CHAPTER

5

Environmental Systems and Ecosystem Ecology

CENTRAL
case study

Saving the Chesapeake Bay Ecosystem

> **I'm 60. Danny's 58. We're the young ones.**
> Grant Corbin, Oysterman in Deal Island, Maryland

> **The Chesapeake Bay continues to be in serious trouble. And it's really no question why this is occurring. For decades, we simply did not manage the bay as a system the way science told us we must. Now all that is changing, and the bay is responding positively. The challenge is to keep it going!**
> Will Baker, President, Chesapeake Bay Foundation

A visit to Deal Island, Maryland, on the Chesapeake Bay reveals a situation that is all too common in modern America: The island, which was once bustling with productive industries and growing populations, is falling into decline. Economic opportunities in the community are few, and its populace is shrinking and "graying" as more and more young people leave to find work elsewhere. In 1930, Deal Island had a population of 1237 residents. In 2010, it was a mere 471 people.

Unlike other parts of the country with similar stories of economic decline, the demise of Deal Island and other bayside towns was not caused by the closing of a local factory, steel mill, or corporate headquarters; it was caused by the collapse of the Chesapeake Bay oyster fishery.

The Chesapeake Bay was once a thriving system of interacting microbes, plants, and animals, including economically important blue crabs, scallops, and fish. Nutrients carried to the bay by streams in its roughly 168,000 km^2 (64,000 mi^2) drainage basin, or **watershed**—the land area that funnels water to a given body of water—nourished fields of underwater grasses that provided food and refuge to juvenile fish, shellfish, and crabs. Hundreds of millions of oysters kept the bay clear by filtering nutrients and phytoplankton (microscopic photosynthetic organisms that drift near the surface) from the water column.

Oysters had been eaten locally for thousands of years by Native Americans and later by early European settlers, but the intensive harvest of bay oysters for export began in the 1830s. By the 1880s, the bay boasted the world's largest oyster fishery. People flocked to the Chesapeake to work on oystering ships or in canneries, dockyards, and shipyards. Bayside towns like Deal Island prospered along with the oyster industry and developed a unique maritime culture that defined the region.

But by 2010, the bay's oyster populations had been reduced to a mere 1% of their abundance prior to commercial harvesting, and the oyster industry in the area was all but wiped out. Perpetual overharvesting, habitat destruction, virulent oyster diseases, and water pollution had nearly eradicated this economically and ecologically important organism from bay waters. The monetary losses associated with the oyster fishery collapse have been staggering, costing the economies of Maryland and Virginia an estimated $4 billion over the last 40 years.

◄ **Chesapeake Bay oystermen hauling in their catch**

▲ **Sorting oysters from the Chesapeake Bay**

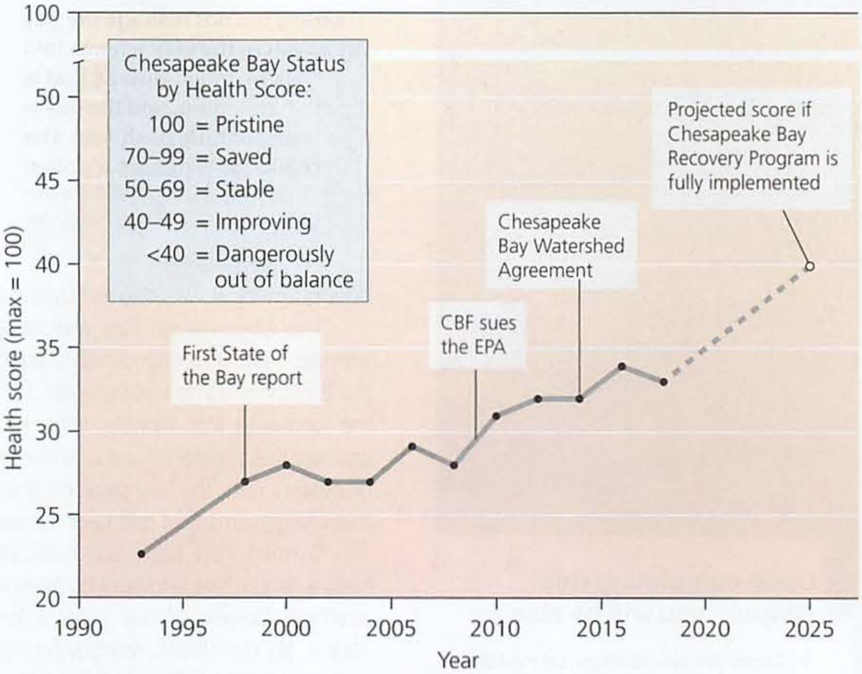
Upon completing this chapter, you will be able to:

- **Describe environmental systems**
- **Define ecosystems and discuss how living and nonliving entities interact in ecosystem-level ecology**
- **Outline the fundamentals of landscape ecology and ecological modeling**
- **Explain ecosystem services and describe how they benefit our lives**
- **Compare and contrast how water, carbon, nitrogen, and phosphorus cycle through the environment and explain how human activities affect these cycles**

One of the biggest impacts on oyster populations in recent decades is the pollution of the Chesapeake Bay by high levels of nutrient runoff, specifically nitrogen and phosphorus from agricultural fertilizers, animal manure, stormwater, and atmospheric compounds produced by fossil fuel combustion. With so few oysters in the bay, elevated nutrient levels have caused phytoplankton populations to increase.

When excessive amounts of phytoplankton die due to overcrowding and competition, they naturally settle to the bay bottom. Once there, they are decomposed by bacteria, a process that consumes dissolved oxygen, causing chronic oxygen depletion of the water, a condition called **hypoxia.** Vast areas of hypoxia in a body of water are referred to as "dead zones." Grasses, oysters, crabs, fish, and other organisms are perishing in dead zones of the Chesapeake Bay or are forced into other areas of the bay. Hypoxia and other human impacts landed the Chesapeake Bay on the Environmental Protection Agency's list of dangerously polluted waters in the United States.

After 25 years of failed pollution control agreements and nearly $6 billion spent on cleanup efforts, the Chesapeake Bay Foundation (CBF), a non-profit organization dedicated to conserving the bay, sued the Environmental Protection Agency (EPA) in 2009 for failing to use its available powers under the Clean Water Act to clean up the bay. The lawsuit instigated federal action, and in 2010, a comprehensive "pollution budget" and restoration plan was developed and implemented by the EPA with the assistance of the District of Columbia, Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia. Unlike previous approaches at restoration that only focused on parts of the Chesapeake Bay, the Chesapeake Bay Watershed Agreement (formalized in 2014) took the holistic approach that a system as complicated as the Chesapeake demanded (**FIGURE 5.1**).



	Indicator	2018 score	Change from 2016	Change from 1998
POLLUTION	Nitrogen	12	–5	–3
	Phosphorus	19	–9	+4
	Dissolved Oxygen	42	+2	+27
	Water Clarity	16	–4	–4
	Toxics	28	0	–2
HABITAT	Forest Buffers	57	0	+4
	Wetlands	42	0	–1
	Underwater Grasses	25	+1	+13
	Resource Lands	33	+1	n/a
FISHERIES	Rockfish	66	0	–4
	Blue Crabs	55	0	+5
	Oysters	10	0	+9
	Shad	10	–1	+8

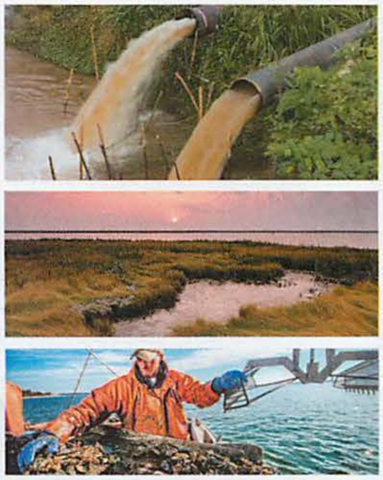


FIGURE 5.1 After a decade of very little improvement, the Chesapeake Bay is finally progressing toward recovery. Numerous parameters that measure the health of the bay—such as nutrient inputs, water quality, and the status of fisheries—are trending upward in recent decades and hope to accelerate in the coming years under a comprehensive management plan. *Data from Chesapeake Bay Foundation, 2016 and 2018 State of the Bay Reports.*

This systemic approach to restoring the Chesapeake Bay appears to be succeeding as the bay's overall health has improved. The system was challenged in 2018, when record rainfall in its watershed flushed large amounts of plant nutrients into the bay. This elevated nitrogen and phosphorus concentrations in bay waters and reduced water clarity as phytoplankton populations increased and eroded soil clouded the water. But even in the face of these conditions, the bay's fisheries, its fields of underwater grasses, and the concentrations of dissolved oxygen in its waters remained stable or improved from 2016, indicating the ecological functioning of the bay is stronger. The bay is now better able to deal with adverse conditions, like those in 2018, without collapsing. Furthermore, oyster restoration efforts are finally showing promise in the Chesapeake (see **THE SCIENCE BEHIND THE STORY**, pp. 112–113), further enhancing the resiliency of the Chesapeake Bay system. If these initiatives can begin to restore the bay to health, Deal Island and other oyster-fishing communities may again enjoy the prosperity they once did on the scenic shores of the Chesapeake.

Earth's Environmental Systems

Understanding the recovery of the Chesapeake Bay involves comprehending the complex, interlinked systems that make up Earth's environment. A **system** is a network of relationships among parts, elements, or components that interact with and influence one another through the exchange of energy, matter, or information. Earth's natural systems include processes that shape the landscape, affect planetary climate, govern interactions between species and the nonliving entities around them, and cycle chemical elements vital to life. Because we depend on these systems and processes for our very survival, understanding how they function and how human activities affect them is an important aspect of environmental science.

System boundaries are often difficult to delineate

There are many ways to delineate natural systems. For instance, scientists sometimes divide Earth's components into "structural spheres" to help make our planet's dazzling complexity comprehensible. The **lithosphere** (p. 35) is the rock and sediment beneath our feet, the planet's uppermost mantle and crust. The **atmosphere** (p. 452) is composed of the air surrounding our planet. The **hydrosphere** encompasses all water—salt or fresh, liquid, ice, or vapor—in surface bodies, underground, and in the atmosphere. The **biosphere** (p. 60) consists of all the planet's organisms and the abiotic (nonliving) portions of the environment with which they interact.

Beyond these broad spheres, natural systems seldom have well-defined boundaries, so deciding where one system ends and another begins can be difficult. Consider a smartphone. It is certainly a system—a network of circuits and parts that interact and exchange energy and information—but where are its boundaries? Is the system merely the phone itself, or does it include the other phones you call and text, the websites you access on it, and the cellular networks that keep it connected? What about the energy grid that recharges the phone's battery, with its transmission lines and distant power plants?

No matter how we attempt to isolate or define a system, we soon see that it has connections to systems larger and smaller than itself. Systems may exchange energy, matter, and information with other systems, and they may contain or be contained within other systems. Thus, where we draw boundaries may depend on the spatial (space) or temporal (time) scale at which we choose to focus.

Assessing questions holistically by taking a systems approach is helpful in environmental science, in which so many issues are multifaceted and complex. Taking a broad and integrative approach poses challenges, because systems often show behavior that is difficult to predict. However, environmental scientists are rising to the challenge of studying systems holistically, helping us to develop comprehensive solutions to complicated problems such as those faced in the Chesapeake Bay.

Systems exhibit several defining properties

It is difficult to understand systems fully just by focusing on their individual components because systems can have **emergent properties,** characteristics not evident in the components alone. Stating that systems possess emergent properties is a lot like saying, "The whole is more than the sum of its parts." For example, if you were to reduce a tree to its component parts (leaves, branches, trunk, bark, roots, fruit, and so on), you would not be able to predict the entire tree's emergent properties, which include the role the tree plays as habitat for birds, insects, fungi, and other organisms. You could analyze the tree's chloroplasts (photosynthetic cell organelles), diagram its branch structure, and evaluate the nutritional content of its fruit, but you would still be unable to understand the tree as habitat, as part of a forest landscape, or as a reservoir for storing carbon.

Systems involve feedback loops

Earth's environmental systems receive inputs of energy, matter, or information; process these inputs; and produce outputs. As a system, for example, the Chesapeake Bay receives inputs of freshwater, sediments, nutrients, and pollutants from the rivers that empty into it. Oystermen, crabbers, and fishermen harvest some of the bay system's output: matter and energy in the form of seafood. This output subsequently becomes input to the nation's economic system and to the body systems of people who eat the seafood.

Sometimes a system's output can serve as input to that same system, a circular process described as a **feedback loop,** which can be either negative or positive. In a **negative feedback loop** (FIGURE 5.2), output that results from a system moving in one direction acts as input that moves the system in the other direction. Input and output essentially neutralize one another's effects, stabilizing the system. As an example, negative feedback regulates body temperature in humans: If we get too hot, our sweat glands pump out water that then evaporates, which cools us down. Or, we just move into the shade. If we get too cold, we shiver, creating heat, or we just move into the sun or put on a sweater. Most systems in nature involve such negative feedback loops. Negative feedback enhances stability, and over time only those systems that are stable will persist.

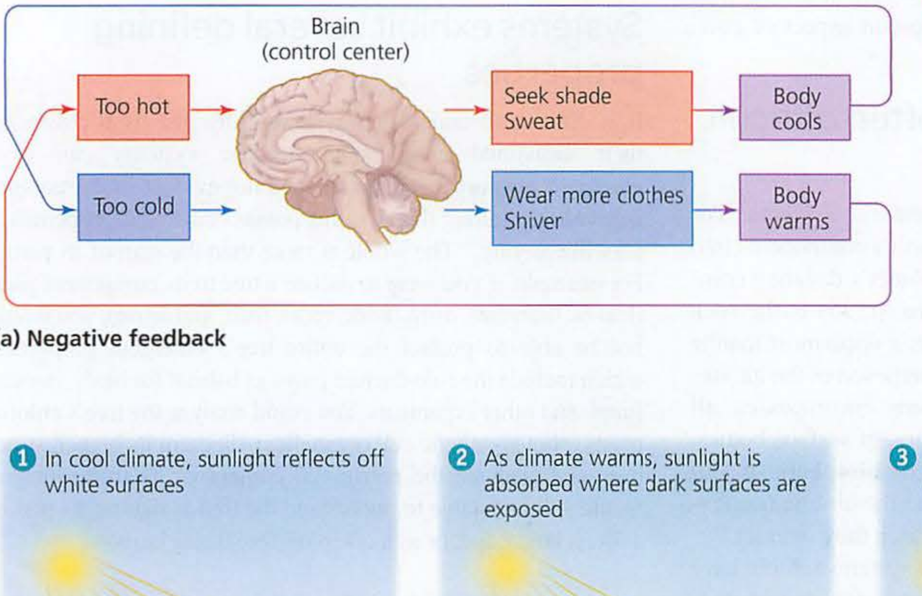
FAQ

But isn't positive feedback "good" and negative feedback "bad"?

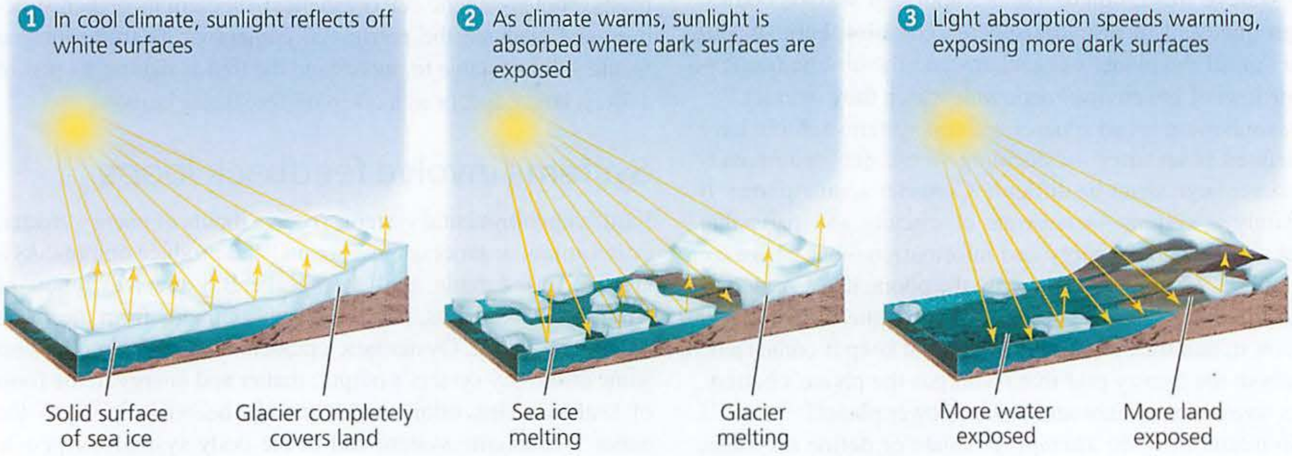
In daily life, positive feedback, such as a compliment, can act as a stabilizing force ("Keep up the good work, and you'll succeed"), whereas negative feedback, such as criticism, can act as a destabilizing force ("You need to change your approach to succeed"). But in environmental systems, it's the opposite! Negative feedback in the environment resists change in systems, enhancing stability and typically keeping conditions within ranges beneficial to life. Positive feedback in the environment, in contrast, exerts destabilizing effects that push conditions to extremes, threatening organisms adapted to the system's normal conditions.

In a system stabilized by negative feedback, when processes move in opposing directions at equivalent rates so that their effects balance out, they are said to be in **dynamic equilibrium.** Processes in dynamic equilibrium can contribute to **homeostasis,** the tendency of a system to maintain constant or stable internal conditions. A system (such as an organism) in homeostasis keeps its internal conditions within a narrow range that allows it to function. However, the steady state of a homeostatic system may itself change slowly over time. For instance, Earth has experienced gradual changes in atmospheric composition and ocean chemistry over its long history, yet life persists and our planet remains, by most definitions, a homeostatic system.

Rather than stabilizing a system, **positive feedback loops** drive the system further toward an extreme. In positive feedback, increased output from a system results in increased input, leading to further increased output, and so on. Exponential growth in a population (pp. 66–67) is one such example. The more individuals there are, the more offspring that can be produced. Another positive feedback cycle that is of great concern to environmental scientists today involves the melting of glaciers and sea ice in the Arctic as a result of global warming (p. 487). Because ice and snow are white, they reflect sunlight and keep surfaces cool. But if the climate



(a) Negative feedback



(b) Positive feedback

FIGURE 5.2 **Feedback loops can stabilize or destabilize systems. (a)** The human body's response to heat and cold involves a negative feedback loop that keeps core body temperatures relatively stable. Positive feedback loops **(b)** push systems away from equilibrium. For example, when Arctic glaciers and sea ice melt because of global warming, darker surfaces are exposed, which absorb more sunlight, causing further warming and further melting.

warms enough to melt the ice and snow, darker surfaces of land and water are exposed, and these darker surfaces absorb sunlight. This absorption warms the surface, causing further melting, which, in turn, exposes more dark surface area, leading to further warming.

Runaway cycles of positive feedback are rare in untouched nature, but they are common in natural systems altered by human activities, and such feedback loops can destabilize those systems. In the Chesapeake Bay, for example, oysters clean the bay's water by filtering phytoplankton, sediments, and nutrients from the water column. When oyster populations were decimated by overharvesting, however, water filtration by oysters declined. With less filtering, concentrations of nutrients and sediments increased in bay waters. Spurred by elevated nutrient levels, phytoplankton populations in the bay exploded, causing hypoxia on the bay bottom and killing many of the remaining oysters. This additional oyster mortality further reduced water filtration in the bay, leading to worsening water quality and even more oyster deaths.

Environmental systems interact

The Chesapeake Bay and the rivers that empty into it provide an example of how systems interact. On a map, the rivers that feed into the bay are a branched and braided network of water channels surrounded by farms, cities, and forests (**FIGURE 5.3**). But where are the boundaries of this system? For a scientist interested in **runoff**—the precipitation that flows over land and enters waterways—and the flow of water, sediment, or pollutants, it may make the most sense to define the bay's watershed as the system. However, for a scientist interested in hypoxia and the bay's dead zones, it may be best to define the watershed together with the bay itself as the system of interest, because their interaction is central to the problem being investigated. Thus, in environmental science, identifying the boundaries of systems depends on the questions being asked.

If the question we are asking about the Chesapeake Bay relates to the dead zones in the bay, then we'll want to define the boundaries of the system to include both the bay's watershed and its **airshed,** the geographic area that produces air pollutants that are likely to end up in a waterway. The hypoxic zones in the bay are due to the extremely high levels of nitrogen and phosphorus delivered to its waters from the 6 states in its watershed and the 15 states in its airshed. In 2017, the bay received an estimated 115 million kg (254 million lb) of nitrogen and 6.8 million kg (15 million lb) of phosphorus. Runoff from agriculture was a major source of these nutrients,

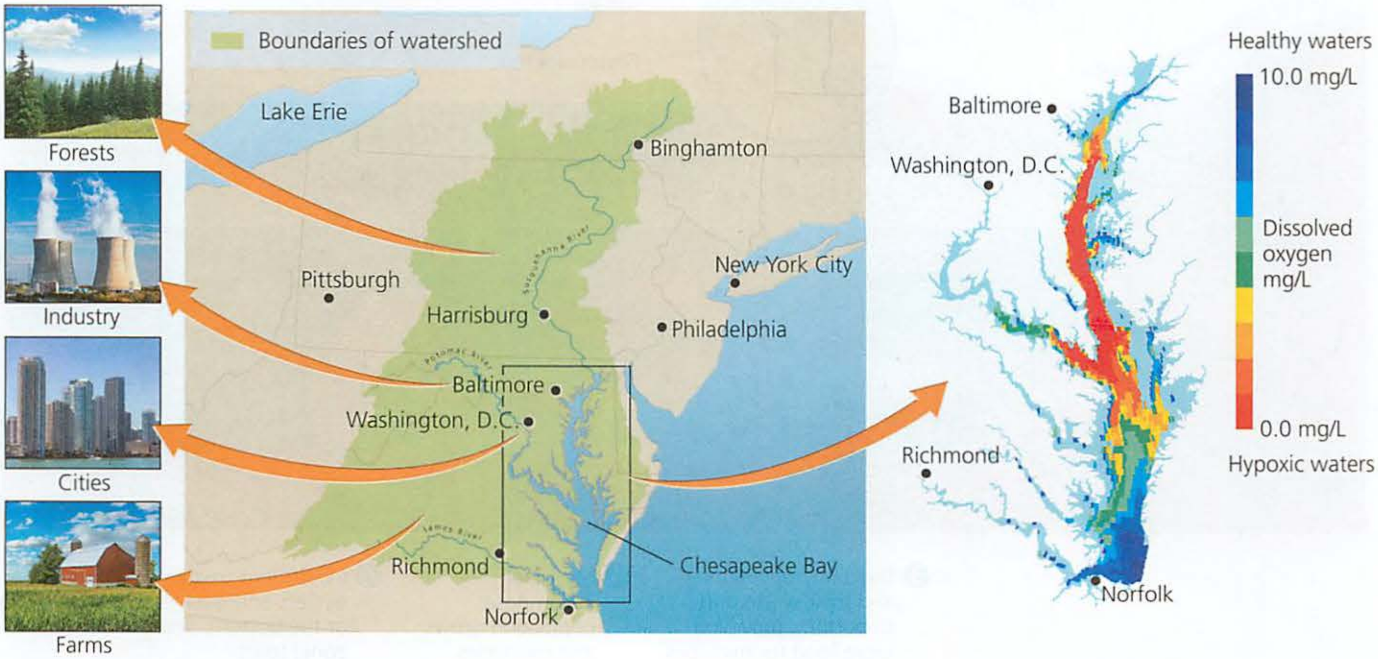
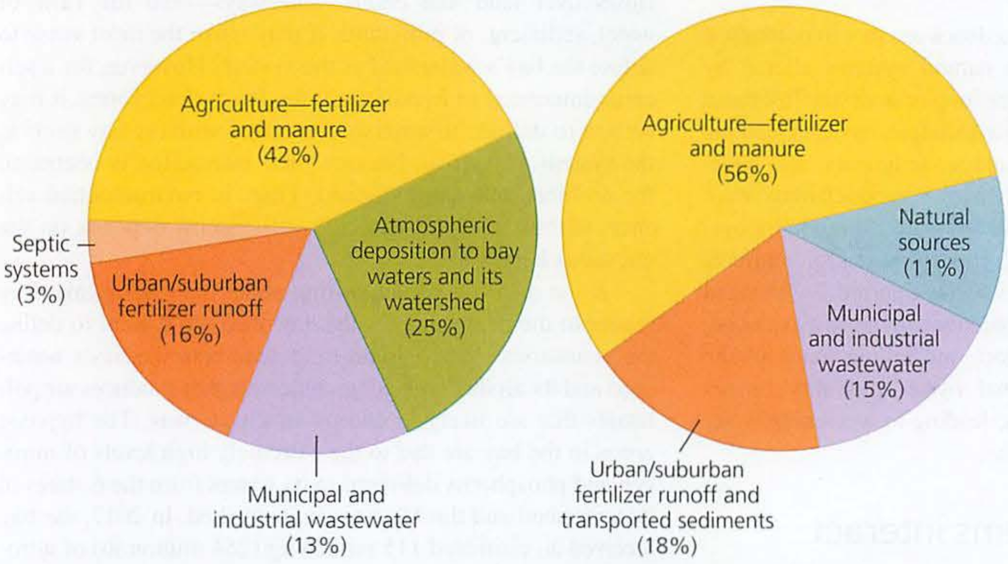


FIGURE 5.3 The Chesapeake Bay watershed encompasses 168,000 km^2 (65,000 mi^2) of land area in 6 states and the District of Columbia. Tens of thousands of streams carry water, sediment, and pollutants from a variety of sources downriver to the Chesapeake, where nutrient pollution has given rise to large areas of hypoxic waters. The zoomed-in map (**at right**) shows dissolved oxygen concentrations in the Chesapeake Bay in 2017. Oysters, crabs, and fish typically require a minimum 3 mg/L of oxygen and are therefore excluded from large portions of the bay where oxygen levels are too low. *Source for figure at right: Marjorie Friedrichs (Virginia Institute of Marine Sciences) and Aaron Bever (Anchor QEA).*

contributing 42% of the nitrogen (**FIGURE 5.4a**) and 56% of the phosphorus (**FIGURE 5.4b**) entering the bay. One-fourth of nitrogen inputs come from atmospheric nitrogenous pollutants released by vehicles and coal-burning power plants.

Elevated nitrogen and phosphorus inputs cause phytoplankton in the bay's waters to flourish. High phytoplankton density leads to elevated mortality as individuals compete for sunlight and nutrients. Dead phytoplankton drift to the bottom of the bay where they are joined by the waste products of zooplankton, tiny creatures that feed on phytoplankton. This increase in organic material on the bay bottom causes an explosion in populations of bacterial decomposers, which deplete the oxygen in bottom waters as they consume the organic matter. Deprived of oxygen, organisms will either flee the area or suffocate. The process of nutrient overenrichment, blooms of phytoplankton, increased production of organic matter, and subsequent ecosystem degradation is known as **eutrophication** (**FIGURE 5.5**).



(a) Sources of nitrogen entering the Chesapeake Bay

(b) Sources of phosphorus entering the Chesapeake Bay

FIGURE 5.4 The Chesapeake Bay receives inputs of (a) nitrogen and (b) phosphorus from many sources in its watershed. *Data from Chesapeake Bay Program, Watershed Model Phase 5.3.2 (Chesapeake Bay Program Office, 2018). Totals for nitrogen do not equal 100% due to rounding.*

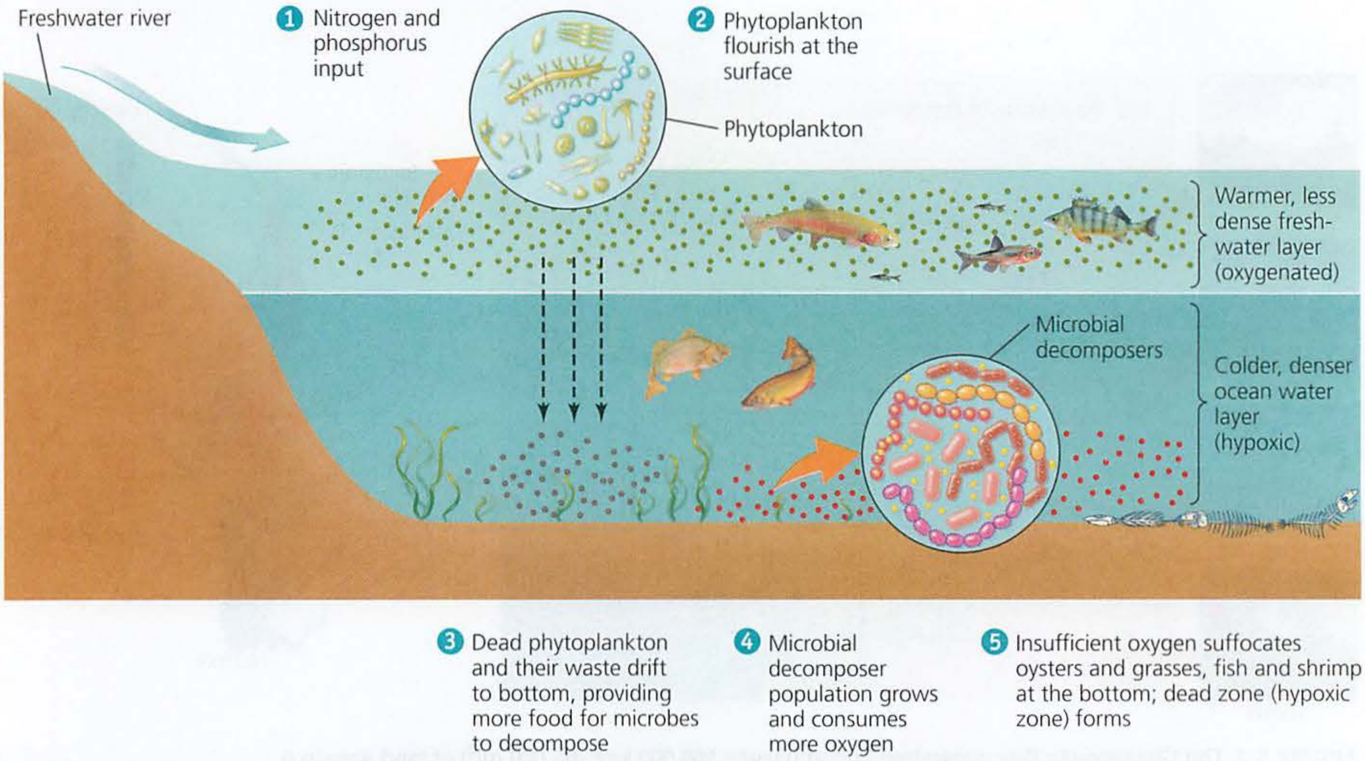


FIGURE 5.5 Excess nitrogen and phosphorus cause eutrophication in aquatic systems such as the Chesapeake Bay. Coupled with stratification (layering) of water, eutrophication can severely deplete dissolved oxygen. ① Nutrients from river water ② boost growth of phytoplankton, ③ which die and are decomposed at the bottom by bacteria. Stability of the surface layer prevents deeper water from absorbing oxygen to replace ④ oxygen consumed by decomposers, and ⑤ the oxygen depletion suffocates or drives away bottom-dwelling marine life. The process of eutrophication occurs in both freshwater and marine environments and gives rise to large areas of hypoxic waters.

Once oxygen levels at the bottom of the bay are depleted, they are slow to recover. Oxygenated fresh water entering the bay from rivers remains stratified in a layer at the surface and is slow to mix with the denser, saltier bay water, limiting the amount of oxygenated surface water that reaches the bottom-dwelling life that needs it. As a result, sedentary creatures living on the bay bottom, such as oysters, suffocate and die.

Ecosystems

An **ecosystem** consists of all organisms and nonliving entities that occur and interact in a particular area at the same time. Animals, plants, water, soil, nutrients—all these and more compose ecosystems. The ecosystem concept builds on the idea of the biological community (Chapter 4), but ecosystems include abiotic components, as well as biotic ones.

The ecosystem concept originated with scientists who recognized that biological entities are tightly intertwined with the chemical and physical aspects of their environment. For instance, in the Chesapeake Bay **estuary**—a water body where rivers flow into the ocean, mixing fresh water with saltwater—aquatic organisms are affected by the flow of water, sediment, and nutrients from the rivers that feed the bay and from the land that feeds those rivers. In turn, the photosynthesis, respiration, and decomposition that these organisms undergo influence the chemical and physical conditions of the Chesapeake's waters.

Ecologists soon began analyzing ecosystems as an engineer might analyze the operation of a machine. In this view, ecosystems are systems that receive inputs of energy, process and transform that energy while cycling various types of matter, and produce outputs (such as heat, water flow, and waste products) that then enter other ecosystems.

Energy flows and matter cycles through ecosystems

Energy flows in one direction through ecosystems. As autotrophs, such as green plants and phytoplankton, convert solar energy to the energy of chemical bonds in sugar through the process of photosynthesis, they perform **primary production.** The total amount of chemical energy produced by autotrophs is termed **gross primary production.** Autotrophs use most of this production to power their own metabolism by cellular respiration, releasing heat energy to the environment as a by-product. The energy that remains after respiration and that is used to generate biomass (such as leaves, stems, and roots) is called **net primary production.** Thus, net primary production equals gross primary production minus the energy used in cellular respiration.

Some plant biomass is subsequently eaten by herbivores, which use the energy they gain from plant biomass for their own metabolism or to generate biomass in their bodies (such as skin, muscle, or bone), termed **secondary production.** Herbivores are then eaten by higher-level consumers, which are, in turn, eaten by yet higher-level consumers. Thus, the chemical energy formed by photosynthesis in plants provides energy to higher and higher levels of consumers. The vast majority of this chemical energy is eventually released to the environment as heat when it is metabolized by producers, consumers, or decomposers (**FIGURE 5.6**). Some of the chemical energy from biomass is not released as heat but rather as low energy from chemical bonds, such as when the chemical bonds break between carbon and oxygen atoms in a molecule of carbon dioxide as a by-product of cellular respiration. Then, when producers and consumers die, their biomass is consumed and metabolized by detritivores and decomposers.

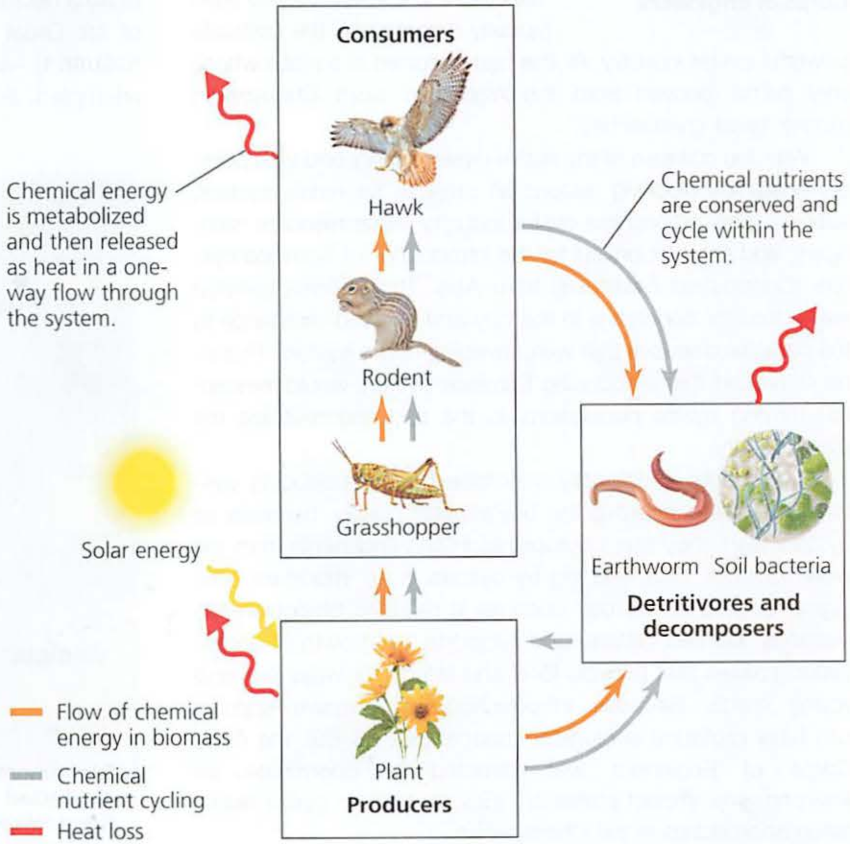


FIGURE 5.6 In ecosystems, energy flows in one direction, whereas chemical nutrients cycle. Light energy from the sun (**yellow arrow**) drives photosynthesis in producers, which begins the transfer of chemical energy in biomass (**orange arrows**) among trophic levels (pp. 81–82) and detritivores and decomposers. Energy exits the system through respiration in the form of heat (**red arrows**). Chemical nutrients (**gray arrows**) cycle within the system. For simplicity, various abiotic components (such as water, air, and inorganic soil content) of ecosystems have been omitted.

→ Go to **Process of Science** on **Mastering Environmental Science**

THE SCIENCE **behind** the **story**

Are We "Turning the Tide" for Native Oysters in Chesapeake Bay?

David Schulte, U.S. Army Corps of Engineers

Back in 2001, the Eastern oyster (*Crassostrea virginica*) was in dire trouble in the Chesapeake Bay. Populations had dropped by 99%, and the Chesapeake's oyster industry, once the largest in the world, had collapsed. Poor water quality, reef destruction, virulent diseases spread by transplanted oysters, and 200 years of overharvesting all contributed to the collapse.

Restoration efforts had largely failed. Moreover, when scientists or resource managers proposed rebuilding oyster populations by significantly restricting oyster harvests or establishing oyster reef "sanctuaries," these initiatives were typically defeated by the politically powerful oyster industry. All this had occurred in a place whose very name (derived from the Algonquin word *Chesepiook*) means "great shellfish bay."

With the collapse of the native oyster fishery and with political obstacles blocking restoration projects for native oysters, support grew among the oyster industry, state resource managers, and some scientists for the introduction of Suminoe oysters (*Crassostrea ariakensis*) from Asia. This species seemed well suited for conditions in the bay and showed resistance to the parasitic diseases that were ravaging native oysters. Proponents argued that introducing Suminoe oysters would reestablish thriving oyster populations in the bay and revitalize the oyster fishery.

Proponents additionally maintained that introducing oysters would also improve the bay's water quality, because as oysters feed, they filter phytoplankton and sediments from the water column. Filter-feeding by oysters is an important ecological service in the bay because it reduces phytoplankton densities, clarifies waters, and supports the growth of underwater grasses that provide food and refuge for waterfowl and young crabs. Because introductions of invasive species can have profound ecological impacts (pp. 88–89), the Army Corps of Engineers was directed to coordinate an environmental impact statement (EIS, p. 172) on oyster restoration approaches in the Chesapeake.

It was in this politically charged, high-stakes environment that Dave Schulte, a scientist with the Corps and doctoral student at the College of William and Mary, set out to determine whether there was a viable approach to restoring native oyster populations. The work he and his team began would help turn the tide in favor of native oysters in the bay's restoration efforts.

One of the biggest impacts on native oysters was the destruction of oyster reefs by a century of intensive oyster harvesting. Oysters settle and grow best on the shells of other oysters, and over long periods this process forms reefs (underwater outcrops of living oysters and oyster shells) that solidify and become as hard as stone. Throughout the bay, massive reefs that at one time had jutted out of the water at low tide had been reduced to rubble on the bottom from a century of repeated scouring by metal dredgers used by oyster-harvesting ships. The key, Schulte realized, was to construct artificial reefs like those that once existed, to get oysters off the bottom—away from smothering sediments and hypoxic waters—and up into the plankton-rich upper waters.

In 2004, armed with the resources available to the Corps, Schulte opted to take a landscape ecology approach to restore patches of reef habitat on 9 complexes of reefs, creating a total of 35.3 hectares (87 acres) of oyster sanctuary near the mouth of the Great Wicomico River in the lower Chesapeake Bay (**FIGURE 1**)—a much larger restoration effort than any previously attempted. Schulte and his team constructed artificial reefs by

FIGURE 1 **Schulte's study was conducted in the Great Wicomico River in Virginia in the lower Chesapeake Bay.**

FIGURE 2 **A water cannon blows oyster shells off a barge and onto the river bottom to create an artificial oyster reef for the experiment.**

spraying oyster shells off barges (**FIGURE 2**). The oyster shells then drifted to the river bottom, forming high-relief reefs in which shells were piled to create a reef that was 25–45 cm (10–18 in.) above the river bottom. They also created low-relief reefs, with shells piled to 8–12 cm (3–5 in.) above the river bottom, that the oysters could colonize, safe from harvesting. Other areas of the river bottom were "unrestored" and left in their natural state.

Oyster populations on the constructed reefs were sampled in 2007, and the results were stunning. The reef complex supported an estimated 185 million oysters, a number nearly as large as the wild population of 200 million oysters estimated to live at that time on the remaining degraded habitat in all of Maryland's waters. Higher constructed reefs supported an average of more than 1000 oysters per square meter—four times more than the lower constructed reefs and 170 times more than unrestored bottom (**FIGURE 3**). Like natural reefs, the constructed reefs began to solidify, providing a firm foundation for the settlement of spat—young, newly settled oysters. In 2009, Schulte's research made a splash when his team published its findings in the journal *Science*, bringing international attention to their study.

After reviewing eight alternative approaches to oyster restoration that involved one or more oyster species, the Corps advocated an approach that avoided the introduction of non-native oysters. Instead, it proposed a combination of native oyster restoration, a temporary moratorium on oyster harvests (accompanied by a compensation program for the oyster industry), and enhanced support for oyster aquaculture in the bay region.

Schulte's restoration project cost roughly $3 million and will require substantial investments if it is to be repeated elsewhere in the bay. This is particularly true in upper portions of the bay, where water conditions are poorer, the oysters are less resistant to disease, and oyster reproduction levels are lower, requiring restored reefs to be "seeded" with oysters. Many scientists contend that expanded reef restoration efforts are worth the cost because they enhance oyster populations and provide a vital service to the bay through water filtering. Some scientists also see value in promoting oyster farming, in which restoration efforts would be supported by businesses instead of taxpayers.

These efforts are encouraged by the continued success of the project. By the summer of 2016, the majority of high-relief reef acreage was thriving, despite pressures from poachers and several years of hypoxic conditions. Moreover, many of the low-relief reefs that were originally constructed eventually accumulated enough new shell to be as tall as the high-relief reefs in the initial experiment—the reef treatment that showed the highest oyster densities in the original experiment. Furthermore, oyster reproduction rates in 2012 were among the highest Schulte had seen during the project, and a follow-up study in 2013 found that spat from the sanctuary reefs were seeding other parts of the Great Wicomico River and increasing oyster populations outside protected areas.

Protected sites for oyster restoration efforts are now being established elsewhere in the bay. Maryland recently designated 3640 hectares (9000 acres) of new oyster sanctuaries—25% of existing oyster reefs in state waters—and seeded these reefs with more than a billion hatchery-raised spat. This movement toward increased protection for oyster populations, coupled with findings of increased disease resistance in bay oysters, has given new hope that native oysters may once again thrive in the waters of the "great shellfish bay."

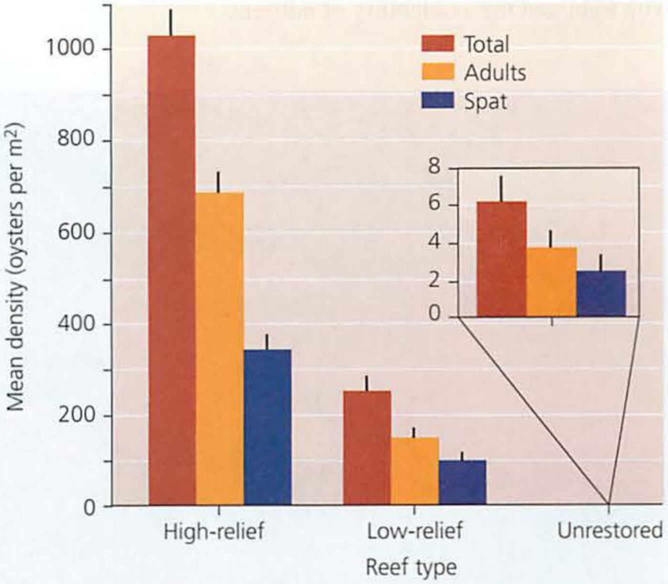


FIGURE 3 **Reef height had a profound effect on the density of adult oysters and spat (newly settled oysters).** Schulte's work suggested that native oyster populations could rebound in portions of Chesapeake Bay if they were provided with elevated reefs and protected from harvest. *Data from Schulte, D. M., R. P. Burke, and R. N. Lipicus, 2009. Unprecedented restoration of a native oyster metapopulation.* Science *325: 1124–1128.*

In contrast to chemical energy, nutrients and other types of matter are generally recycled within ecosystems. Chemical nutrients are recycled because when organisms die and decay, the matter that comprises their body remains in the system.

Ecosystems vary in their productivity

Another way to think of net primary production is that it represents the energy or biomass available for consumption by heterotrophs, organisms that obtain energy by feeding on other organisms. Some plant biomass is eaten by herbivores. Heterotrophs use the energy they gain from plant biomass for their own metabolism, growth, and reproduction. Some of this energy is used by heterotrophs to generate biomass in their bodies (such as skin, muscle, or bone), which is termed secondary production. Plant matter not eaten by herbivores becomes fodder for detritivores and decomposers once the plant dies or drops its leaves.

Ecosystems vary in the rate at which autotrophs convert energy to biomass. The rate at which this conversion occurs is termed **productivity,** and ecosystems whose plants convert solar energy to biomass rapidly are said to have high **net primaryproductivity.** Freshwater wetlands, tropical forests, coral reefs, and algal beds tend to have the highest net primary productivities, whereas deserts, tundra, and open ocean tend to have the lowest (**FIGURE 5.7**). Variation among ecosystems and among biomes (Chapter 4) in net primary productivity results in geographic patterns across the globe (**FIGURE 5.8**). In terrestrial ecosystems, net primary productivity tends to increase with temperature and precipitation. In aquatic ecosystems, net primary productivity tends to rise with light and the availability of nutrients.

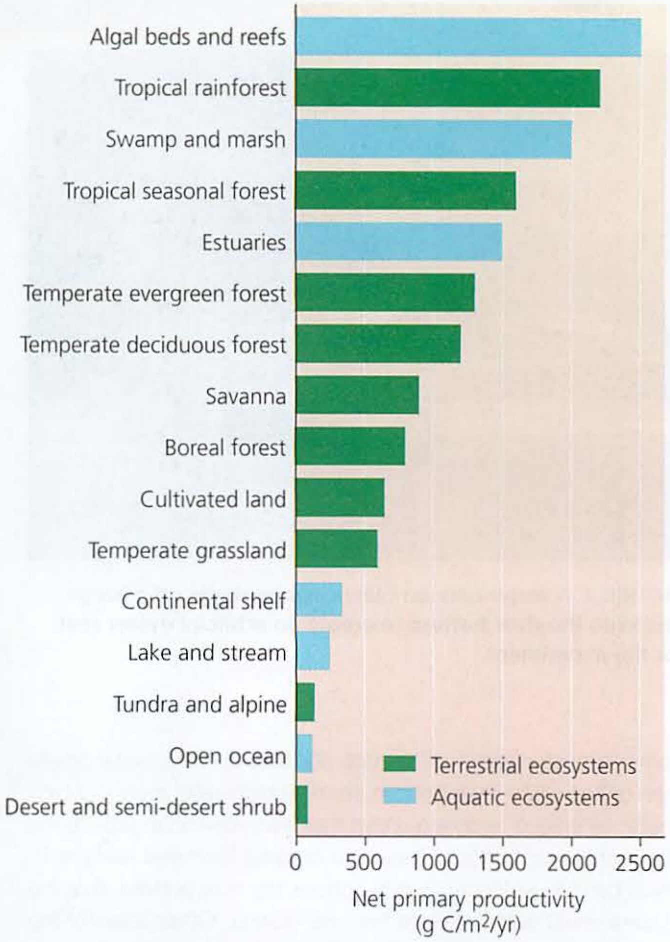


FIGURE 5.7 Net primary productivity varies greatly between ecosystem types. *Data from Whittaker, R. H., 1975.* Communities and ecosystems, *2nd ed. New York, NY: Macmillan.*

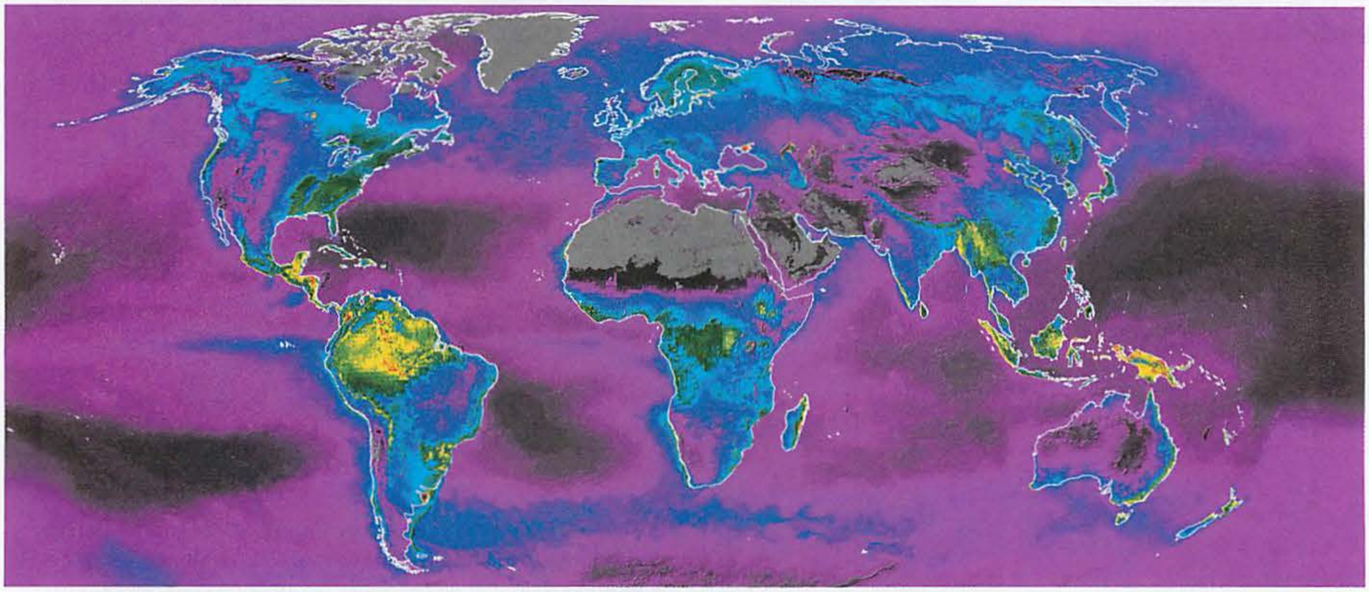


FIGURE 5.8 Net primary production on land varies geographically according to temperature, precipitation, and land use (such as for agriculture, urban development, and forestry). In the world's oceans, net primary production is highest around the margins of continents, where nutrients (of both natural and human origin) run off from land. *Data from NASA, https://science.nasa.gov/earth-science/oceanography/living-ocean/remote-sensing.*

Nutrient availability influences productivity

Nutrients (p. 25) are elements and compounds that organisms require for survival. Organisms need several dozen naturally occurring nutrients to survive. Elements and compounds required in relatively large amounts, such as nitrogen, carbon, and phosphorus, are called **macronutrients.** Nutrients needed in small amounts, such as zinc, copper, and iron, are called **micronutrients.**

Nutrients stimulate production by plants, and lack of nutrients can limit production. The availability of nitrogen or phosphorus frequently is a limiting factor (p. 67) for the growth of photosynthetic organisms. When these nutrients are added to a system, producers show the greatest response to whichever nutrient has been in shortest supply.

Canadian ecologist David Schindler and others demonstrated the effects of phosphorus on freshwater systems in the 1970s by experimentally manipulating entire lakes. In one experiment, his team bisected a 16-ha (40-acre) lake in Ontario with a plastic barrier. To one-half the researchers added carbon, nitrate, and phosphate; to the other they added only carbon and nitrate. Soon after the experiment began, they witnessed a dramatic increase in phytoplankton in the half of the lake that received phosphate, whereas the other half (the control for the experiment, p. 10) continued to host phytoplankton levels typical for lakes in the region (**FIGURE 5.9**). This difference held until shortly after they stopped fertilizing seven years later. At that point, phytoplankton decreased to normal levels in the half that had previously received phosphate.

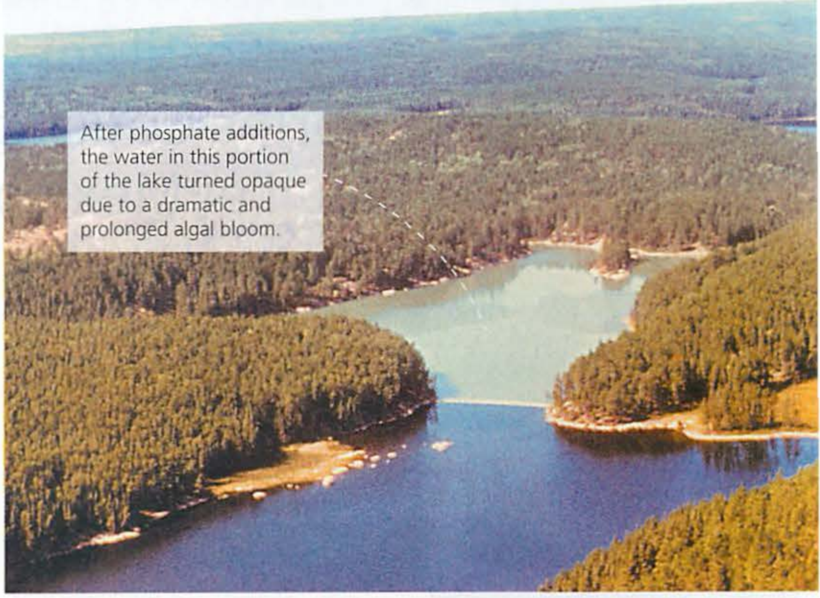

After phosphate additions, the water in this portion of the lake turned opaque due to a dramatic and prolonged algal bloom.

FIGURE 5.9 The upper portion of this lake in Ontario was experimentally treated with the addition of phosphate. This treated portion experienced an immediate, dramatic, and prolonged phytoplankton bloom, identifiable by its opaque waters.

The Chesapeake Bay is not the only water body suffering from eutrophication. Nutrient pollution has led to more than 475 documented hypoxic dead zones (**FIGURE 5.10**), including one that forms each year near the mouth of the Mississippi River (see **THE SCIENCE BEHIND THE STORY**, pp. 116–117). Some are seasonal (like the Chesapeake Bay's), some occur irregularly, and others are permanent. The increase in the number of dead zones—there were 162 documented in the 1980s and only 49 in the 1960s—reflects how human activities are changing the chemistry of waters around the world.

The good news is that in locations where people have reduced nutrient runoff, hypoxic zones have begun to disappear.

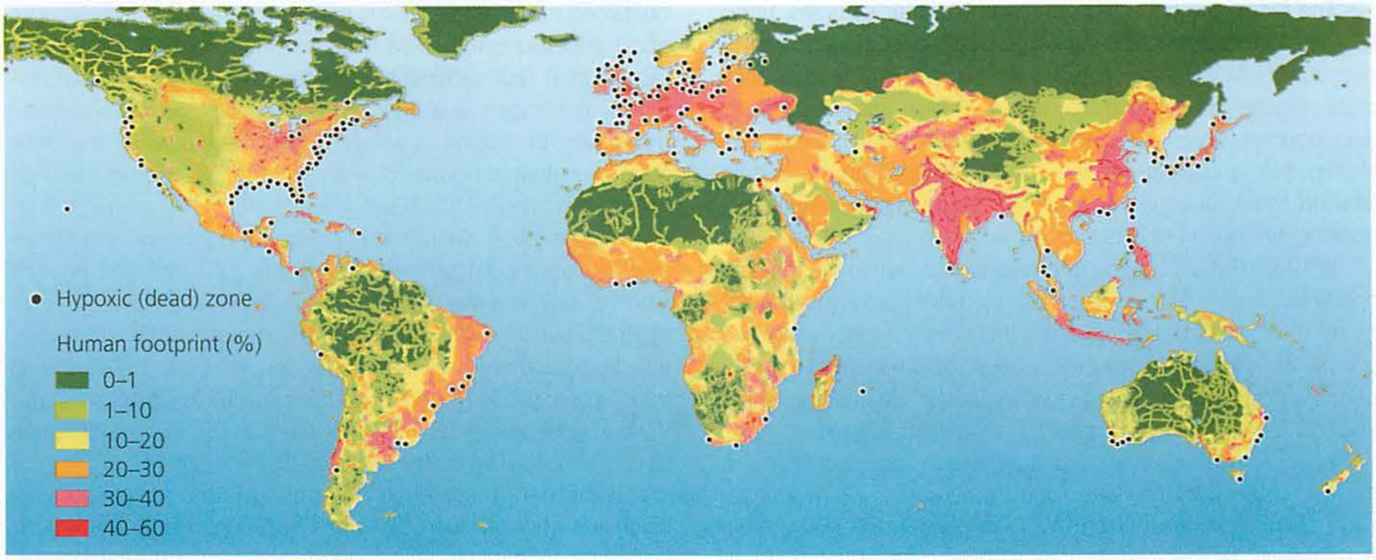


FIGURE 5.10 More than 475 marine dead zones have been recorded across the world. Dead zones (shown by dots on the map) occur mostly offshore from areas of land with the greatest human ecological footprints (here, expressed on a scale of 0 to 100, with higher numbers indicating bigger human footprints). *Data from World Resources Institute, 2018, www.wri.org/our-work/project/eutrophication-and-hypoxia, and Diaz, R. and R. Rosenberg, 2008. Spreading dead zones and consequences for marine ecosystems.* Science *321: 926–929. Reprinted with permission from AAAS.*

THE SCIENCE **behind** the **story**

Are Fertilizers from Midwestern Farms Causing a "Dead Zone" in the Gulf of Mexico?

Dr. Nancy Rabalais, LUMCON

She was prone to seasickness, but Nancy Rabalais cared too much about the Gulf of Mexico to let that stop her. Leaning over the side of an open boat idling miles from shore, she hauled a water sample aboard—and helped launch efforts to breathe life back into the Gulf's "dead zone."

Since that first expedition in 1985, Rabalais, her colleague and husband Eugene Turner, and fellow scientists at the Louisiana Universities Marine Consortium (LUMCON) and Louisiana State University have made great progress in unraveling the mysteries of the region's hypoxia—and in getting it on the political radar screen.

Rabalais and other researchers began by tracking oxygen levels at nine sites in the Gulf every month and continued those measurements for five years. At dozens of other spots near the shore and in deep water, they took less frequent oxygen readings. Sensors, as they are lowered into the water, measure oxygen levels and send continuous readings back to a shipboard computer. Further data come from fixed, submerged oxygen meters that continuously measure dissolved oxygen and store the data.

The team also collected hundreds of water samples, using lab tests to measure levels of nitrogen, salt, bacteria, and phytoplankton. LUMCON scientists logged hundreds of miles in their ships, regularly monitoring more than 70 sites in the Gulf. They also donned scuba gear to view firsthand the condition of shrimp, fish, and other sea life. Such a range of long-term data allowed the researchers to build a "map" of the dead zone, tracking its location and its consequences.

In 1991, Rabalais made that map public, earning immediate headlines. That year, her group mapped the size of the zone at more than 10,000 km^2 (about 4000 mi^2). Bottom-dwelling shrimp were stretching out of their burrows, straining for oxygen. Many fish had fled. The bottom waters, infused with sulfur from bacterial decomposition, smelled like rotten eggs.

The group's years of monitoring also enabled them to explain and predict the dead zone's emergence. As rivers rose each spring (and as fertilizers were applied in the Midwestern farm states), oxygen would start to disappear in the northern Gulf. The hypoxia would last through the summer or fall, until seasonal storms mixed oxygen into hypoxic areas.

The source of the problem, Rabalais said, lay back on land. The Mississippi and Atchafalaya rivers draining into the Gulf were polluted with agricultural runoff, and the nutrient pollution from fertilizers spurred algal blooms whose decomposition by bacteria snuffed out oxygen in wide stretches of ocean water (pp. 109–111). This work had clearly demonstrated the interconnections between freshwater aquatic systems and the Gulf, and how pollutants from farm fields in the upper Midwest could exert effects far away at the mouth of the Mississippi River.

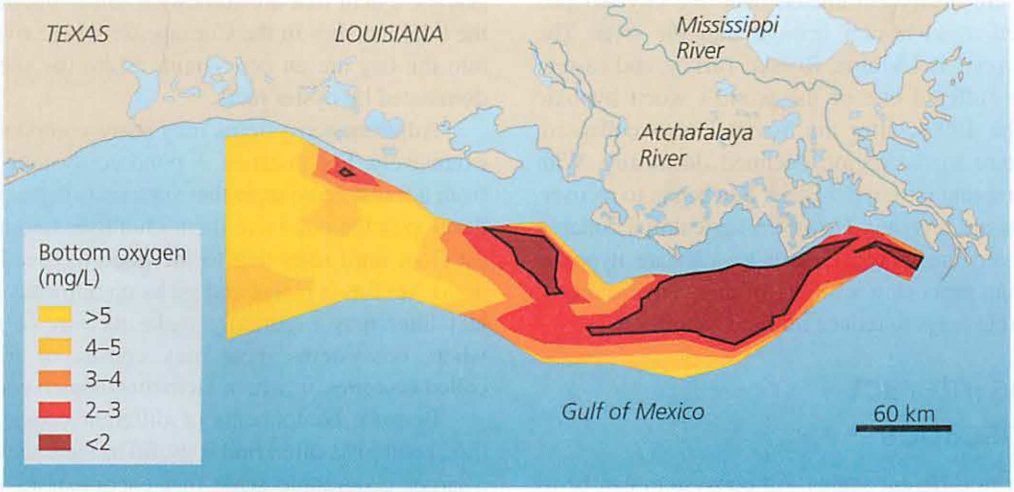
Over time, monitoring linked the dead zone's size to the volume of river flow and its nutrient load. The 1993 flooding of the Mississippi created a zone much larger than the year before, whereas a drought in 2000 brought low river flows, low nutrient loads, and a small dead zone (**FIGURE 1**). Similar relationships between river flow and dead zone size have been seen ever since. In 2005, the dead zone was predicted to be large, but Hurricanes Katrina and Rita stirred oxygenated surface water into the depths, decreasing the dead zone that year.

Many Midwestern farming advocates and some scientists, such as Derek Winstanley, chief of the Illinois State Water Survey, challenged the findings. They argued that the Mississippi naturally carries high loads of nitrogen from runoff and that Rabalais's team had not ruled out upwelling (the wind-driven phenomenon that causes waters from the deep ocean to rise to the surface) in the Gulf as a source of nutrients.

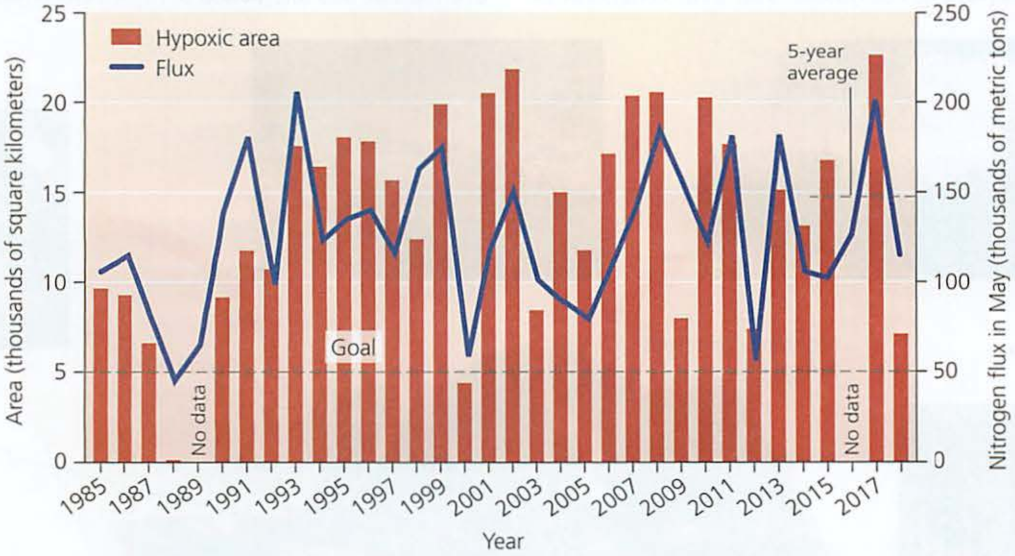
But sediment analyses showed that Mississippi River mud contained many fewer nitrates early in the century, and Rabalais and Turner found that silica residue from phytoplankton blooms increased in Gulf sediments between 1970 and 1989, paralleling rising nitrogen levels. In 2000, a federal integrative assessment team of dozens of scientists laid the blame for the dead zone on nutrients from fertilizers and other sources in the fresh waters emptying into the Gulf.

Then in 2004, while representatives of farmers and fishermen debated political fixes, Environmental Protection Agency water-quality scientist Howard Marshall suggested that to alleviate the dead zone, we'd be best off reducing phosphorus pollution from industry and sewage treatment. His reasoning was this: Phytoplankton need both nitrogen and phosphorus, but there is now so much nitrogen in the Gulf that phosphorus has become the limiting factor on phytoplankton growth.

Since then, research has supported this contention, and scientists now propose that nitrogen and phosphorus should be managed jointly to help reduce the size of the dead zone in the Gulf of Mexico off the Louisiana coast. Moreover, recent research indicates that a federally mandated 30% reduction in



(a) Dissolved oxygen at ocean bottom



(b) Size of hypoxic zone in the northern Gulf of Mexico

FIGURE 1 The map in (a) shows dissolved oxygen concentrations in bottom waters of the Gulf of Mexico off the Louisiana coast in 2018. The darkest areas indicate the lowest oxygen levels, with regions considered hypoxic (<2 mg/L) outlined in black. The dead zone forms to the west of the mouth of the Mississippi River because prevailing currents carry nutrients in that direction. The graph in **(b)** shows that the size of the hypoxic zone (shown by bars) is correlated with the amount of nitrogen pollution entering from the Mississippi River (shown by line), with nutrient delivery being higher in wetter years and lower in years with Midwest drought. The dead zone in 2018 was 7040 km^2 (2720 mi^2), the fourth-smallest since mapping began in 1985. This was attributed to low levels of precipitation reducing nutrient runoff into the Mississippi River. The average size of the dead zone from 2014 to 2018 was nearly 15,000 km^2 (5800 mi^2), and scientists and policymakers aim to reduce its size to 5000 km^2 (1930 mi^2). *Hypoxic zone data from Nancy Rabalais, LUMICON, and R. Eugene Turner, LSU. Nitrogen flux data from USGS, https://nrtwq.usgs.gov/mississippi_loads/#/.*

nitrogen in the river will not be adequate to eliminate the dead zone. Scientists also maintain that large-scale restoration of wetlands along the river and at the river's delta would best filter pollutants before they reach the Gulf.

All this research is guiding a federal plan to reduce farm runoff, clean up the Mississippi, restore coastal wetlands, and shrink the Gulf's dead zone. It has also led to a better understanding of hypoxic zones around the world.

In New York City, hypoxic zones at the mouths of the Hudson and East rivers were nearly eliminated once the city stopped releasing untreated, nutrient-rich sewage into the river. The Black Sea, which borders Ukraine, Russia, Turkey, and eastern Europe, had long suffered one of the world's worst hypoxic zones. Then in the 1990s, after the Soviet Union collapsed, industrial agriculture in the region declined drastically. With fewer fertilizers draining into it, the Black Sea began to recover, and today fisheries are reviving. However, agricultural collapse is not a strategy anyone would choose to alleviate hypoxia. Rather, scientists are proposing a variety of innovative and economically acceptable ways to reduce nutrient runoff.

Ecosystems interact across landscapes

Ecosystems occur at different scales. An ecosystem can be as small as a puddle of water or as large as a bay, lake, or forest. For some purposes, scientists even view the entire biosphere as a single all-encompassing ecosystem. The term *ecosystem* is most often used, however, to refer to systems of moderate geographic extent that are somewhat self-contained. For example, the tidal marshes in the Chesapeake where river water empties into the bay are an ecosystem, as are the sections of the bay dominated by oyster reefs.

Adjacent ecosystems may share components and interact extensively. For instance, a pond ecosystem is very different from a forest ecosystem that surrounds it, but salamanders that develop in the pond live their adult lives under logs on the forest floor until returning to the pond to breed. Rainwater that nourishes forest plants and picks up nutrients from the forest's leaf litter may eventually make its way to the pond. Areas where ecosystems meet may consist of transitional zones called **ecotones,** in which elements of each ecosystem mix.

Because components of different ecosystems may intermix, ecologists often find it useful to view these ecosystems on a larger geographic scale that encompasses multiple ecosystems. In such a broad-scale approach, called **landscape ecology,** scientists study how landscape structure affects the abundance, distribution, and interaction of organisms (**FIGURE 5.11**). Taking

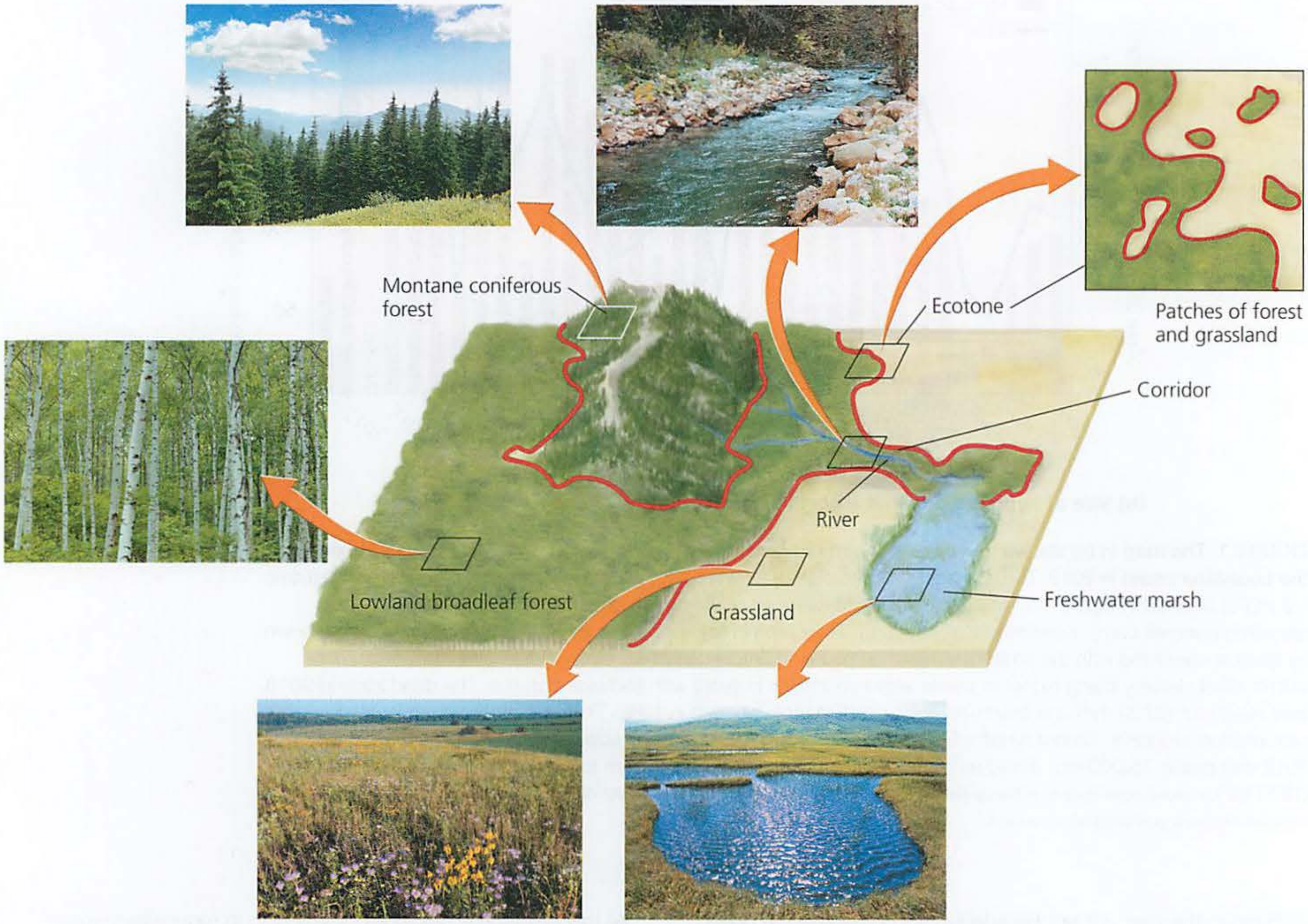


FIGURE 5.11 Landscape ecology deals with spatial patterns above the ecosystem level. This generalized diagram of a landscape shows a mosaic of patches of five ecosystem types (three terrestrial types, a marsh, and a river). Thick red lines indicate ecotones. A stretch of lowland broadleaf forest running along the river serves as a corridor connecting the large region of forest on the left to the smaller patch of forest alongside the marsh. The inset shows a magnified view of the forest-grassland ecotone and how it consists of patches on a smaller scale.

a view across the landscape is important in studying birds that migrate long distances, mammals that move seasonally between mountains and valleys, and fish such as salmon that swim upriver from the ocean to reproduce.

For a landscape ecologist, a landscape is made up of **patches** (of ecosystems, communities, or habitats) arrayed spatially over a landscape in a **mosaic**. Landscape ecology is of great interest to scientists of **conservation biology** (pp. 295–296), the study of the loss, protection, and restoration of biodiversity. Every organism has specific habitat needs, so when its habitat is distributed in patches across a landscape, individuals may need to expend energy and risk predation traveling from one to another. If the patches are far apart, the organism's population may become divided into subpopulations, each occupying a different patch in the mosaic. Such a network of subpopulations, most of whose members stay within their respective patches but some of whom move among patches or mate with members of other patches, is called a **metapopulation.** When patches are still more isolated from one another, individuals may not be able to travel between them at all. In such a case, smaller subpopulations may be at risk of extinction. Conservation biologists aim to avoid these situations by establishing corridors of habitat (see Figure 5.11) that link patches and allow animals to move among them.

Technology helps us practice landscape ecology

A common tool for research in landscape ecology is the **geographic information system (GIS).** A GIS consists of computer software that takes multiple types of data (for instance, on geology, hydrology, topography, vegetation, plant and animal populations, and human infrastructure from both on-ground studies and satellite imagery) and combines them, layer by layer, on a common set of geographic coordinates (**FIGURE 5.12**). The idea is to create a complete picture of a landscape, analyze how elements of the different data sets are arrayed spatially, and determine how they may be correlated.

GIS has become a valuable tool used by geographers, landscape ecologists, resource managers, and conservation biologists. It is being used to guide restoration efforts in the Chesapeake Bay. The *ChesapeakeStat*, a GIS-enabled website that was launched in 2010, enables scientists, educators, policymakers, and citizens to create customized composite maps that overlay parameters important to the bay's health. This tool is being used to assess the bay's current status, the effects of restoration efforts, and progress toward long-term goals.

Modeling helps ecologists understand systems

Another way in which ecologists seek to make sense of the complex systems they study is by working with models.

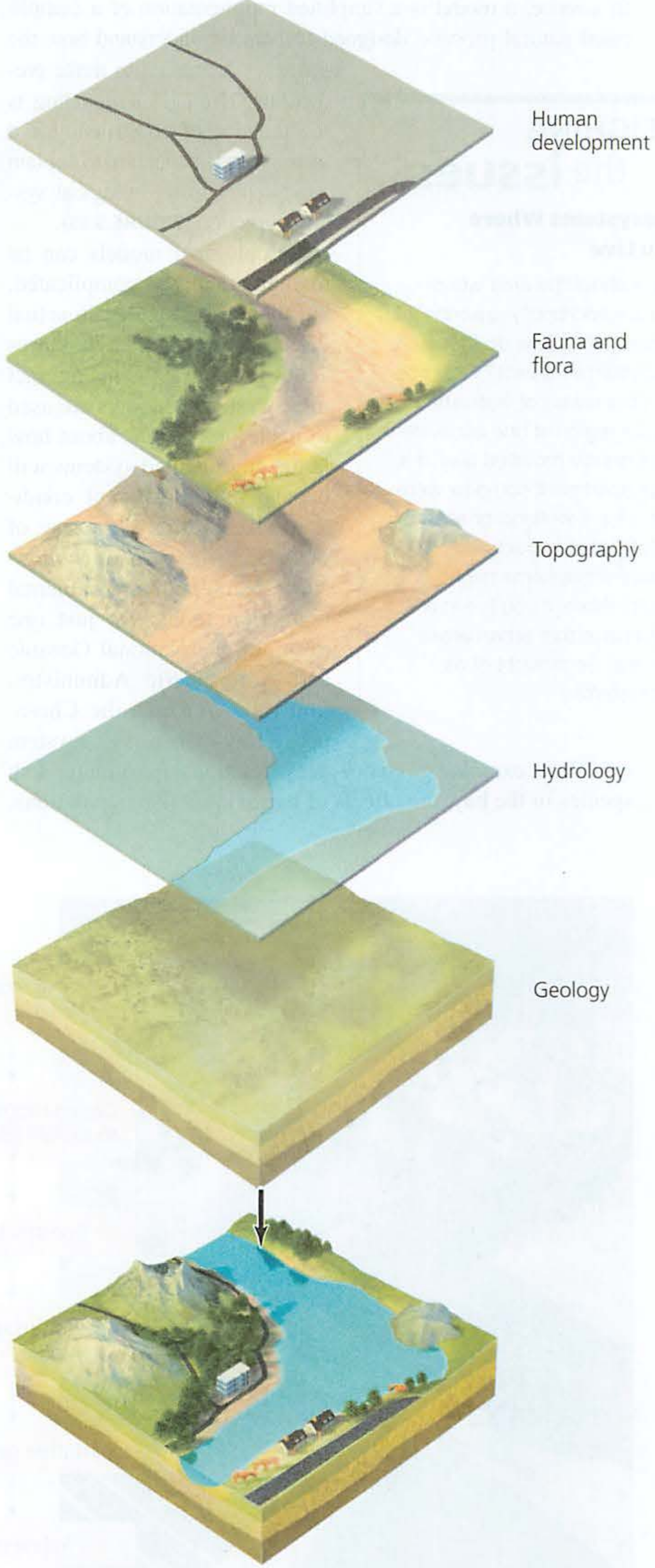


FIGURE 5.12 Geographic information systems (GIS) produce maps that layer various types of data on natural landscape features and human land uses. GIS can be used to explore correlations among these data sets and to aid wildlife conservation and regional planning.

In science, a **model** is a simplified representation of a complicated natural process, designed to help us understand how the process occurs and to make predictions. **Ecological modeling** is the practice of constructing and testing models that aim to explain and predict how ecological systems function (**FIGURE 5.13**).

Ecological models can be mathematically complicated, but they are grounded in actual data and based on hypotheses about how components interact in ecosystems. Models are used to make predictions about how large, complicated systems will behave under different conditions. Accordingly, the use of models is a key part of ecological research and environmental regulation today. As just one example, the National Oceanic and Atmospheric Administration (NOAA) uses the Chesapeake Bay Fisheries Ecosystem model to examine predator–prey relationships among fish species in the bay, the effects of hypoxia on fish populations, and how the distribution of underwater grasses influences blue crab populations (**FIGURE 5.14**). Data from scientific journal articles and direct measurements are used to establish the model's parameters, which are then used to predict the effects of differing fish harvest levels on species and ecosystems in the Chesapeake Bay.

WEIGHING
the issues

Ecosystems Where You Live

Think about the area where you live and briefly describe its ecosystems. How do these ecosystems interact? Describe the boundaries of watersheds in your region. If one ecosystem were greatly modified (say, if a large apartment complex were built atop a wetland or amid a forest), what impacts on nearby ecosystems might result? (*Note:* If you live in a city, realize that urban areas can also be thought of as ecosystems.)

FIGURE 5.14 Blue crabs (*Callinectes sapidus*) are an ecologically and economically important species in the Chesapeake Bay. Reducing hypoxia in bay waters and reestablishing large expanses of underwater grasses (like those shown) are keys to the species' recovery.

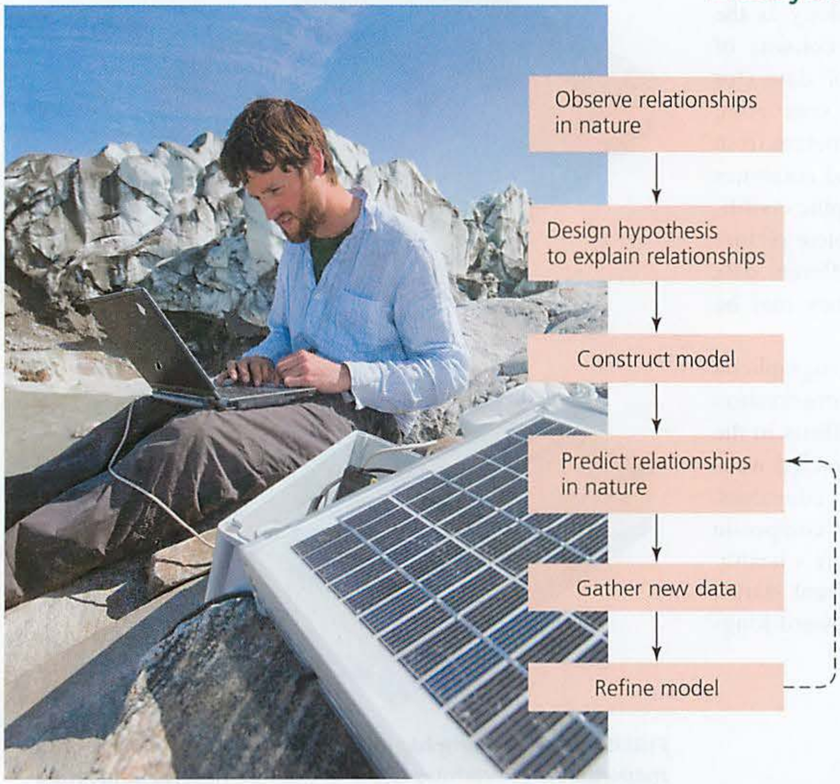


FIGURE 5.13 Ecological modelers observe relationships among variables in nature and then construct models to explain those relationships and make predictions. They test and refine the models by gathering new data from nature and seeing how well the models predict those data.

Ecosystem services sustain our world

Human society depends on healthy, functioning ecosystems. When Earth's ecosystems function normally and undisturbed, they provide goods and services that we could not survive without. As we've seen, we rely not just on natural resources (which can be thought of as goods from nature) but also on the *ecosystem services* (p. 4) that our planet's systems provide (**TABLE 5.1**).

Ecosystem services come from the functioning of healthy ecological systems and the many negative feedback cycles that regulate and stabilize natural systems. Ecosystem services include ecological processes that form the soil that nourishes our crops, purify the water we drink, pollinate the food plants we eat, and break down (some of) the waste and pollution we generate. Ecosystem services also enhance the quality of our lives, ranging from recreational opportunities to pleasing scenery to inspiration and spiritual renewal.

One of the most important ecosystem services is the cycling of chemical nutrients. Through the processes that take place within and among ecosystems, the chemical elements and compounds that sustain life—carbon,

TABLE 5.1 Ecosystem Services

Ecological processes do many things that benefit us:

- Cycle carbon, nitrogen, phosphorus, and other nutrients
- Regulate oxygen, carbon dioxide, stratospheric ozone, and other atmospheric gases
- Regulate temperature and precipitation by phenomena such as ocean currents and cloud formation, and processes such as evaporation and transpiration
- Store and regulate water supplies in watersheds and aquifers
- Form soil by weathering rock, and prevent soil erosion
- Protect against storms, floods, and droughts, mainly by the moderating means of vegetation
- Filter waste, remove toxic substances, recover nutrients, and control pollution
- Pollinate plant crops and control crop pests
- Provide habitat for organisms to breed, feed, rest, migrate, and winter
- Produce fish, game, crops, nuts, and fruits that people eat
- Supply lumber, fuel, metals, fiber crops (such as cotton), feed for livestock, and medicinal compounds
- Provide recreation such as ecotourism, fishing, hiking, birding, hunting, and kayaking
- Provide aesthetic, artistic, educational, spiritual, and scientific amenities

nitrogen, phosphorus, water, and many more—cycle through our environment in complex ways.

Biogeochemical Cycles

Just as nitrogen and phosphorus from fertilizer on Pennsylvania corn fields end up in Chesapeake Bay oysters, all nutrients move through the environment in intricate ways. As we have discussed, whereas energy enters an ecosystem from the sun, flows from organism to organism, and dissipates to the atmosphere as heat, the physical matter of an ecosystem is circulated over and over again.

Nutrients circulate through ecosystems in biogeochemical cycles

Nutrients move through ecosystems in **nutrient cycles** (or **biogeochemical cycles**) that circulate chemical elements or molecules through the atmosphere, hydrosphere, lithosphere, and biosphere. A carbon atom in your fingernail today might have been in the muscle of a cow a year ago, may have resided in a blade of grass a month before that, and may have been part of a dinosaur's tooth 100 million years ago. After we die, the nutrients in our bodies will disperse into the environment and could be incorporated into other organisms far into the future.

Nutrients and other materials move from one **reservoir,** or pool, to another, remaining in each reservoir for varying amounts of time (the **residence time**). The dinosaur, the cow, the grass, and your body are each reservoirs for carbon atoms, as are sedimentary rocks and the atmosphere. The rate at which materials move between reservoirs is termed a **flux.** When a reservoir releases more materials than it accepts, it is called a **source,** and when a reservoir accepts more materials than it releases, it is called a **sink.** FIGURE 5.15 illustrates these concepts in a simple manner.

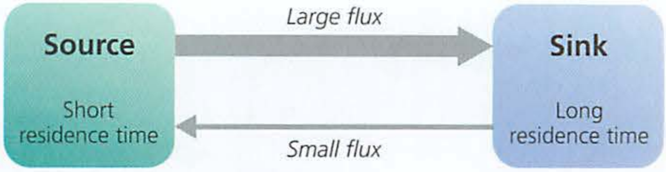


FIGURE 5.15 The main components of a biogeochemical cycle are reservoirs and fluxes. A source releases more materials than it accepts, and a sink accepts more materials than it releases.

As we will see in the following sections, human activities can affect the cycling of nutrients by altering fluxes, residence times, and the relative amounts of nutrients in reservoirs (see **SUCCESS STORY**, p. 124).

The water cycle affects all other cycles

Water is so integral to life and to Earth's fundamental processes that we frequently take it for granted. Water is the essential medium for all manner of biochemical reactions, and it plays key roles in nearly every environmental system, including each of the nutrient cycles we are about to discuss. Water carries nutrients, sediments, and pollutants from the continents to the oceans via surface runoff, streams, and rivers. These materials can then be carried thousands of miles on ocean currents. Water also carries atmospheric pollutants to the surface when they dissolve in falling rain or snow. The **hydrologic cycle,** or *water cycle* (FIGURE 5.16, p. 122), summarizes how water—in liquid, gaseous, and solid forms—flows through our environment.

The oceans are the main reservoir in the water cycle, holding more than 97% of all water on Earth. The fresh water we depend on for our survival accounts for the remaining water, and two-thirds of this small amount is tied up in glaciers, snowfields, and ice caps (p. 392). Thus, considerably less than 1% of the planet's water is in forms that we can readily use—groundwater, surface fresh water, and rain from atmospheric water vapor.

Evaporation and transpiration Water moves from oceans, lakes, ponds, rivers, and moist soil into the atmosphere by **evaporation,** the conversion of a liquid to a gaseous form. Warm temperatures and strong winds speed rates of evaporation. Water also enters the atmosphere by **transpiration,** the release of water vapor by plants through their leaves, or by evaporation from the surfaces of organisms, such as sweating in humans. Transpiration and evaporation act as natural processes of distillation, because water escaping into the air as a gas leaves behind its dissolved substances.

Precipitation, runoff, and surface water Water returns from the atmosphere to Earth's surface as **precipitation** when water vapor condenses and falls as rain or snow. This water may be taken up by plants and used by animals, but much of it flows as runoff into streams, rivers, lakes,

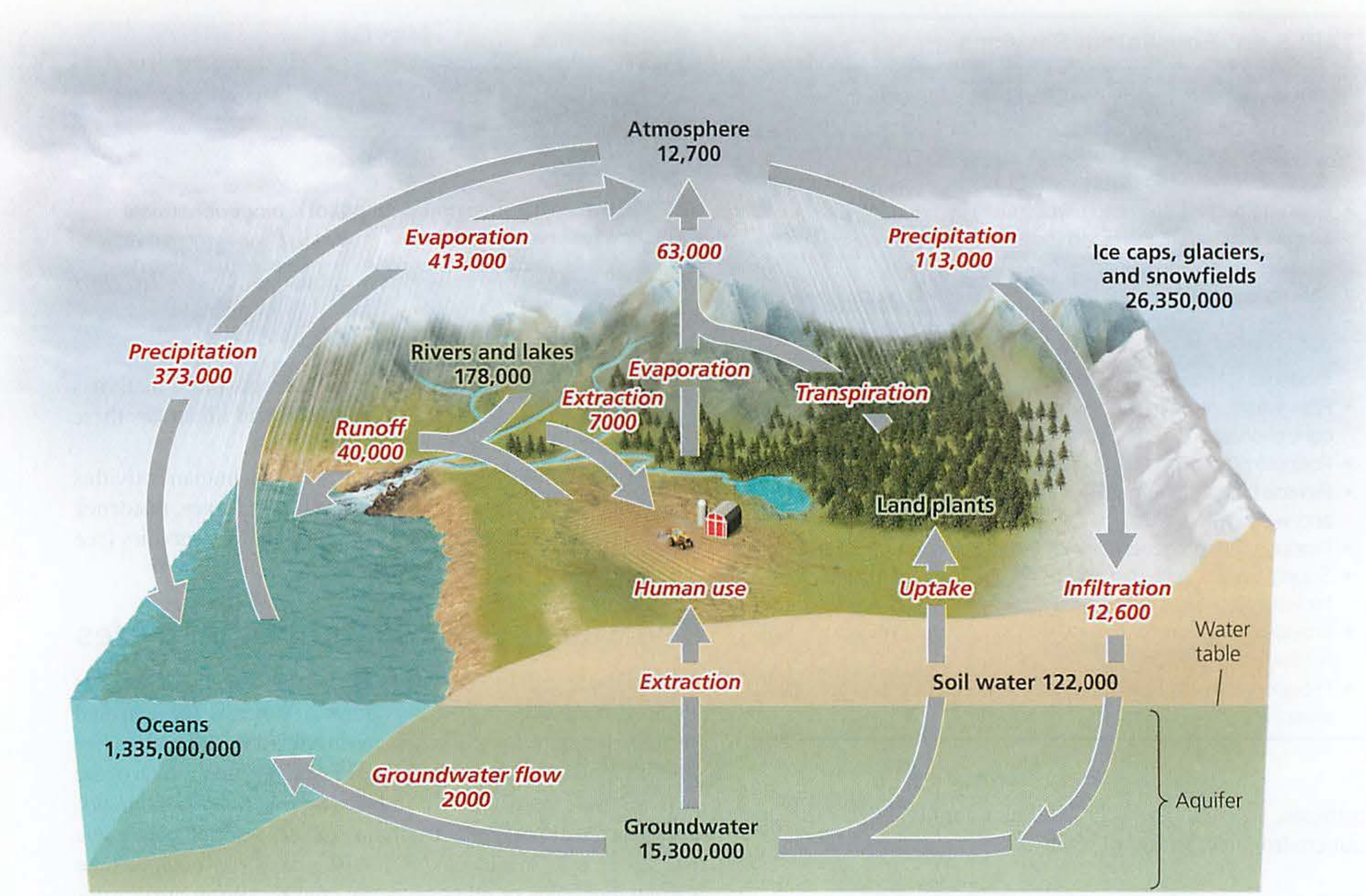


FIGURE 5.16 The water cycle, or hydrologic cycle, summarizes the many routes that water molecules take as they move through the environment. In the figure, reservoir names are printed in black type, and numbers in black type represent reservoir sizes expressed in units of cubic kilometers (km^3). Processes give rise to fluxes (represented by gray arrows), both are printed in italic red type and expressed in km^3 per year. *Data from Schlesinger, W. H., 2013.* Biogeochemistry: An analysis of global change, *3rd ed. London, England: Academic Press.*

ponds, and oceans. Precipitation levels vary greatly from region to region, helping give rise to our planet's variety of biomes (p. 94).

Groundwater Some water soaks down through soil and rock through a process called infiltration, recharging underground reservoirs known as **aquifers** (pp. 392–396). Aquifers are porous regions of rock and soil that hold **groundwater,** water found within the soil. The upper limit of groundwater held in an aquifer is referred to as the **water table.** Aquifers can hold groundwater for long periods of time and can sometimes take hundreds or thousands of years to recharge fully after being depleted. Groundwater becomes surface water when it emerges from springs or flows into streams, rivers, lakes, or the ocean from the soil.

WEIGHING
the issues

Water shortages and you

Has your region ever faced any water shortages or experienced conflicts over water use with neighboring regions? If not, have you recently heard of such conflicts in other regions? Given your knowledge of the water cycle, what solutions would you propose for addressing water shortages in your region?

Our impacts on the water cycle are extensive

Human activity affects every aspect of the water cycle. By damming rivers, we slow the movement of water from the land to the sea, and we increase evaporation by holding water in reservoirs. We remove natural vegetation by clear-cutting and developing land, which increases surface runoff, decreases infiltration and transpiration, and promotes evaporation. Our withdrawals of surface water and groundwater for agriculture, industry, and domestic uses deplete rivers, lakes, and streams and lower water tables. This can lead to water shortages and conflict over water supplies (pp. 407–408).

The carbon cycle circulates a vital nutrient

As the definitive component of organic molecules, carbon is an ingredient in carbohydrates, fats, and proteins and occurs in the bones, cartilage, and shells of all living things. The **carbon cycle** describes the routes that carbon atoms take through the environment (**FIGURE 5.17**).

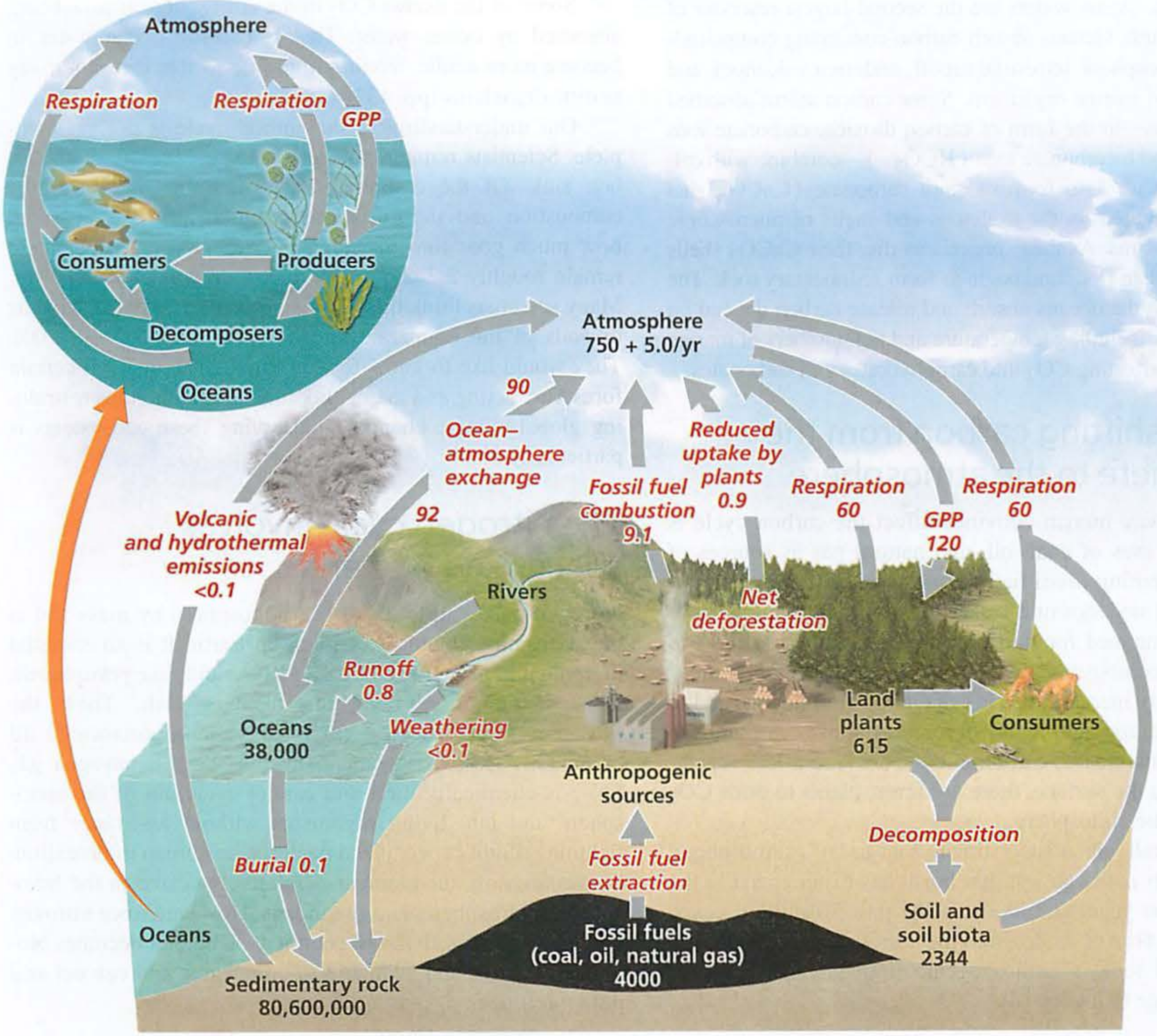


FIGURE 5.17 The carbon cycle summarizes the many routes that carbon atoms take as they move through the environment. In the figure, reservoir names are printed in black type, and numbers in black type represent reservoir sizes expressed in petagrams (units of 10^{15} g) of carbon (note that these values are printed in white type for fossil fuels). Processes give rise to fluxes (represented by gray arrows), both of which are printed in italic red type and expressed in petagrams of carbon per year. In the carbon cycle, plants use carbon dioxide from the atmosphere for photosynthesis (gross primary production, or "GPP" in the figure). *Data from Schlesinger, W. H., 2013.* Biogeochemistry: An analysis of global change, *3rd ed. London, England: Academic Press.*

Photosynthesis, respiration, and food webs Autotrophs pull carbon dioxide out of the atmosphere and out of surface water to use in photosynthesis. They use some of the carbohydrates to fuel cellular respiration, thereby releasing some of the carbon back into the atmosphere and surface water as CO_2. When producers are eaten by primary consumers, which, in turn, are eaten by other animals, more carbohydrates are broken down in cellular respiration, and released as carbon dioxide. The same process occurs as decomposers consume waste and dead organic matter.

Sediment storage of carbon The largest reservoir of carbon, sedimentary rock (p. 38), is formed in ocean basins and freshwater wetlands. When organisms in these habitats die, their remains may settle in sediments, and as layers of sediment accumulate, the older layers are buried more deeply, and experience high pressure for long periods of time. Over millions of years, these conditions can convert the soft tissues of aquatic organisms into fossil fuels—coal, oil, and natural gas—and transform their shells and skeletons into sedimentary rock, such as limestone.

Carbon trapped in sediments and fossil fuel deposits may eventually be released into the oceans or atmosphere by geologic processes such as uplift, erosion, and volcanic eruptions. It also reenters the atmosphere when we extract and burn fossil fuels.

The oceans Ocean waters are the second-largest reservoir of carbon on Earth. Oceans absorb carbon-containing compounds from the atmosphere, terrestrial runoff, undersea volcanoes, and the detritus of marine organisms. Some carbon atoms absorbed by the oceans—in the form of carbon dioxide, carbonate ions (CO_3^{2-}), and bicarbonate ions (HCO_3^-)—combine with calcium ions (Ca^{2+}) to form calcium carbonate ($CaCO_3$), an essential ingredient in the skeletons and shells of microscopic marine organisms. As these organisms die, their $CaCO_3$ shells sink to the ocean floor and begin to form sedimentary rock. The rates at which the oceans absorb and release carbon depend on many factors, including temperature and the numbers of marine organisms converting CO_2 into carbohydrates and carbonates.

We are shifting carbon from the lithosphere to the atmosphere

One major way human activities affect the carbon cycle is through our uses of coal, oil, and natural gas as sources of energy. By mining fossil fuel deposits, we are removing carbon from an underground reservoir, in which it might have otherwise remained for millions of years, and bringing it to surface. By combusting fossil fuels, we release carbon dioxide and greatly increase the flux of carbon from the ground to the air. In addition, cutting down forests removes carbon from vegetation and releases carbon into the air. And if less vegetation is left on the surface, there are fewer plants to draw CO_2 back out of the atmosphere.

As a result, scientists estimate that today's atmospheric CO_2 reservoir is the largest that Earth has experienced in the past 1 million years and likely in the past 20 million years. The ongoing flux of carbon into the atmosphere is the driving force behind today's anthropogenic (human-caused) global climate change (Chapter 18).

Some of the excess CO_2 in the atmosphere is now being absorbed by ocean water. This is causing ocean water to become more acidic, leading to problems that threaten many marine organisms (pp. 437–438).

Our understanding of the carbon cycle is not yet complete. Scientists remain baffled by the so-called missing carbon sink. Of the carbon dioxide we emit by fossil fuel combustion and deforestation, researchers have measured how much goes into the atmosphere and oceans, but there remain roughly 2.3–2.6 billion metric tons unaccounted for. Many scientists think this CO_2 is probably taken up by plants or soils of the temperate and boreal forests (pp. 96–100). They would like to know for sure, though, because if certain forests are acting as a major sink for carbon (and thus restraining global climate change), conserving these ecosystems is particularly vital.

The nitrogen cycle involves specialized bacteria

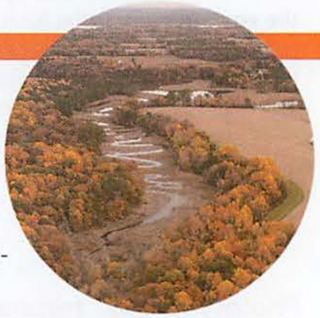
Nitrogen makes up 78% of our atmosphere by mass and is the sixth most abundant element on Earth. It is an essential ingredient in proteins, DNA, and RNA, and, like phosphorus, is an essential nutrient for plant growth. Thus, the **nitrogen cycle** (**FIGURE 5.18**) is of vital importance to all organisms. Despite its abundance in the air, nitrogen gas (N_2) is chemically inert and cannot cycle out of the atmosphere and into living organisms without assistance from lightning, highly specialized bacteria, or human intervention. For this reason, the element is relatively scarce in the lithosphere, hydrosphere, and organisms. However, once nitrogen undergoes the right kind of chemical change, it becomes biologically active and available to organisms, and can act as a potent fertilizer.

SUCCESS **story**

Considering Cost When Saving the Bay

The Chesapeake Bay offers a case study that illustrates the importance of understanding systems, chemistry and the need for taking a systems-level approach to restore ecosystems degraded by human activities. Tools such as landscape ecology, GIS, and ecological modeling aid these efforts by providing a broad view of the Chesapeake Bay ecosystem and how it may react to changes in nutrient inputs and restoration efforts. The Chesapeake Bay Foundation's most recent "State of the Bay" report concluded that the bay's health rating in 2018 was the highest it had been since CBF's founding in 1964, with meaningful improvements in pollution reduction, fisheries recovery, and the restoration of natural habitats in and around the bay (see Figure 5.1, p. 106).

One reason for the recent success is that farmers, residents, resource managers, and local, state, and federal government agencies have embraced a variety of approaches to reduce nutrient inputs into the bay. By educating people about the many inexpensive yet effective steps that can be taken in yards, farms, businesses, and local communities to reduce nutrient inputs into the Chesapeake Bay, saving the bay became something for which everyone can do his or her part.



A forested buffer lining a waterway on agricultural land in Maryland.

→ **Explore the Data** at Mastering Environmental Science

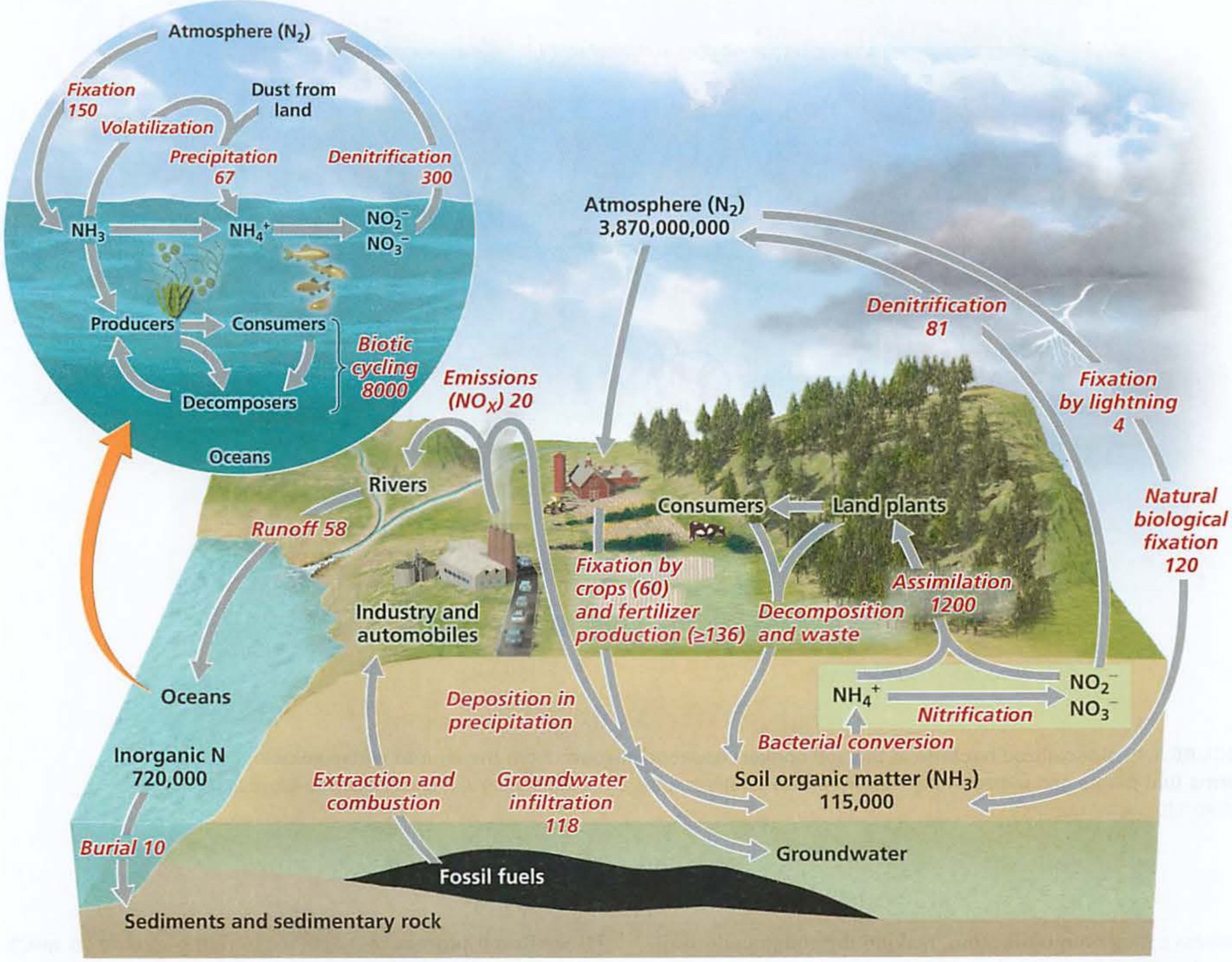


FIGURE 5.18 The nitrogen cycle summarizes the many routes that nitrogen atoms take as they move through the environment. In the figure, reservoir names are printed in black type, and numbers in black type represent reservoir sizes expressed in teragrams (units of 10^{12} g) of nitrogen (note that these values are printed in white type for fossil fuels). Processes give rise to fluxes (represented by gray arrows), both of which are printed in italic red type and expressed in teragrams of nitrogen per year. *Data from Schlesinger, W. H., 2013.* Biogeochemistry: An analysis of global change, *3rd ed. London, England: Academic Press.*

Nitrogen fixation To become biologically available, inert nitrogen gas (N_2) must be "fixed," or combined with hydrogen in nature to form ammonia (NH_3), whose water-soluble ions of ammonium (NH_4^+) can be taken up by plants (**FIGURE 5.19**, p. 125). **Nitrogen fixation** can be accomplished in two ways: by the intense energy of lightning strikes, or when the nitrogen in air comes in contact with particular types of **nitrogen-fixing bacteria** in the soil and water. In the soil, these bacteria live in a mutualistic relationship (pp. 80–81) with many types of plants, including soybeans and other legumes, providing them nutrients by converting nitrogen to a usable form. Some farmers nourish soils by planting crops that host nitrogen-fixing bacteria among their roots.

Nitrification and denitrification Other types of specialized bacteria then perform a process known as **nitrification,** converting NH_4^+ into two nitrite ions, first NO_2^- and then NO_3^-. These water-soluble forms of nitrogen can be taken up by plants and phytoplankton through assimilation and used to fuel their growth. Other sources of these ions are the nitrate-based fertilizers applied to cropland and nitrogenous compounds deposited by air pollution (p. 459).

Animals obtain the nitrogen they need by consuming plants or other animals. Decomposers obtain nitrogen from dead and decaying plant and animal matter, and from the urine and feces of animals. Once decomposers process these nitrogen-rich compounds, they release ammonium ions, a

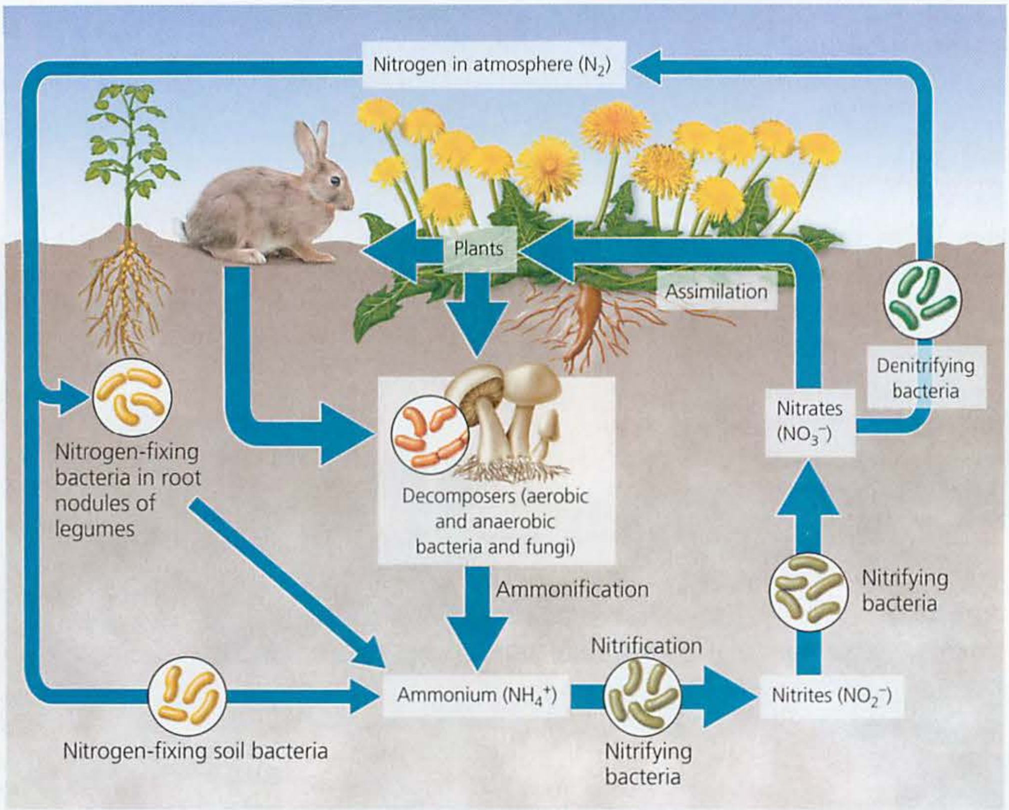


FIGURE 5.19 Specialized bacteria in the soil convert gaseous nitrogen from the air into water-soluble forms that plants can utilize. Other bacteria convert water-soluble forms of nitrogen in the soil back into a gas and return it to the atmosphere.

process called **ammonification,** making the compounds available to nitrifying bacteria to convert again to nitrates and nitrites.

The next step in the nitrogen cycle occurs when **denitrifying bacteria** convert nitrates in soil or water to gaseous nitrogen in a multistep process. Denitrification thereby completes the cycle by releasing nitrogen back into the atmosphere as a gas.

We have greatly influenced the nitrogen cycle

Historically, nitrogen fixation was a **bottleneck,** a step that limited the flux of nitrogen out of the atmosphere and into water-soluble forms. This changed with the research of two German chemists early in the 20th century. Fritz Haber found a way to combine nitrogen and hydrogen gases to synthesize ammonia, a key ingredient in modern explosives and agricultural fertilizers, and Carl Bosch devised methods to produce ammonia on an industrial scale. The **Haber-Bosch process** enabled people to overcome the limits on productivity long imposed by nitrogen scarcity in nature. By enhancing agriculture, the new fertilizers contributed to the past century's enormous increase in human population. Farmers, homeowners, and landscapers alike all took advantage of fertilizers, dramatically altering the nitrogen cycle. Today, using the Haber-Bosch process, our species is fixing at least as much nitrogen as is being fixed naturally. We have effectively doubled the rate of nitrogen fixation on Earth, overwhelming nature's denitrification abilities.

By fixing atmospheric nitrogen to create fertilizers, we increase nitrogen's flux from the atmosphere to Earth's surface. We also enhance this flux by cultivating legume crops whose roots host nitrogen-fixing bacteria. Moreover, we reduce nitrogen's return to the air when we destroy wetlands whose plants host denitrifying bacteria that convert nitrates to nitrogen gas.

When our farming practices speed runoff and allow soil erosion, nitrogen flows from farms into terrestrial and aquatic ecosystems, leading to nutrient pollution, eutrophication, and hypoxia. These impacts have become painfully evident to oystermen and scientists in the Chesapeake Bay, but hypoxia in waters is by no means the only human impact on the nitrogen cycle. When we burn fossil fuels, we release nitric oxide (NO) into the atmosphere, where it reacts to form nitrogen dioxide (NO_2). This compound is a precursor to nitric acid (HNO_3), a key component of acid precipitation (pp. 474–477). We introduce another nitrogen-containing gas, nitrous oxide (N_2O), when anaerobic bacteria break down the tremendous volume of animal waste produced in agricultural feedlots (p. 249). As these examples show, human activities have affected the nitrogen cycle in diverse and often far-reaching ways.

The phosphorus cycle circulates a limited nutrient

The element phosphorus is a key component of cell membranes and of several molecules vital for life, including DNA, RNA, ATP, and ADP (pp. 28–29, 34). Although phosphorus is indispensable for life, the amount of phosphorus in organisms is dwarfed by the vast amounts in rocks, soil, sediments, and the oceans. Unlike the carbon and nitrogen cycles, the **phosphorus cycle** (**FIGURE 5.20**) has no appreciable atmospheric component besides the transport of tiny amounts in windblown dust and sea spray.

Geology and phosphorus availability The vast majority of Earth's phosphorus is contained within sedimentary rocks and is released only by weathering (p. 217), which releases phosphate ions (PO_4^{3-}) into water. Phosphates dissolved in lakes or in the oceans precipitate into solid form, settle to the bottom, and reenter the lithosphere's phosphorus reservoir in sediments. Because most phosphorus is bound up in rock and only slowly released, environmental concentrations of phosphorus available to organisms tend to be very low. This scarcity explains why phosphorus is frequently a limiting factor for plant growth and why an influx of phosphorus into an ecosystem can produce immediate and dramatic effects.

Food webs Aquatic producers take up phosphates from surrounding waters, whereas terrestrial producers take up phosphorus from soil water through their roots. Herbivores acquire phosphorus from plant tissues and, when herbivores are consumed, they pass the phosphorus on to their predators. Animals also pass phosphorus to the soil through the excretion of waste. Decomposers break down phosphorus-rich organisms and their wastes and, in so doing, return phosphorus to the soil.

We affect the phosphorus cycle

People increase phosphorus concentrations in surface waters through runoff of the phosphorus-rich fertilizers we apply to lawns and farmlands. A 2008 study determined that an average hectare of land in the Chesapeake Bay region received a net input of 4.52 kg (10 lb) of phosphorus per year, promoting phosphorus accumulation in soils, runoff into waterways, and phytoplankton blooms and hypoxia in the bay. People also add phosphorus to waterways through releases

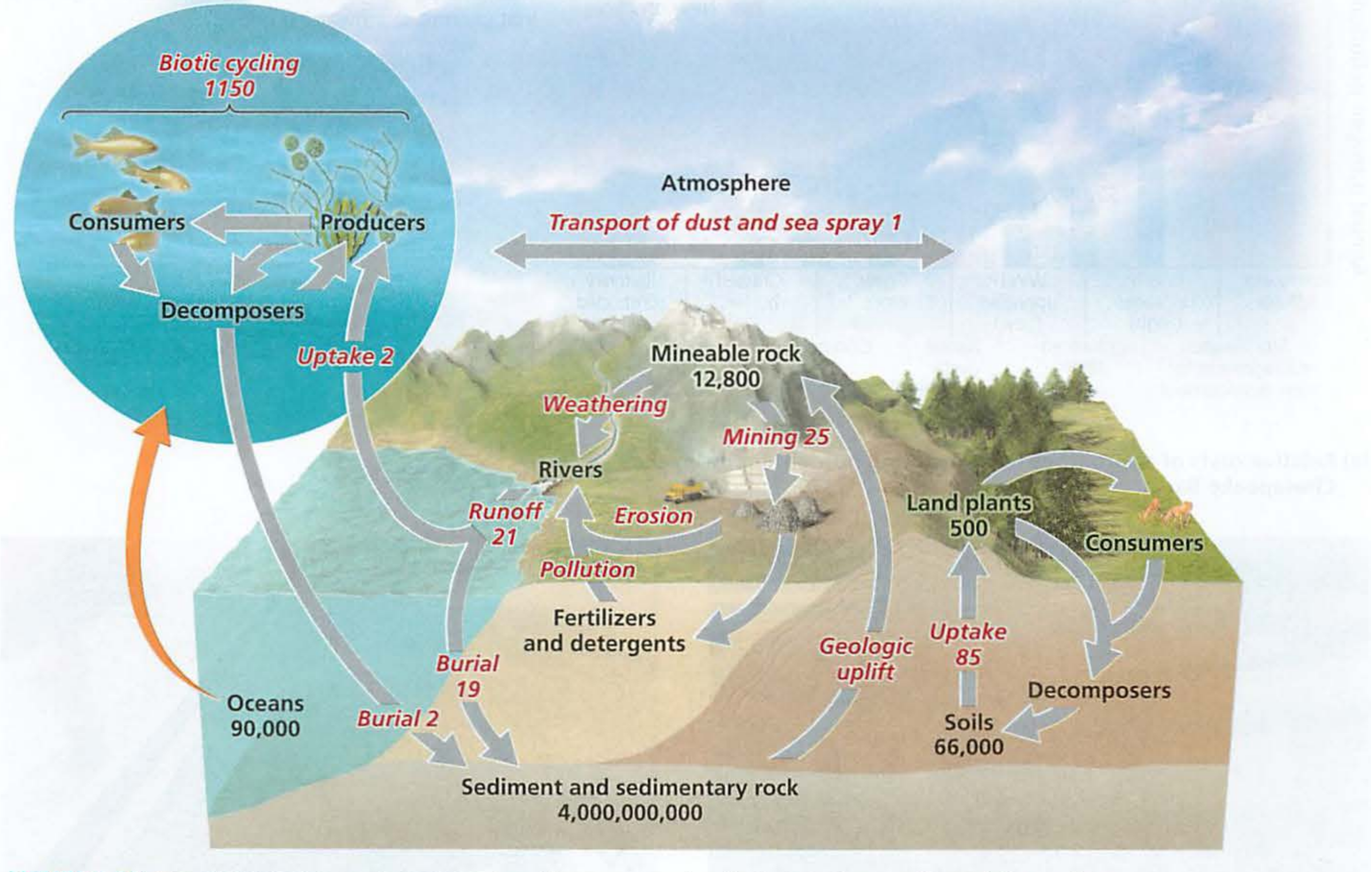


FIGURE 5.20 The phosphorus cycle summarizes the many routes that phosphorus atoms take as they move through the environment. In the figure, reservoir names are printed in black type, and numbers in black type represent reservoir sizes expressed in teragrams (units of 10^{12} g) of phosphorus. Processes give rise to fluxes (represented by gray arrows), both of which are printed in italic red type and expressed in teragrams of phosphorus per year. *Data from Schlesinger, W. H., 2013.* Biogeochemistry: An analysis of global change, *3rd ed. London, England: Academic Press.*

of treated wastewater (pp. 415–416) rich in phosphates from the detergents we use to wash our clothes and dishes.

WEIGHING **the issues**

Nutrient Pollution and Its Financial Impacts

A sizeable amount of the nitrogen and phosphorus that enter the Chesapeake Bay originates from farms and other sources far from the bay, yet it is people living near the bay, such as oystermen and crabbers, who bear many of the negative impacts. Who do you believe should be responsible for addressing this problem? Should environmental policies on this issue be developed and enforced by state governments, the federal government, both, or neither? Explain your answer.

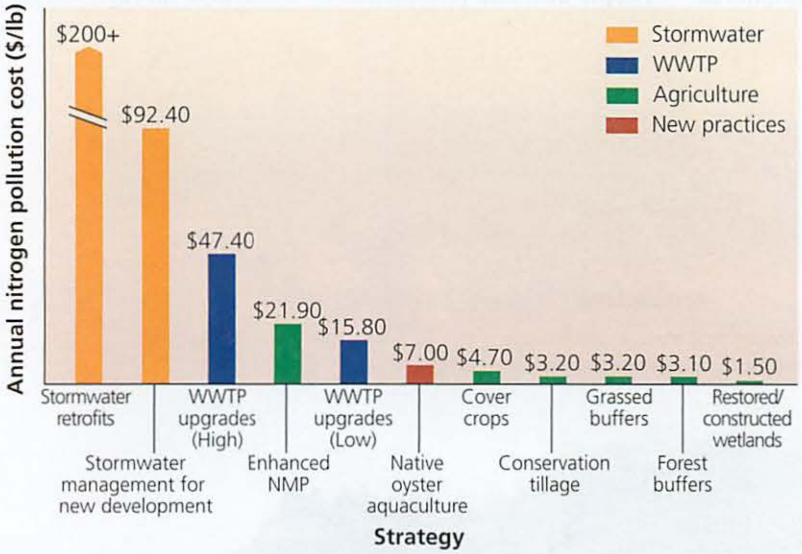
Tackling nutrient enrichment requires diverse approaches

Given our reliance on synthetic fertilizers for food production and fossil fuels for energy, nutrient enrichment of ecosystems will pose a challenge for many years to come. Fortunately, a number of approaches are available to control nutrient pollution in the Chesapeake Bay and other waterways affected by eutrophication, including:

- Reducing fertilizer use on farms and lawns and timing its application to reduce water runoff
- Using "cover crops," such as clover (pp. 233–234), to keep farmland vegetated after cash crops are harvested
- Planting and maintaining vegetation "buffers" around streams that trap nutrient and sediment runoff
- Using natural and constructed wetlands (p. 417) to filter stormwater and farm runoff
- Improving technologies in sewage treatment plants (pp. 415–416) to enhance nitrogen and phosphorus capture
- Upgrading stormwater systems to capture runoff from roads and parking lots
- Reducing fossil fuel combustion to minimize atmospheric inputs of nitrogen to waterways

Some of these methods cost more than others for similar results. For example, planting vegetation buffers and restoring wetlands can reduce nutrient inputs into waterways at a fraction of the cost of some other approaches, such as retrofitting urban areas to capture stormwater runoff (**FIGURE 5.21**).

FIGURE 5.21 Costs for reducing nitrogen inputs into the Chesapeake Bay vary widely (a). These approaches include cover crops planted on agricultural land **(b).** and retrofitting urban areas with gardens that capture stormwater runoff **(c).**

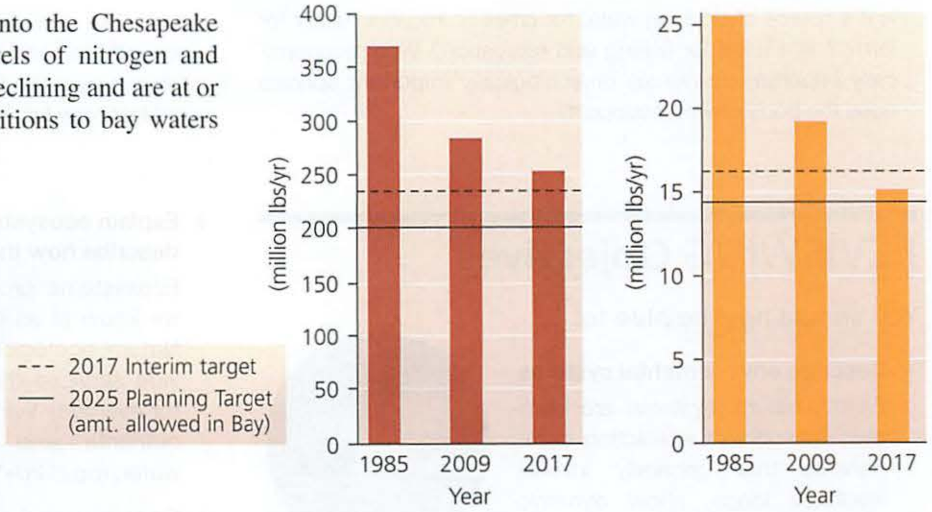


(a) Relative costs of approaches for preventing nutrient inputs to the Chesapeake Bay

(b) Cover crops planted on agricultural land in Virginia

(c) Stormwater capture garden in Baltimore, Maryland

Efforts to control nutrient inputs into the Chesapeake Bay are already paying dividends. Levels of nitrogen and phosphorus entering the bay have been declining and are at or near established targets for nutrient additions to bay waters (**FIGURE 5.22**).



(a) Nitrogen inputs **(b) Phosphorus inputs**

FIGURE 5.22 Inputs of nitrogen (a) and phosphorus (b) to the Chesapeake Bay have been decreasing. Nitrogen inputs in 2017 were slightly higher than the interim target for the year, but phosphorus inputs were lower than the interim target. Further reductions in both nitrogen and phosphorus will be needed to meet the goals for 2025. *Data from Chesapeake Bay Program Watershed Model Phase 5.3.2 (Chesapeake Bay Program Office, 2018).*

CENTRAL CASE STUDY
connect & continue

TODAY, after languishing in a degraded state for decades, the Chesapeake Bay finally has prospects for real recovery, as the federal government and bay states are now managing the bay as a holistic system and working together to save their shared waterway. By studying the environment from a systems perspective and by integrating scientific findings with the policy process, people who care about the Chesapeake Bay and other waterways are working to "bring back" degraded habitats.

While the progress made toward recovery is certainly encouraging, the program's long-term future is uncertain. The federal budget submitted in 2019 by the Trump administration drastically reduced funding for Chesapeake Bay cleanup efforts. Whereas Congress has indicated a willingness to continue the program, if it were to embrace the President's budget, efforts to remedy the bay's will likely collapse. But if the program is continued, the 18 million people living in the bay's watershed have reason to hope that the Chesapeake Bay of tomorrow may be healthier than it is today, thanks to the collaborative efforts of concerned citizens, advocacy organizations, and the federal and bay-state governments.

But as is often the case in environmental science, the challenges faced in places like Deal Island are complex and require equally multifaceted, integrated solutions. Although there are encouraging signs of recovery in bay waters, climate change is causing those same waters to rise (pp. 501–504)—and threaten the island's very existence. The waters of the Chesapeake Bay have risen about 30 cm (1 ft) in the past century, and if sea levels rise another 90 cm (3 ft) as computer models predict will happen, Deal Island will be completely submerged. Saving Deal Island, and numerous other low-lying areas like it will therefore require that we also take on the challenge of lessening the factors causing these changes in Earth's climatic systems.

- **CASE STUDY SOLUTIONS** You are an oysterman in the Chesapeake Bay, and your income is decreasing because the dead zone is making it harder to harvest oysters. One day your senator comes to town, and you are able to have a one-minute conversation with her. What steps would you urge her and her colleagues in Congress to take to help alleviate the dead zone and bring back the oyster fishery? Now suppose you are a Pennsylvania farmer who has learned that the government is offering incentives to farmers to help reduce fertilizer runoff into the Chesapeake Bay. What types of approaches described in this text might you be willing to try, and why?
- **LOCAL CONNECTIONS** Identify the closest body of water to your area that is suffering from eutrophication. Which of the categories shown in Figure 5.4 would likely be the largest sources of nutrient inputs to this body of water? List three approaches for controlling nutrient inputs—like those used in the Chesapeake Bay—that would be well suited for this body of water. For what human activities is the waterway used?

Is it a source of drinking water for cities or irrigation water for farms? Is it used for fishing and recreation? What economically important resources or ecologically important species does the body of water support?

• **EXPLORE THE DATA** How can we most efficiently focus our efforts on reducing plant nutrient inputs into the Chesapeake Bay? ➔ **Explore Data** relating to the case study on Mastering Environmental Science.

REVIEWING Objectives

You should now be able to:

+ **Describe environmental systems**

Earth's natural systems are complex networks of interacting components that generally involve feedback loops, show dynamic equilibrium, and exhibit emergent properties. (pp. 107–111)

+ **Define ecosystems and discuss how living and nonliving entities interact in ecosystem-level ecology**

Ecosystems consist of all organisms and nonliving entities that occur and interact in a particular area at the same time. Matter is recycled in ecosystems, but energy flows in one direction—from producers to higher trophic levels. Input of nutrients can boost productivity—which is the generation of biomass—but an excess of nutrients can alter ecosystems and cause severe ecological and economic consequences. (pp. 111–118)

+ **Outline the fundamentals of landscape ecology and ecological modeling**

Landscape ecology studies how the habitat patches that make up landscape structure influence organisms. Geographic information systems (GIS)—software that overlays multiple types of data on a common set of geographic coordinates—enables landscape ecology to be used increasingly in conservation biology and regional planning. Ecological modeling helps ecologists comprehend the complex systems they study and predict how these systems will react to disturbance. (pp. 118–120)

+ **Explain ecosystem services and describe how they benefit our lives**

Ecosystems provide the "goods" we know of as natural resources. Natural ecological processes provide services that we depend on for everyday living, such as cycling nutrients and purifying drinking water. (pp. 120–121)

+ **Compare and contrast how water, carbon, nitrogen, and phosphorus cycle through the environment and explain how human activities affect these cycles**

Major reservoirs of the hydrologic cycle include the oceans and ice caps, and large fluxes include evaporation, precipitation, and runoff. Most of the carbon on Earth is contained in sedimentary rock, and fluxes include photosynthesis, cellular respiration, and fossil fuel combustion. The major reservoir of nitrogen is the atmosphere, and important fluxes include nitrogen fixation (both by bacteria and by humans) and denitrification. Phosphorus is most abundant in sedimentary rock, and fluxes include the weathering of rocks and human applications of fertilizers. (pp. 121–128)

+ **Explain how human activities affect biogeochemical cycles**

People are affecting Earth's biogeochemical cycles by shifting carbon from fossil fuel reservoirs into the atmosphere, shifting nitrogen from the atmosphere to the planet's surface, and depleting groundwater supplies, among other impacts. Policies that seek to minimize human alterations of cycles, such as the remediation efforts embraced in the Chesapeake Bay, can help us address nutrient pollution. (pp. 122–129)

SEEKING Solutions

1. Once vegetation is cleared from a riverbank, water begins to erode away the bank. This erosion may dislodge more vegetation. Would you expect this to result in a feedback process? If so, which type: negative or positive? Explain your answer. How might we halt or reverse this process?
2. Consider the ecosystem(s) that surround(s) your campus. Describe one way in which energy flows through it and matter is recycled. Now pick one type of nutrient and briefly describe how it moves through this (these) ecosystem(s). Does the landscape contain patches? Can you describe any ecotones?
3. For a conservation biologist interested in sustaining populations of the listed organisms, why would it be helpful to take a landscape ecology perspective? Explain your answer in each case.
   - A forest-breeding warbler that suffers poor nesting success in small, fragmented forest patches
   - A bighorn sheep that must move seasonally between mountains and lowlands
   - A toad that lives in upland areas but travels cross-country to breed in localized pools each spring
4. How do you think we might solve the problem of eutrophication in the Chesapeake Bay? Assess several possible solutions, your reasons for believing they might work, and the likely hurdles we would face. Explain who

should be responsible for implementing these solutions, and why.

5. **THINK IT THROUGH** You are a resource manager assigned to devise a plan to protect a rare species of frog that lives in an area slated for development. You are provided with GIS layers of the area as shown in Figure 5.12. The frogs live in the leaf litter in forests, require ponds for breeding, and cannot travel over large open areas when migrating to breeding ponds. What layers (of those shown in the figure) would be most important for your analysis? Why? How would you use principles of landscape ecology when creating your plan?

CALCULATING **Ecological Footprints**

For many Americans, their desire is to own a suburban home with a weed-free, green lawn. Nationwide, Americans tend about 40.5 million acres of lawn grass. But conventional lawn care involves inputs of fertilizers, pesticides, and irrigation water, not to mention the use of gasoline or electricity for mowing and other care—all of which raise health concerns and affect environmental cycles. Using the figures for a typical lawn in the table, calculate the total amount of fertilizer, water, and gasoline used in lawn care across the nation each year.

	ACREAGE OF LAWN	FERTILIZER USED (LB)	WATER USED (GAL)	GASOLINE USED (GAL)
For the typical quarter-acre lawn	0.25	37	15,700	4.9
For all lawns in your hometown				
For all lawns in the United States	40,500,000			

Data: Chameides, B., 2008. www.huffingtonpost.com/bill-chameides/stat-grok-lawns-by-the-nu_b_115079.html

1. How much fertilizer is applied each year on lawns throughout the United States? Where does the nitrogen for this fertilizer come from? What becomes of the nitrogen and phosphorus that are applied to a suburban lawn but not taken up by grass?
2. Leaving grass clippings on a lawn decreases the need for fertilizer by 50%. What else might a homeowner do to decrease fertilizer use in a yard and the environmental impacts of nutrient pollution?
3. How much gasoline could Americans save each year if they did not take care of their lawns? At today's gas prices, how much money would this save annually?

Mastering Environmental Science

Students Go to **Mastering Environmental Science** for assignments, an interactive e-text, and the Study Area with practice tests, videos, and activities.

Instructors Go to **Mastering Environmental Science** for automatically graded activities, videos, and reading questions that you can assign to your students, plus Instructor Resources.