water), geosphere (land), and biosphere (living things).

3.2 What are the major ecosystem components?

- Ecology is the study of how organisms interact with one another and their nonliving environment of matter and energy. Ecologists focus on one or more levels of organization.
- Ecosystems are composed of abiotic and biotic factors. Species are classified into trophic levels based on how they obtain food. Producers make their own food, while consumers feed on other organisms or the wastes and remains of other organisms.
- Consumers are herbivores, carnivores, omnivores, or decomposers. Decomposers recycle nutrients back to the producers by decomposing the wastes and remains of other organisms.

3.3 What happens to energy in an ecosystem?

- Life is sustained by the one-way flow of energy, mainly from the sun, through the biosphere. Energy flows through ecosystems in food chains and food webs. The amount of energy available to organisms decreases at each successive trophic level.
- Gross primary productivity (GPP) is the rate at which plants convert solar energy into chemical energy. The net primary productivity (NPP) is the rate at which producers use photosynthesis to produce and store chemical energy minus the rate at which they release some of this stored energy through aerobic respiration.

3.4 What happens to matter in an ecosystem?

- The flow of energy drives the cycling of matter within Earth's biosphere. Matter in an ecosystem travels in the form of nutrients. These nutrients cycle in and among ecosystems and the biosphere, geosphere, hydrosphere, and atmosphere.
- Four key nutrient cycles are the water cycle, carbon cycle, nitrogen cycle, and phosphorus cycle. Human activities affect all four cycles.

3.5 How do scientists study ecosystems?

- Scientists use field and laboratory research, in addition to mathematical and other models, to learn about ecosystems.
- Research indicates that four out of nine planetary boundaries, or tipping points, have likely been exceeded. Scientists need to generate more data to determine the current state of these and other possible planetary tipping points.

MindTap If you have been provided with access to a MindTap course, additional resources are available at login.cengage.com.

CHAPTER 3 ASSESSMENT

Review Key Terms

Select the term that best fits the definition. Not all terms will be used.

aerobic respiration	geosphere	phosphorus cycle
anaerobic respiration	greenhouse effect	photosynthesis
Anthropocene	groundwater	primary consumer
aquifer	gross primary productivity	producer
atmosphere	herbivore	secondary consumer
biosphere	Holocene	stratosphere
carbon cycle	hydrologic cycle	surface runoff
carnivore	hydrosphere	tertiary consumer
consumer	net primary productivity	trophic level
decomposer	nitrogen cycle	troposphere
detritivore	nutrient cycle	
food chain	omnivore	
food web		

1. Process in which solar energy interacts with carbon dioxide, water vapor, and other gases in the air; it warms the troposphere
2. Organisms that cannot produce their own nutrients and get them by feeding on other organisms or their wastes and remains
3. Animals that eat both plants and animals
4. A complex network of interconnected food chains
5. Component of Earth's life-support system that consists of a thin spherical envelope of gases surrounding the planet's surface
6. Includes all the water on or near Earth's surface
7. Component of Earth's life-support system where life is found
8. Uses oxygen to convert glucose and other organic molecules back into carbon dioxide and water
9. An organism's feeding level within an ecosystem
10. Precipitation that sinks through soil into underground layers of rock, sand, and gravel
11. The rate at which producers convert radiant energy into chemical energy
12. Continuous movement of elements and compounds that make up nutrients through air, water, soil, rock, and living organisms

Review Key Concepts

13. Name and describe four large-scale systems, or spheres, that sustain life on Earth.
14. Define organism, population, communities, ecosystems, and the biosphere.
15. Which level(s) of organization are the main focus of Vitor Becker's work?
16. Give two examples each of abiotic factors and biotic factors found in a tropical rain forest.
17. What are decomposers? What purpose do they serve in an ecosystem?
18. Summarize the process of photosynthesis.
19. Summarize the process of aerobic respiration.
20. Define and distinguish between a food chain and a food web.
21. Distinguish between gross primary productivity (GPP) and net primary productivity (NPP).
22. Explain how nutrient cycles connect past, present, and future life.
23. How are humans affecting the water, carbon, nitrogen, and phosphorus cycles?
24. Explain why we need more research about the structure and condition of the world's ecosystems.

Think Critically

25. How would you explain the importance of tropical rain forests to people who think such forests have no connection to their lives?
26. Explain why energy from the sun is essential for the cycling of nutrients.
27. Explain the interaction of energy, nutrients, and organisms in an ecosystem.
28. Make a list of the food you ate today. Trace each food item back to a producer species. Diagram the sequence of trophic levels that led to your consumption of that food item.
29. Why are there so few top predators in an ecosystem when compared with the number of primary consumers?
30. What would happen to an ecosystem if
    - **a.** all decomposers and detritus feeders were eliminated?
    - **b.** all producers were eliminated?
    - **c.** all insects were eliminated?
    - **d.** only producers and decomposers existed?
31. Explain the importance of the roles of microbes in the biosphere.
32. Research indicates that we may have exceeded four planetary boundaries. Describe how exceeding each of these boundaries might affect you, your children, or your grandchildren.

Chapter Activities

A. Develop Models: Greenhouse Effect

The greenhouse effect provides the warmth needed to sustain life in Earth's troposphere. The greenhouse effect is produced by an interaction between the sun and Earth's atmosphere (Lesson 3.1). Look at the materials below. Design a model of the greenhouse effect using these or other materials approved by your teacher.

Materials

plastic bottles, glass jars, thermometers, heat lamps

1. Describe how your model will work using a diagram to show the flow of energy through your system. Build and test your model.
2. How did your model demonstrate the greenhouse effect?
3. What are some limitations of your model? How could your model be improved?
4. How could your model be used to test the effect of increased carbon dioxide on atmospheric temperature? Write a hypothesis.

B. Citizen Science

National Geographic Learning Framework

Attitudes | Curiosity
Skills | Collaboration
Knowledge | Critical Species

Plankton are microscopic producers and the primary consumers that form the basis of Earth's ocean food webs (Figure 3-15). Although they may be small, their role in the biosphere is enormous. Earth's ocean ecosystems collectively produce more biomass per year than any other ecosystem.

Yet, plankton populations are declining. Because they are so small and their habitats are so vast and inaccessible, scientists are relying on citizens to help them gather and analyze the data they need.

Join a citizen science project asking volunteers to help collect data on plankton or analyze video footage. Then gather in small groups to discuss your answers to the questions.

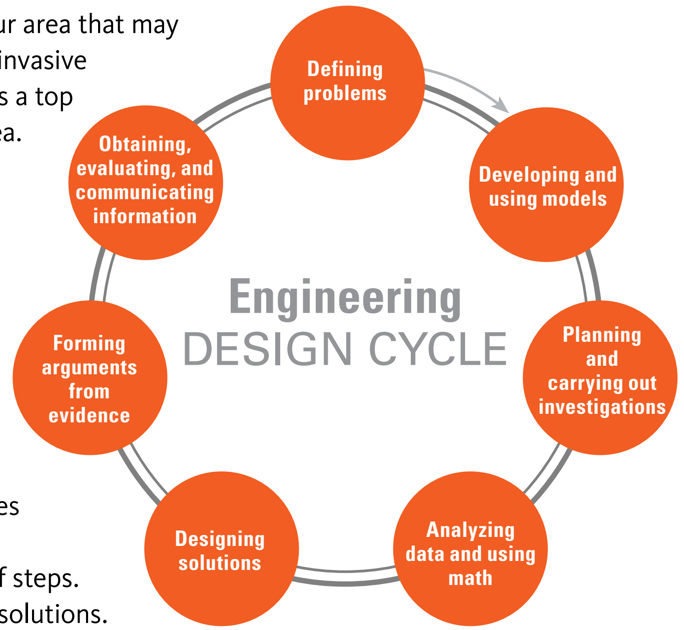
1. What was the name of the project, website, or app that you used? What institution is running the project?
2. Describe your findings and contributions.
3. What was your experience like working on the project? Do you think you will continue?
4. Discuss any ideas you have to improve upon or expand the project.

UNIT 2 PROJECT
DESIGN A SYSTEM TO ASSESS A LOCAL SPECIES

In this challenge, you will get to use your own ingenuity and problem-solving skills. You will work with a team to design a solution to a real environmental problem, build a model of your system, and test it. The problem in this case is related to a single species in your ecosystem. As you well know, the parts of an ecosystem are interconnected: A change in one species' population can affect the entire ecosystem.

Have you heard about a plant or animal species in your area that may be a cause for concern? For example, maybe there is an invasive insect or weed that is affecting local businesses. Perhaps a top predator is disappearing or recently moved into your area. Maybe an important pollinating insect or bird is on the decline and no one knows why. Or maybe a migrating species has changed its patterns. Whether it is an invasive species on the rise, a pollinating species on the decline, or another issue, you will select an organism in your area that needs better monitoring and come up with a new method to capture data about it.

The process of testing an engineering design involves a series of practices similar to the practices used by scientists to test hypotheses. Engineering usually involves many rounds of testing and retesting, so the process of design is often depicted as a cycle rather than a series of steps. Engineers use this cycle to translate ideas into practical solutions.



Defining Problems

1. Look at the list of local species provided by your teacher. Select one species. Use the Internet to learn about the problem associated with your species. Nature centers and university extension offices are also great resources for research.
   - What species will your team focus on? Include the scientific name and the common name.
   - What is the problem associated with the species?
2. Identify a need that underlies the problem.
   - What data might help solve the problem?
   - How could a system of cell phones be used to gather that data?
3. What would a successful solution be able to achieve? List the criteria.
4. Consider a possible population assessment system that uses cell phones. List the design constraints, such as time, equipment, or people.

Developing and Using Models

5. Brainstorm ideas for a solution with your team. Consider the factors provided by your teacher.
6. Discuss two different ideas in more depth with your team. Then choose one idea to carry out.
7. Describe the design of your system both in words and with a diagram or flow chart.
8. Develop a simplified version of your system that your team can use to test your ideas. Keep in mind that you will evaluate your model using the criteria from step 3.

Planning and Carrying Out Investigations

9. Plan a test of your model with your group. Write out your plan in steps.
10. How reliable do you think your data will be? Consider limitations and refine your design accordingly.

11. What social considerations can you think of? Refine your design to make it as safe and ethical as possible.
12. Create your model and carry out your test. Record your data in a table.

Analyzing Data and Using Math

13. Analyze your data. What patterns do you notice?
14. What limitations exist in your data?
15. How well does your system meet each of the criteria from step 3?

Designing Solutions

16. What were the strengths and weaknesses of your design?
17. How can your design be improved? Revise your description and diagram accordingly.

Forming Arguments from Evidence

18. Describe how you revised your design.
19. What evidence justified the change you made?
20. Test your new design and compare the results to your original design.
21. What claims can you make about your solution? Use evidence to support your claims.

Obtaining, Evaluating, and Communicating Information

22. Present your team's solution to the class. Describe how your system works and how it was optimized to meet the criteria. Summarize your testing process and the results.
23. Offer thoughtful and specific criticism of other teams' designs.
24. Conduct follow-up research. Do your data and observations match up with those in the studies?
25. Write a scientific question that could be asked using your proposed design solution.
26. Write a final report. Include recommendations for further changes, testing, and scientific research.

Check out these exciting new **National Geographic** features in *Environmental Science: Sustaining Your World*!

Into the Okavango with National Geographic

Join National Geographic Explorers Steve Boyes and Shah Selbe on a live-data biodiversity survey in the Okavango Delta in Africa. Home to one of the largest elephant populations in the world, this inland delta was declared the 1,000th UNESCO World Heritage Site in 2015. Let the Okavango story be your introduction to the environmental issues that shape our world today.

Citizen Science and National Geographic's BioBlitzes

Learn how to contribute to an understanding of biodiversity through citizen science, the collection and analysis of data from the natural world by the general public and scientists working together. Read about some well-known citizen science projects, including National Geographic's collaboration with the National Parks Service to host student-conducted species inventories in U.S. national parks—most recently, Hawai`i Volcanoes National Park (shown here).

Partners in Sustainability: Nature Museums and Preserves

Meet some great resources for the study of natural history and the environment! National Geographic works with many natural history museums and nature preserves to champion conservation. These organizations often make field guides, walking maps, species specimens, and research archives available to anyone who's interested—and best of all, many are right in your neighborhood.

Monterey Bay Aquarium

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