2 Understanding Ecology and Biodiversity

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Learning Outcomes

After reading this chapter, you should be able to

- Describe the components of the ecological hierarchy.
- Identify characteristics of all ecosystems.
- Explain how energy flows through ecosystems.
- Describe how matter cycles in ecosystems.
- Explain how and why eutrophication occurs.
- Describe the importance of biodiversity and the major threats to it.
- Discuss what is being done to address threats to biodiversity.
- Define the term *planetary boundaries*.

The environment and the study of the environment encompass everything that surrounds us, including all living and nonliving things. **Ecology** is the study of the relationships and interactions between living organisms and their surrounding environment. The term *ecology* derives from the Greek word for "house" or "dwelling," *oikos*, and "study," or *logy*. In other words, ecology is the "study of our house," and it is at the core of what environmental science is about.

The goal of this chapter is to give you a foundation in some key ecological concepts that will be important to studying environmental issues in subsequent chapters. The chapter starts by introducing the idea of the Earth as a system and how ecologists and environmental scientists use a "systems view" or "systems thinking" in the work they do. We will then focus on the study of the environment at the ecosystem scale, considering what ecosystems are, how they are defined, and what some of their key characteristics are. We will review two fundamental ecosystem processes—energy flow and matter cycling—that play a central role in understanding environmental issues.

We then shift to the concept of biodiversity: what it means, why it matters, and what are the major threats to it. The chapter concludes with a brief discussion of an interesting concept known as *planetary boundaries*. These boundaries were developed as a way to help us think of the planet's overall health and to warn us when our actions might be jeopardizing the environment we all depend on. If we think of ecology as the study of our "house," planetary boundaries are a way for us to monitor and stay aware of threats or dangers to the planet we all call home.

2.1 The Earth as a System

Throughout this book, and in the study of environmental science, you will frequently hear the environment described as a system or as being composed of numerous, interconnected systems. What does this mean, and why does it help to think about the environment in terms of systems?

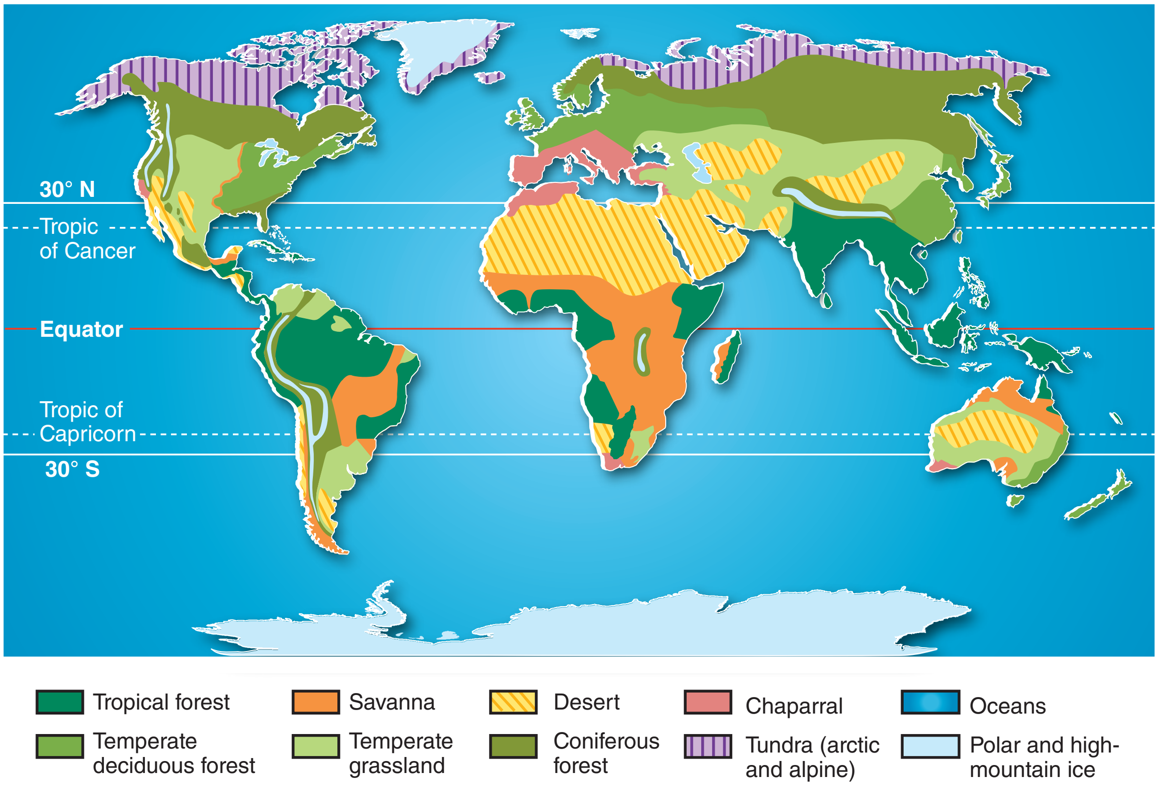
A **system** can be defined as a set of connected or interdependent things that together form a more complex whole. For example, the car you drive is made up of multiple, interacting systems that work together to provide you with mobility. These include the ignition, electrical, braking, steering, cooling, and suspension systems. Likewise, a rain forest in Borneo, a wetland along the Gulf Coast, a mountain stream in the Rockies, or a grassland in the upper Midwest can all be thought of as systems (in this case, ecosystems). Forests, wetlands, streams, grasslands, and other ecosystems all consist of organisms and elements that are interdependent and that together make up a more complex whole.

Given the sheer complexity of the Earth as a system, ecologists and environmental scientists find it helpful to view and study the world at different scales. They do this through an approach known as the ecological hierarchy theory. The **ecological hierarchy** illustrates the relationships between different organisms and organizes those relationships into different levels.

At the first level of the ecological hierarchy are individual organisms, such as a single elephant or bird. Multiple individuals of the same species living in a particular location, such as a herd of elephants or a flock of birds, are considered a **population**, the second level of the ecological hierarchy. A group of populations of different species that interact and live in the same place—such as a forest, stream, or wetland—is known as a **community**, the third level of the ecological hierarchy. This community and its physical environment make up the next level, an **ecosystem**. In other words, ecosystems include the living, or biotic, communities that occupy them, as well as the nonliving, or abiotic, characteristics that often shape the abundance and diversity of life in that location. Different ecosystems connect and interact with one another—for example, a forest ecosystem connects with the stream ecosystem that runs through it—and make up a **landscape**. At an even larger scale, or higher level, ecosystems and landscapes that have similar climate and vegetation can be grouped into **biomes** (see Figure 2.1). Generally speaking, tropical regions characterized by warm temperatures, an abundance of moisture, and relatively constant levels of daylight contain the biomes with the highest number and diversity of organisms.

Figure 2.1: Biomes

Earth's major biomes result primarily from differences in climate. Each biome contains many ecosystems made up of species adapted for life in their specific biome.

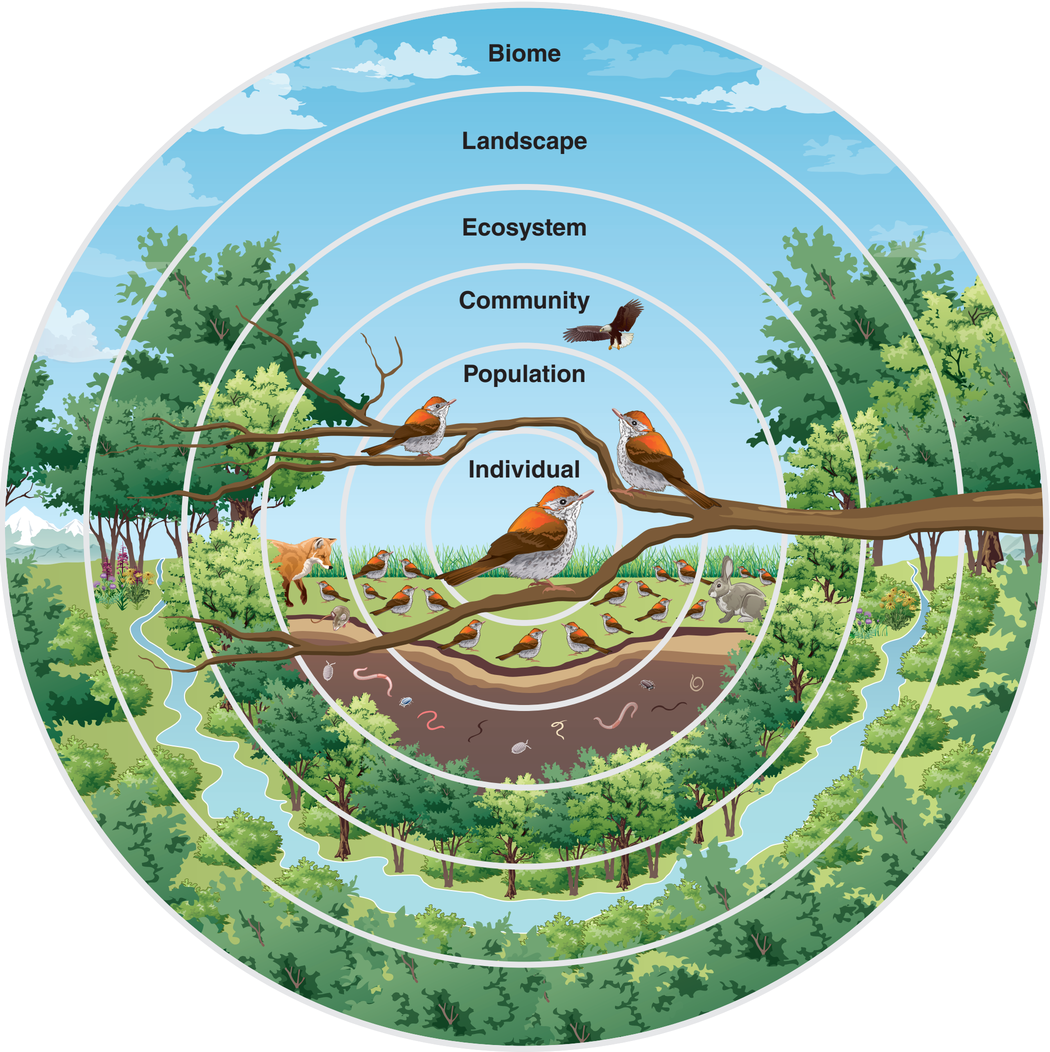


*Adapted from "Global Soil Regions Map," by U.S. Department of Agriculture Natural Resources Conservation Service, 2005 (***http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/worldsoils/?cid=nrcs142p2_054013***).*

Let's use an example to illustrate the ecological hierarchy at work (see Figure 2.2). We'll start with a single bird common to our state of Pennsylvania, the wood thrush. A certain population of wood thrushes breeds and reproduces in a specific forested region near the home of one of the authors. That population of wood thrushes interacts with other populations of birds, mammals, insects, and plants at the community or biotic community scale. The biotic community, combined with the abiotic or nonliving components, make up an ecosystem—in this case a forested ecosystem that the wood thrush favors as habitat. That forest is embedded in a larger landscape of rivers, streams, wetlands, and human-dominated land uses. The forests of Pennsylvania are similar to temperate forests in other regions of the United States and the world and make up part of the temperate forest biome.

Figure 2.2: The ecological hierarchy

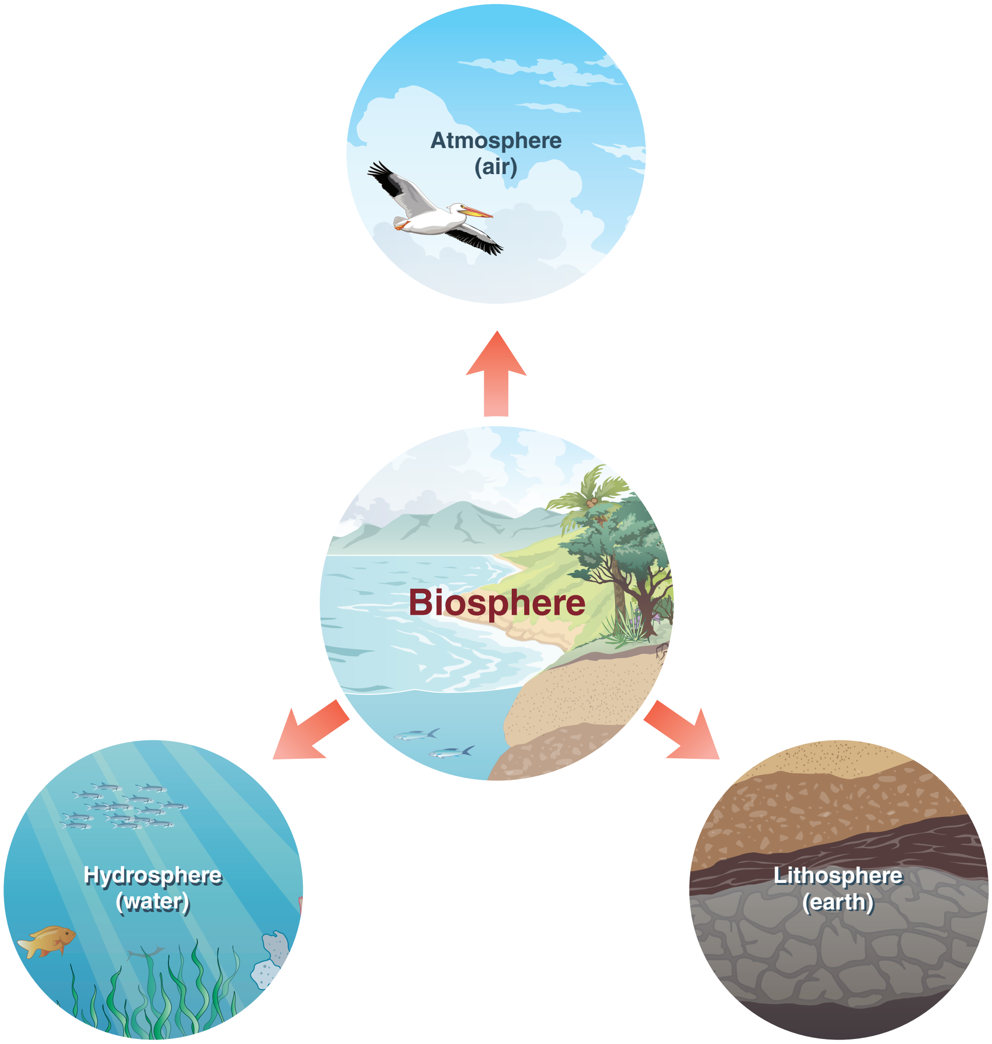
The ecological hierarchy enables ecologists and environmental scientists to study the Earth at different scales.



At the highest scale, or level, the entire planet is made up of four separate but interacting realms or spheres (see Figure 2.3). These four spheres include the lithosphere (or geosphere), the hydrosphere, the atmosphere, and the biosphere. The **lithosphere** is the solid Earth, specifically the upper crust (extending up to 100 kilometers, or 62 miles, below the surface) and the uppermost mantle (extending as far as 2,500 kilometers, or 1,550 miles, below the surface). The **hydrosphere** is the watery parts of our planet: the oceans, rivers, lakes, clouds, groundwater reservoirs, and glaciers that cover three quarters of the Earth's surface. The **atmosphere** is a mixture of gases, mostly nitrogen and oxygen, with smaller amounts of argon, carbon dioxide, and other trace gases. The atmosphere is held to the Earth's surface by gravity and thins rapidly with altitude. Ninety-nine percent of the Earth's

Figure 2.3: The four spheres

The highest scale, or level, of the ecological hierarchy is made up of four spheres. Environmental scientists study interactions among the atmosphere, lithosphere, and hydrosphere. The biosphere is the zone of all three spheres that contains life.



atmosphere is concentrated in the first 30 kilometers (19 miles), but a few traces of atmospheric gases remain even in frigid, near-space conditions thousands of kilometers above the Earth's surface. The **biosphere** is the zone where life exists on Earth. Most life concentrates at or near the surface of the land and ocean, but some bacteria thrive in rocks 4 kilometers (2.5 miles) beneath the surface, some organisms live in deep ocean trenches, and a few windblown microorganisms drift in thin, cold, inhospitable air waves 10 kilometers (6 miles) above the surface. Most of this book will focus on issues and conditions that occur in the biosphere, but we will also examine the lithosphere (energy resources), the hydrosphere (freshwater and ocean resources), and the atmosphere (climate change, air pollution, and ozone depletion).

The concepts of the ecological hierarchy and the four spheres allow us to take something as vast and complex as the entire planet and view it at many different scales. A *systems view* or *systems thinking* helps us see how the pieces within each level connect and interact. **Systems thinking** is an approach to science that considers not just the individual parts of a system but also how they interact and interrelate over time. When we think of the environment as a system, we become more aware of how our actions in one place might have consequences in another. The late ecologist Barry Commoner (1971) summed this up in his first law of ecology: Everything is connected to everything else.

Section 2.2 will home in on one level of the ecological hierarchy—the ecosystem. Much of the work done by ecologists and environmental scientists is at the ecosystem scale, and so it is important to better define and understand what ecosystems are and how they operate.

2.2 Ecosystems as a Concept

Section 2.1 described ecosystems as a collection of living (biotic) and nonliving (abiotic) entities that exist and interact in a particular location and time. For example, the forest ecosystem that is home to the wood thrush is made up of birds, insects, mammals, amphibians, fungi, trees and plants, soils, rocks, and nutrients. Forests and other ecosystems are characterized by a number of factors that are the focus of this section.

Ecosystems Are Open

Virtually all of the Earth's ecosystems are *open* systems, meaning that they receive inputs from surrounding systems and produce outputs. Some of ecosystems' most important inputs and outputs come in the form of energy and matter, which will be described in much greater detail in Section 2.3. For now, it's enough to visualize an ecosystem in much the same way you might view your home, as an open system that relies on inputs of food, energy, and water while producing outputs like solid waste, wastewater, and emissions of air pollutants. Ecologists refer to the energy and matter that flow into, through, and out of an ecosystem as *throughput*.

Ecosystems Are Subject to Feedback Loops

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Clear-cutting forest can create conditions that lead to further deforestation—an example of a positive feedback loop.

As energy and matter flow into and out of ecosystems, and as ecosystems are subject to various kinds of disturbance and change, we often see what are known as *feedback loops*. A **positive feedback loop** causes the system to keep changing further in the same direction. A **negative feedback loop** causes the system to change in the opposite direction.

In nature, a positive feedback loop might occur when a section of a forest is clear-cut, creating light and temperature conditions along the new forest edge that lead to even further loss of trees and worsening deforestation. A negative feedback loop might occur if there were a sudden increase in the population of a certain insect species. This might lead to an equivalent increase in the population of birds and other organisms that prey on or eat that insect, returning the insect population to what it was originally. Positive feedback loops tend to be destabilizing, resulting in continual change, while negative feedback loops tend to be self-correcting or stabilizing.

In other words, don't think of positive feedback loops as "good" or negative feedback loops as "bad." In fact, the opposite is generally the case. Most systems in nature are characterized by negative feedback loops, which result in a dynamic equilibrium or **homeostasis**—the tendency of a system to maintain relatively stable conditions over time.

When a system is experiencing a series of positive feedback loops, changing further and further in the same direction, it's possible that it could reach a threshold or **tipping point**. When this happens, the system collapses or shifts to a new, different state. For example, when water is boiled to a tipping point of 100 °C (212 °F), it turns to vapor. When water is cooled to 0 °C (32 °F), it turns to ice.

A potential tipping point that worries many environmental and climate scientists involves a positive feedback loop from melting permafrost areas in the Arctic. This will be explained in more detail in Chapter 8, but basically, permafrost soils hold large quantities of methane and carbon, which can become carbon dioxide as these soils thaw. Human activities like burning fossil fuels are already raising methane and carbon dioxide levels in the atmosphere. Methane and carbon dioxide are greenhouse gases that trap heat in the atmosphere, and this is increasing temperatures in the Arctic. As temperatures increase, permafrost soils begin to thaw and release more methane and carbon dioxide into the atmosphere. This methane and carbon dioxide leads to further warming and more thawing of permafrost soils, which results in even greater releases of methane and carbon dioxide, and so on. Such a situation could lead to rapid and runaway global warming and climate change, pushing our planet beyond a threshold and over a tipping point.

Ecosystems Provide a Range of Conditions

For a wood thrush to survive in the forested ecosystem in Pennsylvania, it requires certain resources and conditions such as food, water, and reasonable temperatures. When these environmental factors and conditions are present in a way that is most favorable for the wood thrush, they are said to be in the *optimal range*. The entire range over which the wood thrush could survive, even if it did not thrive in an optimal sense, is known as the **range of tolerance**, with the extreme ends of that range known as the *limits of tolerance*. Conditions that fall between the optimal range and the limits of tolerance are known as *zones of stress* because organisms experience increasing stress the further they are from their optimal range.

All living organisms have an optimal range, zones of stress, and limits of tolerance for every abiotic factor they depend on, and these are different for different species. Some species have a very broad optimal range and can tolerate a wide variety of conditions, while other species are more sensitive and have optimal ranges that are narrow. Ecologists refer to a factor that limits growth as a **limiting factor**, meaning that even if other factors and conditions are present in optimal amounts, the absence or shortage of a limiting factor will stress organisms that depend on it. For example, you can give a plant all the water and nutrients you want, but if there is not enough light, the plant will be limited in its growth. Lastly, we generally find that certain species, like the wood thrush, are present in specific habitats, like a temperate forest. Within that forest, the wood thrush occupies a specific **ecological niche**, the combination of conditions and resources needed for it to live. Different species can occupy the same habitat but have very different niches. Different bird species in the same forest habitat can nest in different places, eat different foods, eat at different times of day, and have other differences in their ecological niche that limits competition between them.

2.3 Fundamental Ecosystem Processes: Energy Flow and Matter Cycling

Despite the range of conditions that characterize the ecosystems found in different biomes around the world, all these ecosystems have something in common. With few exceptions, Earth's ecosystems are powered by solar energy, and the organisms within those ecosystems depend on matter in the form of nutrients, water, oxygen, and other gases to survive. This section reviews two fundamental ecosystem processes that will help you better understand life on Earth: energy flow through ecosystems and matter cycling in ecosystems.

Energy Flow Through Ecosystems

The most basic definition of **energy** is the capacity or ability to do work. In ecology, the term *energy* is usually used to define the ability of organisms to do biological work, such as moving, growing, eating, or reproducing. Scientists further divide energy into two basic forms: kinetic and potential. **Kinetic energy** is energy in motion, while **potential energy** is stored energy. The image of a dam is often used to illustrate the difference between these two types of energy.

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A dam represents the difference between kinetic and potential energy. Water held by the dam in a reservoir is potential (stored) energy. When the water is released by opening the gates of the dam, it turns into kinetic energy.

By holding moving water back, a dam is creating a reservoir, which represents accumulated or potential energy. When the gates of the dam are opened and the water starts to move again, that potential energy is converted to kinetic energy. Likewise, gasoline represents a type of potential energy, stored in the chemical bonds among the atoms that compose it. When that gasoline is ignited in the engine of a car, the potential energy held in those chemical bonds is released and converted to the kinetic energy of motion.

Laws of Thermodynamics

There are two fundamental laws or principles that apply to energy. The **first law of thermodynamics** (also known as the law of conservation of energy) states that energy can change from one form to another but cannot be created or destroyed. When we burn gasoline in a car engine, we are converting that chemical energy to the energy of motion and heat, but we end up with the same amount of energy. The **second law of thermodynamics** states that even though the overall amount of energy is conserved, energy conversion will always change that energy from a more useful to a less useful state. Gasoline is a highly useful form of energy because small quantities of it contain great potential to do work, but once combusted it changes to mostly heat energy that is too diffuse to be useful. This tendency for energy to move from a more useful state to a less useful state is known as **entropy**. An important implication of the laws of thermodynamics is that energy conversions tend to be inefficient. Only a small portion of the chemical energy stored in gasoline (typically 15%–25%) is actually converted to mechanical energy.

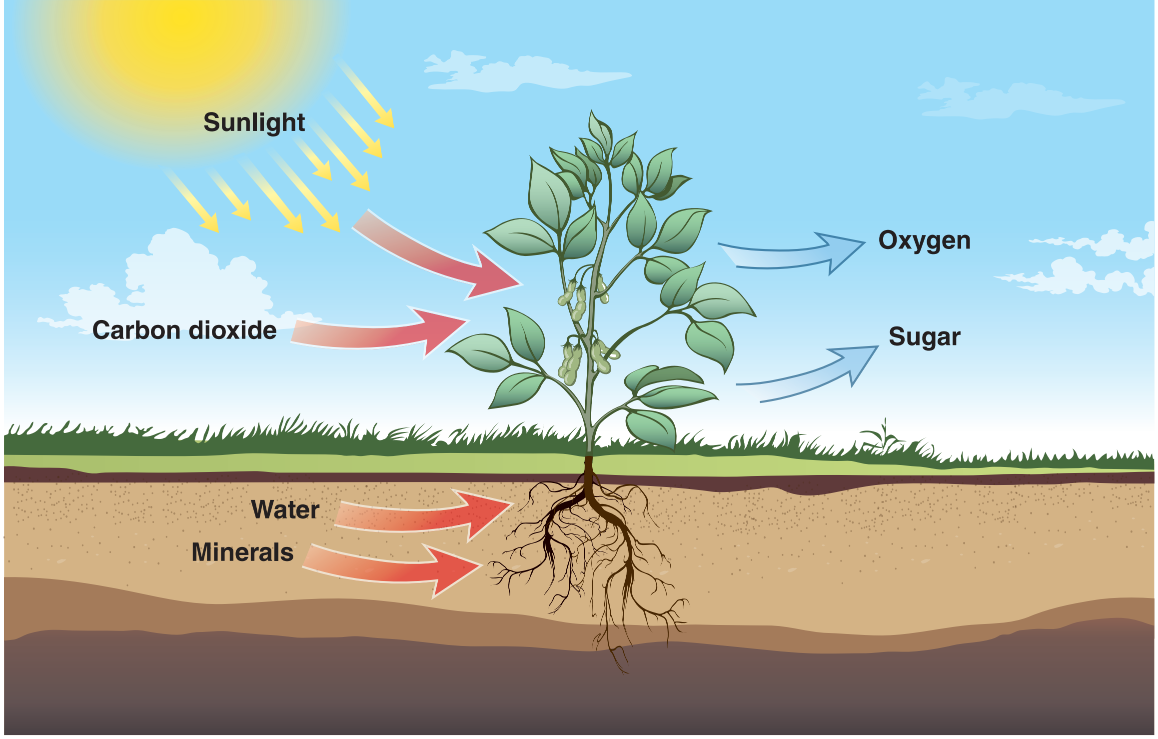
If every energy conversion moves us from a more useful state to a less useful state, we would appear to be doomed to a world of increasing disorder. Yet in the world around us, we see many signs of increasing order—for example, humans, animals, plants, and other organisms being born and growing. So how can this be? The answer lies in the fact that the Earth is an open system subject to inputs of solar energy. That incoming solar (light) energy drives processes that create new stores of potential energy that fuel virtually all the Earth's ecosystems.

Fuel for Life

Most living systems and organisms on the planet are ultimately powered by energy from the sun. The starting point is a group of organisms known as *autotrophs* or **primary producers**: mostly plants, algae, and some types of bacteria. Primary producers take the building blocks of carbon dioxide and water and produce sugar (glucose) molecules with high potential energy content. Primary producers do this through a process known as **photosynthesis**. Photosynthesis is driven by light energy from the sun, as illustrated in Figure 2.4.

Figure 2.4: Photosynthesis

Producers use photosynthesis to convert the basic building blocks of sunlight, carbon dioxide, and water into energy other organisms can use.



The ability of plants and other primary producers to do photosynthesis is really the foundation for life on Earth as we know it. Photosynthesis starts with chlorophyll, which gives plants their green color. Chlorophyll absorbs light energy from the sun and uses it to remove hydrogen atoms from water (H_2O) molecules. The hydrogen is combined with carbon atoms from carbon dioxide (CO_2) to form long chains of glucose molecules, or sugar ($C_6H_{12}O_6$). One by-product of photosynthesis is oxygen (O_2) released to the atmosphere, and this is another way plants and other primary producers can be seen as essential to life as we know it: Plants are sometimes referred to as “the lungs of the planet.” The process of photosynthesis can be summarized in an equation:

$$6CO_2 \text{ (carbon dioxide)} + 6H_2O \text{ (water)} + \text{light energy} = C_6H_{12}O_6 \text{ (glucose)} + 6O_2 \text{ (oxygen)}$$

Glucose molecules produced through photosynthesis represent a form of high-quality potential energy. This energy can be used by primary producers for their own biological functions as well as by other organisms that consume the primary producers. Plants use glucose to build stems, roots, fruit, leaves, and other structural elements. Plants also store glucose for future use and to power a process known as cellular respiration. **Cellular respiration** allows the plant to utilize the potential energy stored in glucose to perform the biochemical processes it needs to grow and survive. Cellular respiration is essentially photosynthesis in reverse:

$$C_6H_{12}O_6 \text{ (glucose)} + 6O_2 \text{ (oxygen)} = 6CO_2 \text{ (carbon dioxide)} + 6H_2O \text{ (water)} + \text{energy}$$

Some of the potential energy that is stored in plants as glucose is also available to other organisms that eat either plants or the animals that eat plants. Just as with plants, these animals use respiration to "burn" the energy stored in the glucose molecules, in the process releasing low-quality heat energy. You can see why energy is described as flowing through ecosystems. Energy enters the system as sunlight and is converted to high-quality potential energy in the form of glucose, utilized by organisms in the environment through respiration, and released as energy that dissipates back into space.

Chains of Energy

Ecologists use the concepts of *producers*, *consumers*, and *decomposers* to describe the flow of energy through an ecosystem. As discussed earlier, autotrophs like plants and algae are producers because they are able to manufacture glucose through the process of photosynthesis. The entire amount of potential energy produced by plants in a given ecosystem is referred to as *gross primary production*. Because plants use much of this energy for their own biochemical needs, the energy that is "left over" for other organisms is called *net primary production*.

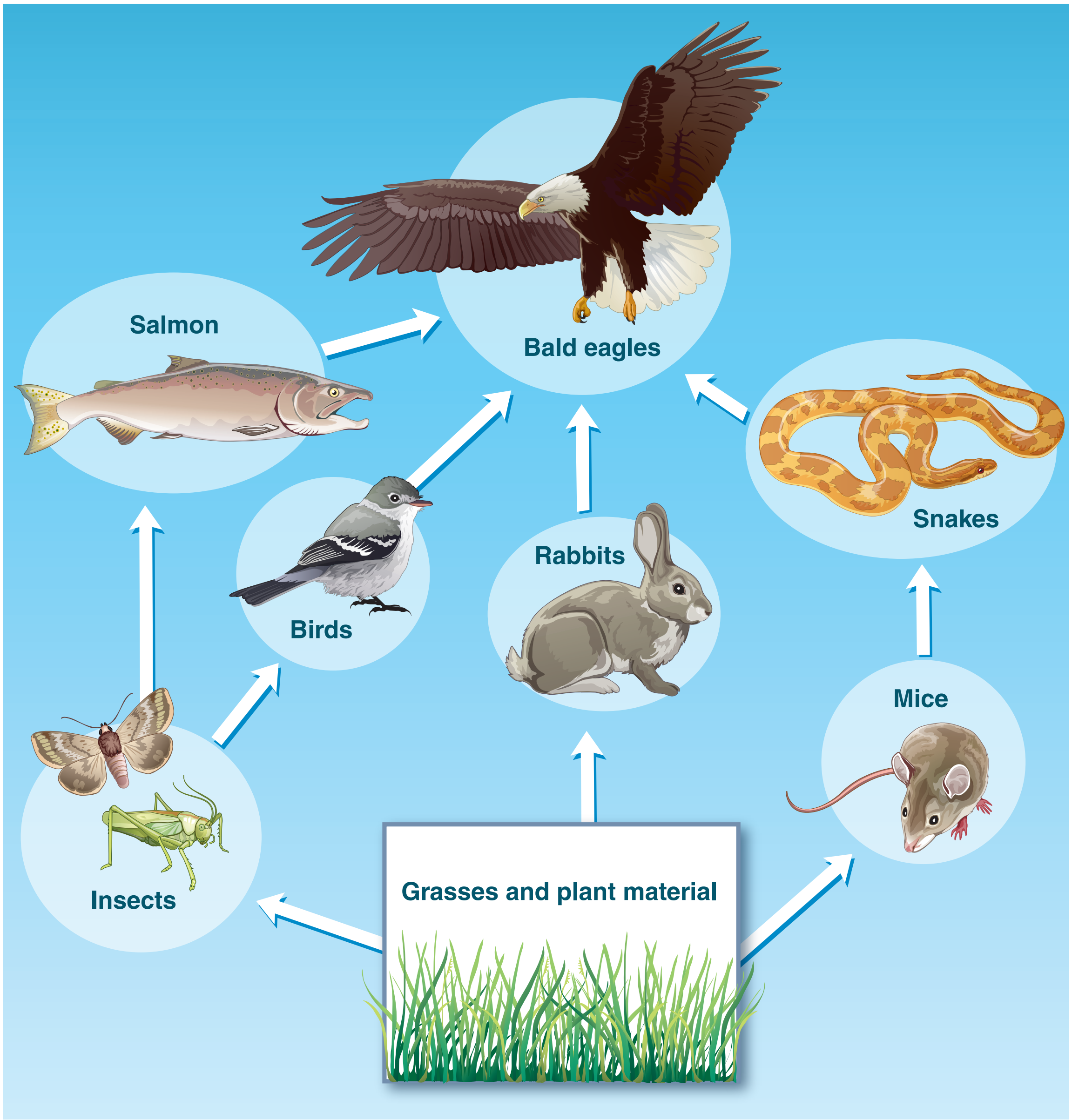
The organisms that rely on plants for some of that "leftover" energy are known as **consumers**. A rabbit that eats grass in an open meadow would be considered a primary consumer, whereas a snake that eats the rabbit would be considered a secondary consumer. A hawk that eats the snake would be considered a tertiary consumer. All of these consumers are known as *heterotrophs*. Recall that primary producers are referred to as *autotrophs*, meaning they can produce their own food (*auto* = "self"; *troph* = "nourish"). In contrast, *heterotrophs* refers to organisms that rely on other organisms for their food (*hetero* = "other"; *troph* = "nourish"). While primary consumers are herbivores (plant eaters), secondary and tertiary consumers can be either carnivores (which eat other animals) or omnivores (which eat both plants and other animals).

Last but not least are what are known as *decomposers*. **Decomposers** break down dead organic material, whether plants or animals, to obtain the energy and nutrients they need. Also known as *saprotrophs* (*sapro* = "rotten"; *troph* = "nourish"), decomposers include bacteria and fungi like mushrooms, as well as scavenging animals like vultures and hyenas. Decomposers play a critical but often overlooked role in breaking down dead organic material and releasing important nutrients that can be reused by producers for a new round of growth.

Energy flows in an ecosystem through *food chains*—for example, the hawk that ate the snake that ate the rabbit that ate the grass. In other words, **food chains** describe simple, linear feeding relationships among organisms. Ecosystems are characterized by many different food chains that combined make up a **food web**, which describes the many feeding relationships in a community (see Figure 2.5).

Figure 2.5: Food web

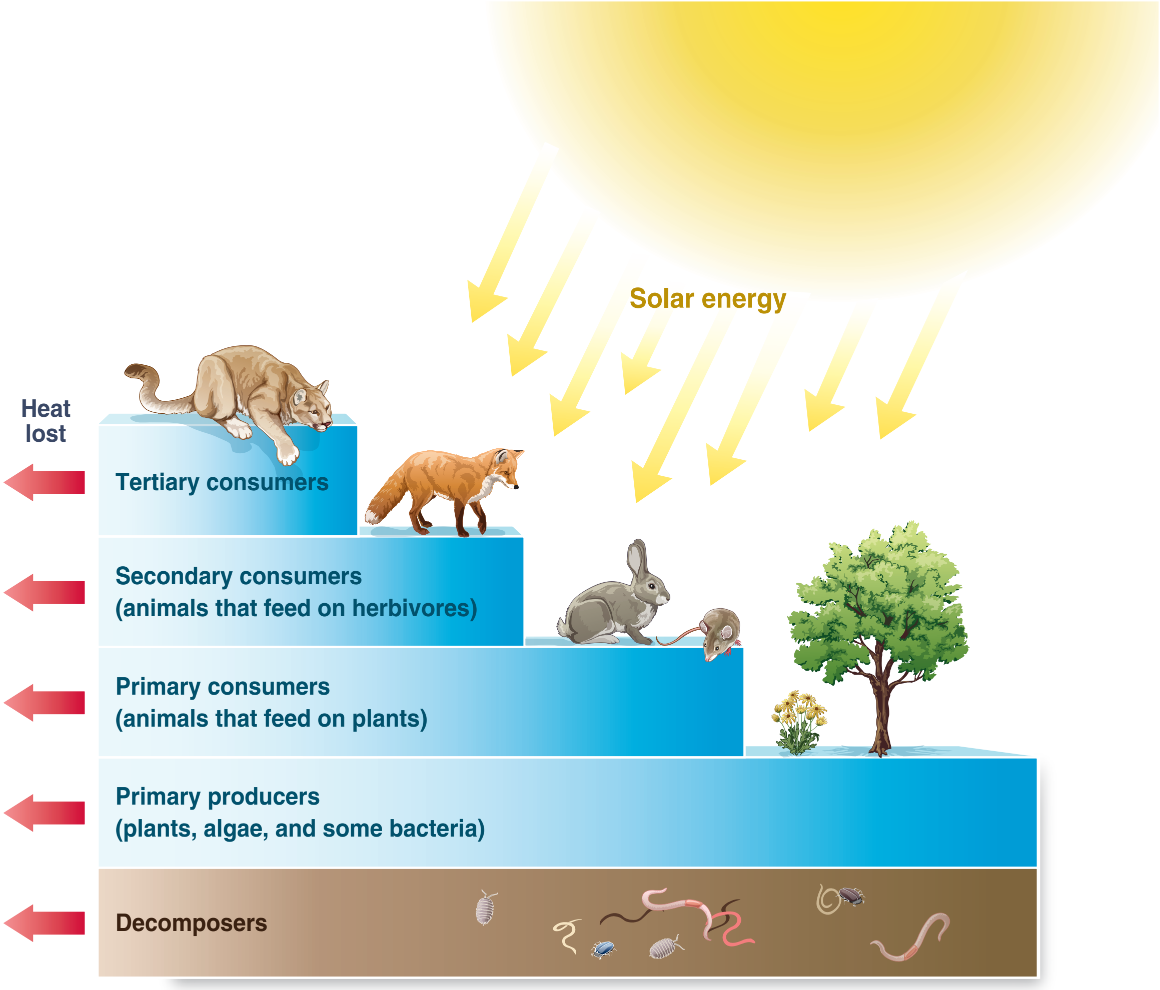
Energy flows in an ecosystem through the food web.



One important characteristic of food chains and food webs is that primary producers are far more abundant than primary consumers, and primary consumers are more abundant than secondary consumers, and so on. Ecologists use the concept of **trophic levels** to explain this. Each link in a food chain is considered a trophic level, and as we move from one trophic level to the next, we lose energy because of the second law of thermodynamics. As a result, trophic levels in ecosystems tend to be characterized by a pyramid shape, with large numbers of organisms at lower trophic levels and few at the top (see Figure 2.6). On average, ecologists estimate that only about 10% of the energy consumed at one trophic level is available to the next level. In other words, 10,000 pounds of grass in a meadow might only support 1,000 pounds of rabbits, which could support 100 pounds of snakes, which could support 10 pounds of hawks. As a result, most food chains are typically characterized by only three or four trophic levels.

Figure 2.6: Trophic levels

Energy enters an ecosystem through an external source (the sun) and flows through the progressive trophic levels of a food chain. On average, about 10% of the net energy produced at one trophic level is passed on to the next level; the rest is lost as heat energy.



Matter Cycling in Ecosystems

The previous section described how energy tends to flow through ecosystems, entering as sunlight and leaving as heat. In contrast, water and chemical elements such as carbon, nitrogen, and phosphorous tend to cycle in ecosystems. Scientists who study such cycles, known as **biogeochemical cycles**, know that the same atom of carbon used by a tree outside your window for photosynthesis may have been exhaled by a human or animal thousands of years ago. This is because of the **law of conservation of matter**, which holds that matter can neither be created nor destroyed. If you look back at the chemical reactions for photosynthesis and respiration, you will see that the carbon, oxygen, and hydrogen take different forms but are always present in the same quantities on both sides of the equation.

This principle of conservation of matter was summed up by the late ecologist Barry Commoner (1971) as "everything must go somewhere," or "there is no away" (p. 39). When we burn fossil fuels like oil and coal, which contain mostly carbon, we are moving that carbon from one place (the deep Earth), where it had been buried for millions of years, and putting it another place (in this case the atmosphere as carbon dioxide). When we mine phosphate deposits to make fertilizer and some of that fertilizer runs into streams and rivers, we are moving phosphorous from one place to another, but it does not go away. The rest of this section will review three critical biogeochemical cycles: carbon, phosphorous, and nitrogen. (The water cycle will be explained in Chapter 5).

The Carbon Cycle

Carbon is a basic building block of organic compounds required for life. Carbon circulates through the biosphere, atmosphere, and hydrosphere and is stored in underground deposits in the lithosphere. Figure 2.7 is a basic illustration of the carbon cycle, showing carbon flows from one reservoir of carbon to another. Recall that carbon in the atmosphere—in the form of carbon dioxide—is utilized by plants for photosynthesis. Some of that carbon is used to build plant tissue, and some of the plant tissue is eaten by animals and converted into their own tissue. Both plants and animals respire, returning some of that carbon to the atmosphere. As animals and plants die, the carbon in their tissue is deposited in the soil, where some is consumed and respired back to the atmosphere by decomposers. Some of the carbon dioxide in the atmosphere is also dissolved in the ocean, where it can be utilized by marine algae and plankton before being deposited in sediments at the bottom of the ocean for long periods.

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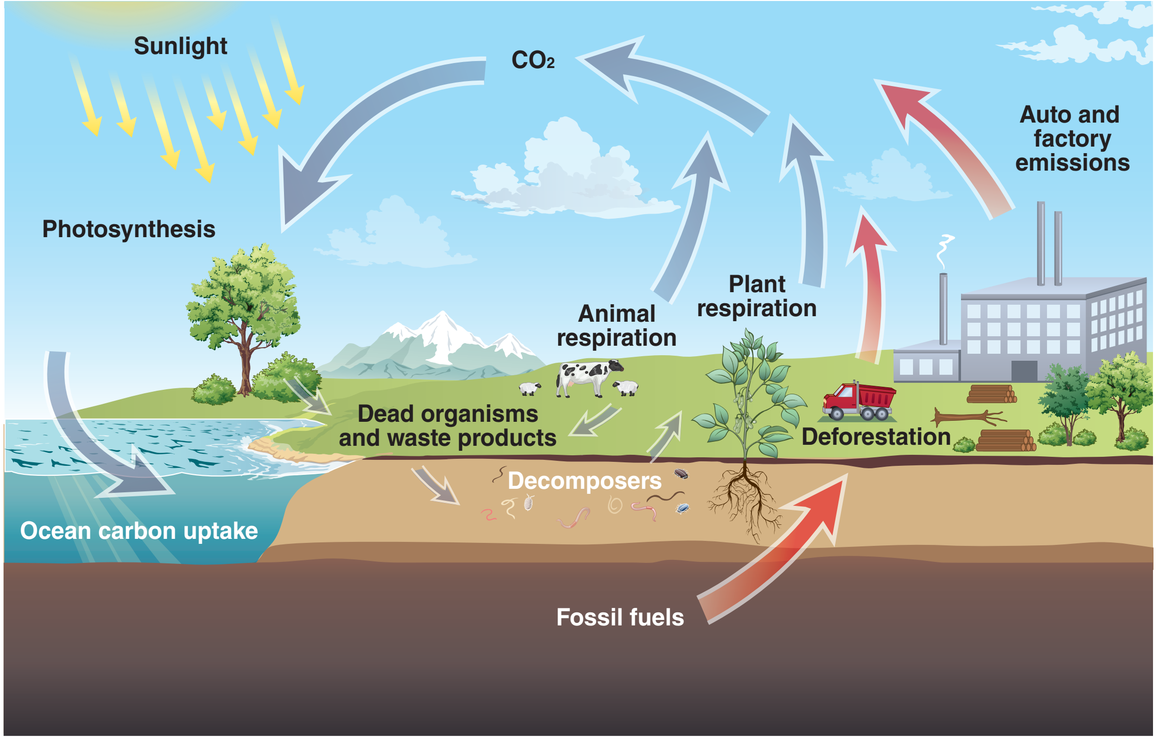
Since the Industrial Revolution, humans have added enormous amounts of carbon dioxide to the atmosphere through our heavy use of coal, oil, and natural gas.

Human activities are having a serious impact on the carbon cycle. Over millions of years, carbon stored in deposits of dead plant and animal tissue has been converted through geologic processes to fossil fuels like coal, oil, and natural gas (more on this in Chapter 7). Since the start of the Industrial Revolution, we have dug and pumped massive amounts of these fuels from the ground and burned them, taking carbon that was in the ground for millions of years and adding it to the atmosphere over just a short period of time. Because we are adding carbon to the atmosphere faster than it can be removed, atmospheric concentrations of carbon dioxide have increased from roughly 270 ppm a century ago to over 400 ppm today (Lindsey, 2018a). Because carbon dioxide is a powerful greenhouse gas in the atmosphere, these higher concentrations are a big reason for global climate change. In addition to burning fossil fuels, other human activities like clearing and burning forests and other vegetation are also adding large amounts of carbon to the atmosphere and altering the global carbon cycle.

Figure 2.7: The carbon cycle

In the carbon cycle, carbon circulates from one pool to another. The scale of human activities—represented here by red arrows—has disrupted that natural cycle and equilibrium.



The Phosphorous Cycle

Phosphorous is an important nutrient for life and is considered a limiting factor in many ecosystems. The major reservoir for this nutrient is phosphate rock or ore. These ores have accumulated over thousands of years and are brought to the Earth's surface through geological uplifting of deep ocean sediment. As these rocks are exposed to rain and other elements, they gradually break down, releasing inorganic phosphate ions. These phosphate ions are carried by water into the soil, where they can either be absorbed by plant roots and utilized as an important nutrient for plant growth or washed out into the oceans, where over time they become part of deep ocean sediments once again. Organic phosphate in plants can be available to primary consumers that eat the plants, as well as secondary consumers and so on through ecosystem food webs. As plants and animals die, decomposers break down their tissue and make phosphorous available again for new plant growth.

Phosphorous is considered a limiting factor or limiting nutrient because most soils contain little phosphate. Because of this, large deposits of phosphorous are mined around the world and incorporated into fertilizers to help promote plant growth. Much of the phosphorous in fertilizer runs off of farm fields and makes its way into streams, rivers, and ultimately the ocean, where it can lead to a serious water pollution problem known as eutrophication (see the case study in Section 2.4). The phosphorous fertilizer that gets taken up by crops ends up being eaten by the animals that eat those plants—usually humans, cows, pigs, or chickens. These animals' waste products also contain some of that phosphorous (remember, there is no away!), and this waste can also find its way into bodies of water and add to the eutrophication problem.

The Nitrogen Cycle

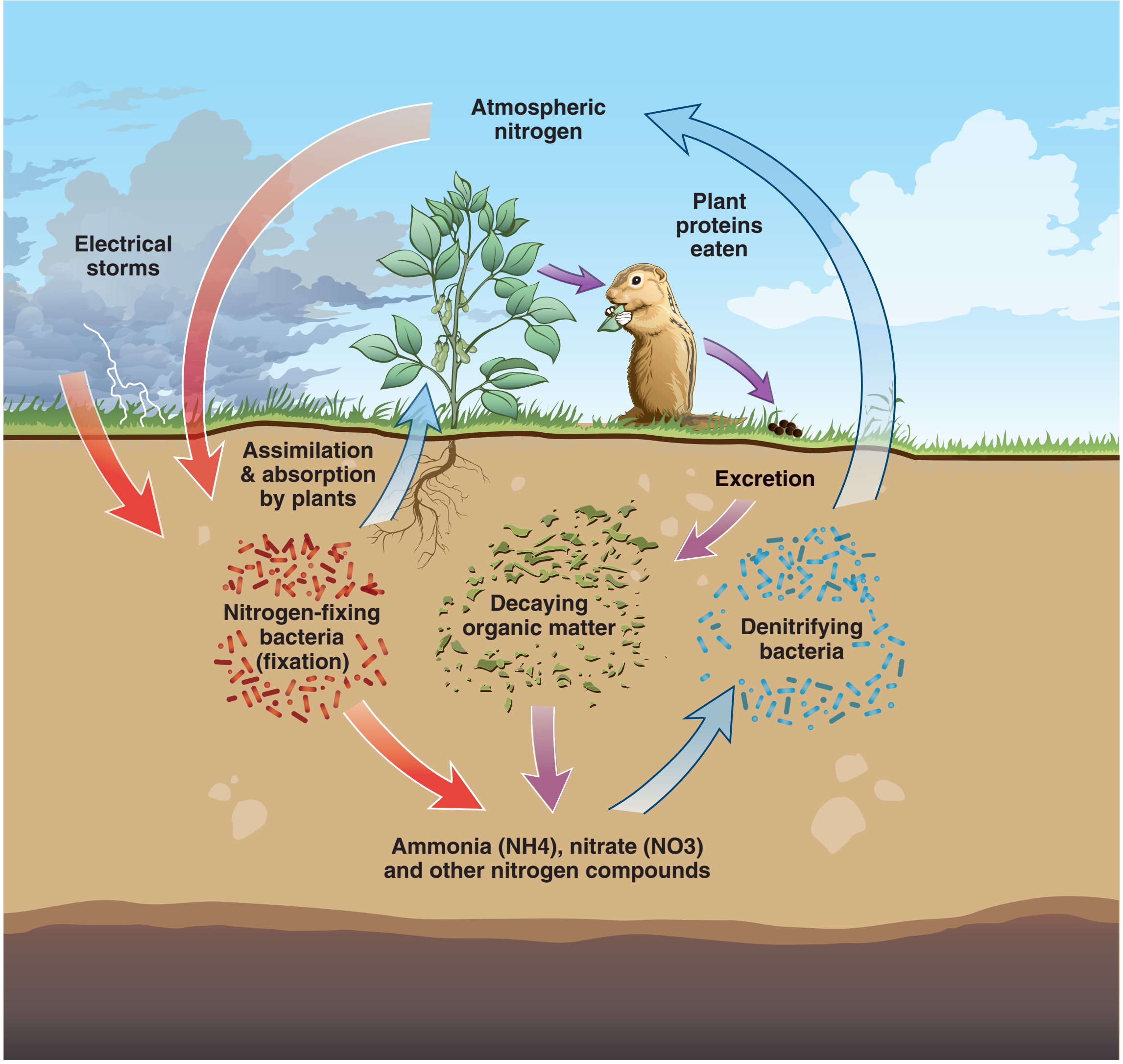
Like phosphorous, nitrogen is also a critical nutrient for all forms of life and can act as a limiting factor in plant growth. The largest pool or reservoir of nitrogen on the planet is air (see Figure 2.8), with nitrogen making up 78% of the volume of the atmosphere. Despite this abundance, plants cannot make use of atmospheric or nonreactive nitrogen. In nature, nitrogen becomes available to plants through two processes: electrical storms and biological fixation by bacteria. The sheer energy of a lightning bolt is enough to break a nonreactive nitrogen molecule (N_2) into two, where N can combine with oxygen to produce nitrogen oxides. These wash out in rain as nitrates and become available to plants for growth. Certain types of soil bacteria are also able to convert nonreactive nitrogen in the air to a usable form through a process known as **nitrogen fixation**. Some of these bacteria live on the roots of certain plants known as legumes (for example, beans and peas) and exist in a form of *symbiosis*, whereby the plants provide what the bacteria need and the bacteria provide for the plant. **Symbiosis** is a close biological interaction between two organisms.

Human modification of the nitrogen cycle occurs because we use industrial processes to remove nitrogen from the atmosphere and turn it into nitrogen fertilizer. This is known as industrial nitrogen fixation, and it requires tremendous amounts of energy to accomplish. Nonreactive nitrogen is removed from the air and combined with hydrogen (usually derived from natural gas) to make ammonia-based fertilizers. As with phosphorous, nitrogen fertilizers are added to farm fields to promote plant growth. And as with phosphorous, nitrogen fertilizers run off into bodies of water and contribute to the pollution problem known as eutrophication.

The carbon, phosphorous, and nitrogen cycles show that matter is cycled in natural systems. In contrast, energy flows into, through, and out of ecosystems. Energy enters the system as sunlight and powers photosynthesis as the basis for most life on the planet. The energy produced by photosynthesis is released as heat or waste energy as plants consume their own stored energy, animals consume plants, and other animals eat those animals. Matter in the form of water, carbon, phosphorous, nitrogen, and other nutrients is taken up by plants and enters food webs, where it generally cycles back to be used again.

Figure 2.8: The nitrogen cycle

Nitrogen circulates from the environment to living organisms and back to the environment. This cycle involves nitrogen-fixing bacteria, which convert nitrogen into forms usable by living organisms, and denitrifying bacteria, which break down nitrogen compounds and return gaseous nitrogen to the atmosphere.



Human interactions in these systems tend to disrupt the cyclical processes and replace them with linear ones. We mine phosphorous and use industrial processes to produce nitrogen, which is added to farm fields to promote plant growth. These nutrients enter other systems, where they can create the pollution problems described in Section 2.4. We then mine and produce more fertilizer and repeat the same process. This approach is not sustainable. One of the biggest challenges in moving from our current systems of economic production to more sustainable systems is to try to mimic or copy the cyclical models we find in nature.

2.4 Case Study: Eutrophication in the Gulf of Mexico

Recall from Section 2.3 that both nitrogen and phosphorous are considered limiting factors or limiting nutrients in most ecosystems. In other words, even if other conditions are favorable for plant growth and other life, the absence or scarcity of nitrogen and phosphorous will limit overall growth. Because this nutrient limitation is true of most farmland, nitrogen and phosphorous are widely applied as fertilizers in commercial farm operations around the world. When some of those fertilizers get washed off of fields and into rivers, streams, lakes, and oceans, it can cause a water pollution problem known as **eutrophication**. Eutrophication leads to sharp declines in dissolved oxygen levels in bodies of water, and this can kill off fish and other marine life. The result is what ecologists refer to as a dead zone.

Defining Eutrophication

What is eutrophication, and why would something "good" (like fertilizer) lead to something "bad" like dead zones? The answer lies in the fact that nitrogen and phosphorous are also limiting nutrients in aquatic (water-based) ecosystems. When excess nitrogen or phosphorous enters a body of water like the Gulf of Mexico, it "fertilizes" and promotes the rapid growth of plantlike phytoplankton (algae and cyanobacteria), commonly referred to as an algae bloom. Under normal conditions, phytoplankton can be a source of food for other marine life, but when eutrophication occurs, the organisms that typically consume phytoplankton can't keep up. This leads to large quantities of phytoplankton eventually dying and sinking to the bottom, where they are decomposed by other bacteria. These bacteria use dissolved oxygen in the water as part of the decomposition process, and this results in sharp declines in oxygen levels. Low oxygen levels can lead to the death and displacement of all kinds of marine life, resulting in dead zones.

Patrick Semansky/Associated Press

Dead fish in the Gulf of Mexico off the Louisiana coast. Fertilizers that wash into bodies of water can cause negative impacts such as algae blooms, eutrophication, and dead zones.

Examining the Problem in the Gulf

Aquatic dead zones can be found in many parts of the world. Environmental scientists estimate that there are over 400 dead zones globally (Diaz & Rosenberg, 2008). In the United States the Gulf of Mexico dead zone is considered the largest, and this has a lot to do with geography. The Gulf of Mexico receives all the water drained from the Mississippi River, and the Mississippi alone drains over 40% of the surface area of the lower 48 states. The Mississippi River basin also includes much of the largest agricultural production areas in the country, where large amounts of nitrogen and phosphorous fertilizers are applied to fields of corn, soybeans, and other commodity crops. Some of the largest animal feedlots and production areas (beef, chicken, and pork, in particular) in the United States are also located in the Mississippi River basin, and the waste products from these animals contain large quantities of nitrogen and phosphorous. When people eat crops grown with nitrogen and phosphorous or eat animals that were fed those crops, they also take in and eventually release most of those nutrients through their waste. Municipal sewage treatment plants strive to remove as much of this nitrogen and phosphorous as possible, but older systems are not very effective at this. Lastly, common fertilizers applied to lawns, gardens, and golf courses also contain nitrogen and phosphorous. All of these sources can add nutrients that run off into nearby bodies of water before being washed down to the sea.

Eutrophication is a regular seasonal occurrence in the Gulf of Mexico. Spring rains and snowmelt coincide with large applications of fertilizer at the start of the growing season. By early summer, hypoxic or low-oxygen conditions start to appear in the Gulf and typically worsen as the summer goes on. Eventually, seasonal storms, including hurricanes, help mix the water in the Gulf and return oxygen to hypoxic areas. Years that are characterized by heavy rains in the upper Midwest and higher river flows in the Mississippi usually result in larger dead zones. In contrast, the Gulf of Mexico dead zone typically shrinks in years of drought. Scientists have been measuring oxygen levels and hypoxic conditions in the Gulf of Mexico since 1985, and the largest annual dead zone ever recorded was in the summer of 2017. That year the Gulf dead zone measured close to 23,300 square kilometers (9,000 square miles), roughly the size of New Jersey (National Oceanic and Atmospheric Administration, 2017).

Applying Our Knowledge

We can use the case study of the Gulf of Mexico dead zone to see how some of the terms and concepts introduced earlier in this chapter apply to the study of ecology and environmental science. First, we need to view the dead zone problem at the *landscape* level, since it involves connections between many different *ecosystems* on land and in the water. To understand what was causing the dead zone and what to do about it, scientists needed to apply *systems thinking*, rather than just looking at one piece of the puzzle. The Gulf of Mexico clearly represents an *open system* receiving inputs of nitrogen and phosphorous from other systems. Phytoplankton blooms can set off short-term *positive feedback loops* as declining oxygen levels drive away organisms that might feed on and control the population of phytoplankton. As oxygen levels drop, marine life moves further away from the *optimal range* and toward the *limits of tolerance*, sometimes resulting in reproductive failure, migration, and death (all examples of stress). A *tipping point* can be reached at which most marine life cannot survive in that area.

The dead zone problem is triggered by nitrogen and phosphorous, which are *limiting factors* introduced to the Gulf ecosystem by human activities. The movement of these nutrients from farms, feedlots, golf courses, lawns, and sewage treatment plants to the Gulf of Mexico is an example of the *law of conservation of matter* and the *cycling of matter*. In the words of Commoner, everything is connected to everything else, everything must go somewhere, and there is no away. Lastly, this case study further illustrates how *linear* human systems are compared to the kinds of *cyclical* systems we see in nature. We mine phosphorous from the ground or extract nitrogen from the atmosphere at great cost. We apply these to crops and feed the crops to animals. We eat the animals, and the nitrogen and phosphorus pollution from fertilizer runoff, animal waste, and our own waste makes its way to the Gulf of Mexico, where it triggers an environmental catastrophe. We then mine more phosphorous, produce more nitrogen, and start the process all over again.

Even though dead zones of a smaller size can occur naturally under certain conditions, the size, scale, and regularity of the dead zones in the Gulf of Mexico and over 400 other regions of the world can be interpreted as a giant “check engine” light. Something is wrong with the way we are currently managing our agricultural, water, and energy resources. The specifics of what is wrong, as well as what can be done to correct the situation, will be the focus of later chapters.

2.5 What Is Biodiversity, and Why Does It Matter?

Up to this point, the chapter has mostly discussed nature and natural systems in technical terms relating to ecosystems, matter, and energy. The Gulf of Mexico case study helped illustrate how those terms apply to a specific environmental problem. But the more important goal of providing this foundational knowledge is to enable you to more fully explore the critical concept of biodiversity. When human activities disrupt ecosystems, as well as energy flow and matter cycling in those ecosystems, biodiversity suffers; as a result, human well-being suffers too.

As discussed in Chapter 1, biodiversity is a measure of the variety of life and organisms in a specific ecosystem. The overall biodiversity on planet Earth is truly amazing. Some biologists estimate that there may be as many as 100 million species on the planet, although most estimates range from 7 million to 10 million (Zimmer, 2011). Of that total, only about 2 million species have been identified to date, suggesting that there is still much we do not understand or appreciate about the diversity of life on Earth. This section will further define and explore biodiversity and why biodiversity is so important. Section 2.6 will review some of the major threats to biodiversity around the world and what is being done to address them.

How Ecologists Characterize and Measure Biodiversity

Ecologists typically characterize biodiversity in four different ways. First, and most common, is to measure biodiversity in terms of **species diversity**, or the number of different species and their relative abundance in a given ecologic community. As previously discussed, species diversity tends to be highest in the tropical regions of the world and decline toward polar regions. In addition, hundreds of scientific studies conducted in different regions of the world have demonstrated that higher rates of species diversity are associated with both increased productivity in ecosystems and greater resilience in response to stress (Tilman, Isbell, & Cowles, 2014). For more on this issue, see *Apply Your Knowledge: How Does Biodiversity Improve Ecological Resilience?*.

Second, **genetic diversity** refers to the variety of genes and genetic material found within a population or species. Generally, the more genetically diverse a population is, the better the chance that population will survive and adapt to environmental changes. This is because increased genetic diversity improves the likelihood that some members of a population will have genetic traits that enable them to withstand disease, drought, or some other form of stress. Those individuals are then able to pass along those genetic traits to future generations. Genetic diversity can be viewed in much the same way that investors approach portfolio diversity. By not "putting all their eggs in one basket," they are able to maintain their portfolio even if some of their investments do not do well.

A third way to think of biodiversity is in terms of *ecosystem diversity*. **Ecosystem diversity** refers to the different types of ecosystems—forests, wetlands, grasslands, and so on—found around the world. Because different ecosystems support different assemblages of species, it's generally the case that higher rates of ecosystem diversity will result in greater species diversity. Different ecosystems provide us with different types and forms of critical ecosystem services. Recall from Chapter 1 that ecosystem services are life-supporting services provided by the natural capital or natural infrastructure of ecosystems. These include water filtration and nutrient cycling. Higher rates of ecosystem diversity result in a greater variety and volume of ecosystem services provided to us by natural systems.

Lastly, ecologists use the term **functional diversity** to describe all of the different ways in which organisms interact with and make use of a specific ecosystem. It's generally the case that an ecosystem with high levels of species diversity will also be characterized by high rates of functional diversity. This is because different species obtain food, reproduce, use resources, and generate waste products in different ways. Understanding of functional diversity is important to the study of ecosystems and biodiversity because it provides greater insight into the actual behaviors and actions of different species and how they relate to one another within that ecosystem.

Apply Your Knowledge: How Does Biodiversity Improve Ecological Resilience?

Michigan's Isle Royale is a 72-kilometer-long (45-mile-long) island located near the Canadian border in Lake Superior. Due to its unique location, the island remains somewhat isolated from the U.S. and Canadian mainland, and researchers use its relatively simple ecosystem to study several North American species interactions. Taking a closer look at the flora and fauna on Isle Royale can help us understand how biodiversity can make ecosystems more resilient.

Isle Royale hosts a variety of familiar North American species, many of which traveled to the island by air, water, and ice long ago. A mix of coniferous and deciduous trees supports primary consumers like squirrels, hares, birds, and moose. In marshy areas, aquatic plants provide food and habitat for beavers, fish, and aquatic insects. Foxes eat some of the smaller critters on Isle Royale, but the top of the food chain is occupied by wolves. Wolves are the only creatures that regularly prey on the formidable moose populations inhabiting the island.

A simplified food web in Figure 2.9 highlights some of the major species interactions on Isle Royale. Take a moment to study this ecosystem and consider the variety of ways that these organisms depend on one another.

(continued)

Apply Your Knowledge: How Does Biodiversity Improve Ecological Resilience? *(continued)*

Each species carries out vital functions for the larger ecosystem. Some organisms represent food sources for others. Some keep specific populations in check through hunting and consumption. Beavers engineer habitat, and ravens consume carrion and redistribute nutrients. Every one of these functions is essential to the larger ecosystem and the life that it supports.

In some cases there might be several species carrying out these ecosystem functions, and in other cases there might only be one or two. According to the food web in Figure 2.9, how many primary producers are providing food for primary consumers? How many predators are controlling the primary consumer populations through predation? Which of these two ecosystem functions will be more resilient if future environmental changes disrupt the ecosystem?

We can see from the food web that several forms of vegetation provide food sources for primary consumers. This gives us an idea of how this part of the ecosystem might respond to future changes. For example, if the balsam fir population was wiped out, the other forms of vegetation might still be able to provide suitable food and habitat for the ecosystem. In this example, the moose population appears to have several other food options.

The top of the food chain is a very different story. If wolves were to disappear, there would be no other species around to keep moose populations in check. This ecosystem function would go away completely, and it would dramatically impact the entire ecosystem.

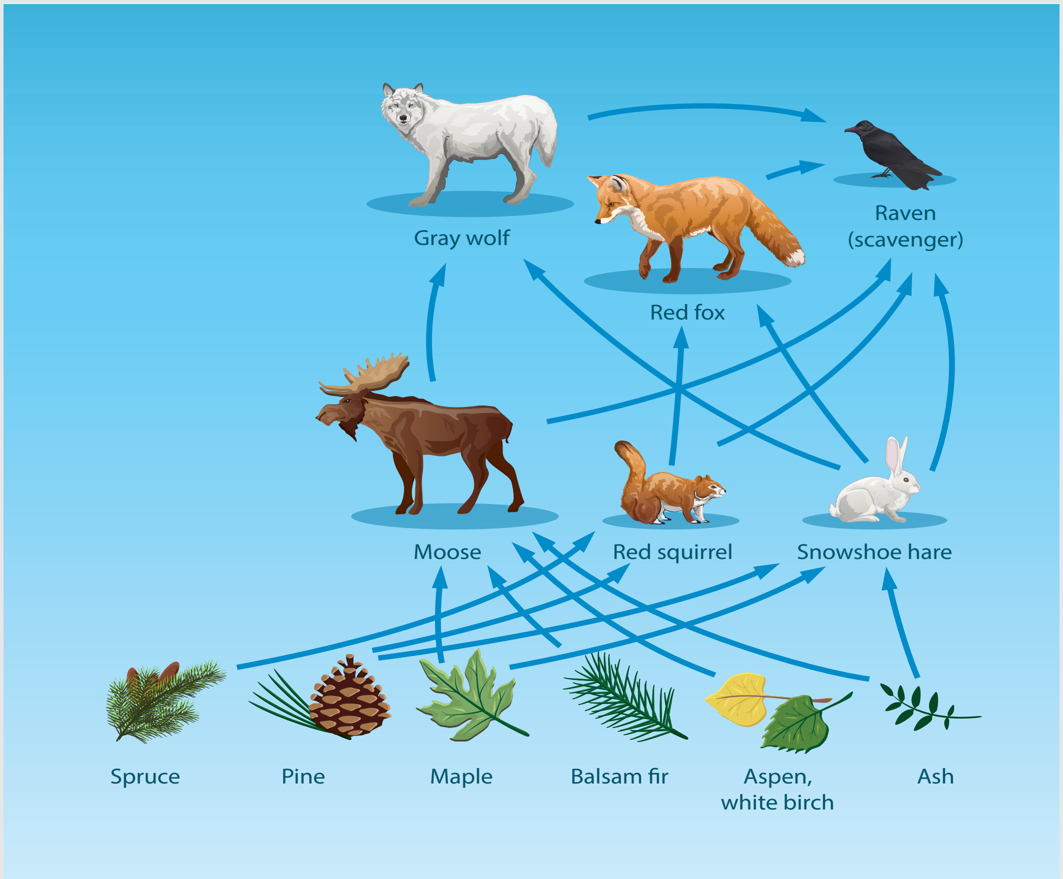
A scenario like this occurred on Isle Royale in the 1970s, when humans introduced a disease that nearly wiped out the wolf population. The moose population exploded, leading to overgrazing and the destruction of forest habitat. With fewer moose kills to redistribute nutrients, forest soils also became less fertile. Before wolf populations could recover, a lack of forage and a rise in moose ticks led to a crash in the moose population. The entire Isle Royale ecosystem was thrown out of balance by just a single species, and populations are still recovering today.

Variety is a good thing for most ecosystems. If you have several species accomplishing a specific task, the ecosystem will be more able to cope with the loss of one or two of those species. Isle Royale has relatively low levels of species biodiversity, especially at the top of the food chain. As a result, the ecosystem underwent massive changes when a new disease was introduced.

Apply Your Knowledge: How Does Biodiversity Improve Ecological Resilience? *(continued)*

Figure 2.9: Isle Royale food web

Removing one organism from an ecosystem's food web can affect the entire ecosystem.



Adapted from Life: The Science of Biology *(7th ed., Figure 55.7, Food Web of Isle Royale National Park), by W. K. Purves, D. E. Sadava, and G. H. Orians, 2004, Sunderland, MA: Sinauer Associates and W. H. Freeman. Copyright 2004 by Sinauer Associates, Inc., and W. H. Freeman & Co.*

How Biodiversity Occurs

Ecologists attribute the amazing diversity of life on Earth to processes of *natural selection* and *evolution*. **Natural selection** refers to a process whereby individual organisms within a population are better able to survive because they possess certain genetic traits. These individuals will reproduce and pass those traits on to their offspring. The result of natural selection is **evolution**, the process whereby the genetic makeup of populations of organisms changes gradually over time.

The combined processes of evolution through natural selection is widely accepted as scientific theory, in part because it can be observed happening in the world today. For example, when farmers apply chemical insecticides to their fields to try to wipe out crop-destroying pests, they typically succeed in killing perhaps only 90%–95% of that population. This is because some individuals possess unique genetic traits that make them resistant to the insecticide. Those few survivors then reproduce and pass that resistance trait on to their offspring. After a few generations, the insect population begins to bounce back as the same insecticide proves less and less effective against the now resistant population (more on this problem in Chapter 4). Farmers then have to switch to a new insecticide or try something else to avoid having their crop destroyed.

An interesting form of evolution is what ecologists refer to as *coevolution*. **Coevolution** is defined as a process whereby two different species that interact closely, such as a predator species and a prey species, also evolve together in a series of genetic changes. Two examples will help illustrate coevolution. One involves a coevolutionary process that benefits both species (that is, it's mutually beneficial). In the other, coevolution occurs as one species seeks an advantage over the other.

In the first case, there are a number of examples of tropical fruit–bearing trees coevolving with fruit-eating birds to the benefit of both. These trees have evolved to grow brightly colored and easy-to-see fruits that are also relatively odorless (to avoid attracting insects). These fruits tend to be difficult to eat "on the branch" and come in a form that birds can swallow whole. After ingesting the highly nutritious fruit, birds move to other regions of the forest and eventually either regurgitate or defecate the seeds, enabling new fruit tree growth.

In contrast, some species evolve to try to fool or discourage predation by other species, leading the prey species to also evolve in what some ecologists refer to as an evolutionary arms race. An example of this form of coevolution involves the rough-skinned newt and the common garter snake. The rough-skinned newt secretes a toxin through its skin known as tetrodotoxin, or TTX, the same toxin found in blowfish. TTX is extremely toxic, and a single newt can secrete enough of this toxin to kill multiple humans. Newts have evolved to produce this toxin in order to discourage other organisms that might prey on them. In response, garter snakes that share the ecosystem with rough-skinned newts have also evolved to develop a resistance to TTX. Over time, newts have evolved to secrete ever more TTX, and natural selection has favored the snakes that have kept up through an even greater resistance to this toxin.

Learn More: Coevolution

These links tell more about the story of the rough-skinned newt and the garter snake.

- https://news.stanford.edu/news/2008/march12/newts-031208.html
- https://www.theatlantic.com/science/archive/2016/06/the-very-long-war-between-snakes-and-newts/486311

How Biodiversity Impacts Species Interactions and Ecosystem Functioning

The diversity of species within an ecosystem influences how species interact with one another. As described briefly earlier in the chapter, different species occupy different ecological niches within an ecosystem. You can think of a niche as an organism's "place" in an ecosystem, including the kinds of food it eats and the places it lives and reproduces. Some animals, known as **generalists**, are more adaptive and flexible than others. Other animals, referred to as **specialists**, have very specific niches. For example, raccoons are often cited as an example of a generalist species because they are found in so many different places and can subsist on so many different types of food sources. In contrast, koalas are only found in a limited area where they can access what is virtually their only food source, eucalyptus leaves. An organism's niche will often be an important factor in determining the ecosystem's *carrying capacity* for that species. The **carrying capacity** is the number of individuals in a population that an ecosystem can support without degrading the ecosystem. Generally, the broader the niche, like that of the raccoon, the greater the carrying capacity.

Ecologists also classify species by whether they are native or nonnative. Native species include plants, animals, and other organisms that exist in a given location through natural processes such as natural selection and evolution. In contrast, nonnative species are those that are introduced to an area intentionally or accidentally. Some nonnative species find an ecological niche in their new habitat that is not disruptive to the native species that were there before them. However, other nonnative species can be extremely disruptive and either compete with or prey on native species. These disruptive, nonnative species are usually referred to as **invasive species**. For example, the mongoose is a small but voracious predator that was introduced from Southeast Asia to Hawaii, Central America, and South America to help control rat populations. However, the mongooses did not limit their hunting to rats, and they have been blamed for declines in bird, reptile, and small mammal populations in these areas.

Two other important categories of species are indicator and keystone. **Indicator species** can be thought of as an early warning or alarm species. Their absence or presence is an indication of a change in environmental conditions. For example, certain types of aquatic plants—like eel grass, water lily, and purple loosestrife—are known to be sensitive to water pollution. Their presence or absence is an indication of good or bad water-quality conditions. **Keystone species** are critical species in an ecosystem, and their absence can affect other species and even alter the entire ecosystem. Keystone species are named after the keystone in an archway, without which the whole arch collapses. An example of a keystone species is the sea otter. Sea otters feed on sea urchins, and sea urchins feed on underwater kelp forests, which provide habitat to many forms of marine life. In locations where sea otter populations have declined (due to hunting, pollution, and diseases spread from land), sea urchin populations have been able to grow. The greater number of sea urchins led to destruction of kelp forests, which in turn affected other species and the entire ecosystem. Keystone species are usually the *apex predators* in a particular food chain, meaning that they are at the top of food chains, with no natural predator of their own. When the population of a keystone species declines or is eliminated from an ecosystem, it can have serious ripple effects on the rest of the organisms in that food chain. This is known as a *trophic cascade*—recall that each link in a food chain is a different trophic level.

Dgwildlife/iStock/Getty Images Plus

Eduardo Baena/iStock/Getty Images Plus

Sea otters are an example of a keystone species because they are vital to the proper functioning of the ecosystem they inhabit. Where sea otter populations have declined, sea urchin populations have exploded and caused further ripple effects in the ecosystem.

Why Biodiversity Is Important

Biodiversity is important to human well-being and survival. As previously discussed, ecosystems with high rates of biodiversity are more productive; better at providing important ecosystem services, including those critical to food security and water quality; and better able to withstand environmental change and disturbances like drought and pest infestations.

Biodiversity is a source of many products and services that most of us depend on directly. For example, it's estimated that over half of all modern medicines have been derived or based on compounds found in nature. This list includes medicines like penicillin, cortisone, and paclitaxel, which are used as antibiotics, birth control, and treatments for inflammation, cancer, and arthritis. Biodiversity is also the basis for entire tourism and recreational hunting and fishing industries. These activities generate billions of dollars in economic activity annually.

Finally, biodiversity can be said to have value to humans for its sheer existence. Individuals might not ever expect to see an elephant or orangutan in their lifetime, but they still might derive joy from simply knowing that such species exist. Environmental economists refer to this as "existence value," and they cite as evidence the millions of dollars that individuals donate to nature conservation causes.

Ecologists and ecological economists sometimes divide those ecosystem services that directly benefit humans into different categories. These include *supporting services* (like photosynthesis and primary production), *provisioning services* (like seafood or lumber from forests), *regulating services* (such as natural water filtration by trees and forests), and *cultural services* (such as recreational tourism and existence value). We can clearly see that biodiversity is a form of natural capital. It provides us with services, products, recreation, and spiritual enjoyment—without which we cannot survive. Given biodiversity's critical importance, Section 2.6 will review the major causes of biodiversity decline. It will also discuss steps being taken at the local, national, and international level to support and preserve biodiversity.

2.6 Threats to Biodiversity and What Can Be Done About Them

Long before humans began wandering the Earth, new species of insects, birds, plants, mammals, and amphibians emerged while others went extinct. Many of these extinctions occurred during one of five mass extinction events that happened millions of years ago. These mass extinction events were triggered by massive volcanic eruptions, asteroid impacts with Earth, or extreme changes in climate. Since then, extinctions continued to occur naturally, but at a gradual rate that ecologists refer to as the background extinction rate. Today, as described in Chapter 1, we are in the early stages of a sixth mass extinction event. However, the primary causes of this current spike in extinction rates—far beyond background extinction rates—are due to human actions and activities.

Threats to Biodiversity

The major threats to biodiversity and major causes of extinction are habitat destruction and fragmentation, introduction of invasive species, overexploitation, pollution, and climate change. The most damaging of these is habitat destruction. Deforestation, draining wetlands, and conversion of grassland and other open spaces to farms and residential developments are all examples of habitat destruction. The links between habitat destruction and biodiversity loss should be obvious. Because animals are adapted to specific ecological niches, they often cannot respond to the destruction of their habitat by simply moving somewhere else. Because of this, generalist species are more likely to withstand destruction of their habitat, compared to specialist species.

Sebastian Kennerknecht/Minden Pictures/SuperStock

This highway cuts through habitat and ends up being a barrier for wildlife—an example of habitat fragmentation. To avoid this, some projects create "wildlife corridors" that allow animals to pass over or under roads, thereby minimizing disruption.

Habitat fragmentation refers to the breaking up of large areas of habitat into smaller and smaller fragments. Habitat fragmentation disrupts food webs, alters reproductive activities, and can even change the microclimate of an ecosystem, all of which can lead to biodiversity decline and extinction.

Invasive species are another major cause of biodiversity decline and extinction, for reasons described earlier. Some invasive species are introduced to a new environment by accident, while others, such as the mongoose, have been introduced with some specific purpose in mind. Either way, invasive species can outcompete or prey on native species to the point of extinction.

Humans have long hunted, fished, and trapped wild animals for food and other necessities, as well as collected plants and other materials to meet their survival needs. When these activities are undertaken on a scale and in a time frame that allows populations to recover and stay relatively constant, they can be considered sustainable. However, over the past 200 years and in many places around the world, these activities have started to occur on a scale that is not sustainable, resulting in what ecologists refer to as overexploitation. Perhaps the most famous example of extinction due to overexploitation is that of the passenger pigeon. These birds were once so widespread over the American Midwest that giant flocks of them would literally darken the sky as they flew overhead. It's estimated that there were once between 3 billion and 5 billion of these birds, and in only a matter of decades, they were hunted to complete extinction for their meat. Other examples of overexploitation include overharvesting whales for meat, poaching elephants and rhinos for ivory, and even overharvesting ginseng root from forested regions of Appalachia for export as a medicinal plant to Asia.

Pollution and climate change are the final two major causes of biodiversity decline and extinction. In addition to eutrophication (see Section 2.4), pollution from oil spills, acid mine drainage from coal mines, and sedimentation from agriculture and land clearance for housing and commercial developments can all impact biodiversity negatively. Climate change is affecting species directly and indirectly. For example, polar bears rely on floating sea ice to help them reach their most important food source, Arctic seals. However, because of climate change, there is less sea ice for the polar bears to use, and as a result some populations of this species are in decline. Elsewhere, climate change is altering habitat, disrupting migration cycles, and modifying animal behavior in ways that are hindering the ability of some species to adapt and survive. Again, these changes tend to have a more serious impact on specialist species than generalist species, since the former are usually less able to adapt.

As factors like habitat destruction, overexploitation, and climate change impact biodiversity, ecologists use a variety of categorization systems to rank just how threatened a particular species might be. A group called the International Union for Conservation of Nature (IUCN) has developed a database of at-risk species and regularly publishes what it calls the IUCN Red List of Threatened Species, which names those species at greatest risk. The IUCN Red List currently includes over 23,000 species that are considered critically endangered, threatened, or vulnerable. Current rates of extinction are estimated to be as much as 100 to 1,000 times higher than "normal" or background rates (see *Learn More: The End of Nature?*), and this is why many ecologists are worried that we are entering a period of a sixth mass extinction.

Learn More: The End of Nature?

On May 6, 2019, the United Nations Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) released a report stating that human actions are transforming the planet and driving species to extinction at "unprecedented" rates. The 1,500-page report, written by 145 expert authors and based on a review of 15,000 scientific studies, represents the most comprehensive review ever undertaken of global threats to biodiversity and the impact this could have on human civilization.

While the IPBES report stressed that it is not "too late" to make a difference, the key takeaways from the document are sobering and staggering. First, the report estimates that as many as 1 million species of plants and animals are threatened with extinction in the coming decades, more than at any other time in human history. This includes more than 40% of amphibian species, almost one third of coral reef species, and over one third of all marine mammals. Second, human activities have now altered over 75% of the global land surface and over 66% of marine environments, transforming habitat and leaving less room for other organisms. Third, climate change and pollution are already driving species to extinction. For example, marine plastic pollution has increased 1,000% since 1980 and has reached a level that now threatens 86% of marine turtles and 44% of seabirds.

bruno dumais/iStock/Getty Images Plus

More than 40% of amphibian species are threatened with extinction.

The IPBES report does not put a direct dollar value on what the extinction of 1 million species would mean for us, but we know enough about biodiversity and ecosystem services to know that human societies would be impacted negatively and severely. A loss of this many species in such a short time would have ripple effects across many economic sectors. Agriculture could be negatively impacted by the loss of pollinating insects (see *Close to Home: Protecting Pollinator Biodiversity* at the end of this section). Fisheries would be impacted by the loss of marine habitat and keystone species. Recreation and tourism could be devastated as formerly pristine areas are increasingly impacted by human actions. And overall, we know that a loss of biodiversity reduces ecosystem productivity and resilience, with hard-to-predict impacts on a wide range of ecosystem services critical to human well-being.

The IPBES report calls for immediate and bold action to address this biodiversity crisis. Recommended actions include investments in protected areas and conservation, stepped-up efforts to slow climate change, and global cooperation to address "transboundary" environmental problems like marine plastic pollution and the transport of invasive species.

More information on the IPBES report can be found here:

- https://www.ipbes.net/news/Media-Release-Global-Assessment
- https://www.ipbes.net/news/ipbes-global-assessment-summary-policymakers-pdf

Taking Action

Recognizing the importance of biodiversity to human well-being, ecologists and other environmental scientists are advocating a number of approaches to address biodiversity loss and extinctions. These approaches include government action at the national and international level as well as efforts by businesses, community organizations, and individuals.

Bicho_raro/iStock/Getty Images Plus

Ecotourism, if properly managed, can educate the public about conservation while protecting animals and environment.

Within the United States the **Endangered Species Act (ESA)** has played an important role in addressing the biodiversity crisis. The ESA lists both endangered species (considered to be in imminent danger of extinction) and threatened species (those that are at risk of becoming endangered). There are currently over 1,300 ESA–listed species. The ESA restricts the direct harvest or overexploitation of these listed species, as well as activities that might impact or destroy their habitat. Well-known ESA–listed species include the grizzly bear, jaguar, manatee, sea otter, sea lion, polar bear, blue whale, killer whale, gray wolf, California condor, and northern spotted owl. While the ESA has had some notable success stories, including the bald eagle, it is not without controversy. Property rights groups argue that the ESA interferes with the rights of individual landowners. Conservation groups argue that the ESA is too focused on protecting individual species rather than broader habitats and landscapes that support those species. Either way, since it was enacted in 1973, the ESA has played an important part in addressing the biodiversity crisis in the United States.

At the international level, there are a number of agreements designed to help protect biodiversity, including the Convention on Biological Diversity and the Convention on International Trade in Endangered Species. The **Convention on Biological Diversity** has three interrelated goals: conserving biodiversity, promoting the sustainable use of biodiversity, and ensuring that the benefits of biodiversity are shared equitably. The **Convention on International Trade in Endangered Species (CITES)** is more narrowly focused on prohibiting and regulating international trade in endangered species. One of the most important accomplishments of CITES was the 1989 ban on international trade in ivory, which helped slow the decline in populations of African elephants. Today scientists working under the CITES structure use DNA testing and other forms of forensic science to track down and prosecute individuals involved in illegal trade in endangered species.

Besides legal and regulatory action to protect biodiversity, there are other steps being taken to address the challenge of species loss and extinction. For example, the Forest Stewardship Council (FSC) is an independent organization that certifies forest management operations as sustainable. Individual consumers and businesses purchasing lumber and other forest products (including coffee) with the FSC label are helping promote forest management practices that protect biodiversity. A similar certification effort related to seafood is known as the Marine Stewardship Council. In regions of the world with high rates of biodiversity, ecotourism can be a way for local communities to benefit from the conservation of nature and often includes the establishment of nature/wildlife preserves and other protected areas. Lastly, there is an entire field of science focused on restoration ecology, an approach to habitat management designed to reverse environmental degradation and restore ecosystems to conditions more favorable to biodiversity.

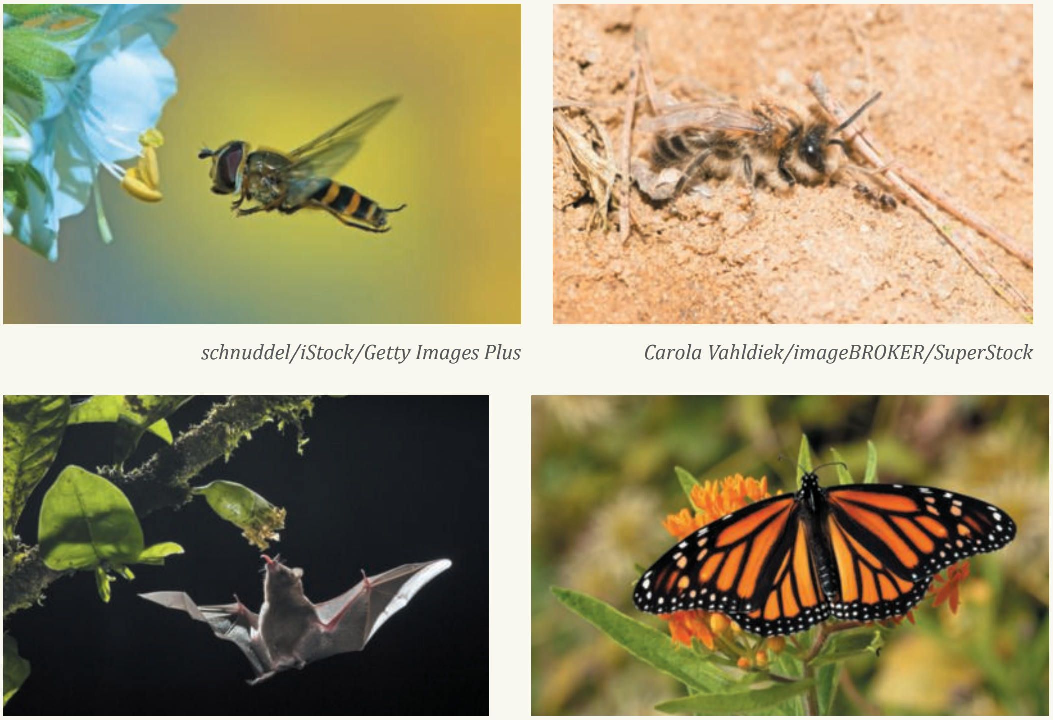
Close to Home: Protecting Pollinator Biodiversity

Honeybees often come to mind when we think of pollination, but pollinators are far more diverse than many of us realize. For example, hoverflies, plasterer bees, Mexican long-tongued bats, and monarch butterflies are all wild pollinators.

Unfortunately, many wild pollinators are threatened, and pollinator biodiversity is in decline. Industrial farming and invasive plant species have replaced native vegetation, making it difficult for wild pollinators to find food. Similarly, ecosystem destruction and fragmentation from human development have reduced the amount of food and habitat available. Pesticide use and drift from aerial spraying is another major threat to many insect pollinators.

So what can we do to reverse some of these trends and support the native pollinators where we live? First, let us meet a few wild pollinators and see if we can get a better sense of what their needs are.

Hoverflies can be seen hovering around the nectar and pollen sources that they feed on. Like many wild pollinators, they prefer to feed on the native plant species that they evolved alongside. Some hoverfly larvae also eat aphids and other pests. In other words, a good alternative to using insecticides is to plant native flowers around farms and gardens to attract those pollinators that prey on pests.


schnuddel/iStock/Getty Images Plus

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Pollinators can come in all shapes and sizes. Top row, from left to right: hoverfly, plasterer bee. Bottom row, from left to right: Mexican long-tongued bat, monarch butterfly.

(continued)

Close to Home: Protecting Pollinator Biodiversity *(continued)*

The plasterer bee takes its name from the smooth interior walls of its underground nests. This kind of habitat is not at all uncommon. The vast majority of pollinating bees live in the ground, hollow plant stems, and woody cavities. They tend to thrive in places that have some bare soil, shrubs, and dead wood to provide habitat. If we want to support a variety of pollinating bees, we need to make sure that they have good places to nest.

The Mexican long-tongued bat depends on plant varieties with larger flowers than most, and one of its main food sources is nectar from agave plants that are native to the southwestern United States. The Mexican long-tongued bat demonstrates that different pollinators require different flowers to thrive. If we want to encourage a variety of wild pollinators, we need to make sure that they have a variety of flowers to choose from.

Perhaps the prettiest wild pollinator is the North American monarch butterfly, which is also famous for its annual migration to overwintering sites in Mexico. These creatures need to fuel up in the late fall before their 4,800-kilometer (3,000-mile) journey south, so flowers that bloom at this time are particularly important to their survival. Like monarchs, many wild pollinators have seasonally specific nutritional needs, and they require flowers that bloom at the right time(s).

Now that you have a better sense of wild pollinator needs and the specific activities that are leading to biodiversity declines, take a moment to plan a theoretical garden for your hometown that would give local pollinators an extra boost. Are there ways you could provide a greater diversity of food sources and habitat? Are there ways that you can avoid using harmful pesticides? Most importantly, is it possible to act on your plan around your home or in your neighborhood? If you want to get serious about protecting wild pollinators, visit Pollinator Partnership at https://pollinator.org. This nonprofit has created planting guides and other online resources to help you create pollinator-friendly yards and gardens.

2.7 Planetary Boundaries

Human-induced environmental change is not necessarily a new thing. Ancient Maya and Roman civilizations were responsible for deforestation of large areas, and agriculture in a region known as Sumer resulted in soil degradation and the collapse of entire communities. However, the kind of human-induced environmental change and destruction we are witnessing today are fundamentally different from those of the past in three important ways.

First, the *pace* of change is much greater now than ever before. Chapter 3 will show how human populations have grown slowly over thousands of years before exploding to over 7.7 billion today. Population growth and technological advances have prompted us to extract and consume far more resources per person than ever before. The net result is that environmental change is happening far faster than ever before.

Second, the *scale* of environmental degradation and change has gone from mostly local/regional to global. The phrase “global environmental change” is relatively new, and it’s only in recent decades that the cumulative impact of human actions began to be felt on a global scale.

Third, the *type* of environmental change we are witnessing today is different from environmental changes of the past. Modern environmental problems are persistent; they compound one another, and more and more of them have the potential to be irreversible over time. For example, each year the chemical industry develops about 1,000 new compounds and produces over 90 million metric tons of chemicals in the form of 70,000 different compounds. Only a small fraction of these compounds are thoroughly tested or really understood before they are released to the environment.

In the past, human actions were just one of many factors shaping ecosystems and the world around us. Today they are the dominant influence on the environment—this is why some refer to the current period as the Anthropocene. To better grasp what the scope of human impact is, a group of scientists with the Stockholm Resilience Centre in Sweden developed the concept of *planetary boundaries*. **Planetary boundaries** are intended to provide a framework for developing a "safe operating space" for humanity with respect to global environmental conditions.

You can think of planetary boundaries in the same way that you and your doctor might consider things like blood pressure, blood sugar, weight, cholesterol levels, lung function, heart rate, and other health indicators. Doctors measure and monitor these indicators to determine if a patient might be at risk of health problems or even death. Likewise, planetary boundaries are a collection of nine Earth-system processes with associated safe and unsafe operating spaces. These nine Earth-system processes include the following:

1. stratospheric ozone depletion
2. biodiversity loss
3. chemical pollution
4. climate change
5. ocean acidification
6. freshwater consumption
7. land use change
8. nitrogen and phosphorous flows to the biosphere and oceans
9. atmospheric aerosol pollution

Of these nine measures, the scientists with the Stockholm Resilience Centre estimate that we have already exceeded a safe operating space in three areas: biodiversity loss, climate change, and human interference with the nitrogen cycle. Other areas of concern include ocean acidification, interference with the phosphorous cycle, freshwater use, and changes in land use. Returning to the analogy of the doctor, the planetary boundaries exercise tells us that we are putting the health of the planet at risk, and this could have direct consequences for our own health and well-being.

Of particular concern is the possibility that we may soon be approaching thresholds or tipping points with respect to some of these indicators. This could result in feedback loops that reinforce and worsen initial conditions, eventually leading to irreversible environmental change. The hope of the group involved in developing the planetary boundaries concept is that we will heed the warning signs and begin to do more to address critical environmental challenges like biodiversity loss before it is too late.

Learn More: Planetary Boundaries

You can learn more about the planetary boundaries from the Stockholm Resilience Centre.

- https://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/the-nine-planetary-boundaries.html
- https://www.stockholmresilience.org/research/planetary-boundaries.html

Bringing It All Together

The goal of this chapter was to provide you with a solid foundation in ecology to prepare you for some of the material presented in subsequent chapters. It is especially important that you understand how ecosystems are defined, how they function, and how the organisms found within them interact and interrelate with one another. This includes grasping the key concepts of energy flow through ecosystems and matter cycling within ecosystems. The Gulf of Mexico dead zone case study helped illustrate how these ecological concepts can be applied to real-world environmental challenges.

This chapter also focused on helping you develop a better understanding of what is meant by biodiversity, why it's important, and why it's under threat. According to the concept of planetary boundaries, biodiversity loss is one of three indicators that our actions are already pushing past safe limits.

Chapter 3 will explain the role that population growth and material consumption play in bringing about this situation. Subsequent chapters will take a closer look at specific environmental challenges related to things like food, water, and energy.

Additional Resources

Ecosystems

The idea of "feedback loops" can be a difficult concept to understand. These two links help illustrate what feedback loops are and how they work in nature.

- https://www.e-education.psu.edu/geog30/node/326
- TED-Ed: Feedback Loops: How Nature Gets Its Rhythms: https://www.youtube.com/watch?v=inVZoI1AkC8&feature=youtu.be

A nice introduction to a number of ecosystem concepts can be found in this video.

- Bozeman Science: Ecosystems: https://www.youtube.com/watch?v=Ot_KmOTYfRA&feature=youtu.be

Energy Flow

This short video helps explain the basics of energy flow in ecosystems.

- http://www.bozemanscience.com/ap-es-008-energy-flow-in-ecosystems

This video provides a fairly detailed look into photosynthesis.

- http://www.bozemanscience.com/photosynthesis

The reintroduction of wolves into Yellowstone National Park provides an interesting case study in how food chains, food webs, and trophic levels work in nature. Reintroducing wolves set off a "trophic cascade" in Yellowstone that has resulted in a number of unexpected but positive ecological impacts. This short video summarizes how that happened.

- Sustainable Human: How Wolves Change Rivers: https://www.youtube.com/watch?v=ysa5OBhXz-Q

Matter Cycling

A good summary of the biogeochemical (carbon, phosphorous, nitrogen) cycles can be found in this video.

- http://www.bozemanscience.com/ap-es-011-biogeochemical-cycles

Eutrophication in the Gulf

This TED Talk by marine scientist Nancy Rabalais and web summary by the Nature Conservancy provide an excellent overview of the Gulf of Mexico dead zone.

- https://www.youtube.com/watch?v=5zWmdHmJMd0
- Gulf of Mexico Dead Zone: https://www.nature.org/en-us/about-us/where-we-work/priority-landscapes/gulf-of-mexico/stories-in-the-gulf-of-mexico/gulf-of-mexico-dead-zone/

Biodiversity

These links help explain the basic idea of what biodiversity is and why it is so important to our own survival and well-being.

- https://thekidshouldseethis.com/post/why-is-biodiversity-so-important-ted-ed
- https://www.csiro.au/en/Research/Environment/Biodiversity/Biodiversity-book/Chapter-1

We know that coevolution can involve two species evolving together in ways that are either mutually beneficial or that resemble an "arms race" as each tries to get the better of the other. These links show both sides of that story, featuring a bird species known as the honeyguide because it literally guides the people it lives with to sources of wild honey.

- https://www.youtube.com/watch?v=6ETvF9z8pc0&feature=youtu.be
- https://www.audubon.org/news/meet-greater-honeyguide-bird-understands-humans

Threats to Biodiversity

The fact that the IPBES report described earlier estimates that over 40% of amphibians worldwide are threatened with extinction is troubling news. This is because amphibians such as frogs are key indicator species that can tell us a lot about the overall health and condition of our environment. The PBS *Nature* documentary *Frogs: The Thin Green Line* tells the story of this decline and what it might mean for us.

- http://www.pbs.org/wnet/nature/frogs-the-thin-green-line-introduction/4763/

A very interesting debate over how best to protect and conserve biodiversity can be summed up as “sparing vs. sharing.” The “sparing” approach generally means setting space aside for nature, while “sharing” implies managing the lands we already use in ways that also allow this land to be available to other species. A nice summary of that debate can be found here.

- https://e360.yale.edu/features/sparing-vs-sharing-the-great-debate-over-how-to-protect-nature

Key Terms

atmosphere A mixture of gases, mostly nitrogen and oxygen, with smaller amounts of argon, carbon dioxide, and other trace gases, held to the Earth’s surface by gravity.

biogeochemical cycles The movement of water and chemical elements such as carbon, nitrogen, and phosphorus between living organisms and their physical environment.

biomes Ecosystems and landscapes that share similar climate and vegetation.

biosphere The zone where life exists on Earth.

carrying capacity The number of individuals in a population that an ecosystem can support.

cellular respiration The process by which cells break down glucose and oxygen to produce energy, water, and carbon dioxide.

coevolution A process whereby two different species that interact closely together, such as a predator species and a prey species, also evolve together in a series of genetic changes.

community In ecology, a group of populations that live in the same place at the same time.

consumers Organisms that rely on plants for energy, whether by eating plants directly or by eating other consumers. Also known as *heterotrophs*.

Convention on Biological Diversity An international agreement with three interrelated goals: conserving biodiversity, promoting the sustainable use of biodiversity, and ensuring that the benefits of biodiversity are shared equitably.

Convention on International Trade in Endangered Species (CITES) An international agreement focused on prohibiting and regulating international trade in endangered species.

decomposers Organisms that break down organic material to obtain the energy and nutrients they need. Also known as *saprotrophs*.

ecological hierarchy A hierarchy that illustrates the relationships between different organisms and organizes those relationships into different levels.

ecological niche The role and position of a species in its environment, including how it obtains food, reproduces, and finds shelter.

ecology The study of the relationships and interactions of living organisms with other living organisms and the surrounding environment.

ecosystem A community of organisms and the community's physical environment; a collection of living (biotic) and nonliving (abiotic) entities that exist, interact, and interrelate in a particular location and time.

ecosystem diversity The variety in ecosystems found around the world.

Endangered Species Act (ESA) A U.S. law that provides a framework for the protection and conservation of endangered and threatened species and their habitats.

energy The capacity or ability to do work. In ecology, the ability of organisms to do biological work (growing, eating, reproducing).

entropy The tendency for energy to move from a more useful state to a less useful state.

eutrophication A water pollution problem in which an influx of nutrients causes excessive plant growth, causing dissolved oxygen levels to decline sharply and thereby killing off fish and other marine life.

evolution The process whereby the genetic makeup of populations of organisms changes gradually over time.

first law of thermodynamics Also known as the law of conservation of energy; a principle which states that energy can change from one form to another but cannot be created or destroyed.

food chains Linear feeding relationships among organisms.

food web A system of many related food chains, or the many, interrelated feeding relationships within a community.

functional diversity The different ways in which organisms interact with and make use of a specific ecosystem.

generalists Species that are more adaptive and flexible and can survive in a variety of different environments and/or subsist on a variety of different foods.

genetic diversity The variety of genes and genetic material found within a population or species.

homeostasis Dynamic equilibrium; the tendency of a system to maintain relatively stable conditions over time.

hydrosphere The watery parts of the Earth: the oceans, rivers, lakes, clouds, groundwater reservoirs, and glaciers that cover three quarters of the Earth's surface.

indicator species Species whose absence or presence is an indication of a change in environmental conditions.

invasive species Nonnative species that can be disruptive and either compete with or prey on native species.

keystone species Critical species in an ecosystem; their absence can affect other species and even alter the entire ecosystem.

kinetic energy Energy in motion.

landscape In ecology, an area of interacting ecosystems.

law of conservation of matter The principle which states that matter can neither be created nor destroyed.

limiting factor A condition or resource that limits a species' growth.

lithosphere The solid Earth, the upper crust and uppermost mantle extending 2,500 kilometers (1,550 miles) below the surface. Also known as the geosphere.

natural selection A process whereby individual organisms within a population are better able to survive because they possess certain genetic traits. These individuals will reproduce and pass those traits on to their offspring.

negative feedback loop A condition wherein an initial change causes a system to reverse that change, essentially stabilizing the system.

nitrogen fixation A process in which certain types of soil bacteria convert nonreactive nitrogen in the air to a usable form.

photosynthesis The process by which plants and other primary producers take sunlight, carbon dioxide, and water to make glucose and oxygen.

planetary boundaries Developed by a group of scientists at the Stockholm Resilience Centre, the concept that there are environmental indicators for safe human habitation on Earth; nine Earth-system processes that serve as measures for planetary health.

population In ecology, multiple individuals of the same species living in a particular location.

positive feedback loop A condition wherein an initial change causes a system to keep changing further in the same direction, moving the system further away from stability.

potential energy Stored energy.

primary producers Organisms that can take the building blocks of carbon dioxide and water and produce sugar (glucose) molecules with high potential energy content. Also known as *autotrophs* or simply *producers*.

range of tolerance The range of conditions in which a species can survive.

second law of thermodynamics A principle which states that energy conversion will always change that energy from a more useful to a less useful state.

specialists Species that occupy very specific niches and require specific conditions to survive.

species diversity The number of different species and their relative abundance in a given ecologic community.

symbiosis A close biological interaction between two organisms.

system A set of connected or interdependent things that together form a more complex whole.

systems thinking An approach to science that considers not just the individual parts of a system but also how they interact and interrelate over time.

tipping point The point at which a series of small, gradual changes suddenly triggers a much larger or significant change.

trophic levels Hierarchal levels in a food chain. Energy is lost with each subsequent level.