chapter 2

Ecosystems: What They Are

Key Topics

1. Ecosystems: A Description
2. The Structure of Ecosystems
3. From Ecosystems to Global Biomes
4. The Human Factor
5. Revisiting the Themes

Barrier islands are found along the east and Gulf coasts of the United States. Plum Island, in Massachusetts, is a nine-mile-long barrier island in the northern part of the state. (See opposite page.) The southern two-thirds of the island is part of the Parker River National Wildlife Refuge, while the northern third is occupied by a host of summer cottages and year-round houses. On the refuge part of the island, sand dunes emerge at the upper edge of the ocean beach and extend back several hundred meters. Occupying the sand dunes is a mosaic of vegetation. The primary dunes, closest to the ocean, are colonized by beach grass (*Ammophila breviguiata*). Behind these dunes is a heathlike low growth, dominated by false heather (*Hudsonia tomentosa*). Farther back, a shrub community is found, where poison ivy and bayberry dominate. Even farther back is the maritime forest, with pitch pine, poplar, wild cherry, and a few other deciduous trees. Here and there is a depression that reaches the water table and is occupied by cranberry plants.

Animals on the barrier island—mice, rabbits, deer, skunks, red foxes, and coyotes—are seldom seen by humans, but leave their tracks on the sand. A diverse bird community can be found here, drawing birders who often find rarities like the peregrine falcon and snowy owl. Life for the plants—especially those close to the ocean—is harsh. The sand holds little water or nutrients, salt spray from the ocean stresses leaf surfaces, and wind either blows loose sand away from plants' roots or piles it up around the plants and buries them. Nevertheless, the barrier island plant community is a functioning system that has endured for centuries.

Cottage Colony. On the northern third of the island, scores of streets were laid out in the early 1900s, and hundreds of small cottages were built. The dunes were either removed or built upon. Now, the only vegetation is a few beach grass plants that lie between the beach and the first houses. There are no dunes to speak of, no shrubs or maritime forest, and no deer or foxes. The entire island would probably end up like this if the wildlife refuge didn't prevent

A barrier island **Plum Island in northern Massachusetts is a nine-mile-long sand island separating the ocean from a bay, a salt marsh, and the upland. The inset shows the northern, developed end of the island.**

further development. The contrast between these "communities" is stark and unforgettable.

From time to time, the environment tests this barrier island, as it tests all barrier islands, with storms. On the southern section, the dunes absorb the powerful waves that pound the beach and wash upward toward the land. After a storm, the beach grass and primary dunes are intact, the back dunes untouched. The dune communities continue to thrive, forming a true barrier to the ocean that protects the fragile salt marshes and land behind the island. On the northern section, however, storms often wash beach sand by the houses and onto the streets, and occasionally a house is swept into the ocean. No one visits the northern Plum Island dunes to view birds or animals, because there are no dunes, birds, or animals to visit or view. In comparison, thousands of visitors enjoy the Parker River National Wildlife Refuge each year for its wildlife and beauty. Moreover, the ecosystems on the refuge provide valuable protection, as well as opportunities for recreational hunting

The Ecosystem Approach. Humans live in environments that, like Plum Island, have a mix of natural and degraded ecosystems. Are there enough ecosystems in good health to continue to make their vital contributions to human well-being and support current human occupations? What are the trends in ecosystem manipulation and conversion throughout the world, such as defor-

earth watch

Taking Stock

Considering how important ecosystems are to human affairs, you might assume that we have a good inventory of them. It turns out, however, that we do not know *what* we have, or much about the *goods and services* specific ecosystems can produce, or how they *respond to changes* brought on by human activities. Nevertheless, we are going to have to manage natural ecosystems more intensely and deliberately if we want to enjoy their benefits in the future. The question is, How can you manage something you do not even know you have, let alone understand how you are affecting it?

In 1995, recognizing this problem, the White House Office of Science and Technology Policy (OSTP) asked the Heinz Center to "create a nonpartisan, scientifically grounded report on the state of the nation's environment." The OSTP asked the center to focus on ecosystems as the best approach to its work. The Heinz Center published its first full report in 2002, called *The State of the Nation's Ecosystems: Measuring the Lands, Waters, and Living Resources of the United States*. [The report is available from Cambridge University Press and on the Internet (www.heinzctr.org/ecosystems).] The report, a collaborative effort involving almost 150 experts from academia, government, environmental organizations, and business, was funded by federal, corporate, and foundation sources.

The report "is written for decision makers and opinion leaders concerned about the 'big picture' of the nation's ecosystems," with the goal of providing unbiased information to be used to form public policy. It divides the lands and waters of the United States into six major types of ecosystem: **coasts and oceans, farmlands, forests, fresh waters, grasslands and shrub lands,** and **urban and suburban areas.** For each type of ecosystem, unique "indicators" are specified—key characteristics that may be used to describe the current status and trends within the ecosystem, to be tracked over time. The indicators, about 100 or so, are organized into 10 categories.

The forest ecosystem illustrates how the 10 categories are made specific for a given type (not all indicator categories are used for each type of ecosystem):

System Dimensions

- *Ecosystem Extent*–forest area and ownership, forest types, forest management categories
- *Fragmentation and Landscape Pattern*–forest pattern and fragmentation

Chemical and Physical Conditions

- *Nutrients, Carbon, and Oxygen*–nitrate in forest streams, carbon storage
- *Contaminants*–not applicable
- *Physical*–not applicable

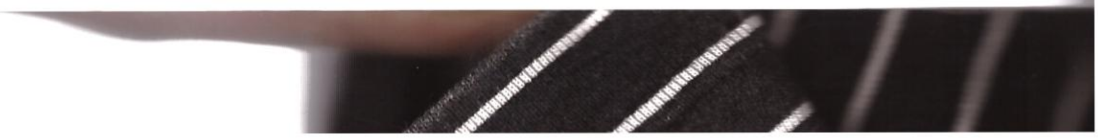
Biological Components

- *Plants and Animals*–at-risk native species, area covered by nonnative plants
- *Communities*–forest age, forest disturbance (fire, insects, disease), fire frequency, forest community types with significantly reduced area
- *Ecological Productivity*–not applicable

Human Uses

- *Food, Fiber, and Water*–timber harvest, timber growth, and harvest
- *Recreation and Other Services*–recreation in forests

The main body of the Heinz Center report presents the indicator data for each type of ecosystem and, in many cases, explains why there are no adequate data to report. Nearly half the indicators show missing data. This is only the first report; future reports will bring the indicator data up to date and address gaps in the data. For now, however, the report represents a landmark for taking the pulse of our nation's ecosystems.



estation and overgrazing? What impacts will the next 50 years of population growth have on ecosystem goods and services? The MEA is attempting to answer these important questions, and it is doing so by adopting the "ecosystem approach," as mentioned in Chapter 1.

Closer to home, in 2002 the Heinz Center of Washington, DC, published a report on ecosystems in the United States, called *The State of The Nation's Ecosystems*. (See "Earth Watch," p. 28.) This report came in response to a government request to create a scientifically based assessment of the state of the nation's environment, and it was carried out by hundreds of scientists from academia, the government, environmental organizations, and the private sector. Like the MEA, the report was organized according to the ecosystem approach. These studies demonstrate that the ecosystem concept has gained universal recognition in the scientific and policy-making communities. To better understand why, we begin this chapter by examining the structure of natural ecosystems.

2.1 Ecosystems: A Description

Biotic Communities. The grouping or assemblage of *plants, animals,* and *microbes* we observe when we study a natural forest, a grassland, a pond, a coral reef, or some other undisturbed area is referred to as the area's **biota** (*bio,* living) or **biotic community**. The plant portion of the biotic community includes all vegetation, from large trees down through microscopic algae. Likewise, the animal portion includes everything from large mammals, birds, reptiles, and amphibians through earthworms, tiny insects, and mites. Microbes encompass a large array of microscopic bacteria, fungi, and protozoans. Thus, the *biotic* community comprises a *plant* community, an *animal* community, and a *microbial* community.

The particular kind of biotic community found in a given area is, in large part, determined by **abiotic** (nonliving, chemical, and physical) factors, such as the amount of water or moisture present, the temperature, the salinity, or the type of soil in the area. These abiotic factors both support and limit the particular community. For example, a relative lack of available moisture prevents the growth of most species of plants, but supports certain species, such as cacti; these kinds of areas are deserts. Land with plenty of available moisture and a suitable temperature supports forests. The presence of water is the major factor that sustains aquatic communities.

Species. The first step in investigating a biotic community may be simply to catalogue all the *species* present. **Species** are the different kinds of plants, animals, and microbes in the community. A given species includes all those individuals which have a strong similarity in appearance to one another and which are distinct in appearance from other such groups (robins vs. redwing blackbirds, for example). Similarity in appearance suggests a close genetic relationship. Indeed, the *biological definition* of a species is the entirety of a population that can interbreed and produce fertile offspring, whereas members of different species generally do not interbreed. Breeding is often impractical or impossible to observe, however, so for purposes of identification, appearance usually suffices.

Populations. Each species in a biotic community is represented by a certain **population**—that is, by a certain number of individuals that make up the interbreeding, reproducing group. The distinction between *population* and *species* is that *population* refers only to those individuals of a certain species that live within a given area, whereas *species* is all inclusive, referring to all the individuals of a certain kind, even though they may exist in different populations in widely separated areas.

Associations. One reason to identify the biotic community is to understand how it fits into the landscape or how it differs from other biotic communities. To identify a biotic community may require an assessment of the corresponding plant community. Vegetation is readily measured and is a strong indicator of the environmental conditions of a site. The most basic kind of plant community is the **association**, defined as a plant community with a definite composition, uniform habitat characteristics, and uniform plant growth. On Plum Island, for example, the **pitch pine/false heather** (*Pinus rigida/Hudsonia tomentosa*) **woodland** association represents a subgroup of the maritime forest (Fig. 2–1).

Figure 2–1 A plant association. The **pitch pine/false heather** (*Pinus rigida/Hudsonia tomentosa*) **woodland** association on Plum Island.

The species within a community depend on and support one another. In particular, certain animals will not be present unless certain plants that provide their necessary food and shelter are present. Thus, the plant community supports (or limits by its absence) the animal community. In addition, every plant and animal species is adapted to cope with the abiotic factors of the region. For example, every species that lives in temperate regions is adapted in one way or another to survive the winter season, which includes a period of freezing temperatures (Fig. 2–2). These interactions among organisms and their environments are discussed in Section 2.2. For now, keep in mind that the populations of different species within a biotic community are constantly interacting with each other and with the abiotic environment.

Ecosystems. This brings us to the concept of an *ecosystem*, which joins together the biotic community *and* the abiotic conditions that it lives in. The ecosystem concept considers the ways populations interact with each other and the abiotic environment to reproduce and perpetuate the entire grouping. As a result, an **ecosystem** is a grouping of plants, animals, and microbes occupying an explicit unit of space and interacting with each other and their environment. For study purposes, an ecosystem is any more or less distinctive biotic community living in a certain environment. Thus, a forest, a grassland, a wetland, a marsh, a pond, a sand dune, and a coral reef, each with its respective species in a particular environment, can be studied as distinct ecosystems. Often, an ecosystem contains a group of associations, like those on the dunes of Plum Island.

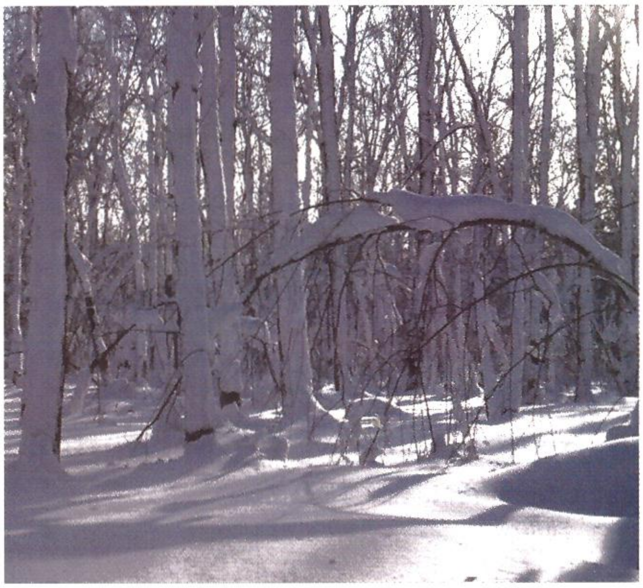
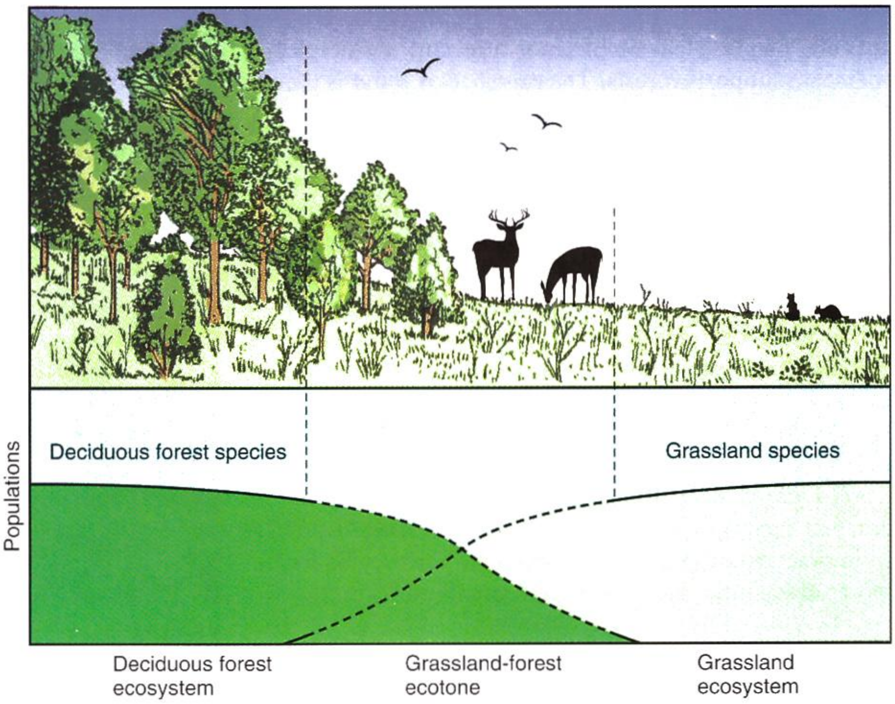


Figure 2–2 Winter in the forest. Many trees and other plants of temperate forests are so adapted to the winter season that they actually *require* a period of freezing temperature in order to grow again in the spring.

Because no organism can live apart from its environment or from interacting with other species, ecosystems are the functional units of sustainable life on Earth. The study of ecosystems and the interactions that occur among organisms and between organisms and their environment belongs to the science of **ecology**, and the investigators who conduct such studies are called **ecologists**.

Ecotone. While it is convenient to divide the living world into different ecosystems, you will find that there are

Figure 2–3 Ecotones on land. Ecosystems are not isolated from one another. One ecosystem blends into the next through a transitional region—an ecotone—that contains many species common to both systems.



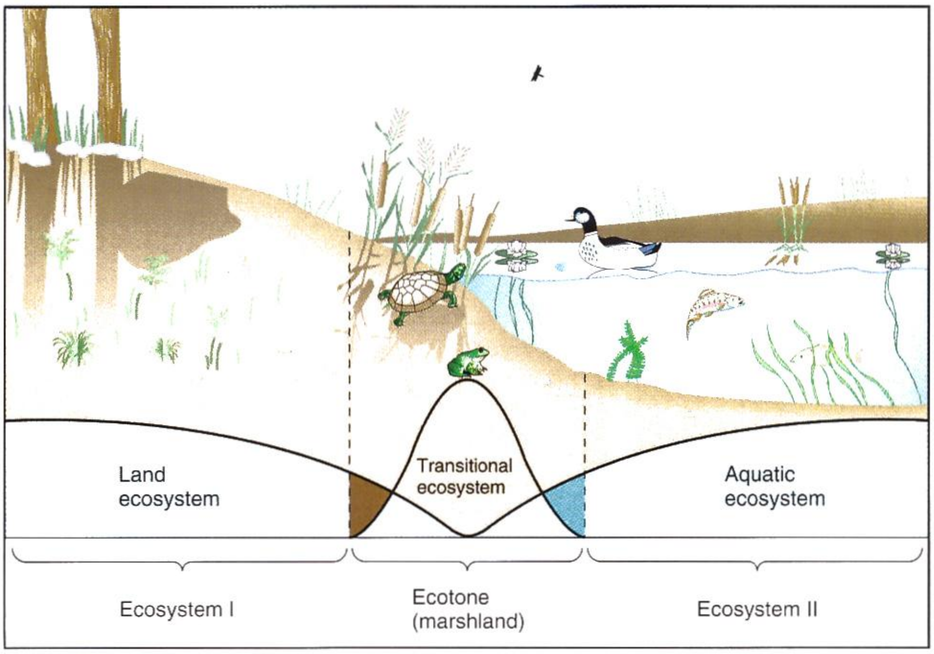


Figure 2–4 Terrestrial-to-aquatic-system ecotone. An ecotone may create a unique habitat that harbors specialized species not found in either of the ecosystems bordering it. Typically, cattails, reeds, and lily pads grow in the ecotone shown, along with several species of frogs and turtles, as well as egrets and herons.

seldom distinct boundaries between ecosystems, and they are never totally isolated from one another. Many species will occupy (and thus be a part of) two or more ecosystems at the same time, or they may move from one ecosystem to another at different times, as in the case of migrating birds. In passing from one ecosystem to another, the one may grade into the other through a transitional region, known as an **ecotone**, that shares many of the species and characteristics of both ecosystems (Fig. 2–3). The ecotone between adjacent systems may also include *unique* conditions that support distinctive plant and animal species; consider, for example, the marshy area that often occurs between the open water of a lake and dry land (Fig. 2–4). Ecotones may be studied as distinct ecosystems in their own right.

Landscapes. What happens in one ecosystem affects other ecosystems. For this reason, ecologists have begun using the concept of **landscapes**—a group of interacting ecosystems. Thus, a barrier island, a saltwater bay, and the salt marsh behind it constitute a landscape. Landscape ecology is the science that studies the interactions among ecosystems.

Biomes. Similar or related ecosystems or landscapes are often grouped together to form major kinds of ecosystems called **biomes**. Tropical rain forests, grasslands, and deserts are biomes. While more extensive than an ecosystem in its breadth and complexity, a biome is still basically a distinct type of biotic community supported and limited by certain abiotic environmental factors. As with ecosystems, there are generally no sharp boundaries between biomes. Instead, one grades into the next through transitional regions.

Likewise, there are major categories of aquatic and wetland ecosystems that are determined primarily by the depth, salinity, and permanence of water in them. Among these ecosystems are lakes, marshes, streams, rivers, estuaries, bays, and ocean systems. As units of study, these aquatic systems may be viewed as ecosystems, as parts of landscapes, or as major biomelike features such as seas or oceans. (The biome category is reserved exclusively for terrestrial systems.) Table 2–1 lists the six major aquatic systems and their primary characteristics.

Biosphere. Regardless of how we choose to divide (or group) and name different ecosystems, they all remain interconnected and interdependent. Terrestrial biomes are connected by the flow of rivers between them and by migrating animals. Sediments and nutrients washing from the land may nourish or pollute the ocean. Seabirds and mammals connect the oceans with the land, and all biomes share a common atmosphere and water cycle.

Therefore, all the species on Earth, along with all their environments, make up one vast ecosystem, often called the **biosphere**. Although the separate local ecosystems are the individual units of sustainability, they are all interconnected to form the biosphere. The concept is analogous to the idea that the cells of our bodies are the units of living systems, but are all interconnected to form the whole body. Carrying the analogy further, to what degree can individual ecosystems be degraded or destroyed before an entire biome, or even the biosphere, is affected? Conversely, to what degree can basic global parameters, such as the atmosphere and the temperature, be altered before major ecosystems on Earth are affected? To begin to understand ecosystems in more depth, in Section 2.2 we discuss how they are structured.

The key terms introduced in Section 2.1 are summarized in Table 2–2.

table 2-1 **Major Aquatic Systems**

Aquatic Systems	Major Environmental Parameters	Dominant Vegetation	Dominant Animal Life	Distribution
Lakes and Ponds (freshwater)	Bodies of standing water; low concentration of dissolved solids; seasonal vertical stratification of water	Rooted and floating plants, phytoplankton	Zooplankton, fish, insect larvae, ducks, geese, herons	Physical depressions in the landscape where precipitation and groundwater accumulate
Streams and Rivers (freshwater)	Flowing water; low level of dissolved solids; high level of dissolved oxygen, often turbid	Attached algae, rooted plants	Insect larvae, fish, amphibians, otters, raccoons, wading birds, ducks, geese, swans	Landscapes where precipitation and groundwater flow by gravity toward oceans or lakes
Inland Wetlands (freshwater)	Standing water, at times seasonally dry; thick organic sediments; high nutrients	Marshes: grasses, reeds, cattails. Swamps: water-tolerant trees. Bogs: sphagnum moss, low shrubs	Amphibians, snakes, numerous invertebrates wading birds, ducks, geese, alligators, turtles	Shallow depressions, poorly drained, often occupy sites of lakes and ponds that have filled in
Estuaries	Variable salinity; tides create two-way currents, often rich in nutrients, turbid	Phytoplankton in water column, rooted grasses like salt-marsh grass, mangrove swamps in tropics with salt-tolerant trees and shrubs	Zooplankton, rich shellfish, worms, crustaceans, fish, wading birds, sandpipers, ducks, geese	Coastal regions where rivers meet the ocean; may form bays behind sandy barrier islands
Coastal Ocean (saltwater)	Tidal currents promote mixing; nutrients high	Phytoplankton, large benthic algae, turtle grass, symbiotic algae in corals	Zooplankton, rich bottom fauna of worms, shellfish, crustaceans, echinoderms; coral colonies, jellyfish, fish, turtles, gulls, terns, ducks, sea lions, seals, dolphins, penguins, whales	From coastline outward over continental shelf; coral reefs abundant in tropics
Open Ocean	Great depths (to 11,000 meters); all but upper 200 m dark and cold; poor in nutrients except in upwelling regions	Exclusively phytoplankton	Diverse zooplankton and fish adapted to different depths; seabirds, whales, tuna, sharks, squid, flying fish	Covering 70% of Earth, from edge of continental shelf outward

2.2 The Structure of Ecosystems

Structure refers to parts and the way they fit together to make a whole system. There are two key aspects to every ecosystem, namely, the biota, or biotic community, and the abiotic environmental factors. The way different categories of organisms fit together is referred to as the **biotic structure**, and the major feeding relationships between organisms constitute the **trophic structure** (*trophic*, feeding). All ecosystems have the same three basic categories of organisms that interact in the same ways.

Trophic Categories

The major categories of organisms are (1) *producers*, (2) *consumers*, and (3) *detritus feeders* and *decomposers*. Together, these groups produce food, pass it along food chains, and return the starting materials to the abiotic parts of the environment, respectively.

Producers. Producers are organisms that capture energy from the Sun or from chemical reactions to convert carbon dioxide (CO_2) to organic matter. Most producers are green plants, which use light energy to convert CO_2 and water to organic compounds such as the sugar glucose and then release oxygen as a by-product. This chemical conversion, which is driven by light energy, is called **photosynthesis**. Plants are able to manufacture all the complex organic molecules that make up their bodies via photosynthesis, along with additional *mineral nutrients* such as nitrogen, phosphorus, potassium, and sulfur, which they absorb from the soil or from water (Fig. 2–5).

Plants use a variety of molecules to capture light energy in photosynthesis, but the most predominant of

table 2-2 Important Terms

Species	All the members of a specific kind of plant, animal, or microbe; a kind given by similarity of appearance or capacity for interbreeding and producing fertile offspring.
Population	All the members of a particular species occupying a given area.
Association	A plant community with a definite composition, uniform habitat characteristics, and uniform plant growth.
Biotic community	All the populations of different plants, animals, and microbes occupying a given area.
Abiotic factors	All the factors of the physical environment: moisture, temperature, light, wind, pH, type of soil, salinity, etc.
Ecosystem	The biotic community together with the abiotic factors; includes all the interactions among the members of the biotic community, and between the biotic community and the abiotic factors, within an explicit unit of space.
Landscape	A group of interacting ecosystems in a particular area.
Biome	A grouping of all the ecosystems of a similar type (e.g., tropical forests or grasslands).
Biosphere	All species and physical factors on Earth functioning as one unified ecosystem.

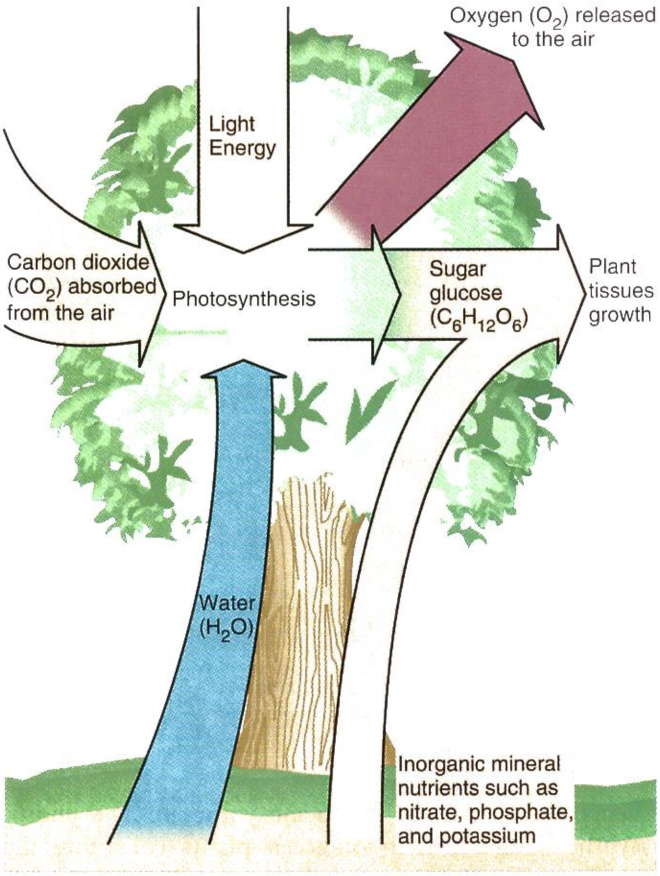


Figure 2-5 Green-plant photosynthesis. The producers in all major ecosystems are green plants.

these is **chlorophyll**, a green pigment. Hence, plants that photosynthesize are easily identified by their green color, such as the beach grass, shrubs, and maritime forest plants on Plum Island. In some plants, additional red or brown photosynthetic pigments (in red and brown algae, for example) may overshadow the green. Producers range in diversity from microscopic photosynthetic bacteria and single-celled algae through medium-sized plants such as grass, daisies, and cacti, to gigantic trees. Every major ecosystem, both aquatic and terrestrial, has its particular producers, which are actively engaged in photosynthesis.

Organic vs. Inorganic. The term **organic** refers to all those materials that make up the bodies of living *organ*isms—molecules such as proteins, fats or lipids, and carbohydrates. Likewise, materials that are specific products of living organisms, such as dead leaves, leather, sugar, wood, coal, and oil, are considered *organic*. By contrast, materials and chemicals in air, water, rocks, and minerals, which exist apart from the activity of living organisms, are considered **inorganic** (Fig. 2–6). Interestingly, there are bacteria that are able to use the energy in some inorganic chemicals to form organic matter from CO_2 and water. This process is called **chemosynthesis**, and these organisms are producers, too.

The key feature of *organic* materials and molecules is that they are constructed in large part from bonded carbon and hydrogen atoms, a structure that is not found among *inorganic* materials. This carbon–hydrogen structure has its origins in photosynthesis, in which hydrogen atoms taken from water molecules and carbon atoms taken from carbon dioxide are joined together to form organic compounds (Fig. 2–5). Green plants use light as the energy source to produce all the complex organic molecules their bodies need from the simple inorganic chemicals that are present in the environment. As this conversion from inorganic to organic occurs, some of the energy from light is stored in the organic compounds.

Autotrophs vs. Heterotrophs. All organisms in the ecosystem *other than the producers* feed on organic matter as their source of energy. These organisms include not only all animals, but also **fungi** (mushrooms, molds, and similar organisms), most bacteria, and even a few higher plants that do not have chlorophyll and thus cannot photosynthesize.

As a result, green plants, which carry on photosynthesis, are absolutely essential to every ecosystem (with the exception of a few, such as deep-sea hydrothermal

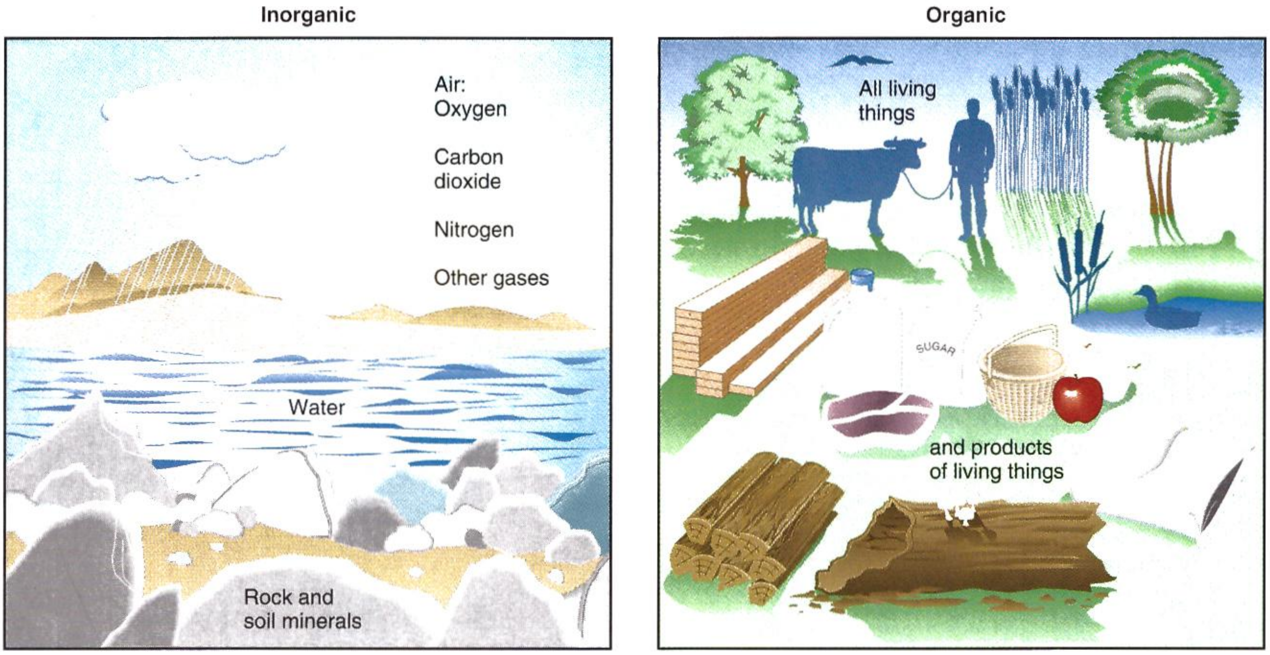


Figure 2–6 Organic and inorganic. Water and the simple molecules found in air, rocks, and soils are *inorganic*. The complex molecules that make up plant and animal tissues are *organic*.

vents, which depend on chemosynthesis). The photosynthesis and growth of green plants constitute the *production* of organic matter, which sustains all other organisms in the ecosystem.

Indeed, all organisms in the biosphere can be categorized as either *autotrophs* or *heterotrophs*, depending on whether they do or do not produce the organic compounds they need to survive and grow. Chemosynthetic bacteria are **autotrophs** (*auto*, self; *troph*, feeding), because they produce their own organic material from inorganic constituents in their environment through the use of an external energy source. The most important and common autotrophs by far, however, are green plants, which use chlorophyll to capture light energy for photosynthesis. All other organisms, which must *consume* organic material to obtain energy, are **heterotrophs** (*hetero*, other). Heterotrophs may be divided into numerous subcategories, the two major ones being **consumers** (which eat living prey) and **detritus feeders** and **decomposers**, both of which feed on dead organisms or their products.

Consumers. Consumers encompass a wide variety of organisms ranging in size from microscopic bacteria to blue whales. Among consumers are such diverse groups as protozoans, worms, fish and shellfish, insects, reptiles, amphibians, birds, and mammals (including humans).

For the purpose of understanding ecosystem structure, consumers are divided into various subgroups according to their food source. Animals—as large as elephants or as small as mites—that feed directly on producers are called **primary consumers** or **herbivores** (*herb*, grass).

Animals that feed on primary consumers are called **secondary consumers**. Thus, elk, which feed on vegetation, are primary consumers, whereas wolves are secondary consumers because they feed on elk (Fig. 2–7). There may also be third (tertiary), fourth (quaternary), or even higher levels of consumers, and certain animals may occupy more than one position on the consumer scale. For instance, humans are primary consumers when they eat vegetables, secondary consumers when they eat beef, and tertiary consumers when they eat fish that feed on smaller fish that feed on algae. Secondary and higher order consumers are also called **carnivores** (*carni*, meat). Consumers that feed on both plants and animals are called **omnivores** (*omni*, all).

Predators, Parasites, Pathogens. In any relationship in which one organism feeds on another, the organism that does the feeding is called the **predator**, and the organism that is fed on is called the **prey**. Predation thus ranges from the classic predator–prey interactions between carnivores and herbivores, to herbivores feeding on plants, and parasites feeding on their hosts. In fact, **parasites** are another important category of consumers. Parasites are organisms—either plants or animals—that become intimately associated with their "prey" and feed on it over an extended period of time, typically without killing it, but sometimes weakening it so that it becomes more prone to being killed by predators or adverse conditions. The plant or animal that is fed upon is called the **host**.

A tremendous variety of organisms may be parasitic. Various worms are well-known examples, but certain protozoans, insects, and even mammals (vampire bats) and plants (dodder) (Fig. 2–8a) are also parasites. Many serious plant diseases and some animal diseases (such as athlete's foot) are caused by parasitic fungi. Indeed, virtually every major

Figure 2–7 Secondary consumers. Gray wolves have brought down an elk.

group of organisms has at least some members that are parasitic. Parasites may live inside or outside their hosts, as the examples shown in Fig. 2–8 illustrate.

In medicine, a distinction is generally made between bacteria and viruses that cause disease (known as **pathogens**), on the one hand, and parasites, which are usually larger organisms, on the other. Ecologically, however, there is no real distinction. Bacteria are foreign organisms, and viruses are organismlike entities feeding on, and multiplying in, their hosts over a period of time and doing the same damage as do other parasites. Therefore, disease-causing bacteria and viruses can be considered highly specialized parasites. Representative examples of producers and consumers, and the feeding relationships among them, are shown in Fig. 2–9.

Detritus Feeders and Decomposers. Dead plant material, such as fallen leaves, branches and trunks of dead trees, dead grass, the fecal wastes of animals, and dead animal bodies, are called **detritus**. Many organisms are specialized to feed on detritus, and these consumers are called detritus feeders or *detritivores*. Earthworms, millipedes, fiddler crabs, termites, ants, and wood beetles are all detritus feeders. As with regular consumers, there are *primary* **detritus feeders** (those which feed directly on detritus), *secondary* **detritus feeders** (those which feed on primary detritus feeders), and so on.

An extremely important group of primary detritus feeders is the *decomposers*, namely, fungi and bacteria. Much of the detritus in an ecosystem—particularly dead

(a) (b) (c)

Figure 2–8 Diversity of parasites. Nearly every major biological group of organisms has at least some members that are parasitic on others. Shown here is (a) dodder, a plant parasite that has no leaves or chlorophyll. The orange "strings" are dodder stems, which suck sap from the host plant. (b) Nematode worms (*Ascaris lumbricoides*), the largest of the human parasites, reach a length of 14 inches (35 cm). (c) Lampreys attached to a whitefish. Lampreys parasitize many fish species.

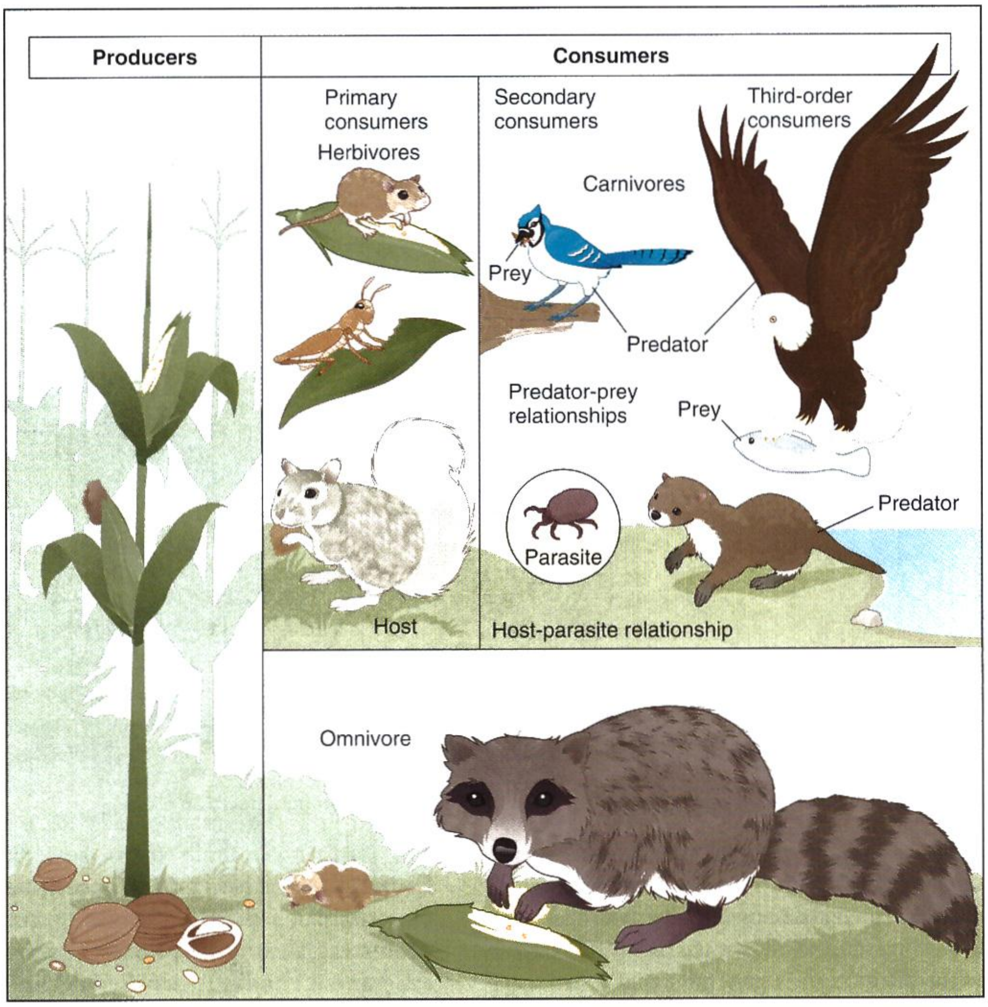


Figure 2-9 **Trophic relationships among producers and consumers.**

leaves and the wood of dead trees or branches—does not appear to be eaten as such, but rots away. Rotting is the result of the metabolic activity of fungi and bacteria. These organisms secrete digestive enzymes that break down wood, for example, into simple sugars that the fungi or bacteria then absorb for their nourishment. Thus, the rotting you observe is really the result of material being consumed by fungi and bacteria. Even though these organisms are called decomposers because of their unique behavior, they are grouped with detritus feeders because their function in the ecosystem is the same. Secondary detritus feeders, such as protozoans, mites, insects, and worms (Fig. 2–10), feed, in turn, upon decomposers. When a fungus or other decomposer dies, its body becomes part of the detritus and the source of energy and nutrients for still more detritus feeders and decomposers.

In sum, despite the diversity of ecosystems, they all have a similar *biotic structure*. All consist of (1) autotrophs, or producers, which produce organic matter that becomes the source of energy and nutrients for (2) heterotrophs, which are various categories of consumers, detritus feeders, and decomposers (Fig. 2–11).

Trophic Relationships: Food Chains, Food Webs, and Trophic Levels

A caterpillar eats an oak leaf, a warbler eats the caterpillar, and a hawk eats the warbler. This a **food chain.** While it is interesting to trace these pathways, it is important to recognize that food chains seldom exist as isolated entities. Caterpillars feed on several kinds of plants, are preyed upon by several kinds of birds, and so on. Consequently, virtually all food chains are interconnected and form a complex *web* of feeding relationships—the **food web.**

Despite the number of theoretical food chains and the complexity of food webs, they all basically lead through a series of steps or levels, namely, from producers to primary consumers (or primary detritus feeders) to secondary consumers (or secondary detritus feeders), and so on. These *feeding levels* are called **trophic levels.** All producers belong to the first trophic level, all primary consumers (in other words, all herbivores) belong to the second trophic level, organisms feeding on these herbivores belong to the third level, and so forth.

Whether you visualize the biotic structure of an ecosystem in terms of food chains, food webs, or trophic

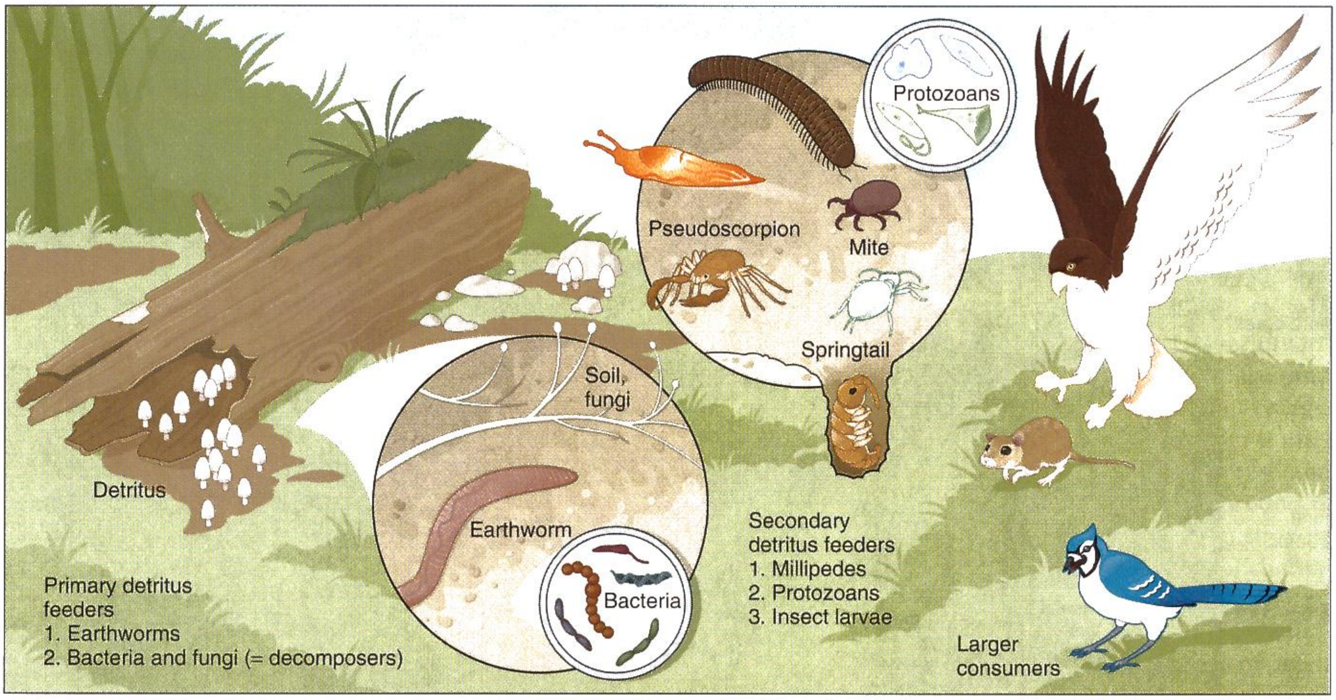


Figure 2–10 **Detritus food web.** The feeding (trophic) relationships among primary detritus feeders, secondary detritus feeders, and consumers.

Autotrophs Make their own organic matter from inorganic nutrients and an environmental energy source	**Heterotrophs** Must feed on organic matter for energy	
Producers	**Consumers**	**Detritus feeders and decomposers:** organisms that feed on dead organic material
Photosynthetic green plants: use chlorophyll to absorb light energy	Primary consumers/herbivores: animals that feed exclusively on plants	Decomposers: fungi and bacteria that cause rotting
Photosynthetic bacteria: use purple pigment to absorb light energy	Omnivores: animals that feed on both plants and animals	Primary detritus feeders: organisms that feed directly on detritus
Chemosynthetic bacteria: use high-energy inorganic chemicals such as hydrogen sulfide	Secondary consumers/carnivores: animals that feed on primary consumers	Secondary and higher orders of detritus feeders: feed on primary detritus feeders
	Higher orders of consumers/carnivores: animals that feed on other carnivores	
	Parasites: plants or animals that become associated with another plant or animal and feed on it over an extended period of time	

Figure 2–11 **Trophic categories.** A summary of how living organisms are ecologically categorized according to feeding attributes.

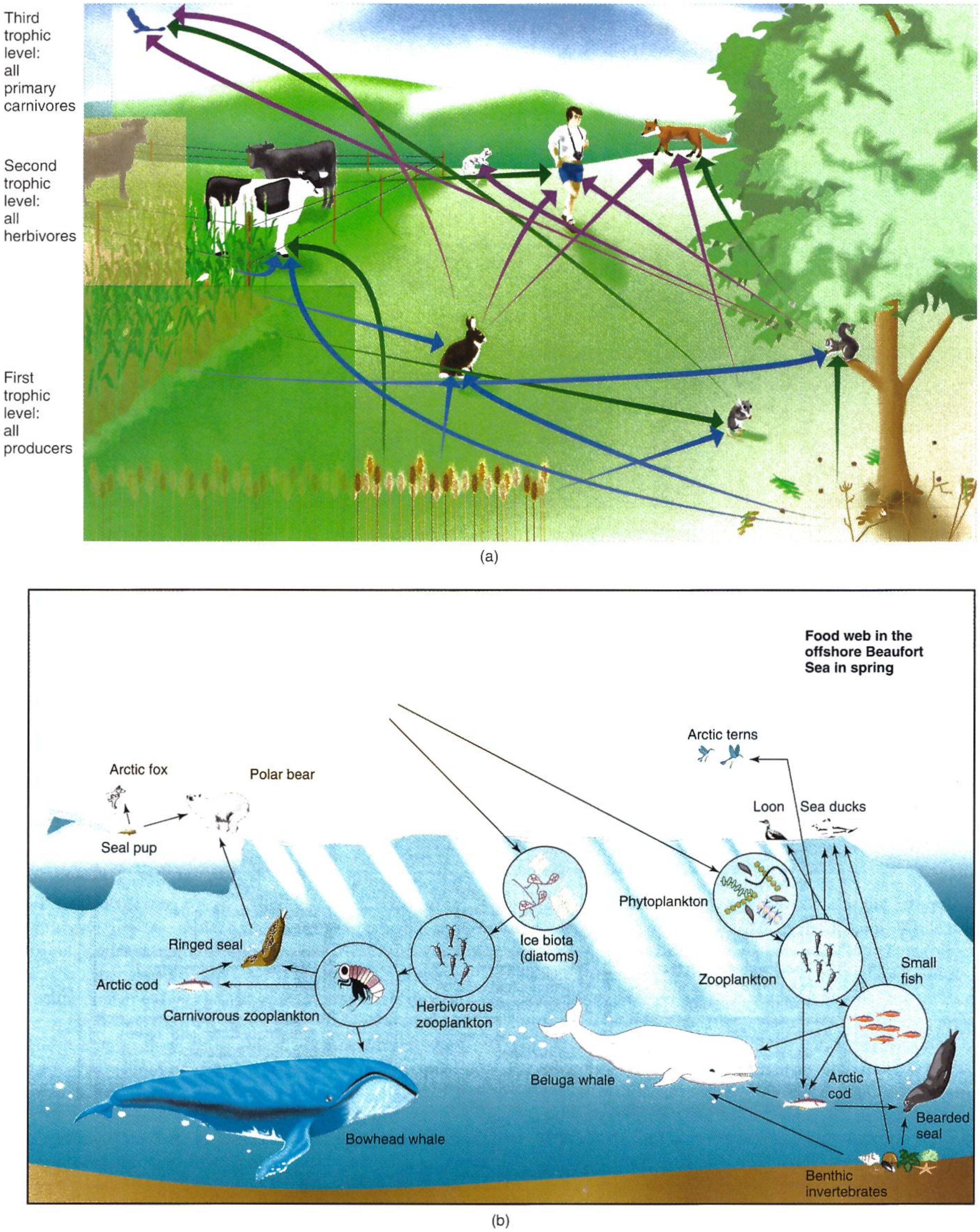


Figure 2-12 Food webs. (a) Specific pathways, such as that from nuts to squirrels to foxes (shown by green arrows), are referred to as *food chains.* A *food web* is the collection of all food chains, which are invariably interconnected (all arrows). Trophic levels, indicated by shading at the left, show that food always flows from producers to herbivores to carnivores. (b) A marine food web.

levels, there is a fundamental movement of the chemical nutrients and stored energy they contain from one organism or level to the next. These movements of energy and nutrients are described in more detail in Chapter 3. A visual comparison of food chains, food webs, and trophic levels is shown in Fig. 2–12.

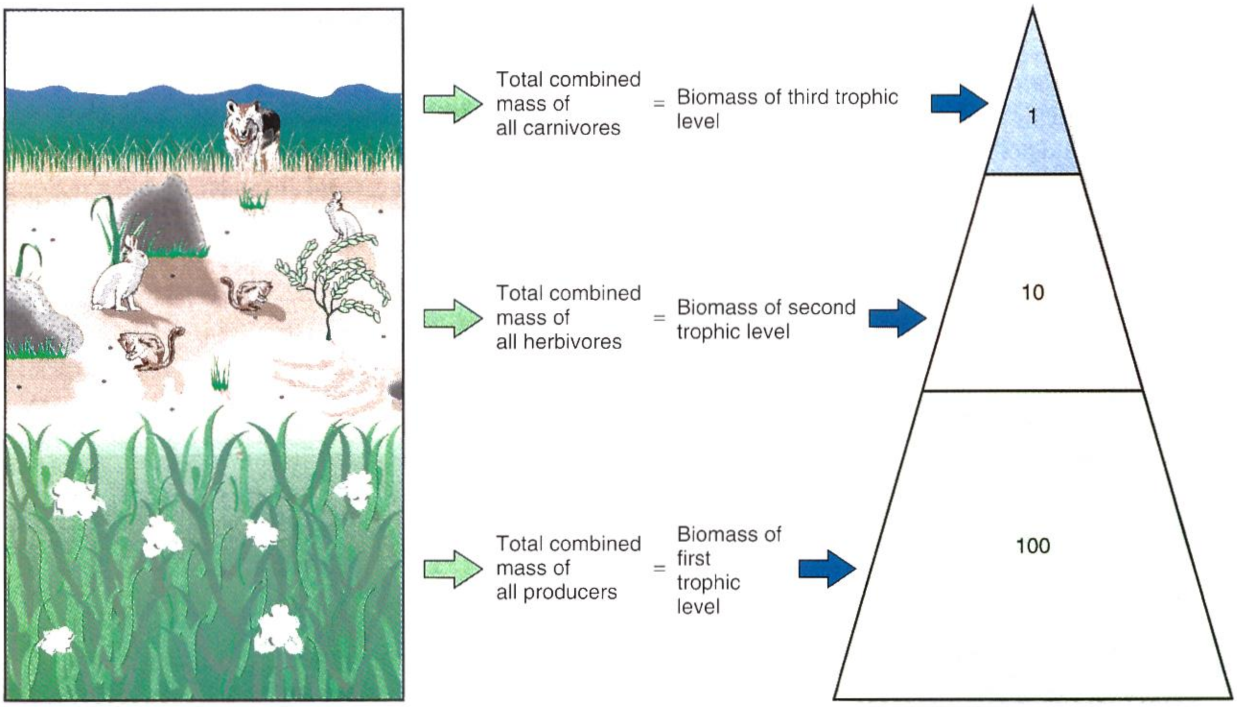
Limits on Trophic Levels. How many trophic levels are there? Usually, there are no more than three or four in terrestrial ecosystems and sometimes five in marine systems. (See Fig. 2-12b.) This answer comes from straightforward observations. The **biomass,** or total combined (net dry) weight (often, per unit area or volume), of all the organisms at each trophic level can be estimated by collecting (or trapping) and weighing suitable samples. In terrestrial ecosystems, the biomass is roughly 90% less at each higher trophic level. For example, if the biomass of producers in a grassland is 1 ton (2,000 lb) per acre, the biomass of herbivores will be about 200 pounds per acre, and that of primary carnivores will be about 20 pounds per acre. At this rate, you can't go through very many trophic levels before the biomass approaches zero. Depicting these relationships graphically gives rise to what is commonly called a **biomass pyramid** (Fig. 2–13).

The biomass decreases so much at each trophic level for three reasons. First, much of the food that is consumed by a heterotroph is not converted to the body tissues of the heterotroph; rather, it is broken down, and the stored energy it contains is released and used by the heterotroph. Second, much of the biomass—especially at the producer level—is never eaten by herbivores and goes directly to the decomposers. Third, carnivores that eat carnivores as prey must be larger than their prey, and there are limits to the size and distribution of ever-larger carnivores roaming over an ever-larger area.

As organic matter is broken down, its chemical elements are released back to the environment, where, in the inorganic state, they may be reabsorbed by autotrophs (producers). Thus, a continuous *cycle of nutrients* is sustained, from the environment through organisms and back to the environment. As organisms eat other organisms, they expend energy to grow and reproduce, and their numbers as species are sustained. The spent energy, on the other hand, is lost as heat given off from bodies (Fig. 2–14). In sum, all food chains, food webs, and trophic levels *must start with producers,* and producers must have suitable environmental conditions to support their growth. Populations of all heterotrophs, including humans, are ultimately limited by what plants produce, in accordance with the concept of the biomass pyramid. Should any factor cause the productive capacity of green plants to be diminished, all other organisms at higher trophic levels will be diminished accordingly.

Nonfeeding Relationships

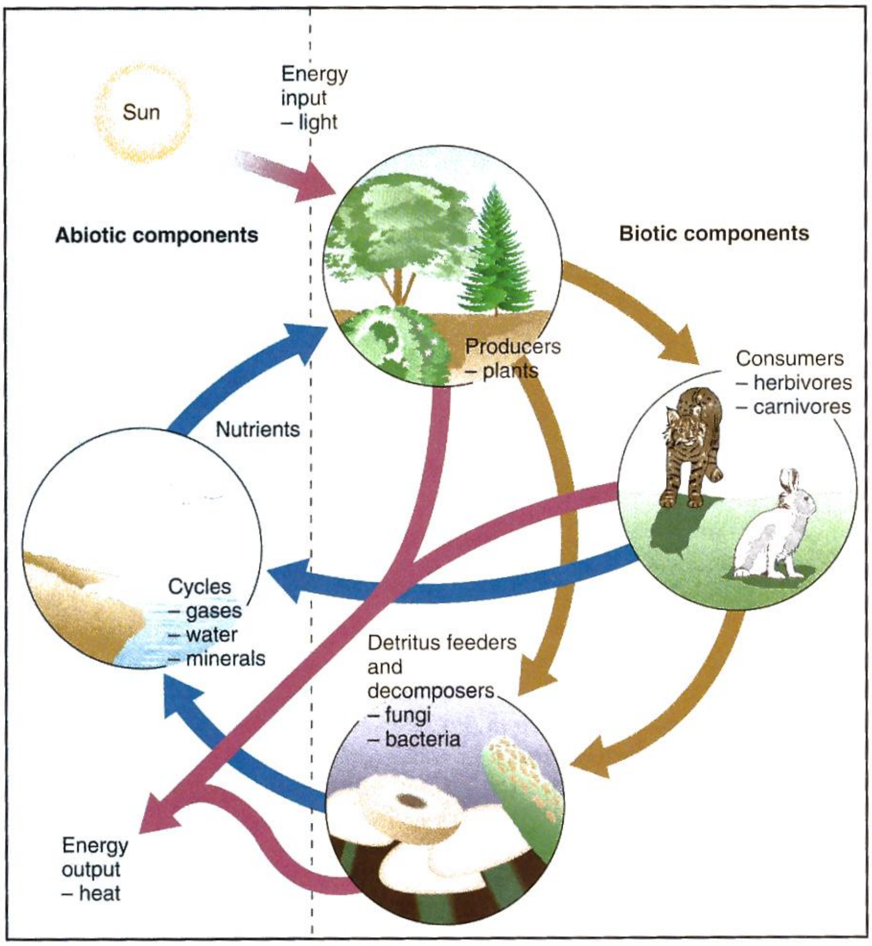
Mutually Supportive Relationships. The overall structure of ecosystems is characterized by their feeding relationships. You may think that one species benefits and



Segments of pyramid show relative biomass at each trophic level

Figure 2–13 **Biomass pyramid.** A graphic representation of the biomass (the total combined mass of organisms) at successive trophic levels has the form of a pyramid.

Figure 2–14 Nutrient cycles and energy flow. The movement of nutrients (blue arrows), energy (red arrows), and both (brown arrows) through the ecosystem. Nutrients follow a cycle, being used over and over. Light energy absorbed by producers is released and lost as heat energy as it is "spent."



the other is harmed to some extent in any feeding relationship. However, many relationships provide a mutual benefit to both species. This phenomenon is called **mutualism**, and it is exemplified by the relationship between flowers and pollinating insects. The insects benefit by obtaining nectar from the flowers, and the plants benefit by being pollinated in the process (Fig. 2–15).

In some cases, the mutualistic relationship has become so close that the species involved are no longer capable of living alone. The group of plants known as *lichens* (Fig. 2–16), for example, are actually composed of two organisms—a fungus and an alga. The fungus provides protection for the alga, enabling it to survive in dry habitats where it could not live by itself, and the alga,

Figure 2–15 A mutualistic relationship. Insects like this honeybee are attracted to flowers by their nectar, a good food source for the bees. As they move from plant to plant, the bees pollinate the flowers, enabling them to set fertile seed for the next generation.

Figure 2–16 Lichens. The crusty-appearing "plants" commonly seen growing on rocks or the bark of trees are actually composed of a fungus and an alga growing in a symbiotic relationship.

which is a producer, provides food for the fungus, which is a heterotroph. These two species living together in close union have a *symbiotic* relationship. However, **symbiosis** by itself simply means that the two organisms "live together" in close union (*sym*, together; *bio*, living); it does not specify a mutual benefit or harm. Therefore, symbiotic relationships may include parasitic relationships as well as mutualistic relationships.

While not categorized as mutualistic, many relationships in an ecosystem may aid its overall sustainability. For example, plant detritus provides most of the food for decomposers and soil-dwelling detritus feeders such as earthworms. Thus, these organisms benefit from plants, but the plants also benefit because the activity of the organisms releases nutrients from the detritus and returns them to the soil, where they can be reused by the plants. Similarly, insect-eating birds benefit from vegetation by finding nesting materials and places among trees, while the plant community benefits because the birds reduce the populations of many herbivorous insects. Even in predator–prey relationships, some mutual advantage may exist. The killing of individual prey that are weak or diseased may benefit the population as a whole by keeping it healthy. Predators and parasites may also prevent herbivore populations from becoming so abundant that they overgraze their environment (which might jeopardize the entire ecosystem).

Competitive Relationships. Considering the complexity of food webs, you might think that species of animals would be in a great "free-for-all" competition with each other. In fact, fierce competition rarely occurs, because each species tends to be specialized and adapted to its own *habitat* or *niche*.

Habitat refers to the kind of place—defined by the plant community and the physical environment—where a species is biologically adapted to live. For example, a deciduous forest, a swamp, and a grassy field are types of habitats. Different types of forests (for instance, coniferous vs. deciduous) provide markedly different habitats and support different species of wildlife.

Even when different species occupy the same habitat, competition may be slight or nonexistent because each species has its own *niche*. An animal's **ecological niche** refers to what the animal feeds on, where it feeds, when it feeds, where it finds shelter, how it responds to abiotic factors, and where it nests. Seeming competitors can coexist in the same habitat, but have separate niches. Competition is minimized because potential competitors are using different resources. (It's like a shopping mall where the stores avoid competition by offering different goods.) For example, woodpeckers, which feed on insects in deadwood, do not compete with birds that feed on seeds. Bats and swallows both feed on flying insects, but they do not compete, because bats feed on night-flying insects and swallows feed during the day. Sometimes the "resource" can be the space used by different species as they forage for food, as in the case of five species of warblers that coexist in the spruce forests of Maine (Fig. 2–17). The birds, which feed at different levels of the forest and on different parts of the trees, exemplify what is called *resource partitioning*. By adapting to each other's presence over time, these species avoid competition, and all of them benefit.

Depending on how a set of resources is "divided up" among species, there may be unavoidable overlap between the niches of the species. All green plants require water, nutrients, and light, and where they are growing in the same location, one species may eliminate others through competition. (That's why maintaining flowers and vegetables against the advance of weeds is a constant struggle.) However, different plant species are also adapted and specialized to particular conditions. Thus, each species is able to hold its own against competition where conditions are well suited to it. The same concepts hold true for species in aquatic and marine ecosystems.

If two species compete directly in many respects, as sometimes occurs when a species is introduced from another continent, one of the two generally perishes in the competition. This is the *competitive exclusion principle*. For example, the introduction of the European rabbit to Australia has led to the decline and disappearance of several small marsupial animal species, due to direct competition for food and burrows.

Abiotic Factors

We now turn to the *abiotic* side of the ecosystem. As noted before, the environment involves the interplay of many physical and chemical factors—**abiotic factors**—that different species respond to. Abiotic factors can be categorized as **conditions** or **resources**. *Conditions* are abiotic factors that vary in space and time, but are not used up or made unavailable to other species. Conditions include temperature (extremes of heat and cold, as well as average temperature), wind, pH (acidity), salinity (saltiness), and fire. Within aquatic systems, for example, the key conditions are salinity (freshwater vs. saltwater), temperature, the texture of the bottom (rocky vs. silty), the depth and turbidity (cloudiness) of the water (determining how much, if any, light reaches the bottom), and currents.

Resources are any factors—biotic or abiotic—that are consumed by organisms. Abiotic resources include water, chemical nutrients (like nitrogen and phosphorus), light (for plants), and oxygen. Abiotic resources also include spatial needs, such as a place on the intertidal rocks or a hole in a tree. Resources, unlike conditions, can be the objects of competition between individuals or species.

The degree to which each abiotic factor is present (or absent) profoundly affects the ability of organisms to survive. However, each species may be affected differently by each factor. This difference in response to environmental factors determines which species may or may not occupy a given region or a particular area within a region. In turn, the organisms that do or do not survive determine the nature of a given ecosystem.

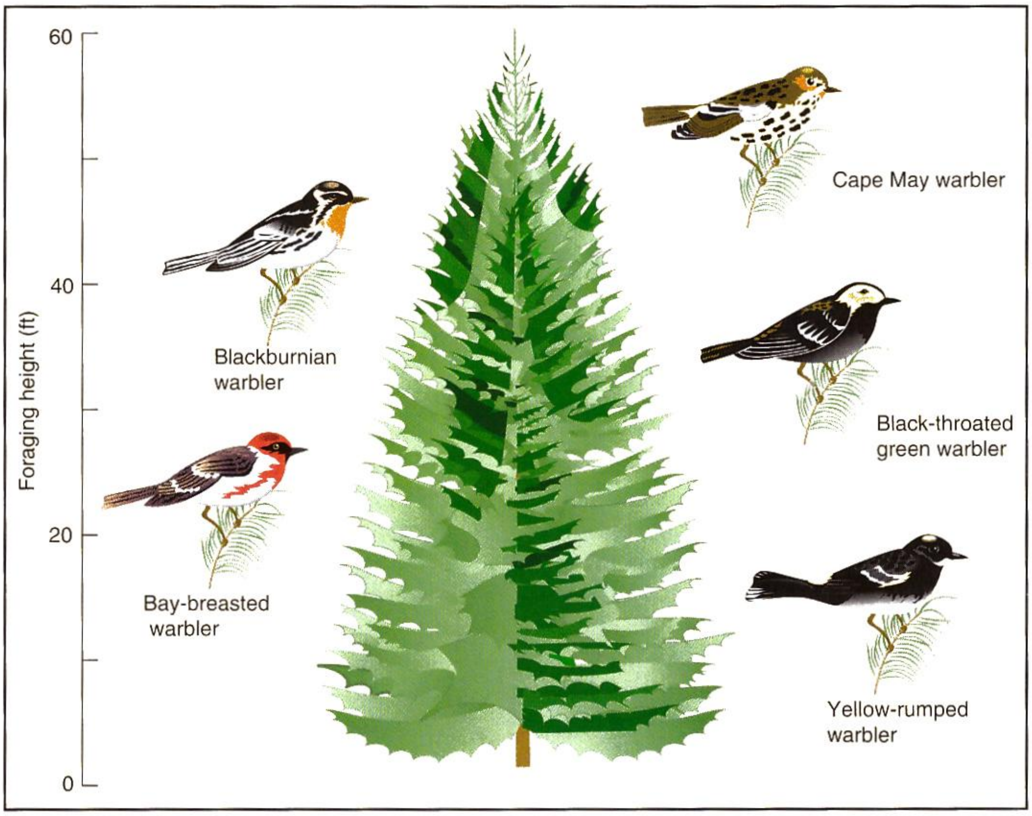


Figure 2–17 Resource partitioning. Five species of North American warblers reduce the competition among themselves by feeding at different levels and on different parts of trees.

Optimum, Zones of Stress, and Limits of Tolerance. *Different species thrive under different environmental regimes.* This principle applies to all living things, both plants and animals. Some survive where it is very wet, others where it is relatively dry. Some thrive in warmth, others in cooler situations. Some tolerate freezing, while others do not. Some require bright sun; others do best in shade. Aquatic systems are divided into freshwater and saltwater regimes, each with its respective fish and other organisms.

Laboratory experiments demonstrate that different species are best adapted to different factors. Organisms can be grown under controlled conditions in which one factor is varied while other factors are held constant. Such experiments demonstrate that, for every factor, there is an **optimum**, a certain level at which the organisms do best. At higher or lower levels the organisms do less well, and at further extremes they may not be able to survive at all. This concept is shown graphically in Figure 2–18. Temperature is shown as the variable in the figure, but the idea pertains to any abiotic factor that might be tested.

The point at which the best response occurs is called the optimum, but this may be a range of several degrees (or other units), so it is common to speak of an *optimal range*. The entire span that allows any growth at all is called the **range of tolerance**. The points at the high and low ends of the range of tolerance are called the **limits of tolerance**. Between the optimal range and the high or low limit of tolerance are **zones of stress**. That is, as the factor is raised or lowered from the optimal range, the organisms experience increasing stress, until, at either limit of tolerance, they cannot survive.

A Fundamental Principle. Not every species has been tested for every possible factor. Based on the consistency of such observations, however, the following is considered to be a fundamental biological principle: *Every species (both plant and animal) has an optimum range, zones of stress, and limits of tolerance with respect to every abiotic factor.*

This line of experimentation also demonstrates that different species vary in characteristics with respect to the values at which the optimum and the limits of tolerance occur. For instance, what may be an optimal amount of water for one species may stress a second and kill a third. Some plants cannot tolerate any freezing temperatures, others can tolerate slight, but not intense, freezing, and some actually require several weeks of freezing temperatures in order to complete their life cycles. Also, some species have a very broad range of tolerance, whereas others have a much narrower range. While optimums and limits of tolerance may differ from one species to another, there may be great overlap in their ranges of tolerance.

The concept of a range of tolerance affects more than just the growth of individuals: Because the health

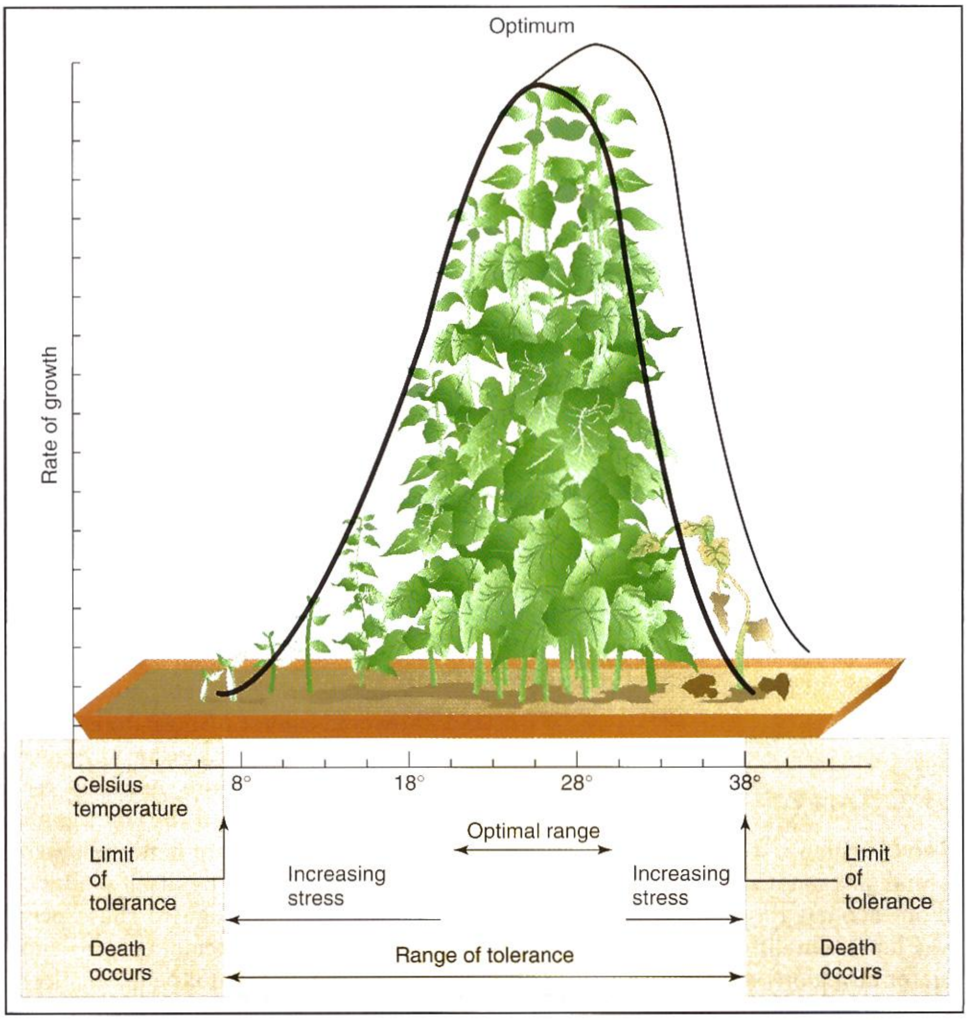


Figure 2–18 **Survival curve.** For every factor influencing growth, reproduction, and survival, there is an optimum level. Above and below the optimum, stress increases, until survival becomes impossible at the limits of tolerance. The total range between the high and low limits is the range of tolerance.

and vigor of individuals affect reproduction and the survival of the next generation, the population is also influenced. Consequently, the population density (individuals per unit area) of a species is greatest where all conditions are optimal, and it decreases as any one or more conditions depart from the optimum. Different ranges of tolerance for different factors contribute significantly to the identity of an ecological niche for a given species.

Law of Limiting Factors. In 1840, Justus von Liebig studied the effects of chemical nutrients on plant growth. He observed that restricting any one of the many different nutrients at any given time had the same effect: *It limited growth.* A factor that limits growth is called, naturally, a **limiting factor**. *Any one factor* being outside the optimal range will cause stress and limit the growth, reproduction, or even survival of a population. This observation is referred to as the **law of limiting factors**, or Liebig's law of minimums.

The limiting factor may be a problem of *too much*, as well as a problem of *too little*. For example, plants may be stressed or killed not only by underwatering or underfertilizing, but also by overwatering or overfertilizing, which are common pitfalls for beginning gardeners. Note also that the limiting factor may change from one time to another. For instance, in a single growing season, temperature may be limiting in the early spring, nutrients may be limiting later, and then water may be limiting if a drought occurs. Also, if one limiting factor is corrected, growth will increase only until another factor comes into play. The organism's genetic potential is an ultimate limiting factor. Thus, a mouse will never grow to the bulk of an elephant, no matter how much you feed it!

Biotic Factors. Observations made since Liebig's time show that his law has a much broader application. That is, growth may be limited not only by abiotic factors, but also by biotic factors. Thus, the limiting factor for a population may be competition or predation from another species. With agricultural crops, for example, there is a constant struggle to keep them from being limited or even eliminated by weeds and insects.

Finally, while one factor may be determined to be limiting at a given time, several factors outside the optimum may combine to cause additional stress or even death. In particular, pollutants may act in a way that causes organisms to become more vulnerable to disease or drought. Such cases are examples of **synergistic effects**, or **synergisms**, which are defined as two or more factors interacting in a way that causes an effect much greater than one would anticipate from the effects of each of the two acting separately.

2.3 From Ecosystems to Global Biomes

We can now use the concepts of optimums and limiting factors to gain a better understanding of why different regions or even localized areas may have distinct biotic communities, creating an amazing variety of ecosystems, landscapes, and biomes.

The Role of Climate

The **climate** of a given region is a description of the average temperature and precipitation—the weather—that may be expected on each day throughout the entire year. (See Chapter 20.) Climates in different parts of the world vary widely. Equatorial regions are continuously warm, with high rainfall and no discernible seasons. Above and below the equator, temperatures become increasingly seasonal (characterized by warm or hot summers and cool or cold winters); the farther we go toward the poles, the longer and colder the winters become, until at the poles it is perpetually winterlike. Likewise, colder temperatures are found at higher elevations, so that there are even snowcapped mountains on or near the equator.

Annual precipitation in any area also may vary greatly, from virtually zero to well over 100 inches (250 cm) per year. Precipitation may be evenly distributed throughout the year or concentrated in certain months, dividing the year into wet and dry seasons.

Different temperature and rainfall conditions may occur in almost any combination, yielding a wide variety of climates. In turn, a given climate will support only those species that find the temperature and precipitation levels optimal or at least within their ranges of tolerance. As indicated in Figure 2–18, population densities will be greatest where conditions are optimal and will decrease as any condition departs from the optimum. A species will be excluded from a region (or local areas) where any condition is beyond its limit of tolerance. How will this variation affect the biotic community?

Biome Examples. To illustrate, let us consider six major types of biomes and their global distribution. Table 2–3 describes these terrestrial biomes and their major characteristics, and Figure 2–19 shows the distribution of, and variations in, the biomes as they occur globally. Within the temperate zone (between 30° and 50° of latitude), the amount of rainfall is the key limiting factor. The **temperate deciduous forest biome** is found where annual precipitation is 30–80 in. (75–200 cm). Where rainfall tapers off or is highly seasonal (10–60 in., or 25–150 cm, per year), **grassland and prairie biomes** are found, and regions receiving an average of less than 10 inches (25 cm) per year are occupied by a **desert biome**.

The effect of temperature, the other dominant parameter of climate, is largely superimposed on that of rainfall. That is, 30 inches (75 cm) or more of rainfall per year will usually support a forest, but temperature will determine the *kind* of forest. For example, broad-leafed evergreen species, which are extremely vigorous and fast growing, but cannot tolerate freezing temperatures, predominate in the **tropical rain forest**. By dropping their leaves and becoming dormant each autumn, deciduous trees are well adapted to freezing temperatures. Therefore, wherever rainfall is sufficient, deciduous forests predominate in temperate latitudes. Most deciduous trees, however, cannot tolerate the extremely harsh winters and short summers that occur at higher latitudes and higher elevations. Therefore, northern regions and high elevations are occupied by the **coniferous forest biome**, because conifers are better adapted to those conditions.

Temperature by itself limits forests only when it becomes low enough to cause **permafrost** (permanently frozen subsoil). Permafrost prevents the growth of trees, because roots cannot penetrate deeply enough to provide adequate support. However, a number of grasses, clovers, and other small flowering plants can grow in the topsoil above permafrost. Consequently, where permafrost sets in, the coniferous forest biome gives way to the **tundra biome** (Table 2–3). At still colder temperatures, the tundra gives way to permanent snow and ice cover.

The same relationship of rainfall effects being primary and temperature effects secondary applies in deserts. Any region receiving less than about 10 inches (25 cm) of rain per year will be a desert, but the unique plant and animal species found in hot deserts are different from those found in cold deserts.

A summary of the relationship between biomes, and temperature and rainfall conditions, is given in Figure 2–20. The average temperature for a region varies with both latitude and altitude, as shown in Figure 2–21.

Microclimate and Other Abiotic Factors

A specific site may have temperature and moisture conditions that are significantly different from the overall, or average, climate of the region in which it is located. For example, a south-facing slope, which receives more direct sunlight in the northern hemisphere, will be relatively warmer and hence also drier than a north-facing slope (Fig. 2–22). Similarly, the temperature range in a sheltered ravine will be narrower than that in a more

table 2-3 **Major Terrestrial Biomes**

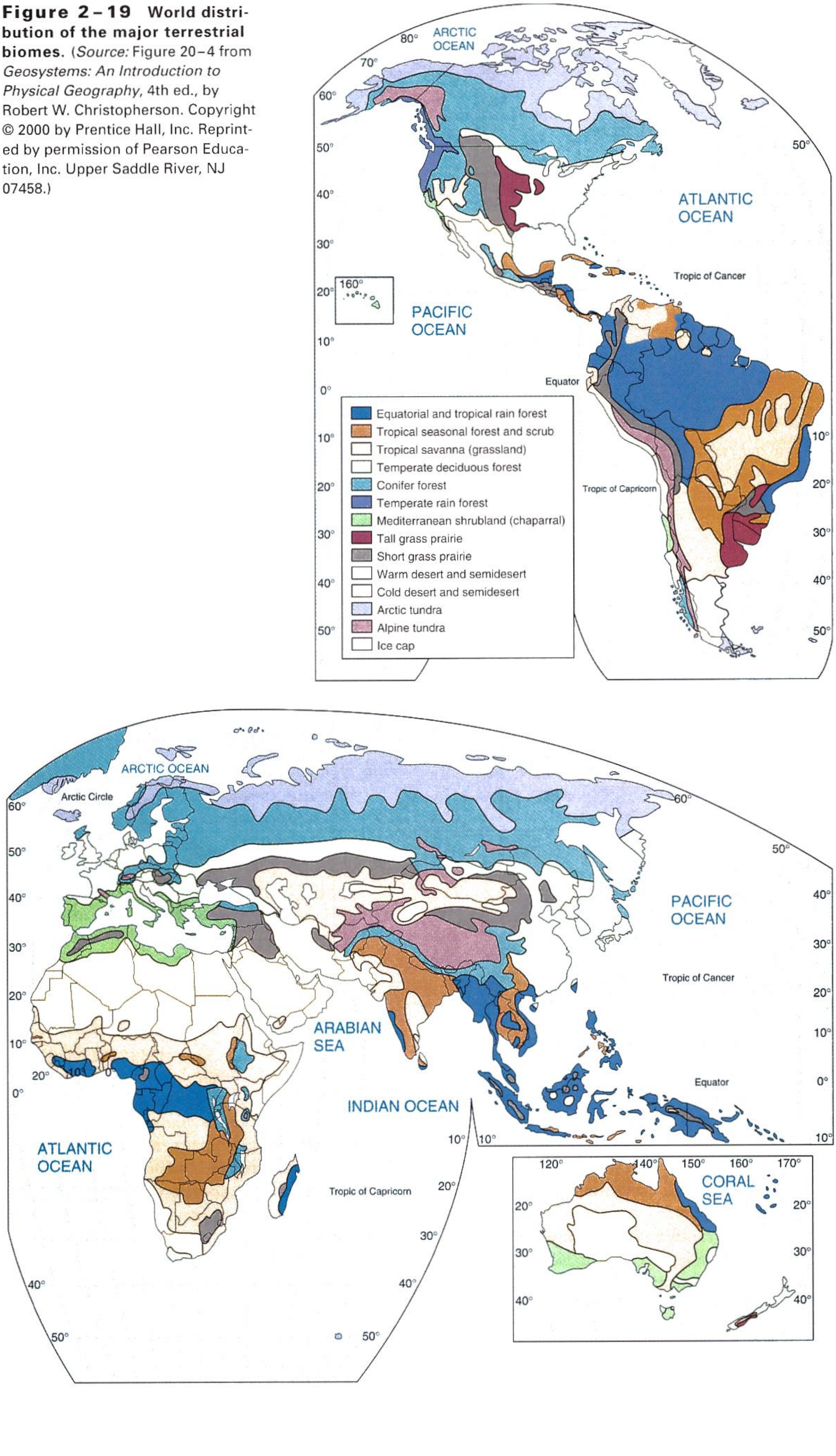
Biome	Climate and Soils	Dominant Vegetation	Dominant Animal Life	Geographic Distribution
Deserts	Very dry; hot days and cold nights; rainfall less than 10 in./yr; soils thin and porous	Widely scattered thorny bushes and shrubs, cacti	Rodents, lizards, snakes, numerous insects, owls, hawks, small birds	N. and S.W. Africa, parts of Middle East and Asia, S.W. United States, northern Mexico
Grasslands and Prairies	Seasonal rainfall, 10 to 60 in./yr; fires frequent; soils rich and often deep	Grass species, from tall grasses in areas with higher rainfall to short grasses where drier; bushes and woodlands in some areas	Large grazing mammals: bison, goats; wild horses; kangaroos; antelopes, rhinos, warthogs, prairie dogs, coyotes, jackals, lions, hyenas; termites important	Central North America, central Asia, subequatorial Africa and South America, much of southern India, northern Australia
Tropical Rain Forests	Nonseasonal; annual average temperature 28°C; rainfall frequent and heavy, average over 95 in./yr; soils thin and poor in nutrients	High diversity of broad-leafed evergreen trees, dense canopy, abundant epiphytes and vines; little understory	Enormous biodiversity; exotic, colorful insects, amphibians, birds, snakes; monkeys, small mammals, tigers, jaguars	Northern South America, Central America, western central Africa, islands in Indian and Pacific Oceans, S.E. Asia
Temperate Forests	Seasonal; temperature below freezing in winter; summers warm, humid; rainfall from 30–80 in./yr; soils well developed	Broad leafed deciduous trees, some conifers; shrubby undergrowth, ferns, lichens, mosses	Squirrels, raccoons, opossums, skunks, deer, foxes, black bears, snakes, amphibians, rich soil microbiota, birds	Western and central Europe, eastern Asia, eastern North America
Coniferous Forests	Seasonal; winters long and cold; precipitation light in winter, heavier in summer; soils acidic, much humus and litter	Coniferous trees (spruce, fir, pine, hemlock), some deciduous trees (birch, maple); poor understory	Large herbivores such as mule deer, moose, elk; mice, hares, squirrels; lynx, bears, foxes, fishers, marten; important nesting area for neotropical birds	Northern portions of North America, Europe, Asia, extending southward at high elevations
Tundra	Bitter cold, except for an 8- to 10-week growing season with long days and moderate temperatures; precipitation low, soils thin and underlain with permafrost	Low-growing sedges, dwarf shrubs, lichens, mosses, and grasses	Year round: lemmings, arctic hares, arctic foxes, lynx, caribou, musk ox; summers: abundant insects, many migrant shorebirds, geese, and ducks	North of the coniferous forest in northern hemisphere, extending southward at elevations above the coniferous forest

exposed location, and so on. The conditions found in a specific localized area are referred to as the **microclimate** of that location. In the same way that different climates determine the major biome of a region, different microclimates result in variations of ecosystems within a biome.

Soil type and topography may also contribute to the diversity found in a biome, because these two factors affect the availability of moisture. In the eastern United States, for example, oaks and hickories generally predominate on rocky, sandy soils and on hilltops, which retain little moisture, whereas beeches and maples are found on richer soils, which hold more moisture, and red maples and cedars inhabit low, swampy areas. In the transitional region between desert and grassland [10–20 inches (25–50 cm) of rainfall per year], a soil capable of holding water will support grass, but a sandy soil with little ability to hold water will support only desert species.

In certain cases, an abiotic factor other than rainfall or temperature may be the primary limiting factor. For example, the strip of land adjacent to a coast frequently receives a salty spray from the ocean, a factor that relatively few plants can tolerate. Consequently, an association of salt-tolerant plants frequently occupies this strip, as on a barrier island. Relative acidity or alkalinity (pH) may also have an overriding effect on a plant or animal community.

Figure 2–19 World distribution of the major terrestrial biomes. (*Source:* Figure 20–4 from *Geosystems: An Introduction to Physical Geography*, 4th ed., by Robert W. Christopherson. Copyright © 2000 by Prentice Hall, Inc. Reprinted by permission of Pearson Education, Inc. Upper Saddle River, NJ 07458.)



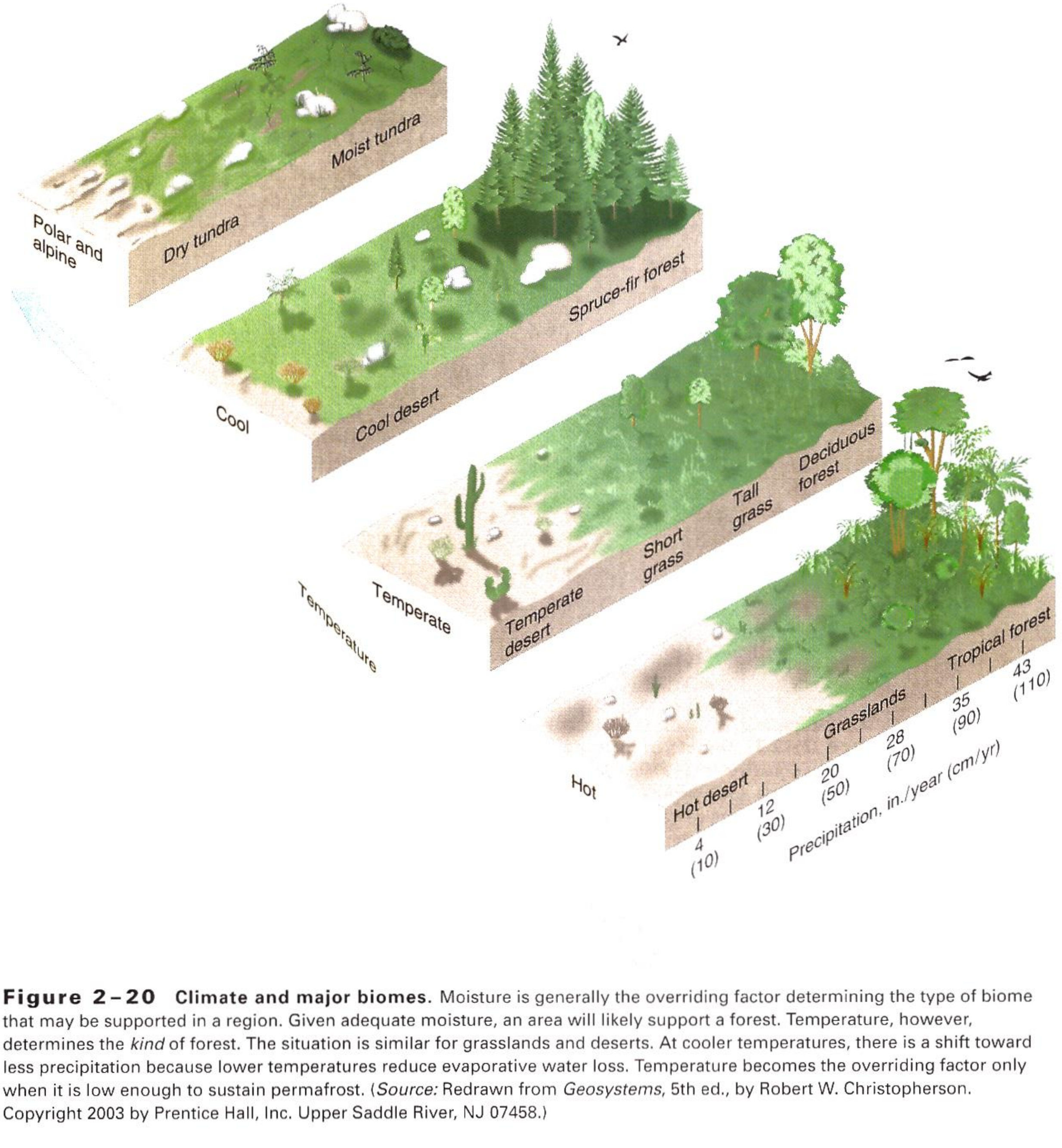


Figure 2-20 Climate and major biomes. Moisture is generally the overriding factor determining the type of biome that may be supported in a region. Given adequate moisture, an area will likely support a forest. Temperature, however, determines the *kind* of forest. The situation is similar for grasslands and deserts. At cooler temperatures, there is a shift toward less precipitation because lower temperatures reduce evaporative water loss. Temperature becomes the overriding factor only when it is low enough to sustain permafrost. (*Source:* Redrawn from *Geosystems*, 5th ed., by Robert W. Christopherson. Copyright 2003 by Prentice Hall, Inc. Upper Saddle River, NJ 07458.)

Biotic Factors

Some biotic factors—that is, factors caused by other species—may be limiting. Grasses thrive when rainfall is more than 30 inches (75 cm). When the rainfall is great enough to support trees, however, increased shade may limit grasses. Thus, the factor that limits grasses from taking over high-rainfall regions is biotic—namely, the overwhelming competition from taller species. The distribution of plants may also be limited by the presence of certain herbivores; elephants, for example, are notorious for destroying woodlands, so their presence leads predominantly to grasslands. (See Fig. 5-14.)

Limiting factors also apply to animals. As with plants, the limiting factor may be abiotic—cold temperatures or lack of open water, for instance—but it is more frequently biotic, such as the absence of a plant community that would otherwise provide suitable food or habitat.

Physical Barriers

A final factor that may limit species to a particular region is the existence of a physical barrier, such as an ocean, a desert, or a mountain range, that species are unable to cross. Thus, species making up the communities on separate continents or remote islands are usually quite different, despite living in similar climates.

When physical barriers are overcome—as when humans knowingly or unknowingly transport a species from one continent to another—the introduced species

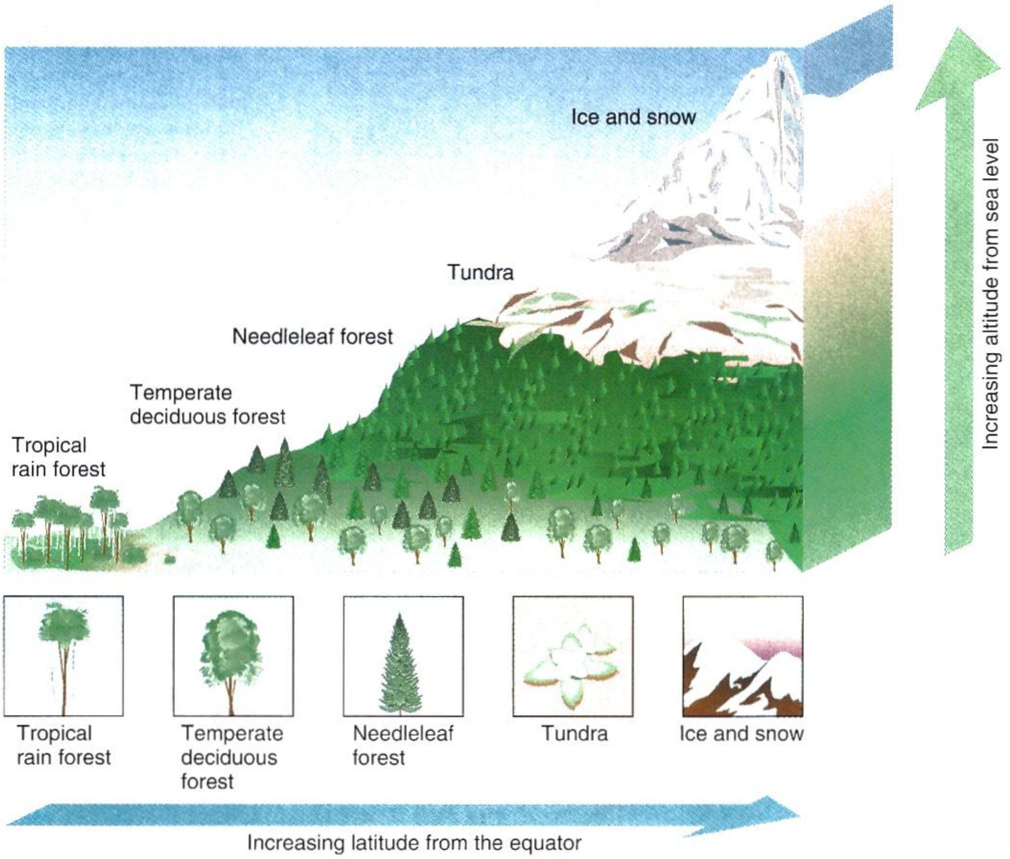


Figure 2-21 Effects of latitude and altitude. Decreasing temperatures, which result in the biome shifts noted in Fig. 2-20, occur with both increasing latitude (distance from the equator) and increasing altitude. (*Source:* Redrawn from *Geosystems*, 5th ed., by Robert W. Christopherson. Copyright 2003 by Prentice Hall, Inc. Upper Saddle River, NJ 07458.)

may make a successful *invasion*. The starling, for example, originally confined to Eurasia, has successfully invaded North America. Additional examples of imported species and their impacts are discussed further in Chapter 4. Note also that humans erect barriers—dams, roadways, aboveground pipelines, cities, and farms—that may block the normal movement of populations and cause their demise. For example, the Atlantic salmon is now an endangered species in some New England states because of the many dams that prevent the migration they require for spawning.

Summary

The biosphere consists of a great variety of environments, both aquatic and terrestrial. In each environment, plant, animal, and microbial species are adapted to all the abiotic factors. In addition, they are adapted to each other, in various feeding and nonfeeding relationships. Each environment supports a more or less unique grouping of organisms interacting with each other and with the environment in a way that perpetuates or sustains the entire group. That is, each environment, together with the species it supports, is an *ecosystem*. Every ecosystem is tied to others through species that migrate from one system to another and through exchanges of air, water, and minerals common to the whole planet. At the same time, each species—and, as a result, each ecosystem—is kept within certain bounds by limiting factors. The spread of each species is limited at some point because that species is unable to tolerate particular conditions, to compete with other species, or to cross some physical barrier. The distribution of species is always due to one or more limiting factors.

2.4 The Human Factor

So far, we have been looking at ecosystems as natural-functioning systems, unaffected by humans. In reality, the impact of humans must be taken into consideration because we have become such a dominant presence on Earth. We have replaced many natural systems with agriculture and urban and suburban developments; we make heavy use of most of the remaining "natural" systems, for wood, food, and other commercial products; and the by-products of our economic activities have polluted and degraded ecosystems everywhere. Our involvement with natural ecosystems is so

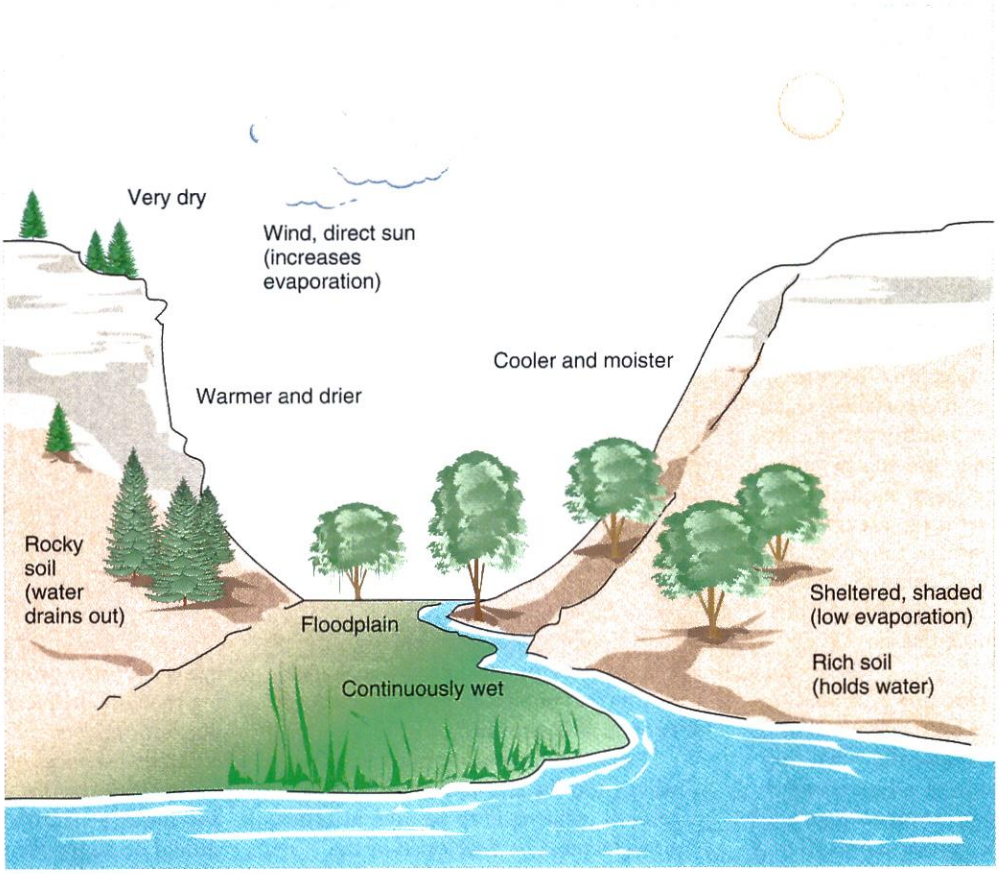


Figure 2–22 Microclimates. Abiotic factors such as terrain, wind, and type of soil create different microclimates by influencing temperature and moisture in localized areas.

pervasive that if we want to continue to enjoy their goods and services, we must learn how to *manage* and sometimes *restore* those ecosystems to keep them healthy and productive (see Ethics, p. 50). A brief look into the past may help you understand the changes that have occurred to make humans such a dominant part of the landscape and may better equip you to deal with the future.

Three Revolutions

Neolithic Revolution. Natural ecosystems have existed and perpetuated themselves on Earth for hundreds of millions of years, while humans are relative newcomers to the scene. Archaeological and anthropological evidence indicates that hominid ancestry goes back at least four million years. The fossil record reveals as many as 14 hominid species. The earliest fully modern humans appeared about 40,000 years ago, when they invaded Europe, and their culture is known as the **Paleolithic** (40,000 to 10,000 years ago).

Paleolithic humans survived in small tribes as hunter–gatherers, catching wildlife and collecting seeds, nuts, roots, berries, and other plant foods (Fig. 2–23). Settlements were never large and were of relatively short duration because, as one area was picked over, the tribe was forced to move on. As hunter–gatherers, these people were much like other omnivorous consumers in natural ecosystems. Populations could not expand beyond the sizes that natural food sources supported, and deaths from predators, disease, and famine were common. In time, however, the hunter–gatherer culture was successful enough to foster population increases, and the pressures of rising populations led to the next stage.

About 12,000 years ago, a highly significant change in human culture occurred when humans in the Middle East began to develop animal husbandry and agriculture. Evidence suggests that this change—the domestication of wild species—can be traced to a shift in the climate—the Younger Dryas episode—which brought first unusually warm and wet, and then cooler and drier, conditions. The cooler and drier conditions made hunting and gathering increasingly difficult.

The development of agriculture provided a more abundant and reliable food supply, but it was a turning point in human history for other reasons as well. Because of its profound effect, it is referred to as a *revolution*—specifically, the **Neolithic Revolution.** Conducting agriculture does not just allow, but *requires*, permanent (or at least long-term) settlements and the specialization of labor. Some members of the settlement specialize in tending crops and producing food, freeing others to specialize in other endeavors. With this specialization of labor in permanent settlements, there

ethics

Can Ecosystems Be Restored?

The human capacity for destroying ecosystems is well established. To some degree, however, we also have the capacity to restore them. In many cases, restoration simply involves stopping the abuse. For example, it has been found that after pollution is curtailed, water quality improves and fish and shellfish gradually return to previously polluted lakes, rivers, and bays. Similarly, forests may gradually return to areas that have been cleared. Humans can speed up the process by seeding, planting seedling trees, and reintroducing populations of fish and animals that have been eliminated.

In some cases, however, specific ecosystems have been destroyed or disturbed to such an extent that they require the efforts of a new breed of scientist: the *restoration ecologist.* Two types of ecosystem that have suffered most in this regard are the *prairie* and *wetland ecosystems.* The potential for restoration of any ecosystem rests on the following three assumptions: (a) Abiotic factors must have remained unaltered or, if not, can at least be returned to their original state. (b) Viable populations of the species formerly inhabiting the ecosystem must still exist. (c) The ecosystem must not have been upset by the introduction of one or more foreign species that cannot be eliminated and that may preclude the survival of reintroduced native species. If these conditions are met, revival efforts have the potential to restore the ecosystem to some semblance of its former state.

Suppose, for example, that the Natural Lands Trust has acquired land in the Great Plains and wishes to restore the prairie that once flourished there. The problems are many. The lack of grazing and regular fires have led to much woody vegetation, exotic species abound in the region and can continuously disperse seeds on the experimental prairie, and there may be no remnants of the original prairie grasses and herbs on the site. How does one proceed? It may help to draw on a primer on ecological restoration published by the Society for Ecological Restoration.[1]

First, an *inventory* must be taken of what is on the site and, from historical records, what used to be present. Then, a *model* must be developed of the desired ecosystem in structural and functional terms, usually based on the use of an existing *reference ecosystem. Goals* are set for the restoration efforts by defining the desired future condition of the site—in particular, how the restored ecosystem will be integrated into its landscape setting. Next, an *implementation plan* is designed that can convert the goals into specific actions. For example, it may be necessary to remove all herbaceous vegetation with herbicides and then plow and plant the land with native grasses. To maintain the prairie, it may be necessary to burn it regularly or, in the case of larger landholdings, to introduce bison. Finally, the results of the implementation plan should be *monitored* and strategies developed for the long-term *protection and maintenance* of the restored ecosystem.

Why should we restore ecosystems? Restoration ecologists Steven Apfelbaum and Kim Chapman cite several compelling reasons.[2] First, we should do so for *aesthetic reasons.* Natural ecosystems are often beautiful, and the restoration of something beautiful and pleasing to the eye is a worthy project that can be uplifting to many people. Second, we should do so for *the benefit of human use.* The ecosystem services of a restored wetland, for example, can be enjoyed by present and future generations. Finally, we should do so for *the benefit of the species and ecosystems themselves.* Nature has value and a right to a continued existence, so people should act to preserve and restore ecosystems and species in order to preserve that right. Do you find these reasons compelling?

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[1] "The SER Primer on Ecological Restoration," www.ser.org/, Society for Ecological Restoration Science & Policy Working Group. 2002.

[2] "Ecological Restoration: A Practical Approach," Ch. 15 in *Ecosystem Management: Applications for Sustainable Forest and Wildlife Resources*, ed. by Mark S. Boyce and Alan Haney (New Haven, CT: Yale University Press, 1997).

is more incentive and potential for technological development, such as better tools, better dwellings, and better means of transporting water and other materials. Trade with other settlements begins, and commerce is thus born. Also, living in settlements permits better care and protection for everyone; therefore, the number of early deaths is reduced. This reduced mortality rate, coupled with more reliable food production, supports population growth, which in turn supports (and is supported by) expanding agriculture. In short, modern civilization had its origins in the invention of agriculture about 12,000 years ago.

Industrial Revolution. For another 11,000-plus years, the human population increased and spread throughout the Earth. Agriculture and natural ecosystems supported the growth of a civilization and culture that increased in knowledge and mastery over the natural world. With the birth of modern science and technology in the 17th and 18th centuries, the human population—by 1800 almost a billion strong—was on the threshold of another revolution: the **Industrial Revolution** (Fig. 2–24). The Industrial Revolution created the modern world, with its global commerce, factories, large cities, and pollution. The Industrial Revolution and its technological marvels were energized by fossil fuels—first coal and then oil and gas. Pollution and exploitation took on new dimensions as the industrial world turned to the extraction of raw materials from all over the world (hence the desire for colonies). In time, every part of Earth was affected by this revolution and continues to be affected even today. As a result, we

Figure 2-23 **Hunter-gatherer culture.** Before the advent of agriculture, all human societies had to forage for their food, as these bushmen from Namibia are doing.

now live in a time of uninterrupted population growth and economic expansion, with all of the environmental problems outlined in Chapter 1.

In this historical progression, natural systems are displaced by the **human system,** a term that refers to our total system, including animal husbandry, agriculture, and all human social and cultural developments. Keep in mind, however, that the human system still depends heavily on goods and services provided by natural ecosystems. If the human system functioned as a true ecosystem, it would recognize this dependence and would also establish sustainable practices in its own right.

Indeed, the human system does have some features in common with natural ecosystems, such as the series of trophic levels from crop producers to human consumers. In other respects, however, it is far off the mark—failing

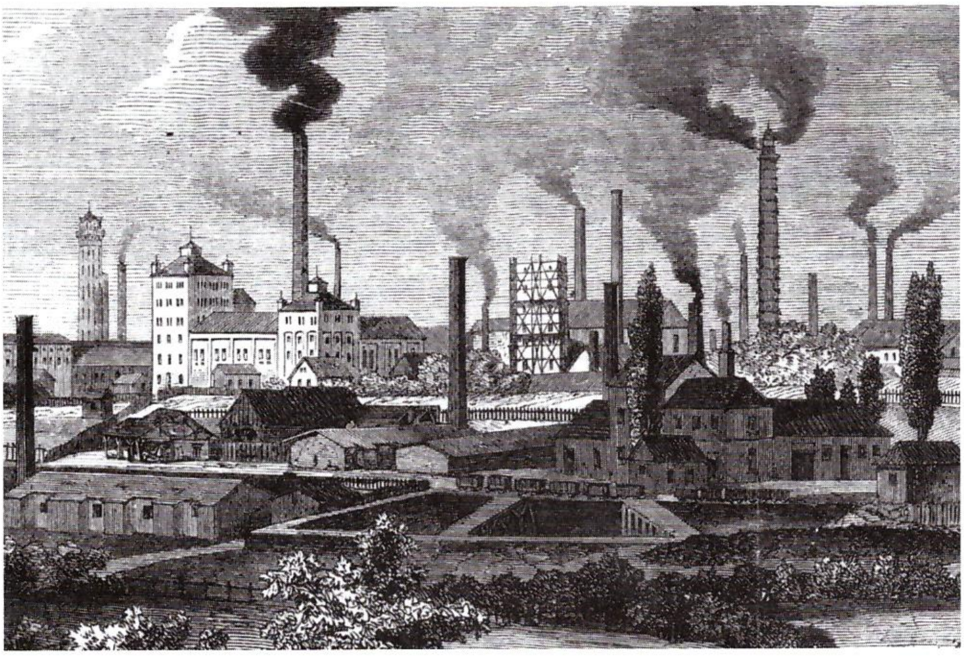

Figure 2-24 **Industrial Revolution.** The Industrial Revolution began in England in the 1700s. Coal was the energy source, and economic growth and pollution were the consequences.

to break down and recycle its "detritus" (for example, trash and chemical wastes) and other by-products. Suffering the consequences of pollution is one example of this gap between the human system and natural ecosystems. Remaining highly dependent on fossil fuels and thereby suffering the buildup of carbon dioxide in the atmosphere is another. A third revolution—an environmental one—is needed.

Environmental Revolution. In Chapter 1, we suggested that a "business as usual" approach in human affairs will not work and that a number of transitions will be necessary to bring about a sustainable society. Some observers have referred to this shift as the **Environmental Revolution**, because the transitions necessary to move the human system from its present state to one that is sustainable are indeed revolutionary. The necessary transitions are discussed in succeeding chapters.

Revolutions suggest overthrowing something, and indeed, what is involved is an overthrow of prevalent attitudes toward our economy and the environment. This does not have to be a violent revolution; it could take place so peacefully that it would take a future generation to look back and realize that a major revolution had occurred. Yet it appears that the options are limited as we look to the future. We can choose to undergo the changes necessary to achieve sustainability by planning properly and learning as we go, or we can ignore the signs of unsustainability and increase our impact on the environment by driving bigger cars (and more of them), living in bigger houses, flying off to more vacations, and, in general, expecting to enjoy more of everything. And the developing world, as it tries desperately to catch up to our living standards, could make the same mistakes we are making, with devastating consequences because there are so many more people there than in the developed world. If we choose to ignore the signs that our current practices are unsustainable, a different kind of environmental revolution will be thrust upon us by the inability of the environment to support an irresponsible human population.

Lester Brown, former president of WorldWatch Institute, said, "There is no middle path. The challenge is either to build an economy that is sustainable or to stay with our unsustainable economy until it declines. It is not a goal that can be compromised. One way or another, the choice will be made by our generation, but it will affect life on Earth for all generations to come." (Worldwatch Institute, State of the World 2000, p. 21)

revisiting the themes

As we revisit the themes at each chapter's end, some of them may only tangentially touch on the subject matter. In this chapter, for example, policy and politics and globalization, two of the three integrative themes, are not particularly relevant to the study of what ecosystems are, so they have been omitted from our review.

Sustainability

Ecosystems are the functional units of sustainable life on earth. They are, in effect, models of sustainability. The continued production of organic matter by primary producers sustains all other life in an ecosystem. That is, nutrient cycling is sustained, and so are the populations of species. Much of this sustainability is accomplished by trophic relationships, with organisms feeding and being fed on. Many other relationships between species aid in overall sustainability. The characteristics of ecosystems that contribute to sustainability are discussed in greater detail in the next two chapters.

Stewardship

If the environmental revolution is accomplished by our deliberate actions to achieve a sustainable future, it will require a broad commitment to the ethic of stewardship, whereby people seek the common good and exercise stewardly care for the environment and for the needs of fellow humans.

Sound Science

The work of ecologists in building up our knowledge of ecosystems and their current status is, in the best sense, sound science. The Heinz Center report, *The State of the Nation's Ecosystems,* lays out a blueprint for identifying the major indicators of ecosystem health and exposes those areas needing more study, as well as evaluating ecosystem statuses and trends.

Ecosystem Capital

The structure of ecosystems and biomes in general represents the fundamental characteristics of natural systems which enable them to provide the goods and services—the ecosystem capital—that humans depend so much upon. In a real sense, humans are trophic consumers, using the organic matter provided by the producers and other consumers. We are part of the food web of many ecosystems, so we can influence (both positively and negatively) the way food webs function. Thus, we must learn to manage these systems in order to keep them healthy and productive.

review questions

1. What is the difference between the biotic community and the abiotic environmental factors of an ecosystem?
2. Define and compare the terms *species*, *population*, *association*, and *ecosystem*.
3. Compared with an ecosystem, what are an ecotone, landscape, biome, and biosphere?
4. Identify and describe the biotic and the abiotic components of the biome of the region in which you live.
5. Name and describe the roles of the three main trophic categories that make up the biotic structure of every ecosystem. Give examples of organisms from each category.
6. How do the terms *organic* and *inorganic* relate to the biotic and abiotic components of an ecosystem?
7. Name and describe the attributes of the two categories into which all organisms can be divided.
8. Give four categories of consumers in an ecosystem and the role that each plays.
9. State the similarities and differences between detritus feeders and decomposers, based on what they do, how they do it, and the kinds of organisms that occupy each category.
10. Differentiate between the concepts of *food chain*, *food web*, and *trophic levels*.
11. Relate the concept of the biomass pyramid to the fact that all heterotrophs depend upon autotrophic production.
12. Describe three nonfeeding relationships that exist between organisms.
13. How is competition among different species of an ecosystem reduced?
14. Differentiate between the two types of abiotic factors. What is the effect on a population when any abiotic factor shifts from the optimum to the limit of tolerance and beyond? What things in addition to abiotic factors may act as limiting factors?
15. Describe how differences in climate cause the Earth to be partitioned into six major biomes.
16. What are three situations that might cause microclimates to develop within an ecosystem?
17. Use what you have learned about ecosystem structure to describe the barrier island ecosystem found on Plum Island.
18. What is significant about each of the following revolutions: Neolithic, Industrial, and Environmental?

thinking environmentally

1. From local, national, and international news, compile a list of the many ways humans are altering abiotic and biotic factors on a local, regional, and global scale. Analyze ways that local changes may affect ecosystems on larger scales and ways that global changes may affect ecosystems locally.
2. Write a scenario of what would happen to an ecosystem or to the human system in the event of one of the following: (a) All producers are killed through a loss of fertility of the soil or through toxic contamination. (b) All parasites are eliminated. (c) Decomposers and detritus feeders are eliminated. Support all of your statements with reasons drawn from your understanding of the way ecosystems function.
3. Consider the various kinds of relationships humans have with other species, both natural and domestic. Give examples of relationships that (a) benefit humans, but harm other species, (b) benefit both humans and other species, and (c) benefit other species, but harm humans. Give examples in which the relationship may be changing—for instance, from exploitation to protection. Discuss the ethical issues involved in changing relationships.
4. Explain how the human system can be modified into a sustainable ecosystem in balance with (i.e., preserving) other natural ecosystems without losing the benefits of modern civilization.