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# Introducing Environmental Science and Sustainability

**Industrial production of chicken requires many inputs, including feed, heating and cooling, and often antibiotics and hormones to accelerate growth.** It also generates waste streams that can lead to air and water pollution if not treated or managed.

One of the best ways to understand our complex relationship with the global environment is to use food as a lens. Culture, price, personal tastes, and availability often determine our food choices. However, we rarely think about how a particular meal comes to our plate, and how its production impacts the environment.

Consider a simple chicken sandwich. To make bread, commercial bakeries rely on wheat from farms that require large amounts of inputs (land, irrigation water, fertilizers, and pesticides) and mechanization (usually diesel-fueled trucks and tractors). Using land for agriculture displaces native plants and animals, excess fertilizers and pesticides enter waterways and flow to the ocean, and burning diesel releases pollutants into the atmosphere. Once wheat is harvested, it is sent to a plant that grinds it into flour. This requires additional energy and produces a stream of organic waste material. The wheat is then shipped to a bakery, which adds water, sugar, yeast, corn syrup, vitamins and minerals, preservatives, oil, and other ingredients—each of which has also been processed and transported. The bread is then packed into plastic bags and delivered to stores and restaurants, hundreds or thousands of miles from where the wheat was grown. Each step uses energy, adds packaging, and generates solid and liquid wastes. Packaging, as well as uneaten or damaged bread, is usually thrown into the garbage and sent to a landfill.

Commercially grown chicken produces even more impact on the environment, since chicken feed grain has to be grown, processed, and delivered to a poultry farm (**photo**). Raising, processing, cooking, packaging, and delivering the chicken all require energy and material inputs and result in pollution and waste. In addition, chickens and other animals are often given antibiotics to make them grow faster. This can lead to antibiotic-resistant diseases, and the antibiotics can disrupt natural ecosystems.

There are more sustainable alternatives to the chicken sandwich. Wheat, grain, and chicken can be grown using methods that greatly reduce impacts on the environment. Foods that are grown near where they are consumed require less energy for transportation. Alternative pest management can reduce demand for pesticides and antibiotics. Bulk packaging and composted food waste can reduce or even eliminate the need for landfills. But even when these practices are adopted, growing and processing food requires land, water, energy, and other inputs.

Humans have developed agriculture over several thousand years. In so doing, we have altered ecosystems, cut down forests, shifted waterways, and driven plants and animals to extinction. At the same time, we have helped some plants and animals—including wheat and chicken, but rats and cockroaches as well—to become dominant species. Our agricultural practices have even contributed to climate change, which in turn forces us to adapt our food production practices. Knowing how something as simple as a choice between two sandwiches can have wide-ranging impacts on the environment is a great point from which to begin to understand the relationship between humans and the environment.

***In Your Own Backyard...***

*Where and by whom is food grown near where you live? Look in your cupboards and refrigerator: Where and by whom are most of the foods you eat grown? How might switching to locally grown foods affect your diet and your food budget?*

## Human Impacts on the Environment

*LEARNING OBJECTIVES*

- Explain how human activities affect global systems.
- Describe the factors that characterize human development and how they impact environment and sustainability.

Earth is remarkably suited for life. Water, important both in the internal composition of organisms and as an external environmental factor affecting life, covers three-fourths of the planet. Earth's temperature is habitable—neither too hot, as on Mercury and Venus, nor too cold, as on Mars and the outer planets. We receive a moderate amount of sunlight—enough to power photosynthesis, which supports almost all the life-forms that inhabit Earth. Our atmosphere bathes the planet in gases and provides essential oxygen and carbon dioxide that organisms require. On land, soil develops from rock and provides support and minerals for plants. Mountains that arise from geologic processes and then erode over vast spans of time affect weather patterns, provide minerals, and store reservoirs of fresh water as ice and snow that melt and flow to lowlands during the warmer months. Lakes and ponds, rivers and streams, wetlands, and groundwater reservoirs provide terrestrial organisms with fresh water.

Earth's abundant natural resources have provided the backdrop for a parade of living things to evolve. Life has existed on Earth for about 3.8 billion years. Although early Earth was inhospitable by modern standards, it provided the raw materials and energy needed for early life-forms to arise and adapt. Some of these early cells evolved over time into simple multicellular organisms—early plants, animals, and fungi. Today, several million species inhabit the planet. A representative sample of Earth's biological diversity ncludes intestinal bacteria, paramecia, poisonous mushrooms, eafhoppers, prickly pear cacti, seahorses, dogwoods, angelfish, laisies, mosquitoes, pitch pines, polar bears, spider monkeys, and oadrunners (**Figure 1.1**).

About 100,000 years ago—a mere blip in Earth's 4.5-billion-ear history—an evolutionary milestone began with the appearance

**gure 1.1 A male greater roadrunner carries a desert spiny ard it has captured.** Life abounds on Earth, and every organism is ked to many others, including humans. Photographed in New Mexico.

of modern humans in Africa. Large brains and the ability to communicate made our species successful. Over time, our population grew; we expanded our range throughout the planet and increasingly impacted the environment with our presence and our technologies. These technologies have allowed many people in the world lives with access to well-lit and air-conditioned buildings, effective medical treatment, high-speed transportation, and uninterrupted food supplies. This has been particularly true in North America, Western Europe, and Japan; increasingly, many urban residents in China, India, South America, and parts of Africa have similar access to wealth and material goods.

Today, the human species is the most significant agent of environmental change on our planet. Our burgeoning population and increasing use of energy, materials, and land transform natural systems to meet our needs and desires. Our activities consume ever-increasing amounts of Earth's abundant but finite resources—rich topsoil, clean water, and breathable air. This alteration of natual systems eradicates many types of ecosystems and thousands upon thousands of unique species that inhabit them. Evidence continues to accumulate that human-induced climate change alters the natural environment in disruptive ways. Human activities are disrupting global **systems**.

**system** A set of components that interact and function as a whole.

This book introduces the major impacts that humans have on the environment. It considers ways to better manage those impacts, while emphasizing that each possible choice has the potential to cause additional impacts. Most important, it explains the value of minimizing human impact on our planet. Our lives and well-being, as well as those of future generations, depend on our ability to manage Earth's environmental resources effectively.

### INCREASING HUMAN NUMBERS

**Figure 1.2**, a nighttime satellite photograph of North America, including the United States, Mexico, and Canada, depicts the home of about 470 million people. The tiny specks of light represent cities, with the great metropolitan areas, such as New York along the northeastern seacoast, ablaze with light.

The driver of all other environmental problems, the one that links all others, is the many people who live in the area shown in this picture. According to the United Nations, in 1950 only eight cities in the world had populations larger than 5 million, the largest being New York, with 12.3 million. By 2011 Tokyo, Japan had 17.8 million inhabitants, with 37.2 million inhabitants in the greater Tokyo metropolitan area. The combined population of the world's 10 largest urban agglomerations was over 200 million (see Table 9.1).

In 2011, the human population as a whole passed a significant milestone: 7 billion individuals. Not only is this figure incomprehensibly large, but also our population grew this large in a brief span of time. In 1960, the human population was only 3 billion (**Figure 1.3**). By 1975, there were 4 billion people, and by 1999, there were 6 billion. The 7.2 billion people who currently inhabit our planet consume great quantities of food and water, use a great deal of energy and raw materials, and produce much waste.

Despite family planning efforts in many countries, population growth rates do not change quickly. Several billion people will be

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**Figure 1.2 Satellite view of North America at night.** This image shows most major cities and metropolitan areas in the United States, Mexico, and Canada.

added to the world in the twenty-first century, so even if we remain concerned about the impacts of a growing population and even if our solutions are effective, the coming decades may be clouded with tragedies. The conditions of life for many people may worsen considerably.

On a global level, nearly one of every two people live in extreme **poverty** (Figure 1.4). One measure of poverty is having a per capita income of less than $2 per day, expressed in U.S. dollars adjusted for purchasing power. More than 2.5 billion people—about 40% of the total world population—currently live at this level of poverty. Poverty is associated with low life expectancy, high infant mortality, illiteracy, and inadequate access to health services, safe water, and balanced nutrition. According to the UN Food and Agricultural Organization, at least 1 billion people (many of them children) lack access to the food needed for healthy, productive lives.

**overty** A condition which people cannot eet their basic needs dequate food, cloth-g, shelter, education, or health.

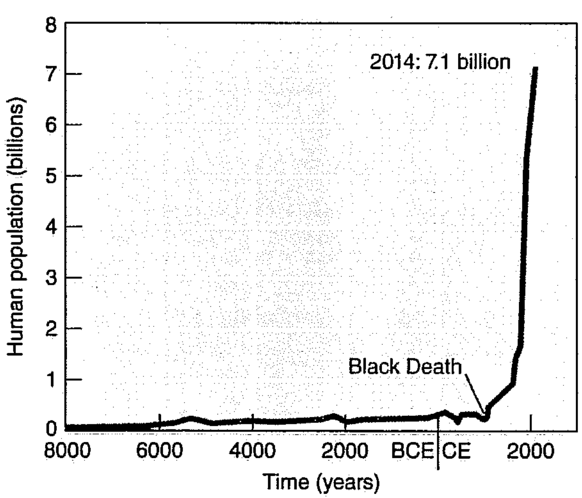
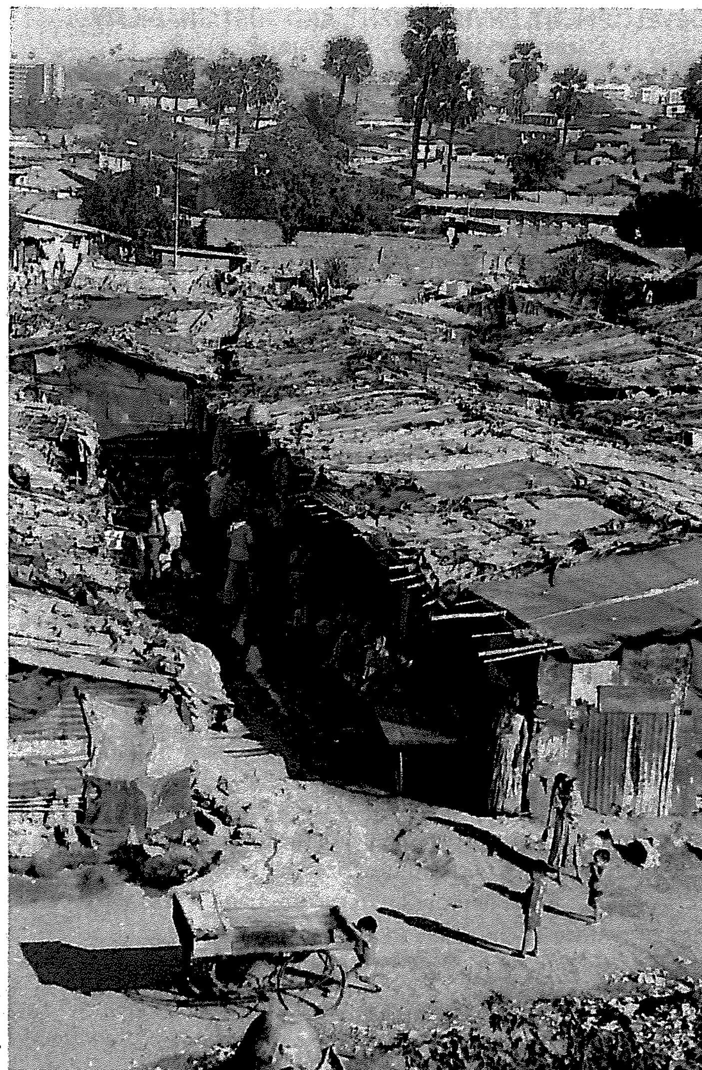



**Figure 1.3 Human population growth.** It took thousands of years for the human population to reach 1 billion (in 1800) but only 130 years to reach 2 billion (1930). It took only 30 years to reach 3 billion (1960), 15 years to reach 4 billion (1975), 12 years to reach 5 billion (1987), 12 years to reach 6 billion (1999), and 13 years to reach 7 billion (2012). (Population Reference Bureau)



Jerry Cooke/Science Source

**Figure 1.4 Slum in Mumbai (Bombay), India.** Many of the world's people live in extreme poverty. One trend associated with poverty is the increasing movement of poor people from rural to urban areas. As a result, the number of poor people living in or around the fringes of cities is mushrooming.

Most demographers (people who study human populations) expect the world population to stabilize before the end of the current century. Worldwide, fertility rates have decereased to a current average of about three children per family, and this average is projected to continue to decline in coming decades. Expert projections for world population at the end of the twenty-first century range from about 8.3 billion to 10.9 billion, depending largely on how fast the fertility rate decreases (see Figure 8.3).

No one knows whether Earth can support so many people indefinitely. Among the tasks we must accomplish is feeding a world population considerably larger than the present one without undermining the natural resources that support us. Our ability to achieve this goal will determine the quality of life for our children and grandchildren.

### DEVELOPMENT, ENVIRONMENT, AND SUSTAINABILITY

Until recently, demographers differentiated countries as highly developed, moderately developed, and less developed. The United States, Canada, Japan, and most of Europe, which represent 19% of the world's population but more than 50% of global economic activity, are **highly developed countries.** Development in this context is based mainly on total wealth of the country. The world's poorest countries, including Bangladesh, Kenya, and Nicaragua, are considered **less developed countries (LDCs).** Cheap, unskilled labor is abundant in LDCs, but capital for investment is scarce. Most LDC economies are agriculturally based, often for only one or a few crops. As a result, crop failure or a lower world market value for that crop is catastrophic to the economy. Hunger, disease, and illiteracy are common in LDCs.

**highly developed countries** Countries th complex industrial bases, low rates of pulation growth, and h per capita incomes.

**less developed countries (LDCs)** Developing countries with a low level of lustrialization, a high fertility rate, a high it mortality rate, and w per capita income (relative to highly eveloped countries).

However, recent decades have seen substantial increases in wealth for many urban residents in previously less developed countries, including China, India, Brazil, and Mexico. These countries have substantial *income disparities,* meaning that other urban residents and most of the rural inhabitants of those remain poor, and lack access to cars, electricity, fresh water, and modern medical technology. Consequently, using the total wealth or income of a country may not usefully describe the well-being of people in that country. More appropriate measures can include the percentage of residents who make more than $2 per day, have access to fresh water and electricity, or have access to education.

*REVIEW*

1. What is one example of a global system?
2. How do the total wealth of a country and income disparity relate to sustainability?

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(a) A trend towards larger homes leads to greater consumption in a number of ways: more energy to heat and cool, more distance to travel between homes, and more furnishings inside the home.

© Whitehotpix / ZUMAPRESS.com

(b) The "tiny house" movement seeks to simplify individual living, and as a consequence reduces consumption. Tiny house occupants have no place to accumulate material goods, and so must be more selective in their purchasing.

**Figure 1.5 Consumption of natural resources.**

## Population, Resources, and the Environment

*LEARNING OBJECTIVES*

- Differentiate between renewable and nonrenewable resources.
- Explain the impact of population and affluence on consumption.
- Define *ecological footprint.*
- Describe the three most important factors that determine human impact on the environment.

The relationships among population growth, use of natural resources, and environmental degradation are complex. We address the details of resource management and environmental problems in this and later chapters, but for now, let us consider two useful generalizations: (1) The resources essential to an individual's survival are small, but a rapidly increasing population tends to overwhelm and deplete local soils, forests, and other natural resources (**Figure 1.5a**). (2) In highly developed countries, individual resource demands are large, far above what is needed for survival. Consumption by people in affluent nations can exhaust resources and degrade the environment on a global scale (**Figure 1.5b**).

### TYPES OF RESOURCES

When examining the effects of humans on the environment, it is important to distinguish between two types of natural resources: nonrenewable and renewable (**Figure 1.6**). **Nonrenewable resources**, which include minerals (such as aluminum, copper, and uranium) and fossil fuels (coal, oil, and natural gas), are present in limited supplies and are depleted by use. Natural processes do not replenish nonrenewable resources within a reasonable period on the human time scale. Fossil fuels, for example, take millions of years to form.

In addition to a nation's population, several other factors affect how nonrenewable resources are used, including how efficiently the resource is extracted and processed as well as how much of it

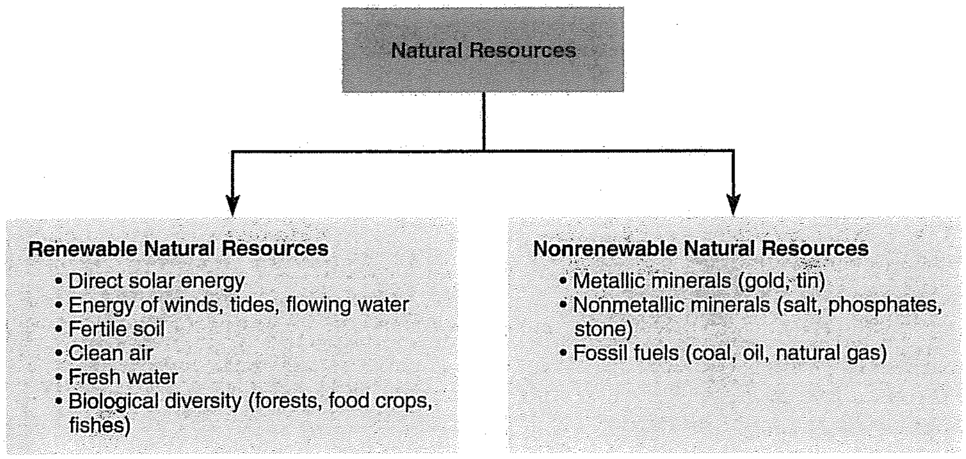



**Figure 1.6 Natural resources.** Nonrenewable resources are replaced on a geologic time scale, and their supply diminishes with use. Renewable resources can be (but are not always) replaced on a fairly short time scale; as will be explained in later chapters, most renewable resources are derived from the sun's energy.

is required or consumed by different groups. People in the United States, Canada, and other highly developed nations tend to consume most of the world's nonrenewable resources. Nonetheless, Earth has a finite supply of nonrenewable resources that sooner or later will be exhausted. In time, technological advances may provide substitutes for some nonrenewable resources. Slowing the rate of population growth and consumption will buy time to develop such alternatives.

Some examples of **renewable resources** are trees, fishes, fertile agricultural soil, and fresh water. Nature replaces these resources fairly rapidly (on a scale of days to centuries), and they can be used forever as long as they are not overexploited in the short term. In developing countries, forests, fisheries, and agricultural land are particularly important renewable resources because they provide food. Indeed, many people in developing countries are subsistence farmers who harvest just enough food so that they and their families can survive.

Rapid population growth can cause the overexploitation of renewable resources. For example, large numbers of poor people must grow crops on land inappropriate for farming, such as on mountain slopes or in tropical rain forests. Although this practice may provide a short-term solution to the need for food, it does not work in the long term: When these lands are cleared for farming, their agricultural productivity declines rapidly, and severe environmental deterioration occurs. Renewable resources are usually only *potentially* renewable. They must be used in a *sustainable* way—in a manner that gives them time to replace or replenish themselves.

The effects of population growth on natural resources are particularly critical in developing countries. The economic growth of developing countries is often tied to the exploitation of their natural resources, usually for export to highly developed countries. Developing countries are faced with the difficult choice of exploiting natural resources to provide for their expanding populations in the short term (to pay for food or to cover debts) or conserving those resources for future generations.

It is instructive to note that the economic growth and development of the United States, Canada, and other highly developed nations came about through the exploitation and, in some cases, the destruction of resources. Continued economic growth in highly developed countries now relies significantly on the importation of these resources from less developed countries. One of the reasons economic growth in highly developed countries has been possible is the uneven distribution of both renewable and nonrenewable resources around the world. Many very poor countries—Ethiopia, for example—have only limited fossil-fuel resources.

## RESOURCE CONSUMPTION

**Consumption** is the human use of materials and energy. Consumption, which is both an economic and a social act, provides the consumer with a sense of identity as well as status among peers. Advertisers promote consumption as a way to achieve happiness. Western culture encourages spending and consumption well beyond that which is necessary for survival.

In general, people in highly developed countries are extravagant consumers; their use of resources is greatly out of proportion to their numbers. A single child born in a highly developed country may have a greater impact on the environment and on resource depletion than 12 or more children born in a developing country. Many natural resources are used to provide the automobiles, air conditioners, disposable diapers, cell phones, DVD players, computers, clothes, newspapers, athletic shoes, furniture, boats, and other comforts of life in highly developed countries. Yet such consumer goods represent a small fraction of the total materials and energy required to produce and distribute them. According to the Worldwatch Institute, a private research institution in Washington, D.C., Americans collectively consume almost 10 billion tons of materials every year. The disproportionately large consumption of resources by highly developed countries affects natural resources and the environment as much as or more than the population explosion in the developing world.

**Unsustainable Consumption** Consumption in a country is unsustainable if the level of demand on its resource base damages the environment or depletes resources to such an extent that future generations will have lower qualities of life. In comparing human impact on the environment in developing and highly developed countries, we see that unsustainable consumption can occur in two ways. First, environmental quality and resource depletion can result from too many people, even if those people consume few resources per person. This is the current situation in many developing nations.

In highly developed countries, unsustainable consumption results when individuals consume substantially more resources than necessary for survival. Both types of unsustainable consumption have the same effect—pollution, environmental degradation, and resource depletion. Many affluent, highly developed countries, including the United States, Canada, Japan, and most of Europe, consume unsustainably: *Highly developed countries represent less than 20% of the world's population, yet they consume significantly more than half of its resources.*

According to the Worldwatch Institute, highly developed countries account for the lion's share of total resources consumed:

- 86% of aluminum used
- 76% of timber harvested
- 68% of energy produced
- 61% of meat eaten
- 42% of the fresh water consumed

These nations also generate 75% of the world's pollution and waste.

## ECOLOGICAL FOOTPRINT

Environmental scientists **Mathis Wackernagel** and **William Rees** developed the concept of ecological footprint to help people visualize what they use from the environment. Each person has an **ecological footprint**, an amount of productive land, fresh water, and ocean required on a continuous basis to supply that person with food, wood, energy, water, housing, clothing, transportation, and waste disposal. The *Living Planet Report 2010*, produced by scientists at the Global Footprint Network, World Wildlife Fund, and Zoological Society of London, estimates that since about 1975, the human population has been consuming more of the productive land, water, and other resources than Earth can support (**Figure 1.7**). In 2010, annual consumption was about 50% more than Earth produces. This is an unsustainable consumption rate.

The *Living Planet Report* estimates that Earth has about 11.4 billion hectares (28.2 billion acres) of productive land and water. If we divide this area by the global human population, we see that each person is allotted about 1.6 hectares (4.0 acres). However, the average global ecological footprint is currently about 2.7 hectares (6.7 acres) per person, which means we humans have an *ecological overshoot.* We can see the short-term results around us—forest destruction, degradation of croplands, loss of biological diversity, declining ocean fisheries, local water shortages, and increasing pollution. The long-term outlook, if we do not seriously address our consumption of natural resources, is potentially disastrous. Either per-person consumption will drop, population will decrease, or both.

In the developing nation of India, the per capita ecological footprint is 0.9 hectare (2.2 acres); India is the world's second-largest country in terms of population, so even though its per capita footprint is low, the country's footprint is high: 986.3 million hectares (**Figure 1.8**). In France, the per capita ecological footprint is 4.9 hectares (12.1 acres); although its per capita footprint is high, France's footprint as a country is 298.1 million hectares, which is lower than India's, because its population is much smaller. In the United States, the world's third-largest country, the per capita ecological footprint is 7.9 hectares (19.5 acres); the U.S. footprint as a country is 2,457 million hectares! If all people in the world had the same lifestyle and level of consumption as the average North American, and assuming no changes in technology, we would need about four additional planets the size of Earth.

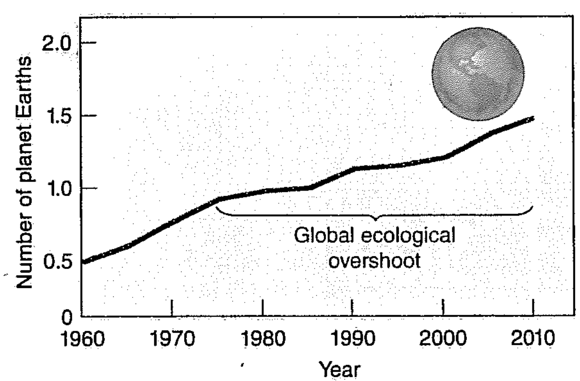
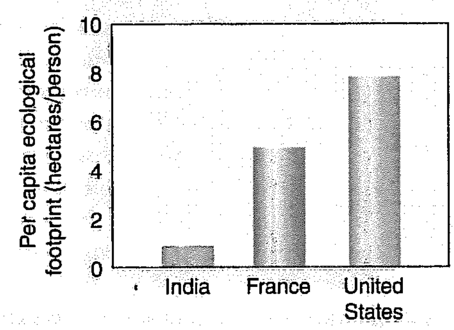
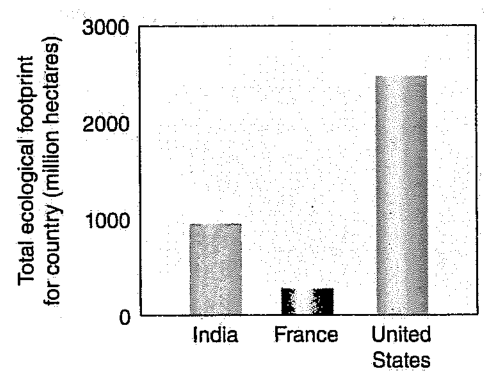



**Figure 1.7 Global ecological overshoot.** Earth's ecological footprint has been increasing over time. By 2010, humans were using the equivalent of 1.5 Earths, a situation that is not sustainable. (Data from World Wildlife Fund, *Living Planet Report 2010*)




(a) The average ecological footprint of a person living in India, France, or the United States. For example, each Indian requires 0.9 hectare (2.2 acres) of productive land and ocean to meet his or her resource requirements.




(b) The total ecological footprint for the countries of India, France, and the United States. Note that India, although having a low per capita ecological footprint, has a significantly higher ecological footprint as a country because of its large population. If everyone in the world had the same level of consumption as the average American, it would take the resources and area of five Earths.

**Figure 1.8 Ecological footprints.** (Data from World Wildlife Fund, *Living Planet Report 2012*)

As developing countries increase their economic growth and improve their standard of living, more and more people in those nations purchase consumer goods. More new cars are now sold annually in Asia than in North America and Western Europe combined. These new consumers may not consume at the high level of the average consumer in a highly developed country, but their consumption has increasingly adverse effects on the environment. For example, air pollution caused by automotive traffic in urban centers in developing countries is terrible and getting worse every year. Millions of dollars are lost because of air pollution–related health problems in these cities. One of society's challenges is to provide new consumers in developing countries (as well as ourselves) with less polluting, less consuming forms of transportation.

## THE *IPAT* MODEL

Generally, when people turn on the tap to brush their teeth in the morning they do not think about where the water comes from or about the environmental consequences of removing it from a river or the ground. Similarly, most North Americans do not think about where the energy comes from when they flip on a light switch or start a car. We do not realize that all the materials in the products we use every day come from Earth, nor do we grasp that these materials eventually are returned to Earth, much of them in sanitary landfills.

Such human impacts on the environment are difficult to assess. They are estimated using the three factors most important in determining environmental impact *(I)*:

1. The number of people *(P)*
2. Affluence, which is a measure of the consumption or amount of resources used per person *(A)*
3. The environmental effects (resources needed and wastes produced) of the technologies used to obtain and consume the resources *(T)*

These factors are related in this way:

$$I = P \times A \times T$$

**lel** A representation f a system; describes ne system as it exists and predicts how nanges in one part of ystem will affect the rest of the system.

In science, a **model** is a formal statement that describes the behavior of a system. The *IPAT* model, which biologist **Paul Ehrlich** and physicist **John Holdren** first proposed in the 1970s, shows the mathematical relationship between environmental impacts and the forces driving them.

For example, to determine the environmental impact of emissions of the greenhouse gas $CO_2$ from motor vehicles, multiply the population times the number of cars per person (affluence/consumption per person) times the average car's annual $CO_2$ emissions per year (technological impact). This model demonstrates that although increasing motor vehicle efficiency and developing cleaner technologies will reduce pollution and environmental degradation, a larger reduction will result if population and per capita consumption are also controlled.

The *IPAT* equation, though useful, must be interpreted with care, in part because we often do not understand all the environmental impacts of a particular technology on complex environmental systems. Motor vehicles are linked not only to global warming from $CO_2$ emissions but also to local air pollution (tailpipe exhaust), water pollution (improper disposal of motor oil and antifreeze), and solid waste (disposal of nonrecyclable automobile parts in sanitary landfills). There are currently more than 600 million motor vehicles on the planet, and the number is rising rapidly.

The three factors in the *IPAT* equation are always changing in relation to one another. Consumption of a particular resource may increase, but technological advances may decrease the environmental impact of the increased consumption. For example, there are more television and computer screens in the average household than there were 20 years ago (increased affluence) and more households (increased population). However, many of the new units are flat screens, which require less materials to produce and less energy to operate (more efficient technology). Thus, consumer trends and choices may affect environmental impact.

Similarly, the average fuel economy of new cars and light trucks (sport-utility vehicles, vans, and pickup trucks) in the United States declined from 22.1 miles per gallon in 1988 to 20.4 miles per gallon in the early 2000s, in part because of the popularity of sport-utility vehicles (SUVs). In addition to being less fuel efficient than cars, SUVs emit more emissions per vehicle mile. More recently, hybrids have helped to increase the average fuel economy (**Figure 1.9**). Such trends and uncertainties make the *IPAT* equation of limited usefulness for long-term predictions.

The *IPAT* equation is valuable because it helps identify what we do not know or understand about consumption and its environmental impact. The National Research Council of the U.S. National Academy of Sciences[1] has identified research areas we must address, including the following: Which kinds of consumption have the greatest destructive impact on the environment? Which groups in society are responsible for the greatest environmental disruption? How can we alter the activities of these environmentally disruptive groups? It will take years to address such

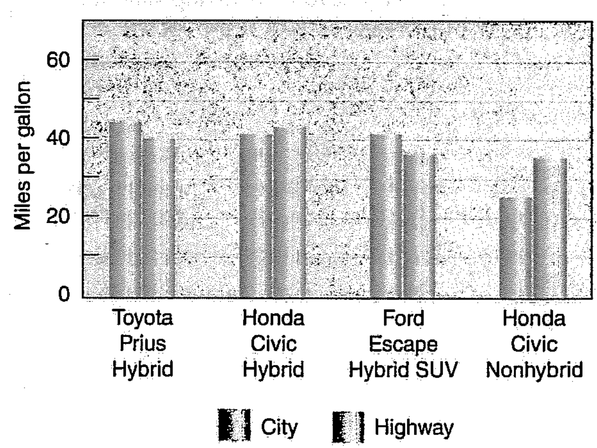



**Figure 1.9 Fuel-efficient hybrids.** Shown are city and highway miles per gallon for three hybrid models available in 2014. (U.S. Department of Energy)

[1]The National Research Council is a private, nonprofit society of distinguished scholars. It was organized by the National Academy of Sciences to advise the U.S. government on complex issues in science and technology.

questions, but the answers should help decision makers in government and business formulate policies to alter consumption patterns in an environmentally responsible way. Our ultimate goal should be to reduce consumption so that our current practices do not compromise the ability of future generations to use and enjoy the riches of our planet.

***REVIEW***

1. How do renewable resources differ from nonrenewable resources?
2. How are human population growth and affluence related to natural resource depletion?
3. What is an ecological footprint?
4. What does the *IPAT* model demonstrate?

## Sustainability

***LEARNING OBJECTIVES***

- Define *sustainability*.
- Relate Garrett Hardin's description of the tragedy of the commons in medieval Europe to common-pool resources today.
- Briefly describe sustainable development.

One of the most important concepts in this text is **sustainability**. A sustainable world is one in which humans can have economic development and fair allocation of resources without the environment going into a decline from the stresses imposed by human society on the natural systems (such as fertile soil, water, and air) that maintain life. When the environment is used sustainably, humanity's present needs are met without endangering the welfare of future generations (**Figure 1.10**). Environmental sustainability applies at many levels, including individual, community, regional, national, and global levels.

**ustainability** The lity to meet current man economic and ocial needs without romising the ability of the environment to support future generations.

- Our actions can affect the health and well-being of natural *ecosystems*, including all living things.
- Earth's resources are not present in infinite supply; our access is constrained by ecological limits on how rapidly renewable resources such as fresh water regenerate for future needs.
- The products we consume can impose costs to the environment and to society beyond those captured in the price we pay for those products.
- Sustainability requires a concerted and coordinated effort of people on a global scale.

Many experts in environmental problems think human society is not operating sustainably because of the following human behaviors:

- We extract nonrenewable resources such as fossil fuels as if they were present in unlimited supplies.

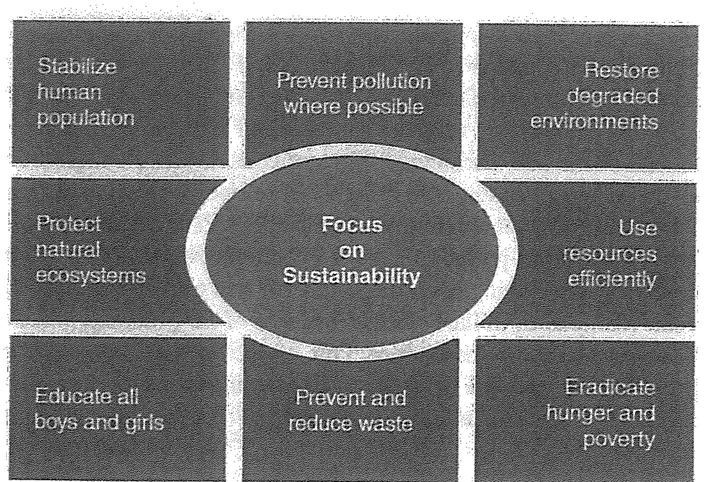
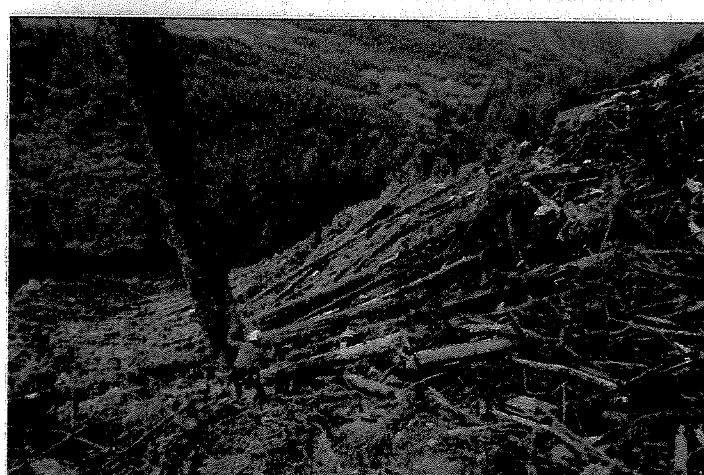



**Figure 1.10 Sustainability.** Sustainability requires a long-term perspective to protect human welfare and natural resource assets, such as the efforts shown here.

- We consume renewable resources such as fresh water and forests faster than natural systems can replenish them (**Figure 1.11**).
- We pollute the environment with toxins as if the capacity of the environment to absorb them is limitless.
- A small fraction of the human population dominates a large percentage of Earth's resources.
- Our numbers continue to grow despite Earth's finite ability to feed us, sustain us, and absorb our wastes.

If left unchecked, these activities could threaten Earth's life-support systems to such a degree that recovery is impossible. If major resources like agricultural land, fisheries, and fresh water are exhausted to the point that they cannot recover quickly, substantial human suffering would result. Thus managing these resources sustainably means more than protecting the environment: sustainability promotes human well-being.



Topham/The Image Works

**Figure 1.11 A logger cuts down the last standing tree on a clear-cut forest slope.** Logging destroys the habitat for forest organisms and increases the rate of soil erosion on steep slopes. Photographed in Canada.

At first glance, the issues may seem simple. Why do we not just reduce consumption, improve technology, and limit population growth? The answer is that various interacting ecological, societal, and economic factors complicate the solutions. Our inadequate understanding of how the environment works and how human choices affect the environment is a major reason that problems of sustainability are difficult to resolve. The effects of many interactions between the environment and humans are unknown or difficult to predict, and we generally do not know if we should take corrective actions before our understanding is more complete.

## SUSTAINABILITY AND THE TRAGEDY OF THE COMMONS

**Garrett Hardin** (1915–2003) was a professor of human ecology at the University of California–Santa Barbara who wrote about human environmental dilemmas. In 1968, he published his classic essay, "The Tragedy of the Commons," in the journal *Science*. He contended that our inability to solve many environmental problems is the result of a struggle between short-term individual welfare and long-term environmental sustainability and societal welfare.

Hardin used the commons to illustrate this struggle. In medieval Europe, the inhabitants of a village shared pastureland, called the commons, and each herder could bring animals onto the commons to graze. If the villagers did not cooperatively manage the commons, each might want to bring more animals onto it. If every herder in the village brought as many animals onto the commons as possible, the plants would be killed from overgrazing, and the entire village would suffer. Thus, an unmanaged commons would inevitably be destroyed by the people who depended on it.

Hardin argued that one of the outcomes of the eventual destruction of the commons would be private ownership of land, because when each individual owned a parcel of land, it was in that individual's best interest to protect the land from overgrazing. A second outcome Hardin considered was government ownership and management of such resources, because the government had the authority to impose rules on users of the resource and thereby protect it.

Hardin's essay has stimulated a great deal of research in the decades since it was published. In general, scholars agree that degradation of the self-governing commons—now called **common-pool resources**—typically is not a problem in closely knit communities. Indeed, sociologist **Bill Freudenberg** has pointed out that medieval commons were successfully managed but became degraded after they were privatized. Economist **Elinor Ostrum** demonstrated that common pool resources can be sustainably managed by communities with shared interests, strong local governance, and community-enforced accountability.

**common-pool [r]esources** Those parts of our environment [a]vailable to everyone [bu]t for which no single individual has responsibility—the [atmo]sphere and climate, water, forests, wildlife, and ocean fisheries.

As one goes from local to regional to global common-pool resources, the challenges of sustainably managing resources become more complex. In today's world, Hardin's parable has particular relevance at the global level. These modern-day commons are experiencing increasing environmental stress (see, for example, the discussion of climate change in Chapter 20). No individual, jurisdiction, or country owns common-pool resources, and they are susceptible to overuse. Although exploitation may benefit only a few, everyone on Earth must pay for the environmental cost of exploitation.

The world needs effective legal and economic policies to prevent the short-term degradation of common-pool resources and ensure their long-term well-being. We have no quick fixes because solutions to global environmental problems are not as simple or short term as are solutions to some local problems. Most environmental ills are inextricably linked to other persistent problems such as poverty, overpopulation, and social injustice—problems beyond the capacity of a single nation to resolve. The large number of participants who must organize, agree on limits, and enforce rules complicates the creation of global treaties to manage common-pool resources. Cultural and economic differences among participants make finding solutions even more challenging.

Clearly, all people, businesses, and governments must foster a strong sense of **stewardship**—shared responsibility for the sustainable care of our planet. Cooperation and commitment at the international level are essential if we are to alleviate poverty, stabilize the human population, and preserve our environment and its resources for future generations.

**stewardship** Shared responsibility for the sustainable care of our planet.

## GLOBAL PLANS FOR SUSTAINABLE DEVELOPMENT

In 1987, the World Commission on Environment and Development released a groundbreaking report, *Our Common Future* (see Chapter 24). A few years later, in 1992, representatives from most of the world's countries met in Rio de Janeiro, Brazil, for the *UN Conference on Environment and Development*. Countries attending the conference examined environmental problems that are international in scope: pollution and deterioration of the planet's atmosphere and oceans, a decline in the number and kinds of organisms, and destruction of forests.

In addition, the Rio participants adopted *Agenda 21*, an action plan of **sustainable development** in which future economic development, particularly in developing countries, will be reconciled with environmental protection. The goals of sustainable development are achieving improved living conditions for all people while maintaining a healthy environment in which natural resources are not overused and excessive pollution is not generated. Three factors—environmentally sound decisions, economically viable decisions, and socially equitable decisions—are necessary for truly sustainable development. To use sustainability as a guiding principle for environmental management requires that we think about how these three factors interact as parts of a complex and interlinked system (**Figure 1.12**).

**sustainable development** As defined by the Brundtland report, economic development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs.

A serious application of the principles of environmental sustainability to economic development will require many changes in such fields as population policy, agriculture, industry, economics,

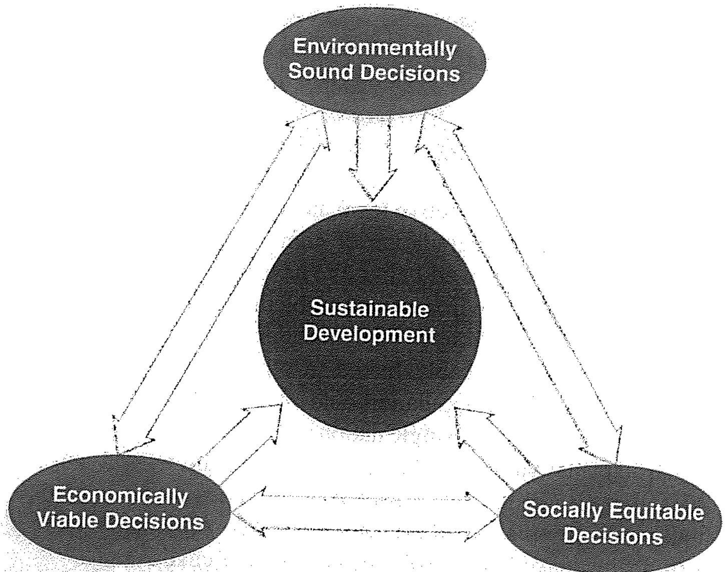



**Figure 1.12 Sustainable development, a systems concept.** Using sustainable development as an organizing principle for environmental management requires us to recognize that economic development, social justice, and the environment are linked in many and complex ways. We must consider whether economic decisions harm the environment or deplete natural resources, whether resource management decisions are socially equitable, and whether societal decisions impact economic opportunities for current and future generations.

and energy use. In 2000, representatives from 189 countries met at the *UN Millennium Summit* and committed their countries to a global partnership with goals known as the *Millennium Development Goals* (see Chapter 8).

Despite such international summits, we have made only limited progress in improving the quality of life for poor people or in solving the world's most serious environmental problems. Many governments have shifted their attention from serious environmental priorities to other challenges such as terrorism, worsening international tensions, and severe economic problems. Meanwhile, scientific warnings about important environmental problems such as global climate change have increased.

Despite the lack of significant change at the international level, some nations, states, and municipalities have made important environmental progress. Many countries have enacted more stringent air pollution laws, including the phasing out of leaded gasoline. More than 100 countries have created sustainable development commissions. Corporations that promote environmentally responsible business practices have joined to form the World Business Council for Sustainable Development. The World Bank, which makes loans to developing countries, has invested billions of dollars in sustainable development projects around the world.

*REVIEW*

1. What is sustainability?
2. What is the tragedy of the commons?
3. What are the three foundations of sustainable development?

## Environmental Science

*LEARNING OBJECTIVES*

- Define *environmental science* and briefly describe the role of Earth systems in environmental science.
- Outline the scientific method.

**Environmental science** encompasses the many interconnected issues involving human population, Earth's natural resources, and environmental pollution. Environmental science combines information from many disciplines, such as biology, geography, chemistry, geology, physics, economics, sociology, demography (the study of populations), cultural anthropology, natural resources management, agriculture, engineering, law, politics, and ethics. **Ecology**, the branch of biology that studies the interrelationships between organisms and their environment, is a basic tool of environmental science.

**environmental science** The interdisciplinary study of humanity's relationship with other organisms and the nonliving physical environment.

Environmental scientists try to establish general principles about how the natural world functions. They use these principles to develop viable solutions to environmental problems—solutions based as much as possible on scientific knowledge. Environmental problems are generally complex, so our understanding of them is often less complete than we would like it to be. Environmental scientists are often asked to reach a consensus before they fully understand the systems that they study. As a result, they often make recommendations based on probabilities rather than precise answers.

Many of the environmental problems discussed in this book are serious, but environmental science is not simply a "doom-and-gloom" listing of problems coupled with predictions of a bleak future. To the contrary, its focus is, and our focus as individuals and as world citizens should be, on identifying, understanding, and finding better ways to manage the stresses that human activities place on environmental resources and systems.

### EARTH SYSTEMS AND ENVIRONMENTAL SCIENCE

One of the most exciting aspects of environmental science and many other fields of science is working out how *systems* that consist of many interacting parts function as a whole. As discussed in the chapter introduction, Earth's climate is a system that in turn is composed of smaller, interdependent systems, such as the atmosphere and ocean; these smaller systems are linked and interact with one another in the overall climate system.

The systems approach provides a broad look at overall processes, as opposed to the details of individual parts or steps. A commuter in city traffic may be quite familiar with the production of $CO_2$ by a car engine, but that knowledge does not automatically translate into an understanding of the global effect of millions of motor vehicles emitting $CO_2$. Thus, using a systems perspective helps scientists gain valuable insights that are not always obvious from looking at individual components within the system.

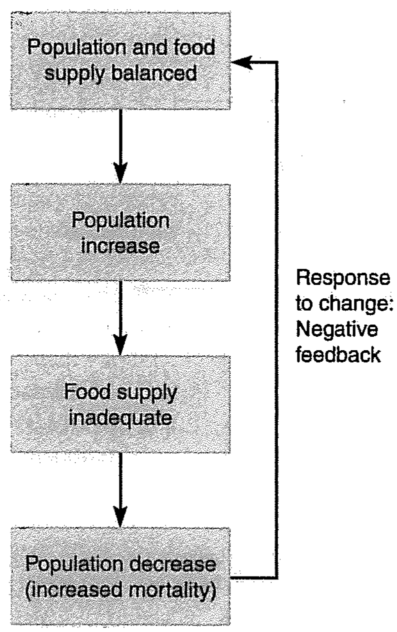
Also, problems arise from *not* thinking about systems. For example, if a company decides to burn waste oil to avoid its leaking into groundwater, pollution shifts from groundwater to the air. A systems perspective would require company executives to think about the trade-offs between the two disposal methods and, more importantly, about alternatives that might avoid generating waste oil in the first place.

Environmental scientists often use models to describe the interactions within and among environmental systems. Many of these models are computer simulations that represent the overall effect of competing factors to describe an environmental system in numerical terms. Models help us understand how the present situation developed from the past or how to predict the future course of events, including the long-term impacts of decisions or choices we make today. Models also generate additional questions about environmental issues. (Appendix III contains an introduction to modeling.)

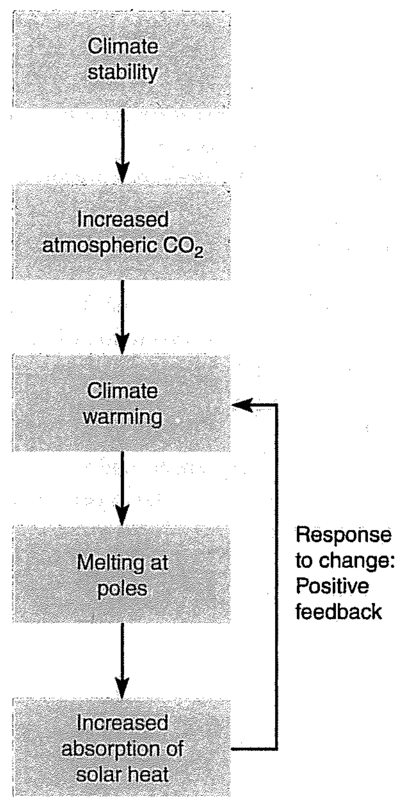
A natural system consisting of a community of organisms and its physical environment is known as an **ecosystem**. In ecosystems, biological processes (such as photosynthesis) interact with physical and chemical processes to modify the composition of gases in the atmosphere, transfer energy from the sun through living organisms, recycle waste products, and respond to environmental changes with resilience. Natural ecosystems are the foundation for our concept of environmental sustainability.

Ecosystems are organized into larger and larger systems that interact with one another (discussed in Chapter 3). At a global level are Earth systems, which include Earth's climate, atmosphere, land, coastal zones, and the ocean. Environmental scientists use a systems approach to try to understand how human activities are altering global environmental parameters such as temperature, $CO_2$ concentration in the atmosphere, land cover, changes in nitrogen levels in coastal waters, and declining fisheries in the ocean.

Many aspects of Earth systems are in a steady state or, more accurately, a **dynamic equilibrium**, in which the rate of change in one direction is the same as the rate of change in the opposite direction. *Feedback* occurs when a change in one part of a system leads to a change in another part. Feedback can be negative or positive. In a **negative feedback system**, a change in some condition triggers a response that counteracts, or reverses, the changed condition (**Figure 1.13a**). A negative feedback mechanism works to keep an undisturbed system in dynamic equilibrium. For example, consider fish in a pond. As the number of fish increases, available food decreases and fewer fish survive; thus, the fish population declines.




(a) **Negative feedback.** In this simplified example, the initial balance between a population of fish and its food supply is ultimately restored. Thus, in a negative feedback system, the response to change opposes the change.




(b) **Positive feedback.** In this simplified example of a positive feedback system, the response to change increases, or amplifies, the deviation from the original point.

**Figure 1.13 Feedback systems.**

In a **positive feedback system**, a change in some condition triggers a response that intensifies the changing condition (**Figure 1.13b**); a positive feedback mechanism leads to greater change from the original condition. Positive feedback can be very disruptive to an already disturbed system. For example, melting of polar and glacial ice can lead to greater absorption of solar heat by the exposed land area, which in turn leads to more rapid melting. As you will see throughout this text, many negative and positive feedback mechanisms operate in the natural environment.

## SCIENCE AS A PROCESS

One key to the successful solution of any environmental problem is a careful evaluation of conditions, causes, and effects. Science—a system for managing and producing information—is the most effective way to do this evaluation. It is important to understand clearly just what science is, as well as what it is not. Many people think of science as a body of knowledge—a collection of facts about the natural world and a search for relationships among these facts. However, science is also a dynamic *process,* a systematic way to investigate the natural world. Scientists seek to describe he apparent complexity of our world with general scientific laws also called *natural laws*). Scientific laws are then used to make predictions, solve problems, or provide new insights.

Scientists collect objective **data** (singular, *datum*), the infor- nation with which science works. Data are collected by obser- ation and experimentation and then analyzed or interpreted. Conclusions are inferred from the available data and are not based n faith, emotion, or intuition.

Scientists publish their findings in scientific journals, and ther scientists examine and critique their work. Confirming the alidity of new results by *repeatability* is a requirement of sci- nce—observations and experiments must produce consistent esults when other scientists repeat them. Scrutiny by other sci- ntists reveals any inconsistencies in results or interpretation, and iese errors are discussed openly. Thus, science is *self-correcting* ver time.

No absolute certainty or universal agreement exists about nything in science. Science is an ongoing enterprise, and gen- rally accepted ideas must be reevaluated in light of newly dis- overed data. Scientists never claim to know the "final answer" bout anything because scientific understanding changes. How- ver, this does not prevent us from using current knowledge in nvironmental science to make environmental decisions. Science presents the best information, and thus the best opportunity to ake informed decisions.

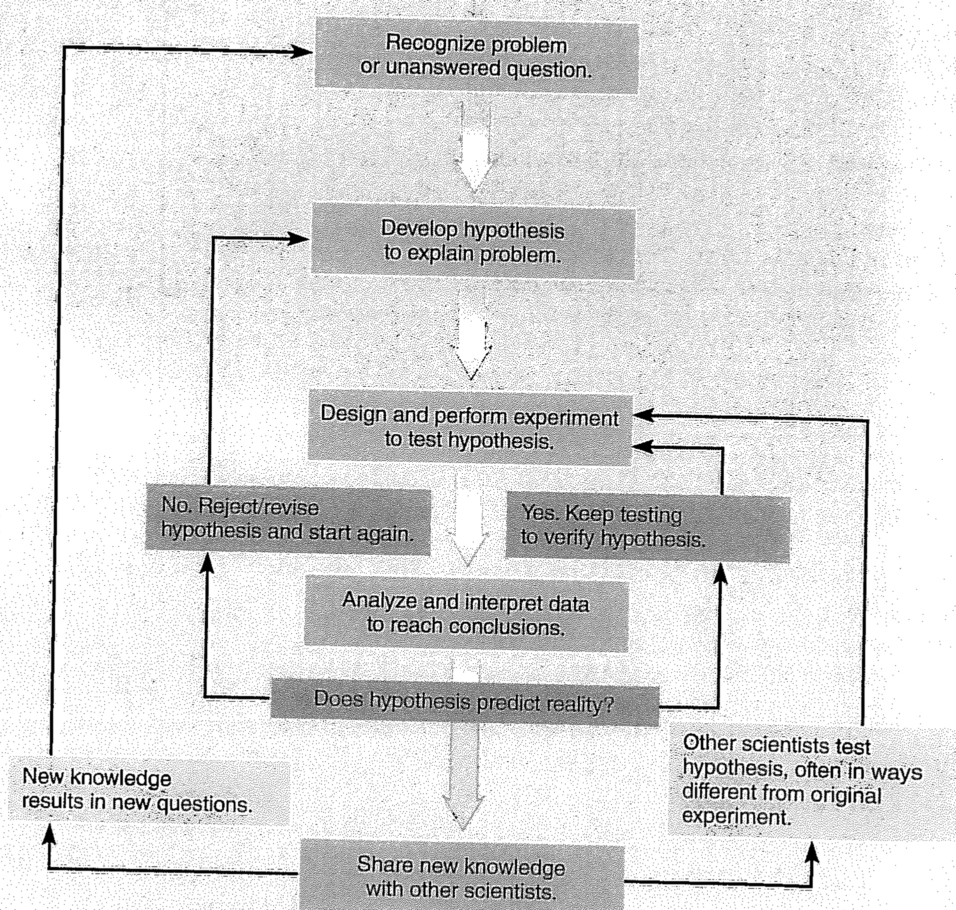
Uncertainty does not mean that scientific conclusions are valid. Overwhelming evidence links exposure to tobacco smoke d the incidence of lung cancer. We cannot ite with absolute certainty which smok- s will get lung cancer, but this uncertainty es not mean no correlation exists between noking and lung cancer. On the basis of available evidence, we say each indi- lual who smokes has an increased *risk* of veloping lung cancer, and we can say with at confidence that far more smokers will velop lung cancer than will nonsmokers.

Importantly, science cannot tell what we *should* do when faced with an environmental challenge, only what result we can expect given different choices. Science can provide better guid- ance than can religion or political preference on what will happen if we release pesticides that eventually reach the ocean or green- house gases that can change the climate. But values, politics, reli- gion, and culture must determine whether we find the loss of waterfowl or changes in the climate worth the benefits we get from spraying pesticides or burning fossil fuels.

**The Scientific Method** The established processes scientists use to answer questions or solve problems are collectively called the **scientific method** (**Figure 1.14**). Although the scientific method has many variations, it basi- cally involves five steps:

**scientific method** The way a scientist ap- proaches a problem by formulating a hypothesis and then testing it by means of an experiment.

1. **Recognize a question or unexplained occurrence in the natural world.** After a problem is recognized, one investigates relevant scientific literature to determine what is already known about it.
2. **Develop a *hypothesis*, or educated guess, to explain the problem.** A good hypothesis makes a prediction that can be tested and possibly disproved. The same factual evidence is often used to formulate several alternative hypotheses; each must be tested.




**ure 1.14 Scientific method.** The basic s of the scientific method are shown in ow. Scientific work rarely proceeds in so ghtforward a manner; examples of additional s are shown in orange.

3. **Design and perform an experiment to test the hypothesis.** An experiment involves collecting data by making careful observations and measurements. Much of the creativity in science involves designing experiments that sort out the confusion caused by competing hypotheses. The process never "proves" anything; instead, it disproves or falsifies alternative hypotheses until only the most plausible hypothesis is left.
4. **Analyze and interpret the data to reach a conclusion.** Does the evidence match the prediction stated in the hypothesis—that is, do the data support or refute the hypothesis? Should the hypothesis be modified or rejected based on the observed data?
5. **Share new knowledge.** Publishing articles in scientific journals or books and presenting the information at meetings permits others to understand and critique methods and findings, and repeat the experiment or design new experiments that either verify or refute the work.

Although the scientific method is usually described as a linear sequence of events, science is rarely as straightforward or tidy as the scientific method implies. Good science involves creativity and openness to new ideas in recognizing questions, developing hypotheses, and designing experiments. Scientific knowledge progresses by trial and error. Many creative ideas end up as dead ends, and temporary setbacks or reversals of direction often occur as knowledge progresses. Scientific knowledge often expands haphazardly, with the "big picture" emerging slowly from confusing and sometimes contradictory details.

Scientific work is often incorrectly portrayed in the media as "new facts" that have just come to light. At a later time, additional "new facts" that question the validity of the original study are reported. If one were to read the scientific papers on which such media reports are based, one would find that the scientists made tentative conclusions based on their data. Science progresses from uncertainty to less uncertainty, not from certainty to greater certainty. Science leads to a better understanding of nature over time, despite the fact that science never "proves" anything.

Most often, many factors influence the processes scientists want to study. Each factor that influences a process is a **variable**. Ideally, to evaluate alternative hypotheses about a given variable, we run experiments that hold all other variables constant so that they do not confuse or mislead us. To test a hypothesis about a variable, two forms of the experiment are done in parallel. In an **experimental group**, we alter the chosen variable in a known way. In a **control group**, we do not alter that variable. In all other respects the two groups are the same. We then ask, "What is the difference, if any, between the outcomes for the two groups?" Any difference is the result of the influence of that variable because all other variables remained the same. Much of the challenge of environmental science lies in designing control groups and in successfully isolating a single variable from all other variables.

**Theories** Theories explain scientific laws. A **theory** is an integrated explanation of numerous hypotheses, each supported by a large body of observations and experiments and evaluated by the peer review process. A theory condenses and simplifies many data that previously appeared unrelated. A good theory grows as additional information becomes known. It predicts new data and suggests new relationships among a range of natural phenomena.

A theory simplifies and clarifies our understanding of the natural world because it demonstrates relationships among classes of data. Theories are the solid ground of science, the explanations of which we are most sure. This definition contrasts sharply with the general public's use of the word *theory*, implying lack of knowledge or a guess—as in, "I have a theory about the existence of life on other planets." In this book, the word *theory* is always used in its scientific sense, to refer to a broadly conceived, logically coherent, and well-supported explanation.

Absolute truth is not possible in science, only varying degrees of uncertainty. Science is continually evolving as new evidence comes to light, and its conclusions are always provisional or uncertain. It is always possible that the results of future experiments will contradict a prevailing theory, which will then be replaced by a new or modified theory that better explains the scientific laws of the natural world.

**Climate Change: Hypotheses and Theory** A dominant theory in environmental science today is that carbon dioxide ($CO_2$) and other gases released from burning fossil fuels has caused and will continue to cause Earth's climate to change. Clearly, however, the climate is a complex system, with many variables that change over a long period. We cannot run an experiment to test the hypothesis that releasing greenhouse gases over a century causes global temperatures to increase. Understanding climate change requires us to observe what is happening, compare those observations to what existing theory predicts will happen, and adapt our theories based on new observations. The theory of climate change draws on physics, chemistry, oceanography, atmospheric science, astronomy, and other scientific fields.

Many of the components of climate theory can be tested directly (**Figure 1.15**). As one example, scientists have tested the hypothesis that some gases, which we call greenhouse gases, can absorb energy (where energy absorption is a variable). In one such experiment, they filled identical containers with air, varied the concentrations of $CO_2$ in the containers, and then added heat. They observed temperature increases in the containers with more $CO_2$. While such experiments do not prove that $CO_2$ absorbs heat, they demonstrate that it is reasonable to think the hypothesis is correct. Indeed, heat absorption by $CO_2$ has been understood for over a century.

Climate scientists have combined this experimental evidence about greenhouse gases with our understanding of other parts of the climate, such as natural variability, solar variability, and reflectivity of ice and other surfaces, to establish a theory of climate change. This theory has uncertainties, but it predicts that as greenhouse gas concentrations increase, global atmospheric temperature will increase, sea level will rise, precipitation patterns will change, and glaciers and ice caps will melt (**Figure 1.16**). As we will see in Chapter 20, observations have confirmed this general theory, while allowing us to refine it and make more reliable predictions about the future. Climate theory does not tell us what we should do to avoid climate change, only what we can expect from different possible decisions.

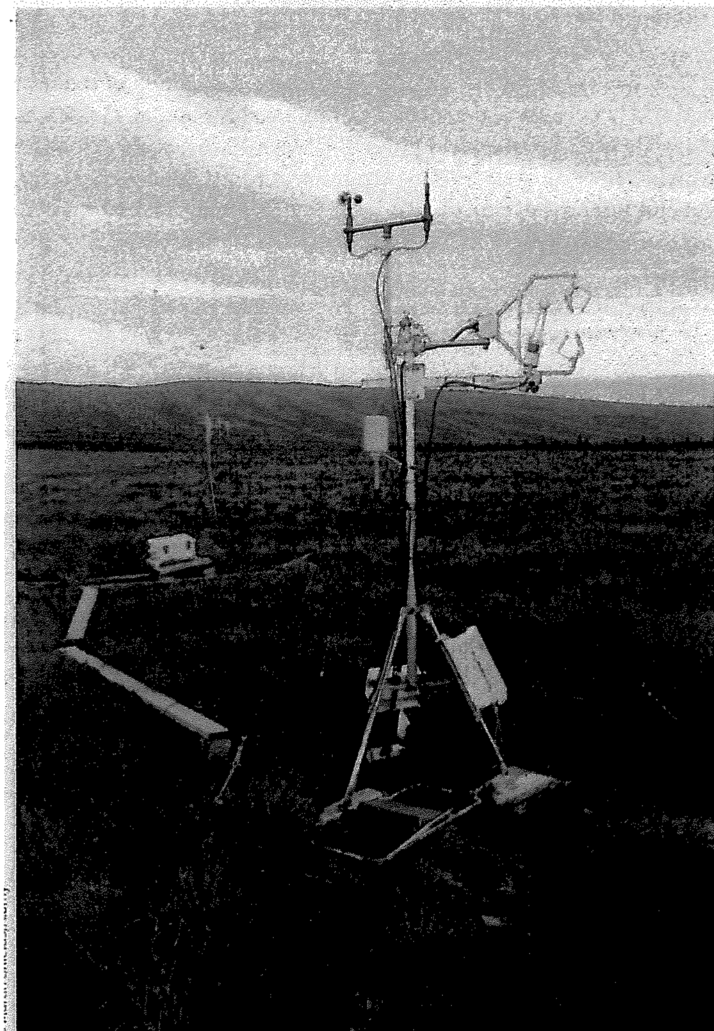


**Figure 1.15 Climate change analysis.** This equipment is part of a long-term project to explore the release of carbon dioxide (a greenhouse gas) from the melting tundra in Alaska.

Carbon dioxide is released by warming, and contributes to warming. Is this an example of a positive feedback or a negative feedback?

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**Figure 1.16 Melting iceberg.** Water streams from an iceberg that was once part of the Ilulisat Kangerlua Glacier, Greenland. While icebergs have broken off of glaciers throughout geologic history, evidence shows that the rate at which glaciers are melting has accelerated rapidly over the past hundred years.

***REVIEW***

1. What is environmental science? Why is a systems perspective so important in environmental science?
2. What are the steps of the scientific method? Does the scientific process usually follow these steps? Why or why not?

## Addressing Environmental Problems

*LEARNING OBJECTIVES*

- List and briefly describe the five stages in addressing environmental problems.
- Briefly describe the history of the Lake Washington pollution problem of the 1950s and how it was resolved.

We have shown the strengths and limitations of science—what science can and cannot do. Before examining the environmental problems in the remaining chapters of this text, let us consider the elements that contribute to addressing those problems. What is the role of science? Given that we can never achieve complete certainty in science, at what point are scientific conclusions considered certain enough to warrant action? Who makes the decisions, and what are the trade-offs?

### ADDRESSING ENVIRONMENTAL PROBLEMS

Viewed simply, there are five stages in addressing an environmental problem (**Figure 1.17**):

1. **Scientific assessment.** The first stage in addressing any environmental problem is scientific assessment, the gathering of information. The problem is defined. Data are then collected, and experiments or simulations are performed.
2. **Risk analysis.** Using the results of a scientific investigation, we can analyze the potential effects of doing nothing or of intervening—what is expected to happen if a particular course of action is followed, including any adverse effects the action might generate. In other words, the risks of one or more remediation (correction or cleanup) options are considered.

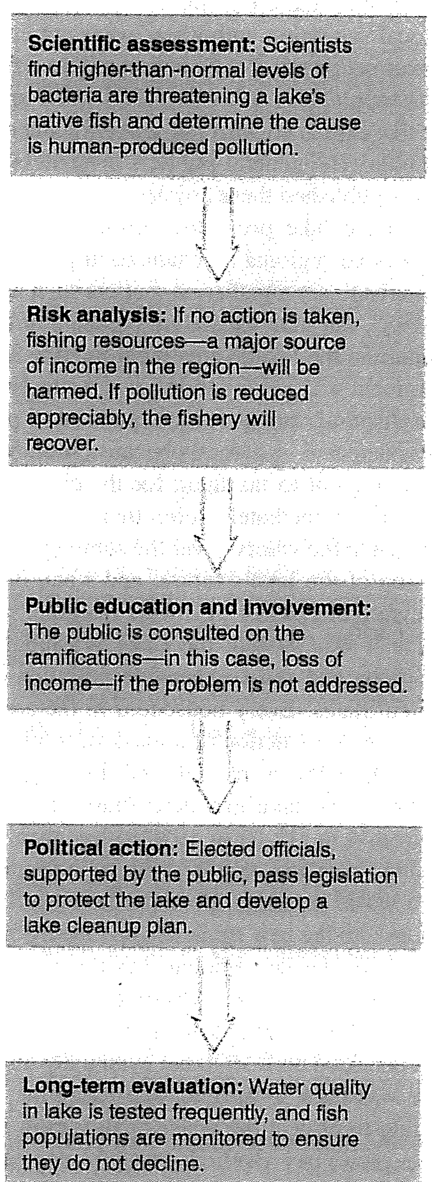



**Figure 1.17 Addressing environmental problems.** These five steps provide a framework for addressing environmental problems, such as the hypothetical example given. Solving environmental problems rarely proceeds in such a straightforward manner.

3. **Public education and involvement.** Public participation and commitment are an essential part of addressing most environmental problems. The public can be a source of both knowledge and values, and many individuals and groups have a stake in the outcome of decisions. People are generally more willing to work together to solve a problem if they have the opportunity to participate from the start.
4. **Political action.** Affected parties select and implement a course of action. Ideally, science provides information on what *can* be done, but in the political process, opinions often differ about how to interpret evidence when selecting a course of action. Often, what people think *should* be done affects their beliefs about science and scientists.
5. **Long-term evaluation.** The results of any action taken should be carefully monitored, both to see if the environmental problem is being addressed and to improve the initial assessment and modeling of the problem.

These five stages represent an ideal approach to systematically addressing environmental problems. In real life, addressing environmental problems is rarely so neat and tidy, particularly when the problem is of regional or global scale, or when those bearing the costs are not those who stand to benefit from a new policy. Quite often, the public becomes aware of a problem, which triggers discussion regarding remediation before the problem has been clearly identified. Also, we often do not know what scientific information is needed until stage 2, 3, or even 4, which means that to make informed decisions, we often need to ask scientists to develop additional research.

To demonstrate the five steps as they operate in an ideal situation, let us consider a relatively simple environmental problem recognized and addressed in the 1950s—pollution in Lake Washington. This problem, unlike many environmental issues we face today, was relatively easy to diagnose and solve.

*CASE IN POINT*

## LAKE WASHINGTON

Lake Washington is a large, deep freshwater lake on the eastern boundary of Seattle (**Figure 1.18**). During the first part of the twentieth century, the Seattle metropolitan area expanded eastward toward the lake from the shores of Puget Sound, putting Lake Washington under increasingly intense environmental pressures. Between 1941 and 1954, 10 suburban sewage treatment plants began operating around the lake. Each plant treated the raw sewage to break down the organic material within it and released the effluent (treated sewage) into the lake. By the mid-1950s, a great deal of treated sewage had been poured into the lake.

Scientists at the University of Washington were the first to note the effects of this discharge on the lake. Their studies indicated that large masses of cyanobacteria (photosynthetic bacteria) were growing in the lake. Cyanobacteria require a plentiful supply

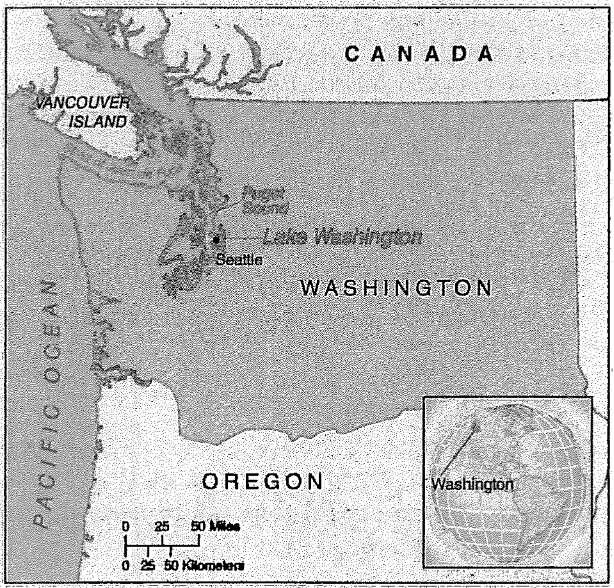



**Figure 1.18 Lake Washington.** This large freshwater lake forms the eastern boundary of Seattle, Washington.

of nutrients such as nitrogen and phosphorus, and deepwater lakes such as Lake Washington do not usually have many dissolved nutrients. The increase in filamentous cyanobacteria indicated that the quality of water in Lake Washington was diminishing.

In 1955, the Washington Pollution Control Commission, citing the scientists' work, concluded that the treated sewage effluent was raising the levels of dissolved nutrients to the point of serious pollution. The sewage treatment was not eliminating many chemicals, particularly phosphorus, a major component of detergents. Mats of cyanobacteria formed a smelly green scum over the surface of the water. The bacteria that decompose cyanobacteria when they die multiplied explosively, consuming vast quantities of oxygen, until the lake's deeper waters could no longer support oxygen-requiring organisms such as fishes and small invertebrates.

Scientific assessment of an environmental problem verifies that a problem exists and builds a sound set of observations on which to base a solution. Scientists predicted that the lake's decline could be reversed: If the pollution was stopped, the lake would slowly recover. They outlined three steps necessary to save the lake:

1. Comprehensive regional planning by the many suburbs surrounding the lake
2. Complete elimination of sewage discharge into the lake
3. Research to identify the key nutrients causing the cyanobacteria to grow

It is one thing to suggest that treated sewage no longer be added to Lake Washington and quite another to devise an acceptable remediation option. Further treatment of sewage could remove some nutrients, but it might not be practical to remove all of them. The alternative was to dump the sewage somewhere else—but where? In this case, officials decided to discharge the treated sewage into Puget Sound. In their plan, a ring of sewers built around the lake would collect the treated sewage and treat it further before discharging it into Puget Sound.

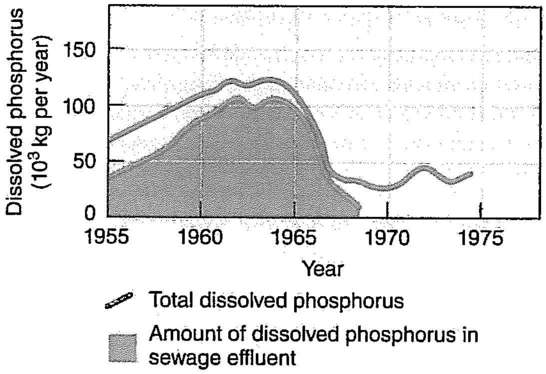
The plan to further treat the sewage was formulated to minimize the environmental impact on Puget Sound. It was assumed that the treated effluent would have less of an impact on the greater quantity of water in Puget Sound. Also, phosphate does not control cyanobacterial growth in Puget Sound as it does in Lake Washington. The growth of photosynthetic bacteria and algae in Puget Sound is largely limited by tides, which mix the water and transport the tiny organisms into deeper water, where they cannot get enough light to grow rapidly.

Despite the Washington Pollution Control Commission's conclusions, local sanitation authorities were not convinced that urgent action was necessary. Public action required further education, and scientists played a key role. They wrote articles for the general public that explained what nutrient enrichment is and what problems it causes. The general public's awareness increased as local newspapers published these articles.

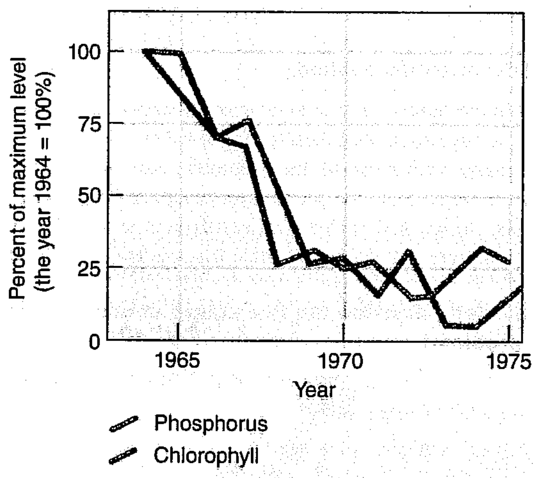
Cleaning up the lake presented serious political problems because there was no regional mechanism in place to permit the many local suburbs to act together on matters such as sewage disposal. In late 1957, the state legislature passed a bill permitting a public referendum in the Seattle area regarding the formation of a regional government with six functions: water supply, sewage disposal, garbage disposal, transportation, parks, and planning. The referendum was defeated, apparently because suburban voters felt the plan was an attempt to tax them for the city's expenses. An advisory committee immediately submitted a revised bill limited to sewage disposal to the voters. Over the summer there was widespread discussion of the lake's future, and when the votes were counted, the revised bill passed by a wide margin.

At the time it was passed, the Lake Washington plan was the most ambitious and most expensive pollution-control project in the United States. Every household in the area had to pay additional taxes for construction of a massive trunk sewer to ring the lake, collect the effluent, treat it, and discharge it into Puget Sound. Meanwhile, the lake had deteriorated further. Visibility had declined from 4 m (12 ft) in 1950 to less than 1 m (3 ft) in 1962 because the water was clouded with cyanobacteria. In 1963, the first of the waste treatment plants around the lake began to divert its effluent into the new trunk sewer. One by one, the others diverted theirs, until the last effluent was diverted in 1968. The lake's condition began to improve (**Figure 1.19**).

Water transparency returned to normal within a few years. Cyanobacteria persisted until 1970 but eventually disappeared. By 1975, the lake was back to normal, and today the lake remains clear. Continuing to protect the water quality even as population around the lake grows has required a systems perspective. Rather than just clean up wastewater, more recent efforts have included strategies that reduce the generation of wastes, such as water recycling and efforts to reduce oil and other industrial wastes.




(a) Dissolved phosphorus in Lake Washington from 1955 to 1974. Note that the level of dissolved phosphorus declined in the lake as the phosphorus contributed by sewage effluent (shaded area) declined.




(b) Cyanobacterial growth from 1964 to 1975, during Lake Washington's recovery, as measured indirectly by the amount of chlorophyll, the pigment involved in photosynthesis. Note that as the level of phosphorus dropped in the lake, the number of cyanobacteria (that is, the chlorophyll content) declined.

**Figure 1.19 Nutrients in Lake Washington compared with cyano bacterial growth.** (From W.T. Edmondson) *The Uses of Ecology: Lake Washington and Beyond.* University of Washington Press (1991).

## ENVIRONEWS

### Green Roofs

A roof that is completely or partially covered with vegetation and soil is known as a *green roof.* Also called *eco-roofs*, green roofs can provide several environmental benefits. For one thing, the plants and soil are effective insulators, reducing heating costs in winter and cooling costs in summer. The rooftop mini-ecosystem filters pollutants out of rainwater and reduces the amount of stormwater draining into sewers. In urban areas, green roofs provide wildlife habitat, even on the tops of tall buildings. A city with multiple green roofs provides "stepping stones" of habitat that enable migrating birds and insects to pass unharmed through the city. Green roofs can also serve as local food resources (see Chapter 18 opener); some restaurants have begun including rooftop gardens for herbs, vegetables, and even beekeeping. Green roofs can also provide an outdoor refuge for people living or working in the building as they allow urban systems to more closely resemble the natural systems they have replaced.

The largest individual green roof in the United States is on the Ford Motor Company factory in Dearborn, Michigan. Planted with nine varieties of hardy plants that require little or no maintenance, the Ford green roof absorbs excess rainwater. This water is naturally cleaned as it passes through a series of wetlands before entering the Rouge River, allowing Ford to avoid costly water treatment.

***REVIEW***

1. What are the steps used to solve an environmental problem?
2. What was the Lake Washington pollution problem of the 1950s? How was it addressed?

## REVIEW OF LEARNING OBJECTIVES WITH SELECTED KEY TERMS

- **Explain how human activities affect global systems.**

Earth consists of many physical and biological **systems**. Its abundant resources have allowed many forms of life to thrive and evolve. Humans, through our growing population and technology, have exploited these resources to the point that we are putting the environment at risk.

- **Describe the factors that characterize human development and how they impact environment and sustainability.**

Human development is typically characterized by factors associated with wealth, such as access to energy resources and medical technology. Historically, **highly developed countries** have represented less than 20% of the global population but account for more than 50% of resource use. **Less developed countries (LDCs)** are developing countries with high **poverty** rates, low levels of industrialization, high fertility rates, high infant mortality rates, and very low per capita incomes (relative to highly developed countries). Increasingly, many of the world's countries, such as China and India, have mixed development, with some urban residents owning considerable wealth but other urban and most rural residents living in poverty.

- **Differentiate between renewable and nonrenewable resources.**

**Renewable resources** are those that nature replaces fairly rapidly (on a scale of days to centuries), and can be used forever as long as they are not overexploited in the short term. **Nonrenewable resources** are present in limited supplies and are depleted by use.

- **Explain the impact of population and affluence on consumption.**

As population increases, people can exceed the capacity of a region to support basic needs for food, shelter, and clean water. When **consumption** by individuals substantially exceeds these basic needs, the resources in a region will be exceeded even more quickly. In either case, consumption that exhausts both **nonrenewable** and **renewable resources** is unsustainable.

- **Define *ecological footprint*.**

An individual's **ecological footprint** is the amount of productive land, fresh water, and ocean required on a continuous basis to supply that person with food, energy, water, housing, material goods, transportation, and waste disposal.

- **Describe the three most important factors that determine human impact on the environment.**

One **model** of environmental impact *(I)* has three factors: the number of people *(P)*; the affluence per person *(A)*, which is a measure of the consumption or amount of resources used per person; and the environmental effect of the technologies used to obtain and consume those resources *(T)*. This model uses an equation to represent the relationship between environmental impacts and the forces that drive them:

$$I = P \times A \times T$$

- **Define *sustainability*.**

**Sustainability** is the ability to meet current human natural resource needs without compromising the ability of future generations to meet their needs; in other words, it is the ability of humans to manage natural resources indefinitely without the environment going into a decline from the stresses imposed by human society on the natural systems that maintain life.

- **Relate Garrett Hardin's description of the tragedy of the commons in medieval Europe to common-pool resources today.**

**Garrett Hardin** contended that our inability to solve many environmental problems is the result of a struggle between short-term individual welfare and long-term environmental sustainability and societal welfare. In today's world, Hardin's parable has particular relevance at the global level. **Common-pool resources** are those parts of our environment that are available to everyone but for which no single individual has responsibility—shared resources such as the atmosphere, fresh water, forests, wildlife, and ocean fisheries.

- **Briefly describe *sustainable development*.**

**Sustainable development** is economic development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs. Three factors—environmentally sound decisions, economically viable decisions, and socially equitable decisions—interact to promote sustainable development.

- **Define *environmental science* and briefly describe the role of Earth systems in environmental science.**

**Environmental science** is the interdisciplinary study of humanity's relationship with other organisms and the nonliving physical environment. Environmental scientists study *systems*; each system is a set of components that interact and function as a whole. A natural system consisting of a community of organisms and its physical environment is an **ecosystem**. Ecosystems are organized into larger and larger systems that interact with one another. At a global level are Earth systems, which include Earth's climate, atmosphere, land, coastal zones, and the ocean.

- **Outline the scientific method.**

The **scientific method** is the way a scientist approaches a problem by formulating a hypothesis and then testing it by means of an experiment. There are many variations of the scientific method, which basically involves these steps: State the problem or unanswered question; develop a **hypothesis**; design and perform an experiment to test the hypothesis; analyze and interpret the **data**; and share the conclusion with others.

- **List and briefly describe the five stages in addressing environmental problems.**

1. Scientific assessment involves gathering information about a potential environmental problem.
2. Risk analysis evaluates the potential effects of intervention.
3. Public education and involvement occur when the results of scientific assessment and risk analysis are placed in the public arena.
4. Political action is the implementation of a particular course of action by elected or appointed officials.
5. Long-term evaluation monitors the effects of the action taken.

- **Briefly describe the history of the Lake Washington pollution problem of the 1950s and how it was resolved.**

Lake Washington exemplifies a successful approach to addressing a relatively simple environmental problem. The pouring of treated sewage into Lake Washington had raised its level of nutrients to the point where the lake supported excessive growth of cyanobacteria. Disposal of the sewage in another way solved the lake's pollution problem.

## Critical Thinking and Review Questions

1. Explain why a single child born in the United States can have a greater effect on the environment than 12 or more children born in a developing country.
2. Do you think it is possible for the world to sustain its present population of 7.2 billion indefinitely? Why or why not?
3. Is consumption driven more by population than affluence in highly developed countries? Less developed countries? Explain the difference.
4. In this chapter, we said the current global ecological footprint is 2.7 hectares (6.7 acres) per person. Do you think it will be higher, lower, or the same in 15 years? Explain your answer.
5. How are the concepts of ecological footprint and the *IPAT* model similar? Which concept do you think is easier for people to grasp?
6. Explain the following proverb as it relates to the concept of environmental sustainability: We have not inherited the world from our ancestors; we have borrowed it from our children.

7. Name an additional example of a common-pool resource other than those mentioned in this chapter.

8. Explain why economic well-being, environment, and ethics all contribute to sustainable development.

9. Give an example of an Earth system.

10. Thomas Henry Huxley once wrote, "The great tragedy of science—the slaying of a beautiful hypothesis by an ugly fact." Explain what he meant, based on what you have learned about the nature of science.

11. In the chapter, the term *model* is defined as a formal statement that describes a situation and that can be used to predict the future course of events. On the basis of this definition, is a model the same thing as a hypothesis? Explain your answer.

12. Some people want scientists to give them precise, definitive answers to environmental problems. Explain why this is not possible, and explain its implications for making decisions about climate change.

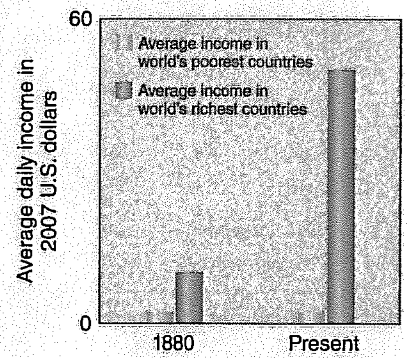
13. Explain why it might be difficult to make a decision about whether to allow farmers to spray pesticides even if we all agree about the negative health effects of the pesticide.

14. Place the following stages in addressing environmental problems in order and briefly explain each: long-term evaluation, public education and involvement, risk analysis, scientific assessment, political action.

15. What does the term *system* mean in environmental science?

16. In what ways do decisions about energy use and climate change that we make today limit the possibilities available to the next generation? Explain your answer.

17. Examine the graph, which shows an estimate of the discrepancy between the wealth of the world's poorest countries and that of the richest countries.




a. How has the distribution of wealth changed from the 1880s to the present? What explains this difference?

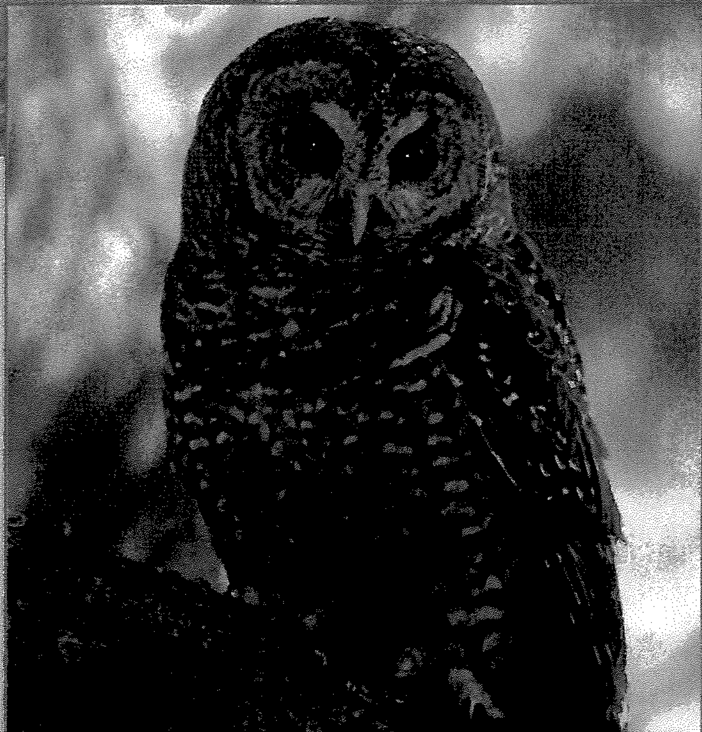
b. Based on the trend evident in this graph, predict what the graph might look like in 100 years.

c. Some economists think that our current path of economic growth is unsustainable. Are the data consistent with this idea? Explain your answer.




## Food for Thought

For one week, keep track of the food you eat. Where does your food come from? How is it packaged? Did you produce any of it yourself, or do you know the individuals who did? Would you be able to eat only foods grown within 100 kilometers of your house? 500 kilometers? Explain the benefits and challenges of trying to do so.



All Canada Photos/Photoshot

# 2

# Environmental Laws, Economics, and Ethics

**Northern spotted owl.** This rare species (*Strix occidentalis caurina*) is found predominantly in old-growth forests in the Pacific Northwest, from northern California to southern British Columbia. Protecting the owl's habitat benefits many other species that reside in the same environment.

uring the late 1980s, an environmental controversy began in western Oregon, Washington, and northern California that continues today. At stake were thousands of jobs and the future of large tracts of *old-growth coniferous forest*, along with the existence of organisms that depend on the forest. The northern spotted owl came to symbolize the confrontation because of its dependence on mature forests for habitat (**see photo**).

Old-growth forests have never been logged. Because most of the forests in the United States were logged at one time or another, less than 10% of old-growth forests remain, and this fraction is decreasing. Most old-growth forests in the United States are found in the Pacific Northwest and Alaska.

Old-growth forests provide biological habitats for many species, including the northern spotted owl and 40 other endangered or threatened species. Provisions of the *Endangered Species Act* require the government to protect the habitat of endangered species; under this law, a 1991 court order suspended logging in about 1.2 million hectares (3 million acres) of forest where the owl lives. The timber industry opposed the moratorium, stating that thousands of jobs would be lost if the area were set aside.

The situation was more complex than simply jobs versus the environment, however. From 1977 to 1987, logging in Oregon's national forests increased by over 15%, while automation in the timber industry eliminated an estimated 12,000 jobs. By the 1980s, the rate at which industry was removing trees would have eliminated most remaining old-growth forests by about 2000.

The 1994 **Northwest Forest Plan** provided federal aid to retrain some timber workers for other careers. Hundreds of former loggers were employed to restore watersheds and salmon habitats in the forests they once logged. The plan, along with previous congressional and administrative actions, reserved about 75% of federal timberlands to safeguard watersheds and protect the northern spotted owl and several hundred other species. Logging was resumed on federal forests in Washington, Oregon, and northern California, but at only about one-fifth of the 1980s level.

Timber-cutting interests were not happy with the plan, and they tried unsuccessfully to revoke or revise the laws. Environmental groups were also unhappy; in 1999 they sued the U.S. Forest Service and the Bureau of Land Management, the two agencies overseeing logging of old-growth forests on federal land, maintaining that these agencies had not adequately carried out the provisions of the plan. The judge agreed that the plan required agencies to survey local endangered and threatened species before approving logging plans. The Forest Service conducted these surveys until 2004, when it discontinued the practice, arguing that they were an inconsequential bureaucratic hurdle.

In mid-2008, responding to lawsuits from the timber industry, the Fish and Wildlife Service released a new management plan that would reduce the protected habitat area by 23%. Critics immediately countered that the decision ignored input from agency scientists. In mid-2009, the Northwest Forest Plan was reinstated as the governing policy.

A weakened species becomes vulnerable to other threats as well. In 2013, the Fish and Wildlife Service approved a plan to remove barred owls from northern spotted owl habitats. The barred owl, native to eastern forests, has become established in areas previously dominated by northern spotted owls.

This chapter examines the environmental history of the United States and the roles of government, economics, and ethics in environmental management.

**In Your Own Backyard...**

*Look into a contested environmental issue in your community. Are they described as environment versus economics? Do you think that's a fair depiction?*

## A Brief Environmental History of the United States

*LEARNING OBJECTIVES*

- Briefly outline the environmental history of the United States.
- Describe the environmental contributions of the following people: George Perkins Marsh, Theodore Roosevelt, Gifford Pinchot, John Muir, Aldo Leopold, Wallace Stegner, Rachel Carson, and Paul Ehrlich.
- Distinguish between utilitarian conservationists and biocentric preservationists.

From the establishment of the first permanent English colony at Jamestown, Virginia, in 1607, the first two centuries of U.S. history were a time of widespread environmental exploitation. Land, timber, wildlife, rich soil, clean water, and other resources were cheap and seemingly inexhaustible. Early European settlers did not dream that the bountiful natural resources of North America would one day become scarce. During the 1700s and early 1800s, most Americans had a **frontier attitude**, a desire to conquer and exploit nature as quickly as possible. Concerns about the depletion and degradation of resources occasionally surfaced, but efforts to conserve were seldom made because the vastness of the continent made it seem that we would always have enough resources.

### PROTECTING FORESTS

The great forests of the Northeast were leveled within a few generations, and shortly after the Civil War in the 1860s, loggers began deforesting the Midwest at an accelerated rate. Within 40 years, they deforested an area the size of Europe, stripping Minnesota, Michigan, and Wisconsin of virgin forest (**Figure 2.1**). By 1897, the sawmills of Michigan had processed 160 billion board feet of white pine, leaving less than 6 billion board feet standing in the whole state.

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**Figure 2.1 Logging operations in 1884.** This huge logjam occurred on the St. Croix River near Taylors Falls, Minnesota.

During the nineteenth century, many U.S. naturalists began to voice concerns about conserving natural resources. **John James Audubon** (1785–1851) painted lifelike portraits of birds and other animals in their natural surroundings. His paintings, based on detailed field observations, aroused widespread public interest in the wildlife of North America. **Henry David Thoreau** (1817–1862), a prominent U.S. writer, lived for two years on the shore of Walden Pond near Concord, Massachusetts. There he observed nature and contemplated how people could economize and simplify their lives to live in harmony with the natural world. **George Perkins Marsh** (1801–1882) was a farmer, linguist, and diplomat at various times during his life. Today he is most remembered for his book *Man and Nature*, which recognized the interrelatedness of human and environmental systems and provided one of the first discussions of humans as agents of global environmental change. Marsh was widely traveled, and *Man and Nature* was based in part on his observations of environmental damage in areas as geographically separate as the Middle East and his native Vermont.

In 1875, a group of public-minded citizens formed the *American Forestry Association*, with the intent of influencing public opinion against the wholesale destruction of America's forests. Sixteen years later, in 1891, the **General Revision Act** gave the president the authority to establish forest reserves on federally owned land. **Benjamin Harrison** (1833–1901), **Grover Cleveland** (1837–1908), and **Theodore Roosevelt** (1858–1919) used this law to remove 17.4 million hectares (43 million acres) of forest, primarily in the West, from logging.

In 1907 angry northwestern congressmen pushed through a bill rescinding the president's powers to establish forest reserves. Theodore Roosevelt, an important contributor to the conservation movement, responded by designating 21 new national forests that totaled 6.5 million hectares (16 million acres). He then signed into law the bill that prevented him and future presidents from establishing additional forest reserves.

Roosevelt appointed **Gifford Pinchot** (1865–1946) as the first head of the U.S. Forest Service. Both Roosevelt and Pinchot were **utilitarian conservationists** who viewed forests in terms of their usefulness for people—such as in providing jobs. Pinchot supported expanding the nation's forest reserves and managing forests scientifically, such as by harvesting trees only at the rate at which they regrow. Today, national forests are managed for multiple uses, from biological habitats to recreation to timber harvest to cattle grazing.

**utilitarian conservationist** A person who values natural resources because of their usefulness for practical purposes but uses them sensibly and carefully.

### ESTABLISHING AND PROTECTING NATIONAL PARKS AND MONUMENTS

Congress established the world's first national park in 1872 after a party of Montana explorers reported on the natural beauty of the canyon and falls of the Yellowstone River; Yellowstone National Park now includes parts of Idaho, Montana, and Wyoming. In 1890, the *Yosemite National Park Bill* established the Yosemite

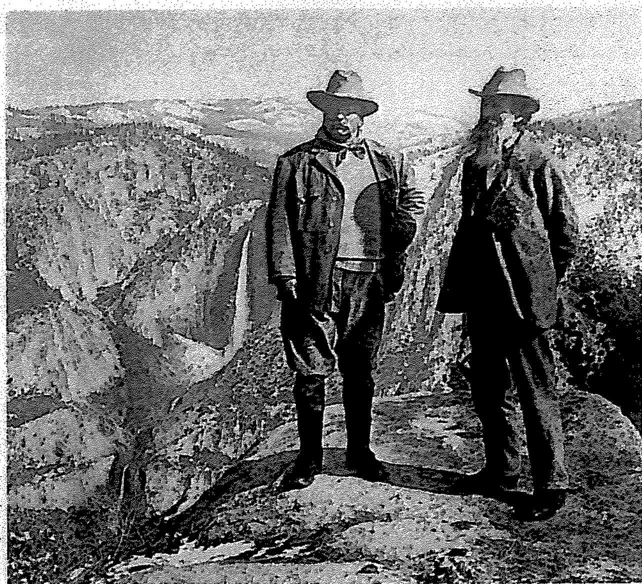

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**Figure 2.2 President Theodore Roosevelt (left) and John Muir.** This photo was taken on Glacier Point above Yosemite Valley, California.

and Sequoia National Parks in California, largely in response to the efforts of a single man, naturalist and writer **John Muir** (1838–1914) (**Figure 2.2**). Muir, a **biocentric preservationist**, founded the *Sierra Club*, a national conservation organization that is still active on a range of environmental issues.

ntric preserva-ist A person who ieves in protecting because all forms fe deserve respect nd consideration.

In 1906, Congress passed the **Antiquities Act**, which authorized the president to set aside certain sites that had scientific, historical, or prehistoric importance, such as the Badlands in South Dakota, as national monuments. By 1916, the U.S. Army was managing 13 national parks and 20 national monuments. (Today the *National Park Service* manages the 58 national parks and 73 national monuments.)

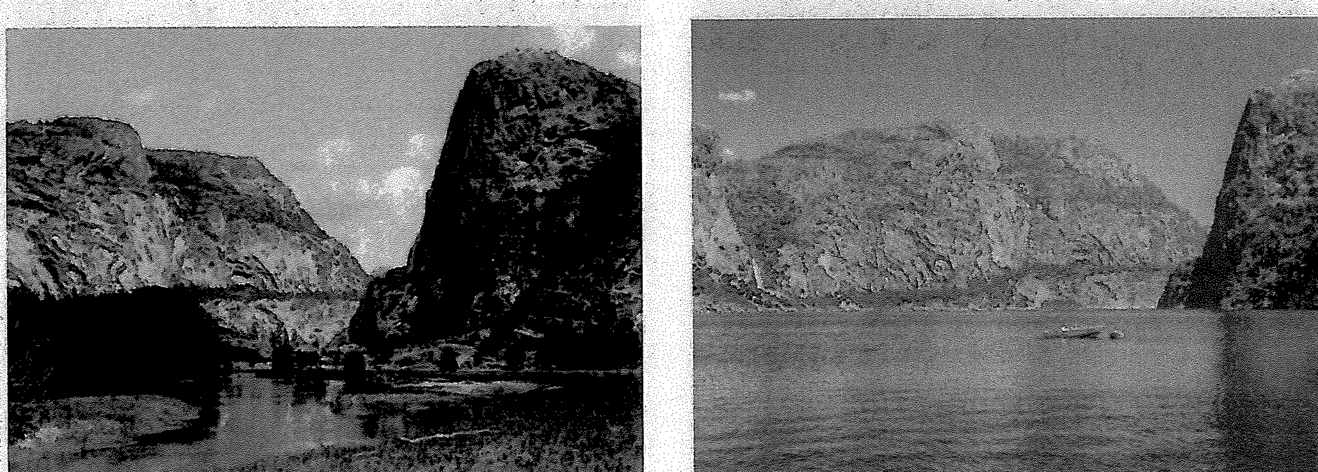
Some environmental battles involving the protection of national parks were lost. John Muir's Sierra Club fought such a battle with the city of San Francisco over its efforts to dam a river and form a reservoir in the Hetch Hetchy Valley (**Figure 2.3**), which lay within Yosemite National Park and was as beautiful as Yosemite Valley. In 1913, Congress voted to approve the dam.

The controversy generated a strong sentiment favoring better protection for national parks, and in 1916 Congress created the National Park Service to manage the national parks and monuments for the enjoyment of the public "without impairment." It was this clause that gave a different outcome to another battle, fought in the 1950s between conservationists and dam builders over the construction of a dam within Dinosaur National Monument. No one could deny that to drown the canyon with 400 feet of water would "impair" it. This victory for conservation established the "use without impairment" clause as the firm backbone of legal protection afforded to U.S. national parks and monuments. Today, discussion is under way to restore Hetch Hetchy, which the state of California estimates would cost as much as $10 billion.

## CONSERVATION IN THE MID-TWENTIETH CENTURY

During the Great Depression, the federal government financed many conservation projects to provide jobs for the unemployed. During his administration, **Franklin Roosevelt** (1882–1945) established the Civilian Conservation Corps, which employed more than 175,000 men to plant trees, make paths and roads in national parks and forests, build dams to control flooding, and perform other activities to protect natural resources.

During the droughts of the 1930s, windstorms carried away much of the topsoil in parts of the Great Plains, forcing many farmers to abandon their farms and search for work elsewhere (see Chapter 14). The *American Dust Bowl* alerted the United States to the need for soil conservation, and in 1935, President Roosevelt formed the *Soil Conservation Service*.



AP Photo/Bancroft Library via Environmental Defense

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**Figure 2.3 Hetch Hetchy Valley in Yosemite.** A view in Hetch Hetchy Valley (left) before and (right) after Congress approved a dam to supply water to San Francisco. (National Archives, WallaceKleck/Terraphotographics/BPS)

**Aldo Leopold** (1886–1948) was a wildlife biologist and environmental visionary who was influential in the conservation movement of the mid- to late-twentieth century. His textbook *Game Management*, published in 1933, supported the passage of a 1937 act in which new taxes on sporting weapons and ammunition funded wildlife management and research. Leopold also wrote philosophically about humanity's relationship with nature and about the need to conserve wilderness areas. In *A Sand County Almanac*, published in 1949, Leopold argued persuasively for a land ethic and the sacrifices such an ethic requires.

Aldo Leopold had a profound influence on many American thinkers and writers, including **Wallace Stegner** (1909–1993), who penned his famous "Wilderness Essay" in 1962. Stegner's essay, written to a commission conducting a national inventory of wilderness lands, helped create support for passage of the Wilderness Act of 1964. Stegner wrote:

> *Something will have gone out of us as a people if we ever let the remaining wilderness be destroyed; if we permit the last virgin forests to be turned into comic books and plastic cigarette cases; if we drive the few remaining members of the wild species into zoos or to extinction; if we pollute the last clean air and dirty the last clean streams and push our paved roads through the last of the silence, so that never again will Americans be free in their own country from the noise, the exhausts, the stinks of human and automotive waste. We simply need that wild country available to us, even if we never do more than drive to its edge and look in. For it can be a means of reassuring ourselves of our sanity as creatures, a part of the geography of hope.*

During the 1960s, public concern about pollution and resource quality began to increase, in large part because of marine biologist **Rachel Carson** (1907–1964). Carson wrote about interrelationships among living organisms, including humans, and the natural environment (**Figure 2.4**). Her most famous work, *Silent Spring*, was published in 1962. In this work, Carson wrote against the indiscriminate use of pesticides.

*Silent Spring* heightened public awareness and concern about the dangers of uncontrolled use of DDT and other pesticides, including poisoning of wildlife and contamination of food supplies. Ultimately, this heightened public awareness led to restrictions on the use of certain pesticides. At about this time, the media began to increase its coverage of environmental incidents, such as hundreds of deaths in New York City from air pollution (1963), closed beaches and fish kills in Lake Erie from water pollution (1965), and detergent foam in a creek in Pennsylvania (1966).

In 1968, when the population of Earth was "only" 3.5 billion people (compared to 7.0 billion in 2011), ecologist **Paul Ehrlich** published *The Population Bomb*. In it, he described the unavoidable environmental damage necessary for Earth to support such a huge population, including soil loss, groundwater depletion, and extinctions. Ehrlich's book triggered public debate on the issue of overpopulation and how to address it effectively. As will be discussed later in this chapter, Ehrlich's *environmental worldview* influenced his theory that the world could comfortably hold only around 1 billion people.

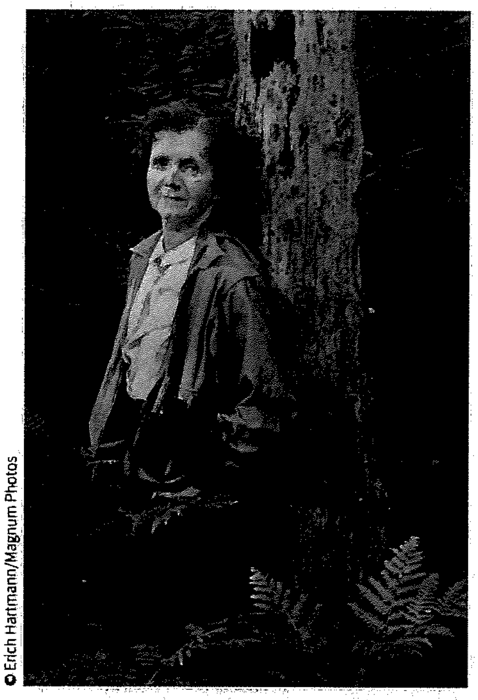

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**Figure 2.4 Rachel Carson.** Carson's book *Silent Spring* heralded the beginning of the environmental movement. Photographed in Maine in 1962.

## THE ENVIRONMENTAL MOVEMENT OF THE LATE TWENTIETH CENTURY

Until 1970, the voices of **environmentalists** were heard in the United States primarily through societies such as the *Sierra Club* and the *National Wildlife Federation*. There was no generally perceived environmental movement until the spring of 1970, when **Gaylord Nelson**, former senator from Wisconsin, urged Harvard graduate student **Denis Hayes** to organize the first nationally celebrated Earth Day. This event awakened U.S. environmental consciousness to population growth, overuse of resources, and pollution and degradation of the environment. On Earth Day 1970, an estimated 20 million people in the United States demonstrated their support for environmental quality by planting trees, cleaning roadsides and riverbanks, and marching in parades. (**Figure 2.5** presents a list of selected environmental events since Earth Day 1970.)

In the years that followed the first Earth Day, environmental awareness and the belief that individual actions could repair the damage humans were doing to Earth became a pervasive, popular movement. Musicians popularized environmental concerns, and many of the world's religions embraced environmental themes such as protecting endangered species.

By Earth Day 1990, the movement had spread around the world, signaling the rapid growth in environmental consciousness; an estimated 200 million people in 141 nations demonstrated to increase public awareness of the importance of individual efforts. Earth Day continues to be a popular event around the world, and many years include an organizing theme, such as "Think Globally, Act Locally" (1990) and "The Face of Climate Change" (2013, **Figure 2.6**).

### 1970s

- **1970** Millions in United States gather for first Earth Day.
- **1972** Scientists report most acid rain in Sweden originates in other countries.
- **1973** Convention on International Trade in Endangered Species of Wild Fauna and Flora protects endangered species.
- **1974** Chlorofluorocarbons are first hypothesized to cause ozone thinning.
- **1976** Dioxin (poisonous chemical) released in industrial accident at pesticide plant in Italy.
- **1979** Worst nuclear accident in U.S. history occurs at Three Mile Island nuclear power plant in Pennsylvania.

### 1980s

- **1982** Convention on the Law of the Sea developed to protect ocean's resources.
- **1984** World's worst industrial accident at pesticide plant in India kills and injures thousands.
- **1985** Scientists discover and measure size of ozone hole over Antarctica.
- **1986** World's worst nuclear accident up to that time occurs at nuclear power plant in Chernobyl, Soviet Union.
- **1986** International Whaling Commission announces moratorium on commercial whaling.
- **1987** Montreal Protocol requires countries to phase out ozone-depleting chemicals.
- **1989** *Exxon Valdez* creates largest spill from an oil tanker in U.S. history.

### 1990s

- **1990** First Intergovernmental Panel on Climate Change (IPCC) Assessment warns of possible global warming.
- **1991** World's worst oil spill occurs in Kuwait during war with Iraq.
- **1992** U.N. conference on Environment and Development (Earth Summit) held in Brazil.
- **1994** International Conference on Population and Development held in Egypt.
- **1995** Second IPCC Assessment warns of human influence on global warming.
- **1997** Forest fires destroy more tropical forests than ever recorded before; Indonesia is particularly hard hit.
- **1999** Human population reaches 6 billion.

### 2000s

- **2000** Treaty on Persistent Organic Pollutants requires countries to phase out certain highly toxic chemicals.
- **2001** Third IPCC Assessment cites strong evidence humans are responsible for most of observed global warming in past 50 years.
- **2001** President Bush decides the United States will not ratify the Kyoto Protocol, which mandates reductions in $CO_2$ emissions to combat global warming.
- **2002** Oil spill off Spain's coast raises awareness of ocean's vulnerability.
- **2004** Record heat waves in Europe highlight threat of climate change.
- **2007** Fourth IPCC Assessment concludes that it is "very likely" that global warming has been caused by human activity.
- **2008** U.S. Supreme Court decides that EPA must regulate $CO_2$.

### 2010s

- **2010** The Deepwater Horizon, an oil drilling platform in the Gulf of Mexico, creates the largest oil spill in U.S. history.
- **2010** At meetings in Cancun, Mexico, over 190 countries agree to a plan for monitoring and reducing greenhouse gas emissions.
- **2010** NASA global temperature data show that 2010 was the hottest year on record.
- **2011** A tsunami in Japan causes severe damage and radiation releases at several Fukushima Daiichi nuclear power plant reactors.
- **2013** A "garbage patch" in South Pacific Ocean discovered, covering at least 700,000 $km^2$ of the ocean surface.
- **2013** The EPA to begin regulating greenhouse gas emissions from coal-fired power plants.
- **2014** Fifth IPCC Assessment concludes with even more confidence that human activities drive our changing climate.

**Figure 2.5 Selected environmental events, 1970 to the present.**

*REVIEW*

- Which occurred first in the U.S. environmental movement: concerns about forest conservation or concerns about pollution?
- Describe how an individual can influence U.S. environmental history or policy.
- Explain how the attitudes of utilitarian conservationists toward environmental policy differ from those of biocentric preservationists.

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**Figure 2.6 Earth Day 2013.** Maria Martinez Head Start students, along with faculty and staff, plant a tree as part of Earth Day events in 2014.

## U.S. Environmental Legislation

*LEARNING OBJECTIVES*

- Explain why the National Environmental Policy Act is the cornerstone of U.S. environmental law.
- Explain how environmental impact statements provide powerful protection of the environment.

By the late 1960s, much of the U.S. public had become increasingly disenchanted with governmental secrecy, and many did not trust industry to work in the public interest. This broad social transformation, which included opposition to the Vietnam War and resistance to racist policies, was reflected in environmental attitudes as well. Galvanized by well-publicized ecological disasters, such as the 1969 oil spill off the coast of Santa Barbara, California, and by overwhelming public support for the Earth Day movement, in 1970 the **Environmental Protection Agency (EPA)** was formed, and the **National Environmental Policy Act (NEPA)** was signed into law. A key provision of NEPA required the federal government to consider the environmental impact of any proposed federal action, such as financing highway or dam construction. NEPA provides the basis for developing detailed **environmental impact statements (EISs)** to accompany every federal recommendation or legislative proposal. These EISs are supposed to help federal officials make informed decisions. Each EIS must include the following:

**environmental mpact statement (EIS)** A document that summarizes tential and expected verse impacts on the ironment associated vith a project as well ıs alternatives to the əposed project; typi-lly mandated by law ›ublic and/or private projects.

1. The nature of the proposal and why it is needed
2. The environmental impacts of the proposal, including short-term and long-term effects and any adverse environmental effects if the proposal is implemented (**Figure 2.7**)
3. Alternatives to lessen the adverse effects of the proposal; providing ways to mitigate the impact of the project

A required step in the EIS process is the solicitation of public comments, which generally provide a broader perspective on the proposal and its likely effects. NEPA established the **Council on Environmental Quality** to monitor the required EISs and report directly to the president. This council had no enforcement powers, and NEPA was originally considered innocuous, generally more a statement of good intentions than a regulatory policy.

During the next few years, environmental activists took people, corporations, and the federal government to court to challenge their EISs and use them to block proposed development. The courts decreed that EISs must be substantial documents that thoroughly analyze the environmental consequences of anticipated projects on soil, water, and organisms. The courts also said that the public must have access to EISs. These rulings put sharp teeth into the law—particularly the provision for public scrutiny, which placed intense pressure on federal agencies to respect EIS findings.

NEPA revolutionized environmental protection in the United States. In addition to overseeing federal highway construction, flood and erosion control, military projects, and many other public works, federal agencies oversee nearly one-third of the land in the United States. Federally owned holdings include extensive fossil-fuel and mineral reserves as well as millions of hectares of public grazing land and public forests, all subject to NEPA. Many states and local governments now require EISs for public (and sometimes private) projects, as do many foreign countries.

NEPA has evolved considerably through four decades of litigation and eight presidential administrations, but the fundamental effect of publicly available information remains. Although almost everyone agrees that NEPA has helped federal agencies reduce adverse environmental impacts of their activities and projects, it has its critics. Environmentalists complain that EISs are sometimes incomplete, include only alternatives that make a predetermined alternative look attractive, or are ignored when decisions are made. Other critics think the EISs delay important projects ("paralysis by analysis") because EISs are too involved, take too long to prepare, and are often the targets of lawsuits.

### ENVIRONMENTAL POLICY SINCE 1970

Although legislation to manage many environmental problems existed before 1970, the regulatory system that exists today was largely put into place during the 1970s. Congress has passed many environmental laws that address a wide range of issues, such as endangered species, clean water, clean air, energy conservation, hazardous wastes, and pesticides (**Table 2.1**). These laws have greatly increased federal regulation of pollution, creating a tough interlocking mesh of laws to improve environmental quality.

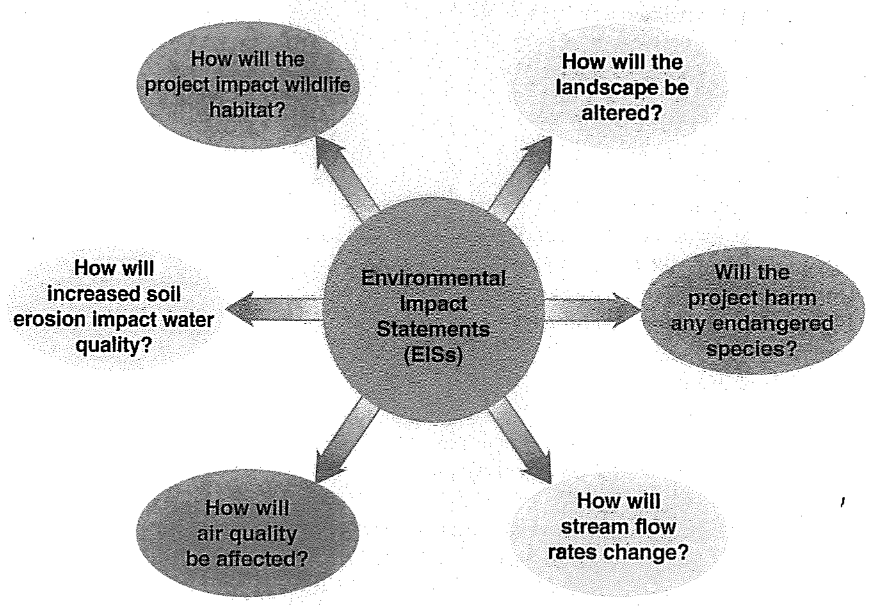



**Figure 2.7 Environmental impact statements.** These detailed statements help federal agencies and the public consider the environmental impacts of proposed activities. When anticipated impacts are likely to be high, decision makers will feel pressure to seek alternative actions.

Many environmental laws contain provisions that allow private citizens to take violators, whether they are private industries or government-owned facilities, to court for noncompliance. These citizen suits have contributed significantly in the enforcement of environmental legislation.

In the early 1980s, President Reagan attempted to reverse the pro-environmental trend by appointing a pro-business EPA administrator, **Ann Gorsuch**, and leaving many top-level positions in the agency unfilled. Congressional and public backlash led to even more restrictive environmental laws. Gorsuch was replaced with **William Ruckleshaus**, who had been the first EPA administrator and was widely respected for having established the agency's credibility and authority. Ruckleshaus advocated a rational, organized approach to environmental regulation that would avoid the "pendulum" effect of stringent and then relaxed environmental regulation.

**Table 2.1 Some Important Federal Environmental Legislation**

*General*
Freedom of Information Act of 1966
National Environmental Policy Act of 1969
National Environmental Education Act of 1990

*Conservation of Energy and Renewable Energy Resources*
Energy Policy and Conservation Act of 1975
Northwest Power Act of 1980
National Appliance Energy Conservation Act of 1987
Energy Policy Act of 1992
American Recovery and Reinvestment Act of 2008

*Conservation of Wildlife*
Fish and Wildlife Act of 1956
Anadromous Fish Conservation Act of 1965
Fur Seal Act of 1966
National Wildlife Refuge System Act of 1966
Species Conservation Act of 1966
Marine Mammal Protection Act of 1972
Marine Protection, Research, and Sanctuaries Act of 1972
Endangered Species Act of 1973
Federal Noxious Weed Act of 1974
Magnuson Fishery Conservation and Management Act of 1976
Whale Conservation and Protection Study Act of 1976
Fish and Wildlife Improvement Act of 1978
Fish and Wildlife Conservation Act of 1980
Fur Seal Act Amendments of 1983
Wild Bird Conservation Act of 1992
National Invasive Species Act of 1996

*Conservation of Land*
General Revision Act of 1891
Taylor Grazing Act of 1934
Soil Conservation Act of 1935
Multiple Use Sustained Yield Act of 1960 (re: national forests)
Wilderness Act of 1964
Land and Water Conservation Fund Act of 1965
Wild and Scenic Rivers Act of 1968
National Trails System Act of 1968
Coastal Zone Management Act of 1972
National Reserves Management Act of 1974
Forest and Rangeland Renewable Resources Act of 1974
Federal Land Policy and Management Act of 1976
National Forest Management Act of 1976
Soil and Water Resources Conservation Act of 1977
Surface Mining Control and Reclamation Act of 1977
Public Rangelands Improvement Act of 1978
Antarctic Conservation Act of 1978
Endangered American Wilderness Act of 1978
Alaska National Interest Lands Act of 1980
Coastal Barrier Resources Act of 1982
Emergency Wetlands Resources Act of 1986
North American Wetlands Conservation Act of 1989
California Desert Protection Act of 1994
Food, Conservation, and Energy Act of 2008 (the latest version of the "farm bill," which has been amended and renamed every 5 years or so since the 1930s)

*Air Quality and Noise Control*
Noise Control Act of 1965
Clean Air Act of 1970
Quiet Communities Act of 1978
Asbestos Hazard and Emergency Response Act of 1986
Clean Air Act Amendments of 1990

*Water Quality and Management*
Refuse Act of 1899
Water Resources Research Act of 1964
Water Resources Planning Act of 1965
Clean Water Act of 1972
Ocean Dumping Act of 1972
Safe Drinking Water Act of 1974
National Ocean Pollution Planning Act of 1978
Water Resources Development Act of 1986
Great Lakes Toxic Substance Control Agreement of 1986
Water Quality Act of 1987 (amendment of Clean Water Act)
Ocean Dumping Ban Act of 1988
Oceans Act of 2000

*Control of Pesticides*
Food, Drug, and Cosmetics Act of 1938
Federal Insecticide, Fungicide, and Rodenticide Act of 1947
Food Quality Protection Act of 1996

*Management of Solid and Hazardous Wastes*
Solid Waste Disposal Act of 1965
Resource Recovery Act of 1970
Hazardous Materials Transportation Act of 1975
Toxic Substances Control Act of 1976
Resource Conservation and Recovery Act of 1976
Low-Level Radioactive Policy Act of 1980
Comprehensive Environmental Response, Compensation, and Liability ("Superfund") Act of 1980
Nuclear Waste Policy Act of 1982
Hazardous and Solid Waste Amendments of 1984
Superfund Amendments and Reauthorization Act of 1986
Medical Waste Tracking Act of 1988
Marine Plastic Pollution Control Act of 1987
Oil Pollution Act of 1990
Pollution Prevention Act of 1990
State or Regional Solid Waste Plans (RCRA Subtitle D) of 1991

Since 1980, the rate of new major environmental legislation has slowed, but environmental policy continues to evolve through administrative actions and the judicial process. In 1994, President Clinton issued an executive order requiring that environmental justice be considered in all regulatory actions. Environmental policy through the Clinton and George W. Bush administrations was characterized by expanded use of cost–benefit analysis in environmental regulation.

The George W. Bush administration placed higher priority on extracting environmental resources than reducing human impacts on the environment. No major environmental laws were passed between 2000 and 2008, and a number of major land-use regulations—such as preserving habitat for the spotted owl—were relaxed. In addition, in some cases states were barred from passing regulations more stringent than those required by the federal government, most notably the attempt by California and 13 other states to impose automobile efficiency standards on cars and light trucks. One of the first acts of the Obama administration was to reverse this prohibition.

In one significant legal case during the George W. Bush administration, Massachusetts sued the EPA to require that greenhouse gases be regulated under the **Clean Air Act (CAA)**. The EPA made two arguments: (1) that the CAA did not authorize climate change regulations and (2) that the CAA was not an appropriate way to manage climate change since it is a global problem, not amenable to local or even national solutions. The Supreme Court disagreed, concluding that greenhouses gases are pollutants emitted into the air and capable of endangering public health or welfare. It further noted that the EPA claim that it *should not* regulate greenhouse gases was inconsistent with the CAA, since the EPA had acknowledged that greenhouse gases contribute to climate change.

The EPA is usually given the job of translating environmental laws into specific regulations. Before the regulations become official, several rounds of public comments allow affected parties to present their views; the EPA is required to respond to all of these comments. Next, the Office of Management and Budget reviews the new regulations. Some regulations proposed by the EPA must be justified by **cost–benefit analysis**, while others (including those under the Clean Air Act) are barred from considering economic impacts. Implementation and enforcement of environmental regulations often fall to state governments, which must send the EPA detailed plans showing how they intend to achieve regulatory goals and standards. Currently, the EPA oversees thousands of pages of environmental regulations that affect individuals, corporations, local communities, and states.

Environmental laws have not always worked as intended. The Clean Air Act of 1977 required coal-burning power plants to outfit their smokestacks with expensive *scrubbers* to remove sulfur dioxide from their emissions but made an exception for tall smokestacks (**Figure 2.8**). This loophole led to the proliferation of tall stacks that have since produced *acid rain* throughout the Northeast. The Clean Air Act Amendments of 1990, described in Chapter 19, go a long way toward closing this loophole. In addition, many environmental regulations are not enforced properly. According to **Oliver Houck** of the Tulane Law School, environmental laws such as the Clean Water Act have compliance rates of about 50%.

Despite imperfections, U.S. environmental legislation has had overall positive effects. Since 1970:

1. Twenty-three national parks have been established, and the National Wilderness Preservation System now totals more than 43 million hectares (107 million acres).
2. Millions of hectares of land vulnerable to erosion have been withdrawn from farming, reducing soil erosion in the United States by more than 60%.
3. Many previously endangered species are better off now than they were in 1970, and the American alligator, California gray whale, bald eagle, and brown pelican have recovered enough to be removed from the endangered species list. (Dozens of other species, however, such as the manatee, ivory-billed woodpecker, polar bear, and Kemp's sea turtle, have suffered further declines or extinction since 1970.)
4. Energy efficiency and conservation technology have improved markedly for buildings, vehicles, and consumer products.

Although we still have a long way to go, pollution-control efforts have been particularly successful. According to the EPA's most recent *Report on the Environment (2008)*:

1. Both emissions and ambient concentrations of six important air pollutants have dropped by at least 25% since 1970, much more in the case of lead. (Carbon dioxide emissions have continued to rise.)
2. Since 1990, levels of wet sulfate, a major component of acid rain, have dropped by about 33%.

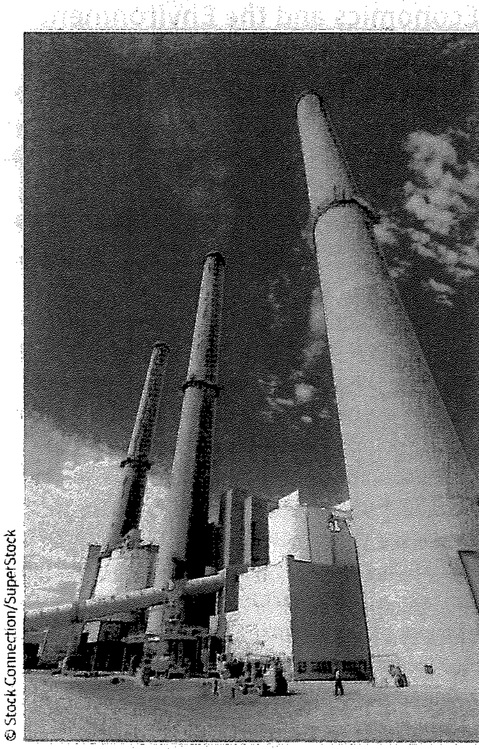




**Figure 2.8 Tall smokestacks.** Such smokestacks, which emit sulfur dioxide from coal-burning power plants, were exempt from the requirement of pollution-control devices under the Clean Air Act of 1977.

3. In 2008, 92% of the U.S. population got its drinking water from community water systems with no violations of EPA standards, up from around 75% in 1993.
4. In 2014, 45% of municipal solid waste was combusted for energy recovery or recovered for composting or recycling, up from 6% in the 1960s. While total municipal solid waste has been increasing, the amount sent to landfills has remained roughly constant since 1980.
5. In 2007, the EPA considered human exposures to contamination to be under control at 93% of listed hazardous waste sites, up from 37% of the sites listed in 2000.

However, not all environmental trends are positive. In some major urban areas, such as Houston and Las Vegas, air quality has begun to deteriorate since about 2000. While technology has reduced environmental impacts of industries and products, population increases have outpaced technological improvements (recall the *IPAT* model from Chapter 1). In addition, despite broad and increasing concern about climate change, no effective U.S. or international policies have been established. Future environmental improvement will require more sophisticated strategies, involving technological and behavior changes.

*REVIEW*

1. Which law is the cornerstone of U.S. environmental law? Why?
2. In what ways has the U.S. environment improved as the result of regulations?

## Economics and the Environment

*LEARNING OBJECTIVES*

- Explain why economists prefer efficient solutions to environmental problems.
- Describe command and control regulation, incentive-based regulation, and cost-effectiveness analysis.
- Give two reasons why the national income accounts are incomplete estimates of national economic performance.

**Economics** is the study of how people use their limited resources to try to satisfy unlimited wants. Economists combine theoretical assumptions about individual and institutional behavior with analytical tools that include developing hypotheses, testing models, and analyzing observations and data. They try to understand the consequences of the ways in which people, businesses, and governments allocate their resources.

Economists who work on environmental problems must take a systems perspective. For example, Nobel Prize–winning economist **Amartya Sen** addresses overlapping issues of environment, poverty, nationalism, gender, and governmental structure (**Figure 2.9**). This approach recognizes the complex interactions among the environment, society, health, and well-being.

Economics, especially as applied to public policy, relies on several precepts. First, economics is utilitarian. This means that all goods and services—including those provided by the environment—have value to people and that those values can be converted into some common currency. Thus, in a market economy such as that of the United States, goods and services have dollar values, which are determined by the amount of money someone is willing to pay for them.

This leads to a second precept, the **rational actor model**. Economists assume two things about all individuals. First, individuals have preferences among different goods and services, which economists refer to as **utility**. Second, individuals can and do spend their limited resources (money and time) in a way that provides them the most utility.

**rational actor model** In economics, the assumption that all individuals spend their limited resources in a fashion that maximizes their individual utilities.

**utility** An economic term referring to the benefit that an individual gets from some good or service. Rational actors try to maximize utility.

Third, in an ideal economy, resources will be allocated efficiently. *Efficiency* is a term economists use to describe multiple individuals getting the greatest amount of goods or services from a limited set of resources. For example, if business plan A will build 9 cars with a given amount of material and number of workers, while business plan B will build 10 equivalent cars with the same resources, business plan B is more efficient and will succeed. To economists, environmental problems arise when market failures occur in one of several ways, principal among which are externalities and inefficiency.

**Externalities** occur when the producer of a good or service does not have to pay the full costs of production. An example is a blacksmith shop next door to a drip-dry laundry. If soot from the blacksmith shop lands on the laundry, then the laundry owner will have to rewash the laundry and try to pass on the additional cost to its customers. Here, the blacksmith shop is causing a negative externality on the laundry and its customers, who in effect pay part of the cost of the blacksmith operation.

**externality** In economics, the effects (usually negative) of a firm that does not have to pay all the costs associated with its production.

A simple solution—advocated by some economists—is to clearly define rights and ownership. If the blacksmith does not have the right to release soot, then the laundry owner can demand

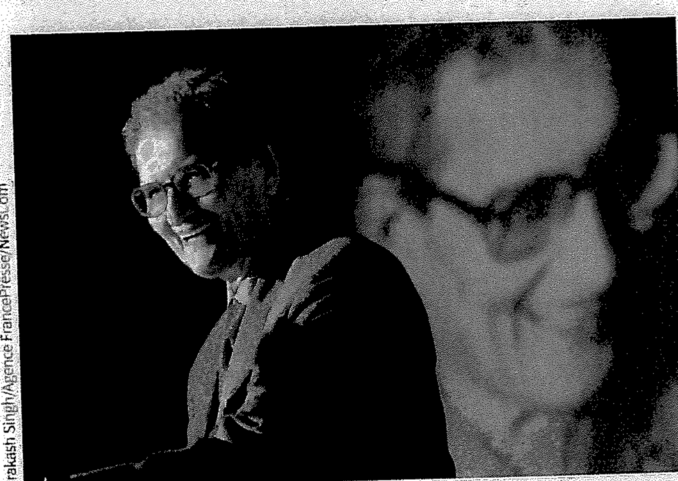

Prakash Singh/Agence FrancePresse/NewsCom

**Figure 2.9 Nobel laureate Amartya Sen.** Economist Amartya Sen's work includes critiques of traditional assumptions about economic valuation of the environment and recognizes the complex, systemic nature of the environment, society, health, and well-being.

compensation for the added cost of business. The blacksmith then has several options—for example, to close the shop, find a way to control the soot, or pay the laundry owner for the extra cost of business. The efficient solution is the one that costs the least money for everyone. If closing the shop costs $10,000 per year, using soot-control equipment costs $200 per year, and paying to rewash laundry costs $500 per year, the blacksmith should choose to control soot. This same solution will occur even if the blacksmith *does* have the right to release soot, since the laundry owner should be willing to pay the blacksmith $200 to use soot-control equipment rather than spending $500 to rewash laundry.

Unfortunately, most environmental externalities are not as clearly defined as the laundry/blacksmith example. Usually, there are many polluters and many affected individuals. A small town may have 5,000 automobiles, each of which generates a different amount of pollution that affects each of 10,000 residents. Damage associated with the releases may depend on time of day as well as where in the town pollution is generated. Even if we could assess those damages, it would be impossible for each driver to compensate each person impacted by the car's emissions. The problem becomes even more extreme for climate change, where billions of individuals generate and are affected by greenhouse gases.

Several economic solutions exist for cases of multiple polluters, all of which rely on the idea that we can identify an efficient or **optimal amount of pollution.** At this optimum, the cost to society of having less pollution is offset by the benefits to society of the activity creating the pollution. To find this optimum requires that we identify the **marginal cost of pollution**, which refers to the cost of a small additional amount of pollution. Determining the marginal cost of pollution involves assessing pollution damage to health, property, agriculture, and aesthetics. Pollution can also reduce **ecosystem services (see Table 5.1)**, which are benefits to humans—including clean water and fresh air—provided by natural systems. Determining the marginal cost of pollution is generally not an easy process.

Similarly, the **marginal cost of abatement** is the cost associated with reducing (abating) a small additional amount of pollution. Untreated wastewater from a pulp mill contains a variety of chemicals and suspended wood fibers. The cost of filtering the fibers is relatively low, requiring mechanical screening. The cost of removing inorganic chemicals, however, may be quite high (see Chapter 21). The societal benefit of filtering is relatively high compared to the benefit of removing a small amount of a chemical. If we insist that only perfectly pure water comes out of the pulp mill, the cost of paper will be extremely high.

**Figure 2.10** demonstrates how the marginal cost of pollution and the marginal cost of abatement lead to an optimal amount of pollution. The green line represents the marginal cost of abatement, and the red line the marginal cost of pollution. When the amount of pollution being generated is high, abatement costs are relatively low. Similarly, when pollution concentration is low, abatement costs are high; in this case, the benefit of additional control is low. Pollution is at an optimal level when marginal costs of pollution and abatement are equal (the point at which the red and green lines intersect). When that is the case, the economic system is efficient, meaning that society would be worse off with either more *or less* pollution. If a pulp mill operating at that optimal level were to spend an additional $1 on control equipment, the value to society of the reduction in pollution would be less than $1.

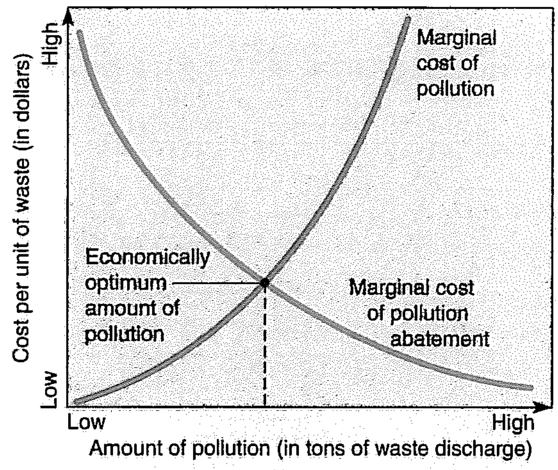



**Figure 2.10 Economic optimality and pollution.** This figure represents the economically optimal level of pollution in an efficient market. The upward-sloping curve (red line) represents the cost of damage associated with pollution at various levels. As pollution rises, the social cost (in terms of human health and a damaged environment) increases sharply. The downward-sloping curve (green line) represents the cost of reducing pollution to a lower, less damaging level. The intersection of these two curves is the economically optimal point, where a shift in either direction (more or less pollution) will lead to lower total societal benefits.

It is unusual to find unregulated economic systems at the point of economic optimality. In unregulated markets, those who pollute often must pay only a fraction of the total costs of pollution. Thus, the marginal cost of pollution faced by the polluter (private cost) is substantially lower than the marginal cost of pollution faced by society as a whole. This is represented by **Figure 2.11**, which contains two marginal cost of pollution curves. The marginal cost curve on the left (red line) is the societal marginal cost of pollution, which includes that faced by the polluter. To the right of this is the private marginal cost of pollution curve (blue line), which is the fraction of the overall marginal cost paid by the polluter. Without some sort of regulation, the amount of pollution generated will be determined by the point at which the private marginal cost of pollution is equal to the marginal cost of abatement (intersection of green and blue lines). Substantially more pollution may be generated at this intersection than is optimal from a societal perspective.

## STRATEGIES FOR POLLUTION CONTROL

Economists favor market-based solutions to environmental externality problems. Historically, many environmental regulations have been **command and control** solutions. This means the EPA or other government agency requires that a particular piece of equipment be installed to limit emissions to water, air, or soil. Industries regulated in this fashion often object that they are thereby discouraged from developing lower-cost alternatives that would achieve the same level of pollution control for less money.

Command and control regulations may result in pollution levels that are lower or higher than the economically optimum level; for this reason, they are not popular with economists.

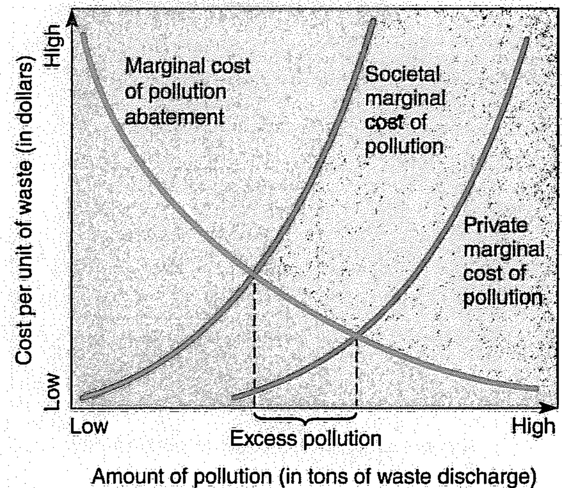



**Figure 2.11 Inefficiency arising from different marginal costs.** This figure represents the marginal costs of pollution faced by society (red line), the private marginal cost of pollution faced by the polluter (blue line), and the marginal cost of abatement (green line). The polluter will generate pollution at the point where the private marginal cost of pollution intersects with the marginal cost of abatement. At this point, substantially more pollution is generated than is optimal from a societal perspective.

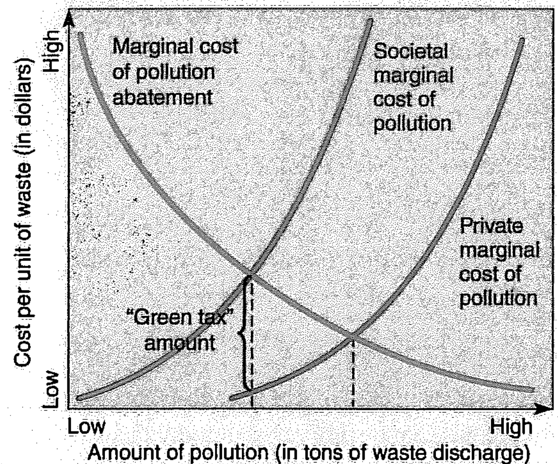



**Figure 2.12 The corrective effect of "green taxes."** This figure represents the marginal costs of pollution faced by society (red line), the private marginal cost of pollution faced by the polluter (blue line), and the marginal cost of abatement (green line). A tax is assessed on the polluter equal to the difference between the private marginal cost of pollution and the social marginal cost of pollution. As a result, the entire private marginal cost curve is shifted upward. If the tax is designed well, the cost faced by the polluter will be identical to the marginal societal cost of pollution.

Consequently, most economists, whether they have progressive or conservative views, prefer **incentive-based regulations** over command and control ones. Two major incentive-based approaches that have met with mixed policy success are environmental taxes and *tradable permits. Cost-effectiveness analysis* is a cost–benefit-based approach for prioritizing diverse environmental regulations.

A popular incentive-based approach for regulating pollution, particularly in Europe, involves imposing an **emission charge** on polluters. In effect, this charge is a tax on pollution. Economists propose such "green taxes" to correct what they perceive as distortions in the market caused by not including the external cost of driving an automobile or cutting down trees or polluting streams. The purpose of this tax is to force polluters to pay the full cost of pollution. If the tax is set at the correct level, the private marginal cost of pollution will be equivalent to the societal cost of pollution. This is depicted in **Figure 2.12**.

Many European countries have restructured their taxes to take into account environmentally destructive products and activities. Germany increased taxes on gasoline, heating oil, and natural gas while simultaneously lowering its income tax. One result was an increase in carpooling. There were concerns, however, about whether Germany's energy-intensive industries could remain competitive with industries in countries without similar energy taxes. The Netherlands introduced a tax on natural gas, electricity, fuel oil, and heating oil that includes incentives for energy efficiency; income taxes were decreased to offset the tax burden on individuals. Electricity and fuel use has declined as a result. Finland has implemented a carbon dioxide tax. Sweden introduced taxes on carbon and sulfur while simultaneously reducing income taxes. These charges increase the cost of polluting or of overusing natural resources. They also are usually *revenue-neutral* since they are offset by rebates or reductions in other taxes.

If taxes are set at the correct level, users will react to the increase in cost resulting from emission charges by decreasing pollution or decreasing consumption. However, it can be very difficult to identify the economically optimal level of taxation, and taxes on pollution are almost always set too low to have the desired effect on the behavior of people or companies. It is difficult to enact such taxes, especially in the United States, because people object to paying a tax on something they perceive as "free," and they tend to doubt that such taxes will be revenue-neutral.

While environmental taxes are designed to identify and replicate the societal cost of pollution, **tradable permits** rely on identifying the optimal level of pollution. Government sets a cap on pollution and then issues a fixed number of tradable permits (sometimes called **marketable waste-discharge permits**), allowing holders to emit a specified amount of a given pollutant, such as sulfur dioxide. A permit owner can decide whether to generate the pollution or sell the permit, ideally choosing the option that earns the most money. Once the market for permits has been established, industries that can easily reduce emissions will do so and then sell their extra permits to industries that cannot.

Tradable permits can also be designed to reduce emissions over time. The Clean Air Act Amendments of 1990 included a plan to cut acid rain–causing sulfur dioxide emissions by issuing tradable permits for coal-burning electricity utilities. The amount of allowable pollution decreases with each trade. This approach has been effective. Sulfur dioxide emissions are being reduced ahead of schedule at about 50% of the original projected cost.

**Cost-effectiveness analysis** is an increasingly common regulatory tool. Rather than setting an optimum level of pollution, cost-effectiveness analysis asks, "If we establish this regulation, how much will it cost to achieve some outcome?" Here, the outcome is lives saved or years of life saved. Thus, a regulatory action that costs $5,000 per saved life would be preferable to one that costs $10,000 per saved life. This approach could be used to compare a wide range of interventions, from banning pesticides to requiring catalytic converters on cars.

### CRITIQUES OF ENVIRONMENTAL ECONOMICS

Two classes of critiques are leveled at economic approaches to environmental regulation. First, it is difficult to assess the true costs of environmental damage by pollution and pollution abatement. The impacts of pollution on people and nature are extremely uncertain. We often do not know how effective pesticides are at eliminating pests, or whether a pesticide harms humans. If we do not understand the economic benefits of ecosystem services, they may be undervalued. Trying to place a value on quality of life or on damage to natural beauty can be highly controversial (**Figure 2.13**). As you will see in the next few chapters, the web of relationships within the environment is intricate, and environmental systems may be more vulnerable to pollution damage than is initially obvious. When the optimal level of pollution is highly uncertain, too many or too few permits may be issued, and green taxes may be set too high or too low.

Second, we do not all agree that economics is an appropriate decision tool. Economics may not take the risks of unanticipated environmental catastrophes into account and may not consider dynamic changes over time. Utilitarian economics does not account for fairness, so even if society were better off overall, some individuals might lose out. Many people distrust economic approaches to environmental regulation, since they are so strongly associated with industry groups. Economists assign prices based on what people can or do pay for things. This means that the knowledge that a pristine stream or songbird exists will not have much impact in an economic assessment. Additionally, economics dictates that if it is inefficient to save a species, we should not do so. This idea clashes with many religious and ethical beliefs.

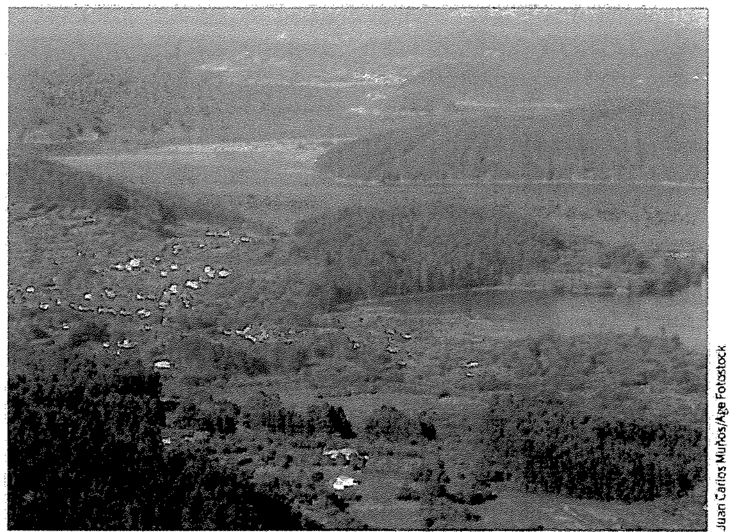



**Figure 2.13 Agriculture, timber, and scenic beauty at Coruña, Spain.** The value of the environment derives from many factors that constitute a complex, interrelated system. These factors include aesthetics, recreation, agriculture, real estate, and ecosystem services. It can be difficult or impossible to accurately assess the monetary value of all possible options for an area such as this one.

### NATURAL RESOURCES, THE ENVIRONMENT, AND NATIONAL INCOME ACCOUNTS

Because much of our economic well-being flows from natural, rather than human-made, assets, we should include the use and misuse of natural resources and the environment in national income accounts. **National income accounts** represent the total income of a nation for a given year. Two measures used in national income accounting are *gross domestic product (GDP)* and *net domestic product (NDP)*. Both GDP and NDP provide estimates of national economic performance used to make important policy decisions.

Unfortunately, current national income accounting practices are misleading and incomplete because they do not incorporate environmental factors. At least two important conceptual problems affect the way national income accounts currently handle the economic use of natural resources and the environment. These problems involve costs and benefits of pollution control and depletion of **natural capital**, which refers to Earth's resources and processes that sustain living organisms (**Figure 2.14**).

**Natural Resource Depletion** If a firm produces some product (output) but in the process wears out a portion of its plant and

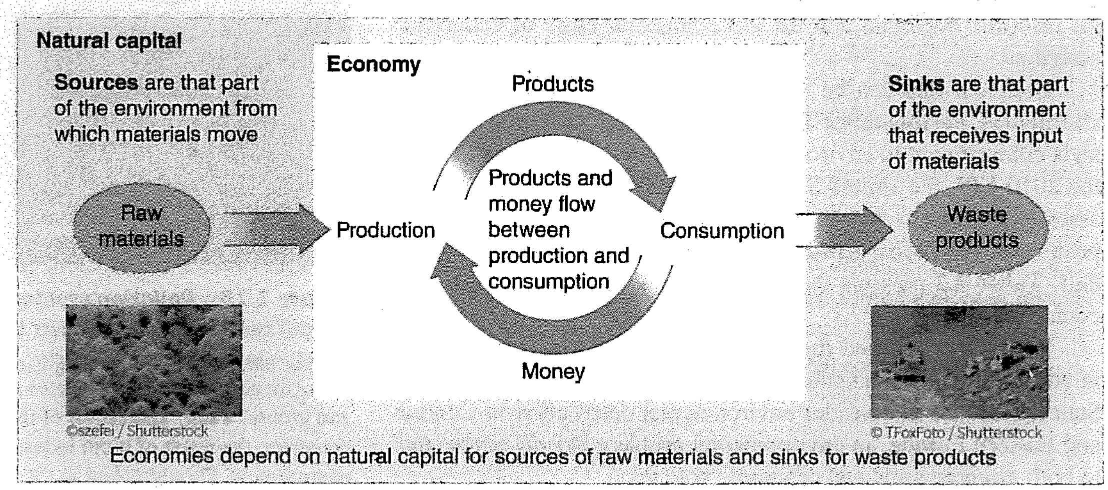



**Figure 2.14 Natural capital and the environment.** Goods and services (products) and money (to pay for the products) flow between businesses (production) and consumers (consumption). Economies depend on natural capital to provide sources for raw materials and sinks for waste products.

equipment, the firm's output is counted as part of GDP, but the depreciation of capital is subtracted in the calculation of NDP. Thus, NDP is a measure of the net production of the economy after a deduction for used-up capital. In contrast, when an oil company drains oil from an underground field, the value of the oil produced is counted as part of the nation's GDP, but no offsetting deduction to NDP is made to account for the nonrenewable resources used up.

**The Cost and Benefits of Pollution Control at the National Level** Imagine that a company has the following choices: It can produce $100 million worth of output and, in the process, pollute the local river by dumping its wastes. Alternatively, by properly disposing of its wastes, it can avoid polluting but will only get $90 million of output. Under current national income accounting rules, if the firm chooses to pollute, its contribution to GDP is larger ($100 million rather than $90 million). National income accounts attach no explicit value to a clean river. In an ideal accounting system, the economic cost of environmental degradation (loss of natural capital) would be subtracted in the calculation of a firm's contribution to GDP, and activities that improve the environment—because they provide real economic benefits—would be added to GDP.

Discussing the national income accounting implications of resource depletion and pollution may seem to trivialize these important problems. However, because GDP and related statistics are used regularly in policy analyses, abstract questions of measurement may turn out to have significant effects. Economic development experts have expressed concern that some poor countries, in attempting to raise their GDPs as quickly as possible, overexploit their natural capital and impair the environment. If "hidden" resource and environmental costs were explicitly incorporated into official measures of economic growth, policies that harm the environment might be modified.

Similarly, in industrialized countries, political debates about the environment have sometimes emphasized the impact on GDP of proposed pollution-control measures rather than the impact on overall economic welfare. Better accounting for environmental quality might refocus these debates on the more relevant question of whether, for any given environmental proposal, the benefits (economic and noneconomic) exceed the cost. One option is to replace GDP and NDP with a more comprehensive measure of national income accounting that includes estimates of both natural resource depletion and the environmental costs of economic activities.

One tool that can be used alongside the GDP is the **Environmental Performance Index (EPI)**, which assesses a country's commitment to environmental and resource management. In the 2010 EPI, the United States ranked 61st out of 163 countries assessed, which is below the rankings of most Western European countries. Most African countries are ranked in the bottom half. **Table 2.2** presents the 2010 EPI rankings of some selected countries.

We have examined the roles of government and economics in addressing environmental concerns, particularly in the United States. Now let us consider environmental destruction in Central and Eastern Europe, an environmental problem closely connected to both governmental and economic policies.

**Table 2.2 Environmental Performance Index Scores and Rankings for Select Countries**

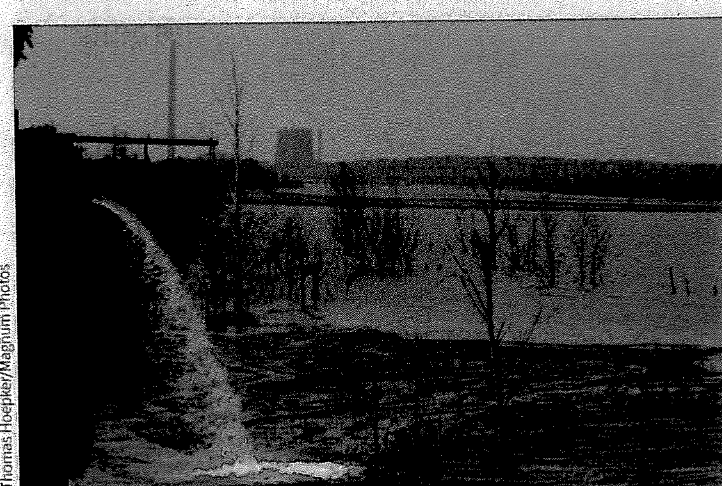
| *Country* | *2010 EPI Score* | *2010 EPI Ranking** |
|---|---|---|
| New Zealand | 73.4 | 15 |
| Sweden | 86.0 | 4 |
| Finland | 74.7 | 12 |
| United Kingdom | 74.2 | 14 |
| Canada | 66.4 | 46 |
| Japan | 72.5 | 20 |
| Iceland | 93.5 | 1 |
| Costa Rica | 86.4 | 3 |
| United States | 63.5 | 61 |
| Mexico | 67.3 | 43 |
| China | 49.0 | 121 |
| Sierra Leone | 32.1 | 163 |
| India | 48.3 | 123 |
| Niger | 37.6 | 158 |

Canada ranks highest among North American countries. The lowest-ranked countries are in sub-Saharan Africa.
*Out of 163 countries
*Source:* www.yale.edu/epi

*CASE IN POINT*

## ENVIRONMENTAL PROBLEMS IN CENTRAL AND EASTERN EUROPE

The fall of the Soviet Union and communist governments in Central and Eastern Europe during the late 1980s revealed a grim legacy of environmental destruction (**Figure 2.15**). Over the previous decades, the value of natural capital had been ignored. Water was so poisoned from raw sewage and chemicals that it could not be used for industrial purposes, let alone for drinking. Unidentified



© Thomas Hoepker/Magnum Photos

**Figure 2.15 Pollution problems in former communist countries.** This section of a river near Espenhain in Saxony is covered in a scummy layer of chemical wastes. Note the coal-fired power plant in the background, one of many sources that contaminated soils, surface water, and ground water. Thousands of these sites exist in former communist countries, the result of rapid industrialization without regard for the environment. Photographed in the late 1990s.

chemicals leaked out of dumpsites into the surrounding soil and water, while fruits and vegetables were grown nearby in chemical-laced soil. Power plants emitted soot and sulfur dioxide into the air, producing a persistent chemical haze. Buildings and statues eroded, and entire forests died because of air pollution and acid rain. Crop yields fell despite intensive use of chemical pesticides and fertilizers. One of the most polluted areas in the world was the "Black Triangle," which consisted of the bordering regions of the former East Germany, northern Czech Republic, and southwest Poland.

Many Central and Eastern Europeans suffered from asthma, emphysema, chronic bronchitis, and other respiratory diseases as a result of breathing the filthy, acrid air. By the time most Polish children were 10 years old, they suffered from chronic respiratory diseases or heart problems. The levels of cancer, miscarriages, and birth defects were extremely high. Life expectancies are still lower in Eastern Europe than in other industrialized nations; in 2011, the average Eastern European lived to age 71, which was 10 years less than the average Western European.

The economic assumption behind communism was one of high production and economic self-sufficiency, regardless of damages to the environment and natural resources, and so pollution in communist-controlled Europe went largely unchecked. Meeting industrial production quotas always took precedence over environmental concerns, even though production was not carried out for profit. It was acceptable to pollute because clean air, water, and soil were granted no economic value. The governments supported heavy industry—power plants, chemicals, metallurgy, and large machinery—at the expense of the more environmentally benign service industries. As a result, Central and Eastern Europe were overindustrialized with old plants that lacked pollution-abatement equipment.

Communism did little to encourage resource conservation, which can curb pollution. Neither industries nor individuals had incentives to conserve energy because energy subsidies and lack of competition allowed power plants to provide energy at prices far below its actual cost.

More recently, while switching from communism to democracies with market economies, Central and Eastern European governments have faced the overwhelming responsibility of improving the environment. Although no political system in transition will make the environment its first priority, several countries have formulated environmental policies based on the experiences of the United States and Western Europe over the past several decades. However, experts predict it will take decades to clean up the pollution legacy of communism. How much will it cost? The figures are staggering. For example, according to one United Nations estimate, improving the environment in what was formerly East Germany will cost up to $300 billion. This represents the loss of natural capital during the 1960s, 1970s, and 1980s. Eastern Europeans today are paying the costs of their parents' environmental neglect.

The environment of countries in the former Soviet bloc is slowly improving. Some, such as Hungary, Poland, and the Czech Republic, have been relatively successful in moving toward market economies. They generate enough money to invest in environmental cleanup. Latvia, Lithuania, and Slovakia ranked above the United States in the 2010 EPI Assessment. In other countries, such as Romania and Bulgaria, the transition to a market economy has not been as smooth. Economic recovery has been slow in these countries, and severe budgetary problems have forced the environment to take a backseat to political and economic reform. ■

## ENVIRONEWS ON CAMPUS

### Greening Higher Education

No longer restricting their environmental education to the classroom, students at many colleges and universities are identifying environmental problems on their campuses, then mapping out and implementing solutions. The tremendous success of many of these efforts has required understanding the campus as a system and demands the cooperation of faculty, administrators, staff, and students. Real-life environmental situations become educational opportunities. Notable examples include the following:

- The 2010 Game Day Challenge, in which 77 colleges and universities diverted over 2,500 tons of waste from landfills during home football game days.
- The Rebel Recycling program at the University of Nevada–Las Vegas, which accepts materials from off campus and collects reusable materials during dorm moveouts. The program was based on the senior thesis of an environmental studies major who continues to run it.
- Participation by hundreds of campuses in the American College and University Presidents' Climate Commitment.
- The reduction of hazardous wastes in chemistry labs across the United States, a result of a student/faculty effort to develop "microscale" experiments at Bowdoin College in Maine.

Overall, student efforts nationally include recycling programs on 80% of campuses and have resulted in a total annual savings of nearly $17 million from 23 campus conservation projects, ranging from transportation initiatives to energy and water conservation, reuse and recycling, and composting. Organizations such as the Campus Ecology program associated with the National Wildlife Federation, the Sierra Student Coalition, the Campus Climate Challenge, and the American Association of Sustainability in Higher Education reflect an increasing level of environmental stewardship found at the nation's institutions of higher learning.

See www.aashe.org

*REVIEW*

1. What do economists mean by "efficient" regulation?
2. When might command and control regulations be more or less effective than economics-based policies?
3. What does the EPI measure that the GNP does not?

## Environmental Justice

*LEARNING OBJECTIVE*

- Define *environmental justice* and explain why climate change is an environmental justice issue.

Over the past several decades, there has been increasing recognition that low-income and minority communities in both rural and urban areas face more environmental threats such as pollution and hazardous waste facilities and have fewer environmental amenities such as parks, trees, and clean air. At the same time, members of those communities have less of a voice in planning, including decisions about siting industrial facilities, sanitary landfills, and major transportation routes. Beginning in the late 1970s, environmental sociologist **Robert Bullard** at Clark Atlanta University identified patterns of injustice in Houston. For example, Bullard found that six of Houston's eight incinerators were located on less expensive land in predominantly black neighborhoods.

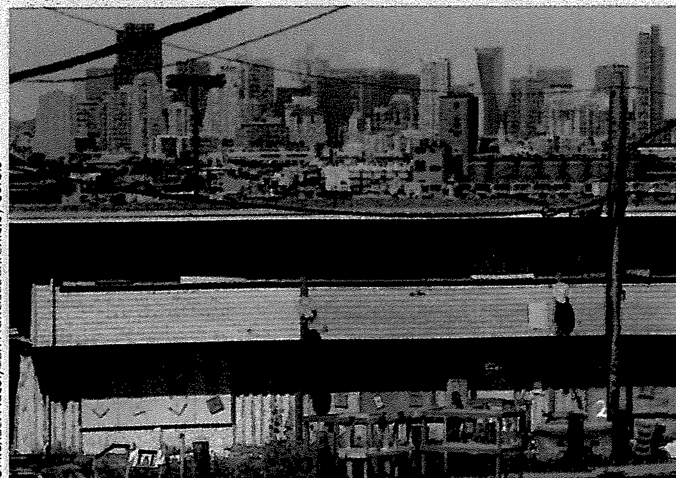
In addition, residents of low-income communities frequently have less access to other factors that influence health, including quality healthcare, fresh foods, and educational opportunities. The high incidence of asthma in many minority communities is an example of a health condition that may be caused or exacerbated by exposure to environmental pollutants. Few studies have examined how environmental pollutants interact with other socioeconomic factors to cause health problems. Those studies that have been done often fail to conclusively tie exposure to environmental pollutants to the health problems of poor and minority communities.

A 1997 health study of residents in San Francisco's Bayview–Hunters Point area found that hospitalizations for chronic illnesses were almost four times higher than the state average. Bayview–Hunters Point is heavily polluted. It has 700 hazardous waste facilities, 325 underground oil storage tanks, and two Superfund sites. Currently, little scientific evidence shows to what extent a polluted environment is responsible for the disproportionate health problems of poor and minority communities. Progress is being made: The EcoCenter at Heron's Head Park Partnership won a 2010 Achievements in Environmental Justice Award from the EPA for developing an environmental justice education center for the Bayview–Hunters Point neighborhoods (**Figure 2.16**).

### ENVIRONMENTAL JUSTICE AND ETHICAL ISSUES

Environmental decisions such as where to locate a hazardous waste landfill have important ethical dimensions. The most basic ethical dilemma centers on the rights of the poor and disenfranchised versus the rights of the rich and powerful. Whose rights should have priority in these decisions? The challenge of **environmental justice** is to find and adopt equitable solutions that respect all groups of people, including those not yet born. Viewed ethically, environmental justice is a fundamental human right. Although we may never completely eliminate environmental injustices of the past, we have a moral imperative to prevent them today so that the negative effects of pollution do not disproportionately affect any segment of society.

**environmental ...stice** The right of ... citizen, regardless ...f age, race, gender, class, or other fac... ...) adequate protec... ...om environmental hazards.



©Michael Macor/San Francisco Chronicle / Corbis

**Figure 2.16 Bay View - Hunters Point.** This housing project was among the last parts of the old neighborhood to be replaced.

In response to these concerns, a growing environmental justice movement has emerged at the grassroots level as a strong motivator for change. Advocates of the environmental justice movement call for special efforts to clean up hazardous sites in low-income neighborhoods, from inner-city streets to rural communities. Many environmental justice groups base their demands on the inherent "rightness" of their position. Other groups want science to give their demands legitimacy. Many advocates cite the need for more research on human diseases that environmental pollutants may influence.

### MANDATING ENVIRONMENTAL JUSTICE AT THE FEDERAL LEVEL

In 1994, President Clinton signed an executive order requiring all federal agencies to develop strategies and policies to ensure that their programs do not discriminate against poor and minority communities when decisions are made about where future hazardous facilities are located. The first response to President Clinton's initiative came in 1997 when the Nuclear Regulatory Commission (NRC) rejected a request to build a uranium processing plant near two minority neighborhoods in northern Louisiana. The commission decided that racial considerations were a factor in site selection because the applicant had ruled out all potential sites near predominantly white neighborhoods. This NRC decision sent a message that the U.S. government will protect the rights of vulnerable members of society.

### ENVIRONMENTAL JUSTICE AT THE INTERNATIONAL LEVEL

Environmental justice applies to countries as well as to individuals (**Figure 2.17**). Although it is possible to reduce and dispose of

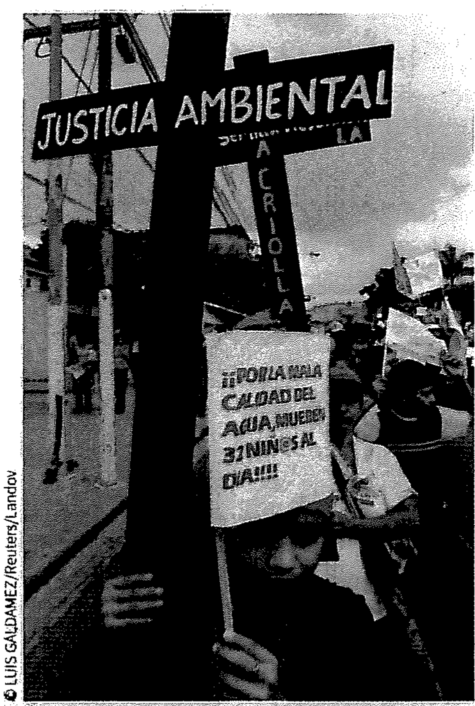





**Figure 2.17 International environmental justice.** Protestors march for "justicia ambiental," or environmental justice. Photographed in San Salvador.

waste in an environmentally sound manner, industrialized countries have sometimes chosen to send their waste to other countries. (As industrialized nations develop more stringent environmental standards, disposing of hazardous waste at home becomes much more expensive than sending it to a developing nation, where property values and labor costs are lower.) Some waste is exported for legitimate recycling, but other waste is exported strictly for disposal.

The export of solid and hazardous wastes by the United States, Canada, Japan, and the European Union was highly controversial in the 1980s. Developing nations in Africa, Central and South America, and the Pacific Rim of Asia, as well as Eastern and Central European countries, often imported hazardous wastes in return for hard currency. In 1989, the UN Environment Programme developed a treaty, the **Basel Convention**, to restrict the international transport of hazardous waste. Originally, the treaty allowed countries to export hazardous waste only with the prior informed consent of the importing country as well as of any countries that the waste passed through in transit. In 1995, the Basel Convention was amended to ban the export of *any* hazardous waste from industrialized to developing countries.

At the 1996 meeting of the Association for the Advancement of Sustainability in Higher Education, scholar **Bill McKibben** described climate change not only as an environmental justice issue but also as "the greatest social justice issue of all times." He argues that more than any other issue in history, climate change has the most inequitable distribution of benefits (the use of fossil fuels by a small but very wealthy percentage of the world's population) and risks (the adverse effects of climate change on a large but very poor percentage of the world's population).

*REVIEW*

1. Is environmental justice a local issue, an international issue, or both? Explain.

## Environmental Ethics, Values, and Worldviews

*LEARNING OBJECTIVES*

- Define *environmental ethics.*
- Define *environmental worldview* and discuss distinguishing aspects of the Western and deep ecology worldviews.

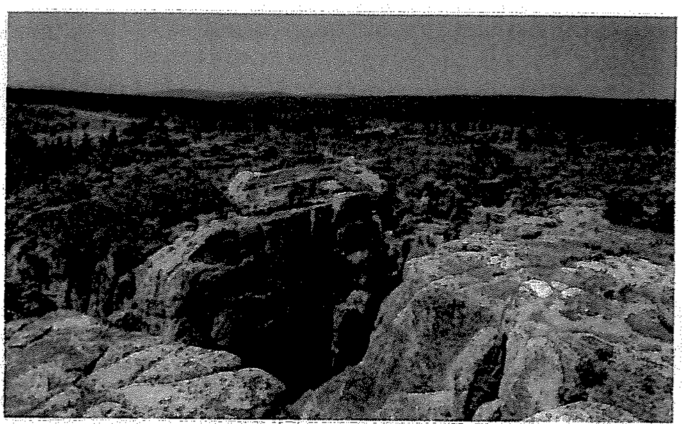
We now shift our attention to the worldviews of different individuals and societies and how those worldviews affect our ability to understand and solve sustainability problems. **Ethics** is the branch of philosophy that is derived through the logical application of human values. These **values** are the principles that an individual or society considers important or worthwhile. Values are not static entities but change as societal, cultural, political, and economic priorities change. Ethics helps us determine which forms of conduct are morally acceptable or unacceptable, right or wrong. Ethics plays a role in whatever types of human activities involve intelligent judgment and voluntary action. When values conflict, ethics helps us choose which value is better, or worthier, than other values.

### ENVIRONMENTAL ETHICS

**Environmental ethics** examines moral values to determine how humans should relate to the natural environment. Environmental ethicists consider such questions as the role we should play in determining the fate of Earth's resources, including other species. Another question is whether we should develop an environmental ethic that is acceptable in the short term for us as individuals but also in the long term for our species and the planet. These are difficult intellectual issues that involve political, economic, societal, and individual trade-offs.

**environmental ethics** A field of applied ethics that considers the moral basis of environmental responsibility and the appropriate extent of this responsibility.

Environmental ethics considers not only the rights of people living today, both individually and collectively, but also the rights of future generations (**Figure 2.18**). This aspect of environmental ethics is critical because the impacts of today's activities and technologies are changing the environment. In some cases, these impacts may be felt for hundreds or even thousands of years. Addressing issues of environmental ethics puts us in a better position to use science, government policies, and economics to achieve long-term environmental sustainability.



©Jon Bilous / Shutterstock

**Figure 2.18 Dolly Sods National Wilderness.** The United States has chosen to protect many areas, such as the Dolly Sods National Wilderness in West Virginia, so that they will be available for enjoyment and use by future generations.

## ENVIRONEWS

### Religion and the Environment

A new degree of commitment to environmental issues has grown steadily in many religious faiths and organizations. Many of the world's major religions have collaborated in conferences on religious perspectives and the natural environment. Here are several examples:

- In 2000, more than 1,000 religious leaders met at the Millennium World Peace Summit of Religious and Spiritual Leaders. Protecting the environment was a major topic of discussion.
- In 2001, the U.N. Environment Programme and the Islamic Republic of Iran sponsored an International Seminar on Religion, Culture, and Environment. They considered ways to counter environmental degradation.
- In 2006, the Evangelical Climate Initiative, which includes traditionally conservative evangelicals in the United States, identified global warming as an important religious issue requiring responsible stewardship and attention to future generations.
- The 2010 Baha'i Social and Economic Development Conference focused on the role of religion in dealing with global environmental challenges.
- In 2014, Roman Catholic Pope Francis I identified climate change as a "moral issue."
- On April 3, 2014, evangelical Christians around the United States gathered for a "Day of Prayer and Action" on climate change.

## ENVIRONMENTAL WORLDVIEWS

Each of us has a particular **worldview**—a commonly shared perspective based on a collection of our basic values that helps us make sense of the world, understand our place and purpose in it, and determine right and wrong behaviors. These worldviews lead to behaviors and lifestyles that may or may not be compatible with environmental sustainability. Some worldviews share certain fundamental beliefs, whereas others are mutually exclusive. A worldview that is considered ethical in one society may be considered irresponsible or even sacrilegious in another. The following are two extreme, opposing **environmental worldviews**: the Western worldview and the deep ecology worldview. These two worldviews, admittedly broad generalizations, are near opposite ends of a spectrum of worldviews relevant to problems of global sustainability, and each approaches environmental responsibility in a radically different way.

**environmental worldview** A worldview that helps us make sense of how the environment works, our place in the environment, and right and wrong environmental behaviors.

The **Western worldview**, also known as the *expansionist worldview*, is *anthropocentric* (human-centered) and utilitarian. This perspective mirrors the beliefs of the eighteenth-century *frontier attitude*, a desire to conquer and exploit nature as quickly as possible. The Western worldview also advocates the inherent rights of individuals, accumulation of wealth, and unlimited consumption of goods and services to provide material comforts. According to the Western worldview, humans have a primary obligation to humans and are therefore responsible for managing natural resources to benefit human society. Thus, any concerns about the environment are derived from human interests.

**Western worldview** An understanding of our place in the world based on human superiority over nature, the unrestricted use of natural resources, and increased economic growth to manage an expanding industrial base to benefit society.

The **deep ecology worldview** is a diverse set of viewpoints that dates from the 1970s and is based on the work of the late **Arne Naess**, a Norwegian philosopher, and others. The principles of deep ecology, as expressed by Arne Naess in *Ecology, Community, and Lifestyle*, include the following:

**deep ecology worldview** An understanding of our place in the world based on harmony with nature, a spiritual respect for life, and the belief that humans and all other species have an equal worth.

1. All life has intrinsic value. The value of nonhuman life-forms is independent of the usefulness they may have for narrow human purposes.
2. The richness and diversity of life-forms contribute to the flourishing of human and nonhuman life on Earth.
3. Humans have no right to reduce this richness and diversity except to satisfy vital needs.
4. Present human interference with the nonhuman world is excessive, and the situation is rapidly worsening.
5. The flourishing of human life and cultures is compatible with a substantial decrease in the human population. The flourishing of nonhuman life requires such a decrease.
6. Significant improvement of life conditions requires changes in economic, technological, and ideological structures.
7. The ideological change is mainly that of appreciating the quality of life rather than adhering to a high standard of living.
8. Those who subscribe to the foregoing points have an obligation to participate in the attempt to implement the necessary changes.

Compared to the Western worldview, the deep ecology worldview represents a radical shift in how humans relate themselves to the environment. The deep ecology worldview stresses that all forms of life have the right to exist and that humans are not different or separate from other organisms. Humans have an obligation to themselves and to the environment. The deep ecology worldview advocates sharply curbing human population growth. It does not favor returning to a society free of today's technological advances but instead proposes a significant rethinking of our use of current technologies and alternatives. It asks individuals and societies to share an inner spirituality connected to the natural world.

Most people today do not fully embrace either the Western worldview or the deep ecology worldview. The Western worldview emphasizes the importance of humans as the overriding concern in the grand scheme of things. In contrast, the deep ecology worldview is **biocentric** (life-centered) and views humans as one species among others. The planet's natural resources could not support its more than 7 billion humans if each consumed the high level of goods and services sanctioned by the Western worldview. On the other hand, if all humans adhered completely to the tenets of deep ecology, it would entail giving up many of the material comforts and benefits of modern technology.

The world as envisioned by the deep ecology worldview could support only a fraction of the existing human population (recall the discussion of ecological footprints in Chapter 1). These worldviews, although not practical for widespread adoption, are useful to keep in mind as you examine various environmental issues in later chapters. In the meantime, think about your own worldview and discuss it with others. Listen carefully to their worldviews, which will probably be different from your own. Thinking leads to actions, and actions lead to consequences. What are the short-term and long-term consequences of your particular worldview? We must develop and incorporate a long-lasting, environmentally sensitive worldview into our culture if the environment is to be sustainable for us, for other living organisms, and for future generations.

*REVIEW*

1. What is environmental ethics?
2. What are worldviews? How do Western and deep ecology worldviews differ?

## REVIEW OF LEARNING OBJECTIVES WITH SELECTED KEY TERMS

**• Briefly outline the environmental history of the United States.**

The first two centuries of U.S. history were a time of widespread environmental exploitation. During the 1700s and early 1800s, Americans saw nature primarily as resources to be used. During the nineteenth century, naturalists became concerned about conserving natural resources. The earliest conservation legislation revolved around protecting land—forests, parks, and monuments. By the late twentieth century, environmental awareness had become pervasive, and a suite of environmental laws were in place.

**• Describe the environmental contributions of the following people: George Perkins Marsh, Theodore Roosevelt, Gifford Pinchot, John Muir, Aldo Leopold, Wallace Stegner, Rachel Carson, and Paul Ehrlich.**

**George Perkins Marsh** wrote about humans as agents of global environmental change. **Theodore Roosevelt** appointed **Gifford Pinchot** as the first head of the U.S. Forest Service. Pinchot supported expanding the nation's forest reserves and managing forests scientifically. The Yosemite and Sequoia National Parks were established, largely in response to the efforts of naturalist **John Muir**. In *A Sand County Almanac*, **Aldo Leopold** wrote about humanity's relationship with nature. **Wallace Stegner** helped create support for passage of the Wilderness Act of 1964. **Rachel Carson** published *Silent Spring*, alerting the public to the dangers of uncontrolled pesticide use. **Paul Ehrlich** wrote *The Population Bomb*, which raised the public's awareness of the dangers of overpopulation.

**• Distinguish between utilitarian conservationists and biocentric preservationists.**

A **utilitarian conservationist** is a person who values natural resources because of their usefulness for practical purposes but uses them sensibly and carefully. A **biocentric preservationist** is a person who believes in protecting nature because all forms of life deserve respect and consideration.

**• Explain why the National Environmental Policy Act is the cornerstone of U.S. environmental law.**

The **National Environmental Policy Act (NEPA)**, passed in 1970, stated that the federal government must consider the environmental impact of a proposed federal action, such as financing a highway or constructing a dam. NEPA established the **Council on Environmental Quality** to monitor required **environmental impact statements (EISs)** and report directly to the president.

**• Explain how environmental impact statements provide powerful protection of the environment.**

By requiring EISs that are open to public scrutiny, NEPA initiated serious environmental protection in the United States. NEPA allows citizen suits, in which private citizens take violators, whether they are private industries or government-owned facilities, to court for noncompliance.

**• Explain why economists prefer efficient solutions to environmental problems.**

Economists assume that individuals behave as **rational actors** who seek to maximize **utility**. Groups of individuals behaving according to these assumptions result in economic **efficiency**, the greatest possible total societal benefit. Solutions that are inefficient will spend more on abatement than the pollution costs or will spend less on abatement than pollution reductions are worth.

- **Describe command and control regulation, incentive-based regulation, and cost-effectiveness analysis.**

Governments often use **command and control regulations**, which are pollution-control laws that require specific technologies. **Incentive-based regulations** are pollution-control laws that work by establishing emission targets and providing industries with incentives to reduce emissions. **Cost-effectiveness analysis** is an economic tool used to estimate costs associated with achieving some goal, such as saving a life.

- **Give two reasons why the national income accounts are incomplete estimates of national economic performance.**

**National income accounts** are a measure of the total income of a nation's goods and services for a given year. An **externality** is a harmful environmental or social cost that is borne by people not directly involved in buying or selling a product. Currently, national income accounting does not include estimates of externalities such as depletion of **natural capital** and the environmental cost of economic activities.

- **Define *environmental justice* and explain why climate change is an environmental justice issue.**

**Environmental justice** is the right of every citizen, regardless of age, race, gender, social class, or other factor, to adequate protection from environmental hazards. The primary benefit associated with climate change is energy from fossil fuels, which are available to the world's wealthier people, while the risks of climate change are spread across a much larger group of much poorer people.

- **Define *environmental ethics*.**

**Environmental ethics** is a field of applied **ethics** that considers the moral basis of environmental responsibility and the appropriate extent of this responsibility. Environmental ethicists consider how humans should relate to the natural environment.

- **Define *environmental worldview* and discuss distinguishing aspects of the Western and deep ecology worldviews.**

An **environmental worldview** is a worldview that helps us make sense of how the environment works, our place in the environment, and right and wrong environmental behaviors. The **Western worldview** is an understanding of our place in the world based on human superiority and dominance over nature, the unrestricted use of natural resources, and increased economic growth to manage an expanding industrial base. The **deep ecology worldview** is an understanding of our place in the world based on harmony with nature, a spiritual respect for life, and the belief that humans and all other species have an equal worth.

## Critical Thinking and Review Questions

1. Briefly describe each of these aspects of U.S. environmental history: protection of forests, establishment and protection of national parks and monuments, conservation in the mid-20th century, and the environmental movement of the late twentieth century.
2. Describe the environmental contributions of two of the following: George Perkins Marsh, Theodore Roosevelt, Gifford Pinchot, John Muir, Aldo Leopold, Wallace Stegner, Rachel Carson, or Paul Ehrlich.
3. If you were a member of Congress, what legislation would you introduce to deal with each of these problems?
   - **a.** Toxic materials from a major sanitary landfill are polluting some rural drinking-water wells.
   - **b.** Acid rain from a coal-burning power plant in a nearby state is harming the trees in your state. Loggers and foresters are upset.
   - **c.** Oceanfront property is at risk from sea-level rise caused by global warming.
4. Explain why the National Environmental Policy Act is considered the cornerstone of U.S. environmental law. Research some examples of when it has been effective and when it has not.
5. Based on what you have learned in this chapter, do you think the economy is part of the environment, or is the environment part of the economy? Explain your answer.
6. Following the 2010 oil platform collapse and associated oil spill in the Gulf of Mexico, Congress began considering new laws regulating deep-ocean oil drilling. Do you think command and control or incentive-based regulations would be more effective? Explain.
7. Can economic approaches to environmental management adequately account for the complex interactive systems that make up the environment? Why or why not?
8. The Environmental Performance Index has detractors among both environmentalists and industry groups. Based on what you have learned in this chapter, suggest reasons for each group to object to it.
9. Can economic solutions be used to address environmental justice concerns? Explain your answer.
10. Do you agree or disagree with the idea that climate change is an environmental justice issue? Explain your position.
11. Describe how environmental destruction in formerly communist countries relates to natural capital.
12. Determine whether each of these statements reflects the Western worldview, the deep ecology worldview, or both:
    - **a.** Species exist for humans to use.
    - **b.** All organisms, humans included, are interconnected and interdependent.
    - **c.** Humans and nature exist in unity.
    - **d.** Humans are a superior species capable of dominating other organisms.
    - **e.** Humans should protect the environment.
    - **f.** Nature should be used, not preserved.
    - **g.** Economic growth will help Earth manage an expanding human population.

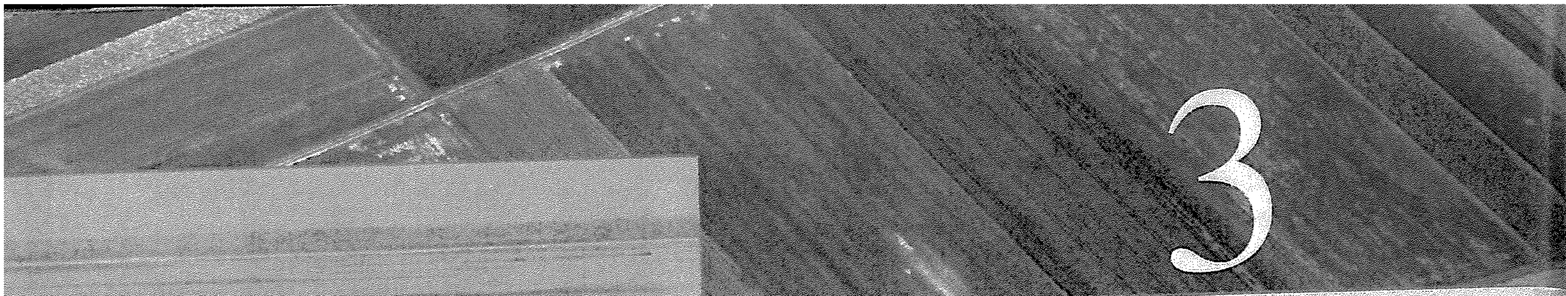
- **h.** Humans have the right to modify the environment to benefit society.
- **i.** All forms of life are intrinsically valuable and have the right to exist.

**13.** What is this cartoon trying to say? When do you think this cartoon was published?


© Steve Greenberg

## Food for Thought

Several generations ago, many people in cities raised edible plants and animals at their homes. Now, however, local zoning laws prohibit livestock and even vegetable gardens in many urban areas. Research zoning laws about growing food in your area, or a nearby town if you live in a rural area. What foods are people allowed to raise at home? What, if any, are the environmental concerns about raising plants and animals for personal consumption in urban areas?



# 3

# Ecosystems and Energy

**Cordgrass (*Spartina*) in a Chesapeake Bay salt marsh.**

A salt marsh in the Chesapeake Bay on the East Coast of the United States contains an assortment of organisms that interact with one another and are interdependent in a variety of ways. This bay is an estuary, a semi-enclosed body of water found where fresh water from a river drains into the ocean. Estuaries, which are complex *systems* under the influence of tides, gradually change from unsalty fresh water to salty ocean water. In the Chesapeake Bay, this change results in freshwater marshes at the head of the bay, brackish (moderately salty) marshes in the middle bay region, and salt marshes on the ocean side of the bay.

A Chesapeake Bay salt marsh consists of flooded meadows of cordgrass (**see photo**). Few other plants are found because high salinity and tidal inundations produce a challenging environment in which only a few plants survive. Both cordgrass and microscopic algae (photosynthetic aquatic organisms) are eaten directly by some animals, and when they die, their remains provide food for other salt marsh inhabitants.

Two major kinds of animal life are noticeably abundant in a salt marsh, insects and birds. Insects, particularly mosquitoes and horseflies, number in the millions. Birds nesting in the salt marsh include seaside sparrows, laughing gulls, and clapper rails. Many other species live in salt marshes. Large numbers of invertebrates, such as shrimps, lobsters, crabs, barnacles, worms, clams, and snails, seek refuge in the water surrounding the cordgrass. Here they eat, hide from predators to avoid being eaten, and reproduce.

Chesapeake Bay marshes are an important nursery for numerous marine fishes—spotted sea trout, Atlantic croaker, striped bass, and bluefish, to name just a few. These fishes typically reproduce in the open ocean, and the young then enter the estuary, where they grow into juveniles.

Almost no amphibians inhabit salt marshes—the salty water dries out their skin—but a few reptiles, such as the northern diamondback terrapin (a semi-aquatic turtle), have adapted. The terrapin spends its time basking in the sun or swimming in the water searching for food—snails, crabs, worms, insects, and fish. Although a variety of snakes live in the dry areas adjacent to salt marshes, only the northern water snake, which preys on fish, is adapted to salty water.

The meadow vole is a small rodent that lives in the salt marsh. Meadow voles are excellent swimmers and scamper about the salt marsh day and night. They eat mainly insects and cordgrass leaves, stems, and roots.

Add to all these visible plants and animals the unseen microscopic world of the salt marsh—countless algae, protozoa, fungi, and bacteria—while considering the environmental challenges these organisms face, and the complexity of a salt marsh ecosystem becomes clear.

In this chapter we begin our study of ecology, which is central to environmental science. Throughout the chapter, which focuses on energy flow, we will encounter many examples from the salt marsh ecosystem.

**In Your Own Backyard...**

*Water quality in the Chesapeake Bay has deteriorated over the years as increasing levels of sediment, sewage, and fertilizer from the land have polluted the water. Identify a body of water near where you live. Does it have similar pollution problems? Why or why not?*

## What Is Ecology?

*LEARNING OBJECTIVES*

- Define *ecology*.
- Distinguish among the following ecological levels: population, community, ecosystem, landscape, and biosphere.

**Ernst Haeckel**, a 19th-century scientist, developed the concept of **ecology** and named it—*eco* from the Greek word for "house" and *logy* from the Greek word for "study." Thus, *ecology* literally means "the study of one's house." The environment—one's house—consists of two parts, the **biotic** (living) environment, which includes all organisms, and the **abiotic** (nonliving, or physical) surroundings, which include living space, temperature, sunlight, soil, wind, and precipitation (**Figure 3.1**).

**ecology** The study systems that include interactions among anisms and between organisms and their abiotic environment.

Ecologists study the vast complex web of relationships among living organisms and their physical environment. Areas of study include, but are not limited to, why organisms are distributed the way they are, why some species are more abundant than others, how the ecological roles of different organisms in their environment vary, and how the interactions between organisms and their environment help to maintain the overall health of our living world.

The focus of ecology is local or global, specific or generalized, depending on what questions the scientist is trying to answer.

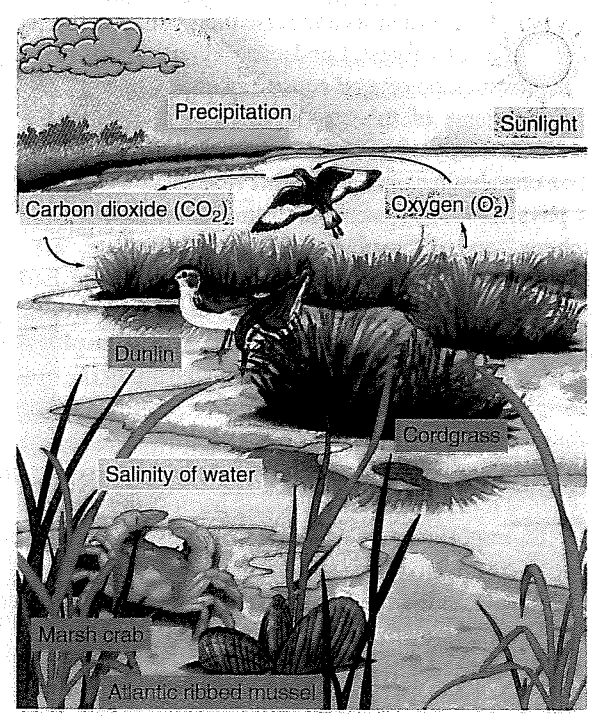



**Figure 3.1 Some abiotic and biotic components of a Chesapeake Bay salt marsh.** Shown is a mudflat at low tide. Abiotic (nonliving) components are labeled in yellow and biotic (living) components, in green.

One ecologist might determine the temperature or light requirements of a single oak species in a forest, another might study all the organisms that live in that forest, and yet another might examine how nutrients flow between the forest and surrounding areas.

Ecology is the broadest field within the biological sciences, and it is linked to every other biological discipline. The universality of ecology links subjects that are not traditionally part of biology. Geology and earth science are extremely important to ecology, especially when ecologists examine the physical environment of planet Earth. Chemistry and physics are also important; in this chapter, for example, knowledge of chemistry is necessary to understand photosynthesis, and principles of physics illuminate the laws of thermodynamics. Humans are biological organisms, and our activities have a bearing on ecology. Even economics and politics have profound ecological implications, as was discussed in Chapter 2.

How does the field of ecology fit into the organization of the biological world? Ecologists are most interested in the levels of biological organization that include or are above the level of the individual organism (**Figure 3.2**). Individuals of the same **species** occur in **populations**. A population ecologist might study a population of polar bears or a population of marsh grass. Population ecology is discussed in Chapter 5, and human populations in Chapters 8 and 9. Species are considered further in Chapter 16.

**species** A group of similar organisms whose members freely interbreed with one another in the wild to produce fertile offspring; members of one species generally do not interbreed with other species of organisms.

**population** A group of organisms of the same species that live in the same area at the same time.

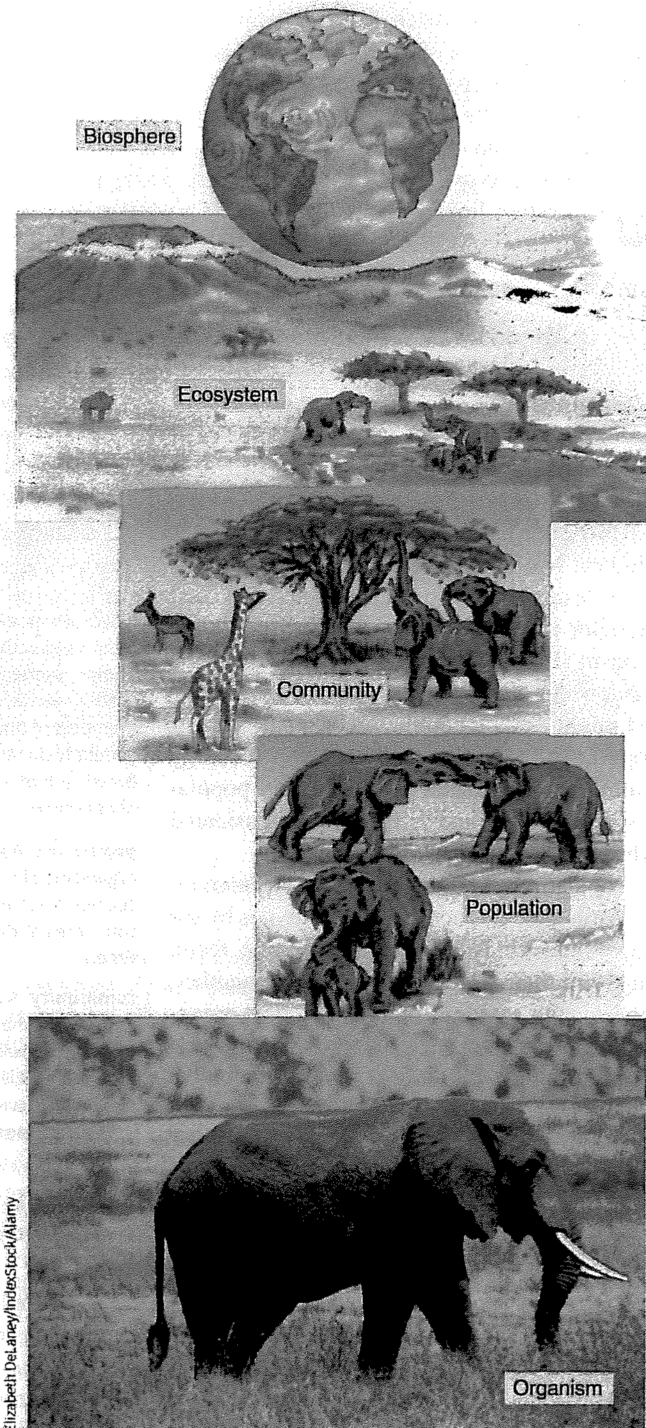
Populations are organized into **communities**. Ecologists characterize communities by the number and kinds of species that live there, along with their relationships with one another. A community ecologist might study how organisms interact with one another—including feeding relationships (who eats whom)—in an alpine meadow community or in a coral reef community (**Figure 3.3**).

**community** A natural association that consists of all the populations of different species that live and interact within an area at the same time.

*Ecosystem* is a more inclusive term than *community*. An **ecosystem** includes all the biotic interactions of a community, as well as the interactions between organisms and their abiotic environment. Like other *systems*, an ecosystem consists of multiple interacting and inseparable parts and processes that form a unified whole. An ecosystem—whether terrestrial or aquatic—is a system in which all the biological, physical, and chemical components of an area form a complex, interacting network of energy flow and materials cycling. An ecosystem ecologist might examine how energy, nutrients, organic (carbon-containing) materials, and water affect the organisms living in a desert ecosystem, a forest, or a coastal bay ecosystem.

**ecosystem** A community and its physical environment.

The ultimate goal of ecosystem ecologists is to understand how ecosystems function. This is not a simple task, but it is important because ecosystem processes collectively regulate the global cycles of water, carbon, nitrogen, phosphorus, and sulfur essential to the survival of humans and all other organisms. As humans increasingly alter ecosystems for their own uses, the




Elizabeth DeLaney/IndexStock/Alamy

**Figure 3.2 Levels of ecological organization.** Ecologists study the levels of biological organization from individual organisms to the biosphere.

natural functioning of ecosystems is changed, and we must determine whether these changes will affect the sustainability of our life-support system.

**Landscape ecology** is a subdiscipline of ecology that studies ecological processes operating over large areas. Landscape ecologists examine the connections among ecosystems found in a

Gerald Nowak/WaterFrame/Age Fotostock

**Figure 3.3 Coral reef community.** Coral reef communities have the greatest number of species and are the most complex aquatic community. This close-up of a coral reef in the Caribbean Sea off the coast of Mexico shows a green moray eel, French grunts, and several species of coral. Today many coral reefs worldwide are threatened by global climate change. How can they be protected from warming temperatures?

particular region. Consider a simple **landscape** consisting of a forest ecosystem located adjacent to a pond ecosystem. One connection between these two ecosystems might be great blue herons, which eat fishes, frogs, insects, crustaceans, and snakes along the shallow water of the pond but often build nests and raise their young in the secluded treetops of the nearby forest. Landscapes, then, are based on larger land areas that include several ecosystems.

**landscape** A region that includes several interacting ecosystems.

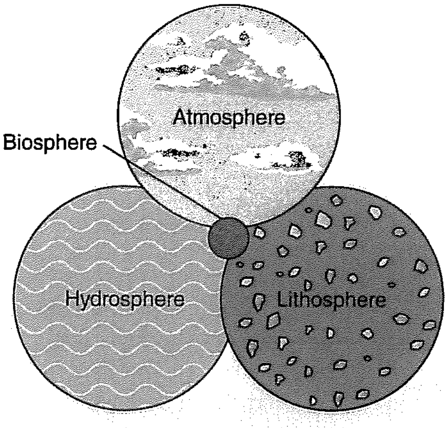
The organisms of the **biosphere**—Earth's communities, ecosystems, and landscapes—depend on one another and on the other realms of Earth's physical environment: the atmosphere, hydrosphere, and lithosphere (**Figure 3.4**). The **atmosphere** is the gaseous envelope surrounding Earth; the **hydrosphere** is Earth's supply of water—liquid and frozen, fresh and salty, groundwater and surface water. The **lithosphere** is the soil and rock of Earth's crust. Ecologists who study the biosphere examine global interrelationships among Earth's atmosphere, land, water, and organisms.

**biosphere** The parts of Earth's atmosphere, ocean, land surface, and soil that contain all living organisms.

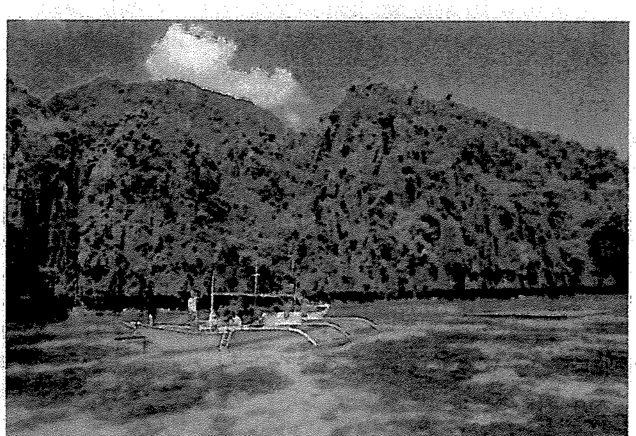
The biosphere is filled with life. Where do these organisms get the energy to live? And how do they harness this energy? Let's examine the importance of energy to organisms, which survive only as long as the environment continuously supplies them with energy. We will revisit the importance of energy as it relates to human endeavors in many chapters throughout this text.

*Review*

1. What is ecology?
2. What is the difference between a community and an ecosystem? Between an ecosystem and a landscape?




(a) Earth's four realms, represented as intersecting circles, are a system of interrelated parts.





(b) In this scene, photographed on Palawan Island, Philippines, the atmosphere contains a cumulus cloud, which indicates warm, moist air. The jagged rocks, formed from volcanic lava flows that have eroded over time, represent the lithosphere. The shallow water represents the hydrosphere. The biosphere includes the green vegetation and humans in the boat as well as the coral reefs visible as darker areas in the water.

**Figure 3.4 Earth's four realms.**

## The Energy of Life

LEARNING OBJECTIVES

- Define *energy* and explain how it is related to work and to heat.
- Use an example to contrast potential energy and kinetic energy.
- Distinguish between open and closed systems.
- State the first and second laws of thermodynamics, and discuss the implications of these laws as they relate to organisms.
- Write summary reactions for photosynthesis and cellular respiration, and contrast these two biological processes.

**Energy** is the capacity or ability to do work. In organisms, any biological work—such as growing, moving, reproducing, and maintaining and repairing damaged tissues—requires energy. Energy exists in several forms: chemical, radiant, thermal, mechanical, nuclear, and electrical. *Chemical energy* is energy stored in the bonds of molecules; for example, food contains chemical energy, and organisms use the energy released when chemical bonds are broken and new bonds form. *Radiant energy* is energy, such as radio waves, visible light, and X-rays, that is transmitted as electromagnetic waves (**Figure 3.5**). *Solar energy* is radiant energy from the sun; it includes ultraviolet radiation, visible light, and infrared radiation. *Thermal energy* is **heat** that flows from an object with a higher temperature (the heat source) to an object with a lower temperature (the heat sink). *Mechanical energy* is energy involved in the movement of matter. Some of the matter contained in atomic nuclei can be converted into *nuclear energy*. *Electrical energy* is energy that flows as charged particles. You will encounter these forms of energy throughout the text.

Biologists generally express energy in units of work (*kilojoules, kJ*) or units of heat (*kilocalories, kcal*). One kilocalorie is the energy required to raise the temperature of 1 kg of water by 1°C, equal to 4.184 kJ. The kcal is the unit that nutritionists use to express the energy content of the foods we eat.

Energy can exist as stored energy, called **potential energy**, or as **kinetic energy**, the energy of motion. Think of potential energy as an arrow on a drawn bow, which equals the work the archer did when drawing the bow to its position (**Figure 3.6**). When the string is released, the bow's potential energy is converted to the arrow's kinetic energy of motion. Similarly, the cordgrass that a meadow vole eats has chemical potential energy in the bonds of its molecules. As molecular bonds in the cordgrass are broken by cellular respiration, this energy is converted to kinetic energy and heat as the meadow vole swims in the salt marsh. Thus, energy changes from one form to another.

The study of energy and its transformations is called **thermodynamics**. When considering thermodynamics, scientists use the word *system* to refer to a group of atoms, molecules, or objects being studied.[1] The rest of the universe other than the system is known as the *surroundings*. A **closed system** is self-contained; that is, it does not exchange energy with its surroundings (**Figure 3.7**).[2] Closed systems are very rare in nature. In contrast, an **open system** exchanges energy with its surroundings. This text discusses many kinds of open systems. For example, a city is an open system with an input of energy (as well as food, water, and consumer goods). Outputs from a city system include energy (as well as manufactured goods, sewage, and solid waste). On a global scale, Earth is an open system dependent on a continual supply of energy from the sun.

Regardless of whether a system is open or closed, two laws about energy apply to all things in the universe: the first and second laws of thermodynamics.

[1] The meaning of *system* in thermodynamics is different from the meaning of *system* in environmental science (a set of components that interact and function as a whole).

[2] In thermodynamics, an *isolated system* does not exchange energy *or* matter with the surroundings.

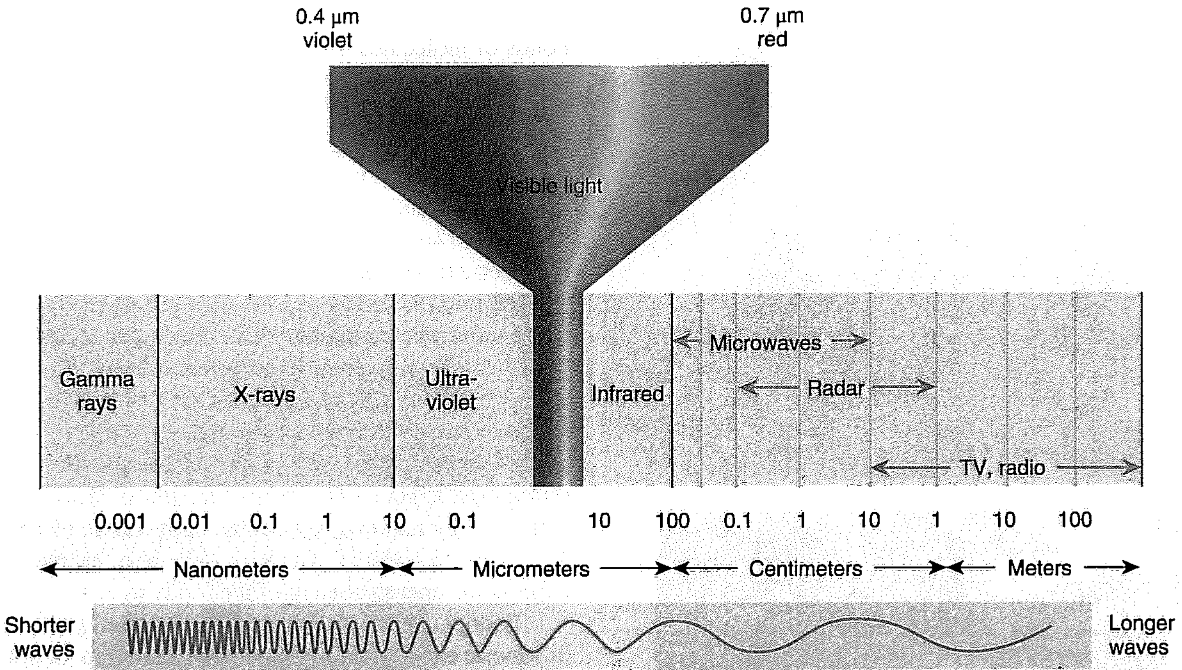
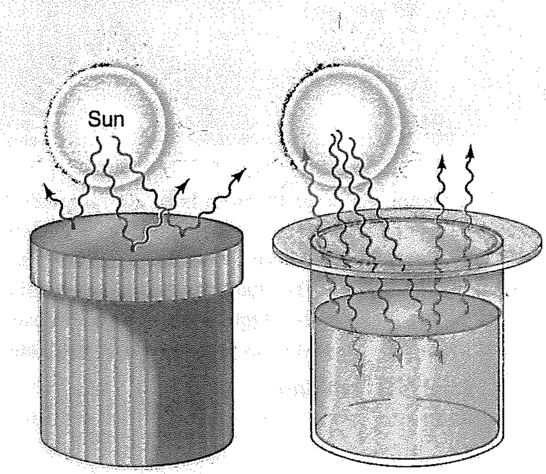



**Figure 3.5 The electromagnetic spectrum.** The shortest wavelengths are gamma rays, and the longest are TV and radio waves. Visible light occurs between ultraviolet and infrared radiation.


**Figure 3.6 Potential and kinetic energy.** Potential energy is stored in the drawn bow (shown) and is converted to kinetic energy as the arrow speeds toward its target. Photographed at the 2008 Summer Olympic Games in Beijing, China.




(a) Closed system. Energy is not exchanged between a closed system and its surroundings. A thermos bottle is an approximation of a closed system. Closed systems are rare in nature.

(b) Open system. Energy is exchanged between an open system and its surroundings. Earth is an open system because it receives energy from the sun, and this energy eventually escapes Earth as it dissipates into space.

**Figure 3.7 Closed and open systems, with regard to energy.**

## THE FIRST LAW OF THERMODYNAMICS

**-st law of thermo-dynamics** Energy nnot be created or troyed, although it n change from one form to another.

According to the **first law of thermodynamics,** an organism may absorb energy from its surroundings, or it may give up some energy into its surroundings, but the total energy content of the organism and its surroundings is always the same. As far as we know, the energy present in the universe at its formation, approximately 15–20 billion years ago, equals the amount of energy present in the universe today. This is all the energy that will ever be present in the universe. Similarly, the energy of any system and its surroundings is constant. A system may absorb energy from its surroundings, or it may give up some energy into its surroundings, but the total energy content of that system and its surroundings is always the same.

The first law of thermodynamics specifies that an organism cannot create the energy it requires to live. Instead, it must capture energy from the environment to use for biological work, a process involving the transformation of energy from one form to another. In photosynthesis, plants absorb the radiant energy of the sun and convert it into the chemical energy contained in the bonds of carbohydrate (sugar) molecules. Similarly, some of that chemical energy may later be transformed by an animal that eats the plant into the mechanical energy of muscle contraction, enabling the animal to walk, run, jump, slither, fly, or swim.

### THE SECOND LAW OF THERMODYNAMICS

As each energy transformation occurs, some energy is changed to heat that is released into the cooler surroundings. No other organism can ever reuse this energy for biological work; it is "lost" from the biological point of view. It is not really gone from a thermodynamic point of view because it still exists in the surrounding physical environment. Similarly, the use of food to enable us to walk or run does not destroy the chemical energy once present in the food molecules. After we have performed the task of walking or running, the energy still exists in the surroundings as heat.

**ond law of thermo-imics** When energy converted from one m to another, some f it is degraded into , a less usable form it disperses into the environment.

According to the **second law of thermodynamics**, the amount of usable energy available to do work in the universe decreases over time. The second law of thermodynamics is consistent with the first law; that is, the total amount of energy in the universe is not decreasing with time. However, the total amount of energy in the universe available to do work decreases over time.

Less-usable energy is more diffuse, or disorganized. **Entropy** is a measure of this disorder or randomness; organized, usable energy has low entropy, whereas disorganized energy such as heat has high entropy. Entropy is continuously increasing in the universe in all natural processes, and entropy is not reversible. Another way to explain the second law of thermodynamics, then, is that entropy, or disorder, in a system increases over time.

An implication of the second law of thermodynamics is that no process requiring an energy conversion is ever 100% efficient because much of the energy is dispersed as heat, resulting in an increase in entropy. (*Efficiency* in this context refers to the amount of useful work produced per total energy input.) An automobile engine, which converts the chemical energy of gasoline to mechanical energy, is between 20% and 30% efficient. That is, only 20% to 30% of the original energy stored in the chemical bonds of the gasoline molecules is actually transformed into mechanical energy, or work. In our cells, energy use for metabolism is about 40% efficient, with the remaining energy given to the surroundings as heat.

Organisms are highly organized and at first glance appear to refute the second law of thermodynamics. As organisms grow and develop, they maintain a high level of order and do not become more disorganized. However, organisms maintain their degree of order over time only with the constant input of energy. That is why plants must photosynthesize and why animals must eat food. When relating the second law of thermodynamics to living organisms, the organisms' surroundings must also be considered. Throughout its life, as a plant takes in solar energy and photosynthesizes, it continually breaks down the products of photosynthesis to supply its own energy needs. This breakdown releases heat into the environment. Similarly, as an animal eats and processes food to meet its energy needs, it releases heat into the surroundings. When an organism and its surroundings are taken into account, both laws of thermodynamics are satisfied.

### PHOTOSYNTHESIS AND CELLULAR RESPIRATION

Energy is stored in living things as carbon compounds. **Photosynthesis** is the biological process in which light energy from the sun is captured and transformed into the chemical energy of carbohydrate (sugar) molecules (**Figure 3.8**). Photosynthetic pigments such as *chlorophyll*, which gives plants their green color, absorb radiant energy. This energy is used to manufacture the carbohydrate glucose ($C_6H_{12}O_6$) from carbon dioxide ($CO_2$) and water ($H_2O$), a process that also releases oxygen ($O_2$).

**Photosynthesis:**

$$\mathbf{6CO_2 + 12H_2O + radiant\ energy \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2}$$

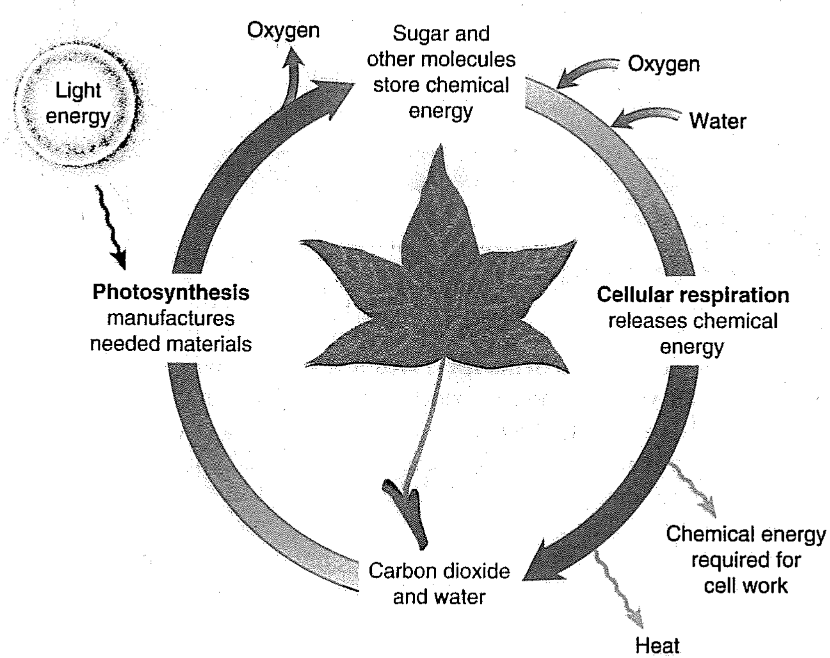
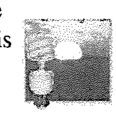



**Figure 3.8 Photosynthesis and cellular respiration make up a system.** These processes occur continuously in the cells of living organisms. Note that energy flow is *not* cyclic; energy enters living organisms as radiant energy and leaves organisms for the surroundings as heat energy. Given that increasing levels of $CO_2$ in the atmosphere are linked to climate warming, which process—photosynthesis or cellular respiration—could help reduce warming if it was increased significantly? Explain your answer.



The chemical equation for photosynthesis is read as follows: 6 molecules of carbon dioxide plus 12 molecules of water plus light energy are used to produce 1 molecule of glucose plus 6 molecules of water plus 6 molecules of oxygen. (See Appendix I, Review of Basic Chemistry.)

Plants, some bacteria, and algae perform photosynthesis, a process essential for almost all life. Photosynthesis provides these organisms with a ready supply of energy in carbohydrate molecules, which they use as the need arises. The energy can also be transferred from one organism to another—for example, from plants to the organisms that eat plants. Oxygen, which many organisms require when they break down glucose or similar foods to obtain energy, is a byproduct of photosynthesis.

The chemical energy that plants store in carbohydrates and other molecules is released within the cells of plants, animals, or other organisms through **cellular respiration**. In *aerobic* cellular respiration, molecules such as glucose are broken down in the presence of oxygen and water into carbon dioxide and water, with the release of energy (see Figure 3.8).

**Aerobic cellular respiration:**

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

Cellular respiration makes the chemical energy stored in glucose and other food molecules available to the cell for biological work, such as moving around, courting, and growing new cells and tissues. All organisms, including green plants, respire to obtain energy. Some organisms do not use oxygen for this process. *Anaerobic* bacteria that live in waterlogged soil, stagnant ponds, animal intestines, or deep-sea hydrothermal vents respire in the absence of oxygen.

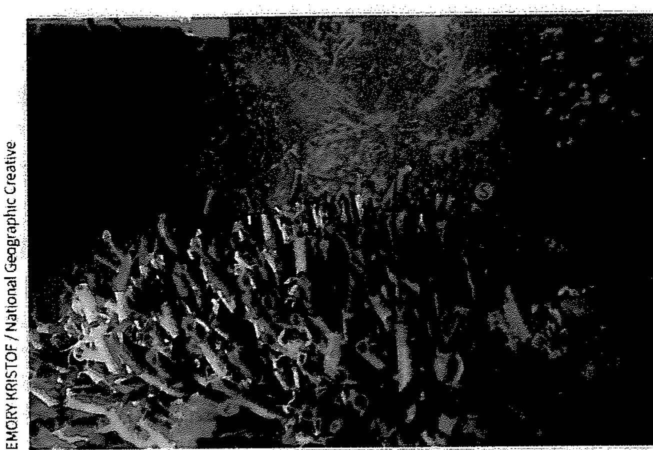
CASE IN POINT

## LIFE WITHOUT THE SUN

The sun is the energy source for almost all ecosystems. A notable exception was discovered in the late 1970s in a series of deep-sea **hydrothermal vents** in the Eastern Pacific where seawater had penetrated and been heated by the radioactive rocks below. During its time within Earth, the water had been charged with inorganic compounds, including hydrogen sulfide ($H_2S$).

Although no light is available for photosynthesis there, hydrothermal vents support a rich ecosystem that contrasts with the surrounding "desert" of the deep-ocean floor. Giant, blood-red tube worms almost 3 m (10 ft) in length cluster in great numbers around the vents (**Figure 3.9**). Other animals around the hydrothermal vents include shrimp, crabs, clams, barnacles, and mussels.

Scientists initially wondered what the ultimate source of energy is for the species in this dark environment. Most deep-sea ecosystems depend on the organic material that drifts down from surface waters; that is, they depend on energy derived from photosynthesis. But hydrothermal vent ecosystems, now known to exist in hundreds of places, are too densely clustered and too productive to depend on chance encounters with organic material from surface waters.



EMORY KRISTOF / National Geographic Creative

**Figure 3.9 Hydrothermal vent ecosystem.** Bacteria living in the tissues of these tube worms extract energy from hydrogen sulfide to manufacture organic compounds. These worms lack digestive systems and depend on the organic compounds the bacteria provide, along with materials filtered from the surrounding water. Also visible in the photograph are some crabs (white).

The base of the *food web* in these aquatic oases consists of certain bacteria that survive and multiply in water so hot (exceeding 200°C, or 392°F) that it would not remain in liquid form were it not under such extreme pressure. These bacteria function as producers, but they do not photosynthesize. Instead, they obtain energy and make carbohydrate molecules from inorganic raw materials by carrying out **chemosynthesis**. Chemosynthetic bacteria possess enzymes (organic catalysts) that cause the inorganic molecule hydrogen sulfide to react with oxygen, producing water and sulfur or sulfate. Such chemical reactions provide the energy to support these bacteria and other organisms in deep-ocean hydrothermal vents. Many of the vent animals consume the bacteria directly by filter feeding. Others, such as the giant tube worms, obtain energy from chemosynthetic bacteria that live symbiotically inside their bodies. ■

*Review*

1. Distinguish among energy, work, and heat.
2. Is water stored behind a dam an example of potential or kinetic energy? What would cause the water to convert to the other form of energy?
3. Is a rabbit an example of a closed system or an open system? Why?
4. When coal is burned in a power plant, only 3% of the energy in the coal is converted into light in a lightbulb. What happens to the other 97% of the energy? Explain your answer using the laws of thermodynamics.
5. Distinguish between photosynthesis and cellular respiration. Which organisms perform each process?

## The Flow of Energy through Ecosystems

LEARNING OBJECTIVES

- Define *energy flow*, *trophic level*, and *food web*.
- Summarize how energy flows through a food web, incorporating producers, consumers, and decomposers in your explanation.
- Describe typical pyramids of numbers, biomass, and energy.
- Distinguish between gross primary productivity and net primary productivity, and discuss human impact on the latter.

With the exception of a few ecosystems such as hydrothermal vents, energy enters ecosystems as radiant energy (sunlight), some of which plants trap during photosynthesis. The energy, now in chemical form, is stored in the bonds of organic molecules such as glucose. To obtain energy, animals eat plants, or they eat animals that ate plants. All organisms—plants, animals, and microorganisms—respire to obtain some of the energy in organic molecules. When cellular respiration breaks these molecules apart, the energy becomes available for work such as repairing tissues, producing body heat, or reproducing. As the work is accomplished, the energy escapes the organism and dissipates into the environment as heat (recall the second law of thermodynamics). Ultimately, this heat radiates into space. Once an organism has used energy, that energy becomes unusable for all other organisms. The movement of energy just described is called **energy flow**.

**ergy flow** The pas- e of energy in a one- lirection through an ecosystem.

### PRODUCERS, CONSUMERS, AND DECOMPOSERS

The organisms of an ecosystem are divided into three categories on the basis of how they obtain nourishment: producers, consumers, and decomposers (**Figure 3.10**). Virtually all ecosystems contain representatives of all three groups, which interact extensively, both directly and indirectly, with one another.

**Producers**, also called **autotrophs** (Greek *auto*, "self," and *tropho*, "nourishment"), manufacture organic molecules from simple inorganic substances, generally $CO_2$ and water, usually using the energy of sunlight. In other words, most producers perform the process of photosynthesis. Producers incorporate the chemicals they manufacture into their own bodies, becoming potential food resources for other organisms. Whereas plants are the most significant producers on land, algae and certain types of bacteria are important producers in aquatic environments. In the salt marsh ecosystem discussed in the chapter introduction, cordgrass, algae, and photosynthetic bacteria are important producers.

Animals are **consumers** that use the bodies of other organisms as a source of food energy and bodybuilding materials. Consumers are also called **heterotrophs** (Greek *heter*, "different," and *tropho*, "nourishment"). Consumers that eat producers are **primary consumers** or **herbivores** (plant eaters). Rabbits and deer are examples of primary consumers, as is the marsh periwinkle, a type of snail that feeds on algae in the salt marsh ecosystem.

**Secondary consumers** eat primary consumers, whereas **tertiary consumers** eat secondary consumers—a mouse eats plants, a snake eats the mouse, a hawk eats the snake. Both secondary and tertiary consumers are flesh-eating **carnivores** that eat other

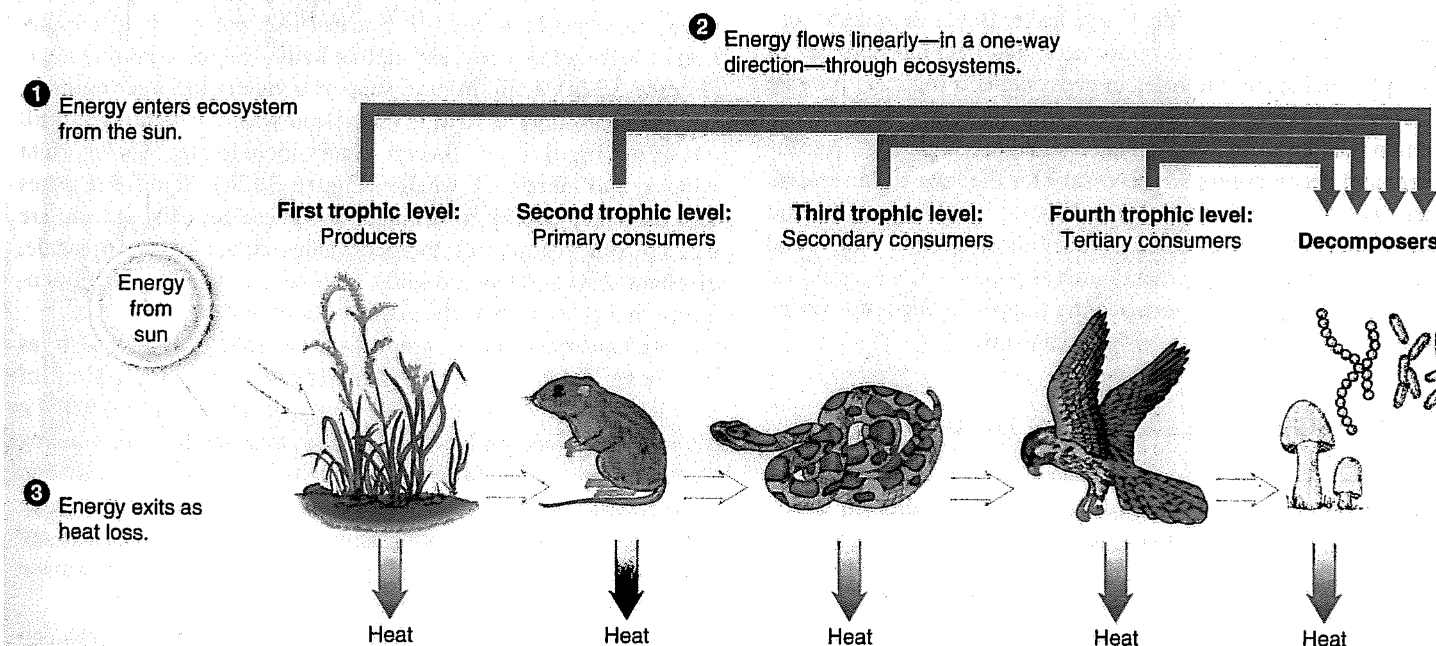



**Figure 3.10 Energy flow among producers, consumers, and decomposers.** In photosynthesis, producers use the energy from sunlight to make organic molecules. Consumers obtain energy when they eat producers or other consumers. Decomposers, such as bacteria and fungi, obtain energy from wastes and dead organic material from producers and consumers. During every energy transaction, some energy is lost to biological systems as it disperses into the environment as heat.

animals. Lions, lizards, and spiders are examples of carnivores, as are the northern diamondback terrapin and the northern water snake in the salt marsh ecosystem. Other consumers, called **omnivores**, eat a variety of organisms, both plant and animal. Bears, pigs, and humans are examples of omnivores; the meadow vole, which eats both insects and cordgrass in the salt marsh ecosystem, is also an omnivore.

Some consumers, called **detritus feeders** or **detritivores**, consume detritus, organic matter that includes animal carcasses, leaf litter, and feces. Detritus feeders, such as snails, crabs, clams, and worms, are especially abundant in aquatic environments, where they burrow in the bottom muck and consume the organic matter that collects there. Marsh crabs are detritus feeders in the salt marsh ecosystem. Earthworms, termites, beetles, snails, and millipedes are terrestrial (land-dwelling) detritus feeders. An earthworm actually eats its way through the soil, digesting much of the organic matter contained there. Detritus feeders work with microbial decomposers to destroy dead organisms and waste products.

**Decomposers**, also called **saprotrophs** (Greek *sapro*, "rotten," and *tropho*, "nourishment"), are heterotrophs that break down dead organic material and use the decomposition products to supply themselves with energy. They typically release simple inorganic molecules (e.g., $CO_2$) and mineral salts that producers can reuse. Bacteria and fungi are important decomposers. For example, during the decomposition of dead wood, sugar-metabolizing fungi first invade the wood and consume simple carbohydrates, such as glucose and maltose. When these carbohydrates are exhausted, other fungi, often aided by termites with symbiotic bacteria in their guts, complete the digestion of the wood by breaking down cellulose, the main carbohydrate of wood.

Ecosystems such as the Chesapeake Bay salt marsh contain a variety of producers, consumers, and decomposers, all of which play indispensable roles in ecosystems. Producers provide both food and oxygen for the rest of the community. Consumers maintain a balance between producers and decomposers. Detritus feeders and decomposers are necessary for the long-term survival of any ecosystem because, without them, dead organisms and waste products would accumulate indefinitely. Without microbial decomposers, important elements such as potassium, nitrogen, and phosphorus would remain permanently trapped in dead organisms, unavailable for new generations of organisms.

## THE PATH OF ENERGY FLOW: WHO EATS WHOM IN ECOSYSTEMS

In an ecosystem, energy flow occurs in **food chains**, in which energy from food passes from one organism to the next in a sequence (see Figure 3.10). Each level, or "link," in a food chain is a **trophic level** (recall that the Greek *tropho* means "nourishment"). An organism is assigned a trophic level based on the number of energy transfer steps from the source of energy to that level. Producers (organisms that photosynthesize) form the first trophic level, primary consumers (herbivores) the second trophic level, secondary consumers (carnivores) the third trophic level, and so on. At every step in a food chain are decomposers, which respire organic molecules from the carcasses and body wastes of all members of the food chain.

**trophic level** An rganism's position in food chain, which is termined by its feeding relationships.

Simple food chains rarely occur in nature because few organisms eat just one kind of organism. More typically, the flow of energy and materials through an ecosystem takes place in accordance with a range of food choices for each organism involved. In an ecosystem of average complexity, numerous alternative pathways are possible. A hawk eating a rabbit is a different energy pathway than a hawk eating a snake. A **food web** is a more realistic **model** of the flow of energy and materials through an ecosystem (**Figure 3.11**). A food web helps us visualize feeding relationships that indicate how a community is organized.

**food web** A representation of the interlocking food chains that connect all organisms in an ecosystem.

The most important thing to remember about energy flow in ecosystems is that it is linear, or one way. Energy moves along a food chain or food web from one organism to the next as long as it has not been used for biological work. Once an organism has used energy, that energy is lost as heat and is unavailable for any other organism in the ecosystem.

*CASE IN POINT*

## HOW HUMANS HAVE AFFECTED THE ANTARCTIC FOOD WEB

Although the icy waters around Antarctica may seem an inhospitable environment, a complex food web is found there. The base of the food web consists of microscopic, photosynthetic algae present in vast numbers in the well-lit, nutrient-rich water. A huge population of herbivores—tiny, shrimplike **krill**—eat these marine algae (**Figure 3.12a**). Krill, in turn, support a variety of larger animals. A major consumer of krill is the baleen whale, which filters krill out of the frigid water. Baleen whales include blue whales, right whales, and humpback whales (**Figure 3.12b**). Squid and fishes also consume krill in great quantities. These animals, in turn, are eaten by other carnivores: toothed whales such as the sperm whale, elephant seals and leopard seals, king penguins and emperor penguins, and birds such as the albatross and the petrel.

Humans have had an impact on the Antarctic food web, as they have had on most other ecosystems. Before the advent of whaling, baleen whales consumed huge quantities of krill. Until a global ban on hunting large whales was enacted in 1986, whaling steadily reduced the number of large baleen whales in Antarctic waters. As a result of fewer whales eating krill, more krill became available for other krill-eating animals, yet krill populations are thought to have been limited in part by the lack of nutrients once provided in the wastes of baleen whales.

Now that commercial whaling is regulated, it is hoped that the number of large baleen whales will slowly increase, and that appears to be the case for some species. However, the populations of most baleen whales in the Southern Hemisphere are still a fraction of their pre-whaling levels. It is not known whether baleen whales will return to their former position of dominance in terms of krill consumption in the food web. Biologists will continue to

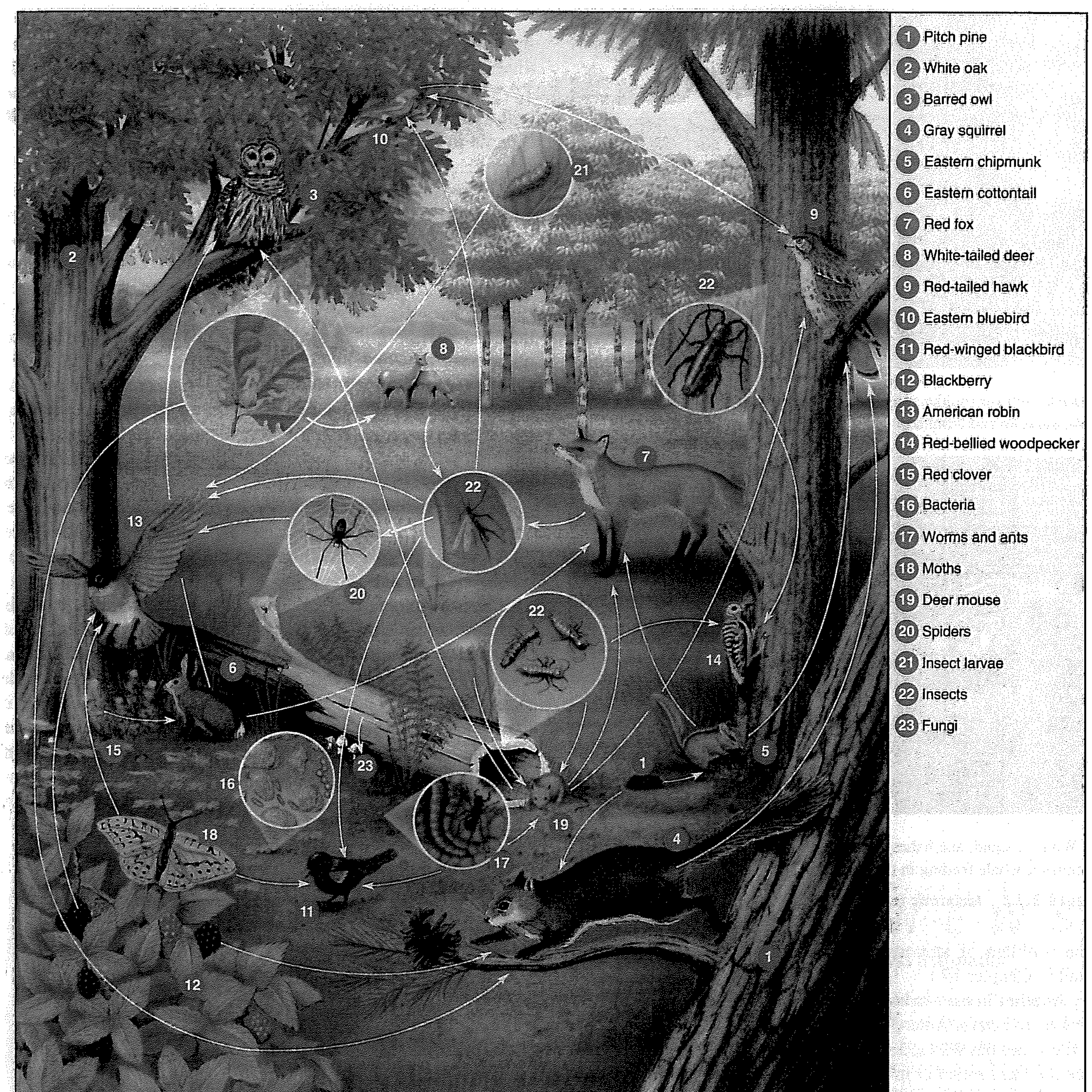
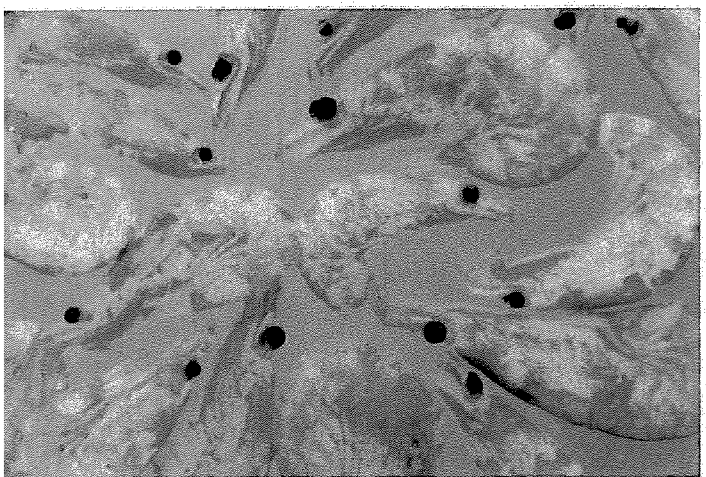


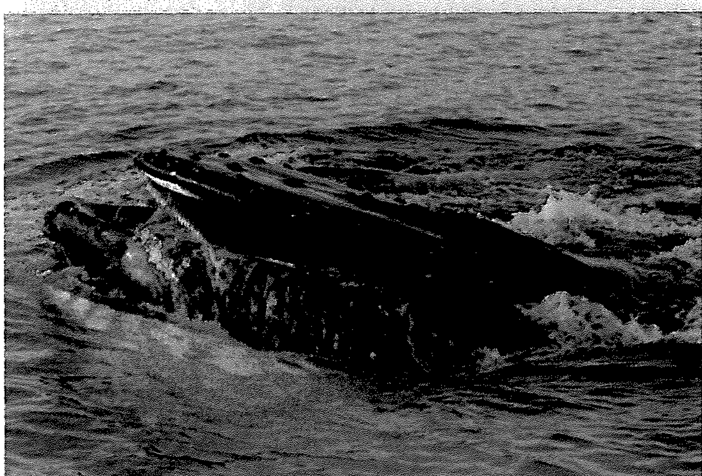

**Figure 3.11 Food web at the edge of an eastern deciduous forest.** This food web is greatly simplified compared to what actually happens in nature. Groups of species are lumped into single categories such as "spiders" and "fungi," other species are not included, and many links in the web are not shown.

monitor changes in the Antarctic food web as the whale populations recover.

Thinning of the ozone layer in the stratospheric region of the atmosphere over Antarctica has the potential to cause long-term effects on the entire Antarctic food web. Ozone thinning allows more of the sun's ultraviolet radiation to penetrate to Earth's surface. Ultraviolet radiation contains more energy than visible light and can break the chemical bonds of some biologically important molecules, such as deoxyribonucleic acid (DNA). Scientists are concerned that ozone thinning over Antarctica may damage the algae that form the base of the food web in the Southern Ocean. Increased ultraviolet radiation is penetrating the surface waters around Antarctica, and algal productivity has declined, probably as a result of increased exposure to ultraviolet radiation.



(a) Krill, tiny shrimplike animals, live in large swarms and eat photosynthetic algae in and around the pack ice.



(b) Whales, squid, and fishes consume vast numbers of krill. Shown is a humpback whale feeding in the Antarctic.

**Figure 3.12 Antarctic food web.**

(The problem of stratospheric ozone depletion is discussed in detail in Chapter 19.)

Another human-induced change that may be responsible for declines in certain Antarctic populations is global climate change. As the water has warmed in recent decades around Antarctica, less pack ice has formed in many areas during winter months, and the summer ice-free period has increased. Large numbers of marine algae are found in and around the pack ice, providing a critical supply of food for the krill, which reproduce in the area. Years with below-average pack ice cover mean fewer algae, which mean fewer krill reproducing. Also, researchers are finding direct damage to krill from ocean acidification associated with the warming temperatures. Scientists have demonstrated that low krill abundance coincides with unsuccessful breeding seasons for penguins and fur seals, which struggle to find food during warmer winters. Scientists are concerned that climate change will continue to decrease the amount of pack ice and increase ocean acidification, which will reverberate through the food web. (Global climate change, including the effect on Adélie penguins in Antarctica, is discussed in Chapter 20.)

To complicate matters, some commercial fishermen have started to harvest krill to make fishmeal for aquaculture industries (discussed in Chapter 18). Scientists worry that the human harvest of krill may endanger the many marine animals that depend on krill for food. ■

## ECOLOGICAL PYRAMIDS

An important feature of energy flow is that most of the energy going from one trophic level to the next in a food chain or food web dissipates into the environment as a result of the second law of thermodynamics. **Ecological pyramids** often graphically represent the relative energy values of each trophic level. There are three main types of pyramids—a pyramid of numbers, a pyramid of biomass, and a pyramid of energy.

A **pyramid of numbers** shows the number of organisms at each trophic level in a given ecosystem, with greater numbers illustrated by a larger area for that section of the pyramid (**Figure 3.13**). In most pyramids of numbers, the organisms at the base of the food chain are the most abundant, and fewer organisms occupy each successive trophic level. In the Antarctic food web, for example, the number of algae is far greater than the number of krill that feed on the algae; likewise, the number of krill is greater than the number of baleen whales, squid, and fishes that feed on krill.

Inverted pyramids of numbers, in which higher trophic levels have *more* organisms than lower trophic levels, are often observed among decomposers, parasites, tree-dwelling herbivorous insects, and similar organisms. One tree may provide food for thousands of leaf-eating insects, for example. Pyramids of numbers are of limited usefulness because they do not indicate the biomass of the organisms at each level, and they do not indicate the amount of energy transferred from one level to another.

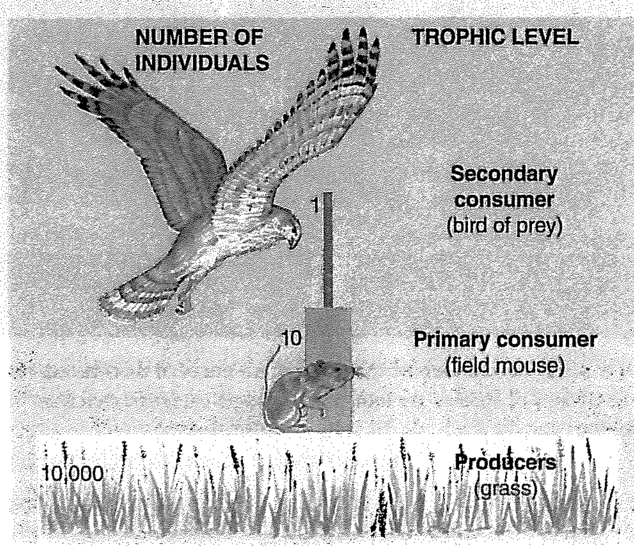



**Figure 3.13 Pyramid of numbers.** This pyramid is for a hypothetical area of temperate grassland; in this example, 10,000 grass plants support 10 mice, which support one bird of prey. Based on the number of organisms found at each trophic level, a pyramid of numbers is not as useful as other ecological pyramids. It provides no information about biomass differences or energy relationships between one trophic level and the next. (Note that decomposers are not shown.)

A **pyramid of biomass** illustrates the total biomass at each successive trophic level in an ecosystem. **Biomass** is a quantitative estimate of the total mass, or amount, of living material; it indicates the amount of fixed energy at a particular time. Biomass units of measure vary: Biomass is represented as total volume, as dry weight, or as live weight. Typically, pyramids of biomass illustrate a progressive reduction of biomass in succeeding trophic levels (**Figure 3.14**). For example, if one assumes about a 90% reduction of biomass for each succeeding trophic level, 10,000 kg of grass should support 1000 kg of grasshoppers, which in turn support 100 kg of toads. The 90% reduction in biomass is used for illustrative purposes only; actual field numbers for biomass reduction in nature vary widely. By this logic, however, the biomass of toad eaters such as snakes could be, at most, only about 10 kg. From this brief exercise, it is apparent that although carnivores do not eat vegetation, a great deal of vegetation is required to support them.

A **pyramid of energy** illustrates the energy content, often expressed as kilocalories per square meter per year, of the biomass of each trophic level in an ecosystem (**Figure 3.15**). These pyramids always have large energy bases and get progressively smaller through succeeding trophic levels. Energy pyramids show that most energy dissipates into the environment when going from one trophic level to the next. Less energy reaches each successive trophic level from the level beneath it because organisms at the lower level use some energy to perform work, and some energy is lost. (Remember, because of the second law of thermodynamics, no biological process is ever 100% efficient.) Energy pyramids explain why there are so few trophic levels: Food webs are short because of the dramatic reduction in energy content at each trophic level. (See "You Can Make a Difference: Vegetarian Diets" in Chapter 18 for a discussion of how the eating habits of humans relate to food chains and trophic levels.)

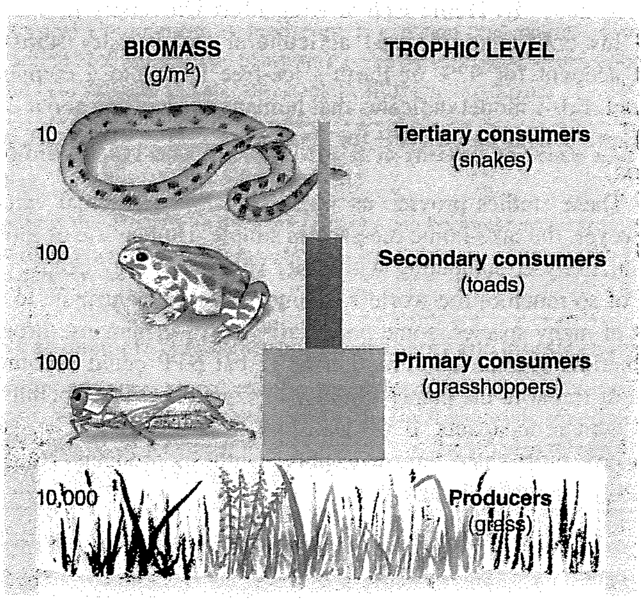



**Figure 3.14 Pyramid of biomass.** This pyramid is for a hypothetical area of temperate grassland. Based on the biomass at each trophic level, pyramids of biomass generally have a pyramid shape with a large base and progressively smaller areas for each succeeding trophic level. (Note that decomposers are not shown.)

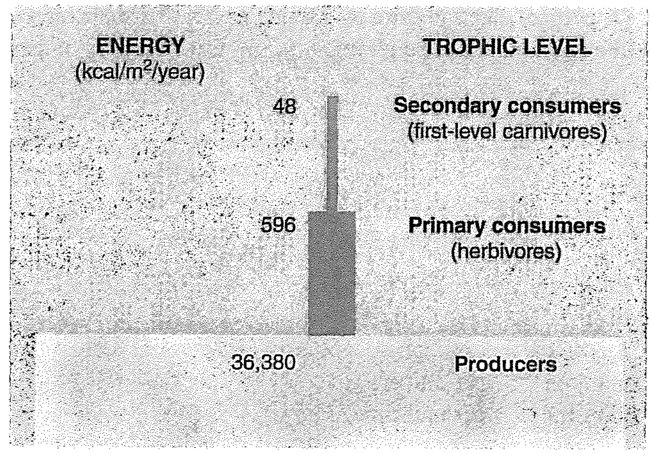



**Figure 3.15 Pyramid of energy.** This pyramid indicates how much energy is present in the biomass at each trophic level in a salt marsh in Georgia and how much is transferred to the next trophic level. Note the substantial loss of usable energy from one trophic level to the next; this loss occurs because of the energy used metabolically and given off as heat. (Note that decomposers are not shown. The 36,380 kcal/m²/year for the producers is gross primary productivity, or GPP, discussed shortly.) (After J. M. Teal. Energy flow in the salt marsh ecosystem of Georgia. *Ecology*, Vol. 43 [1962]).

## ECOSYSTEM PRODUCTIVITY

The **gross primary productivity (GPP)** of an ecosystem is the rate at which energy is captured during photosynthesis. (Gross and net primary productivities are referred to as *primary* because plants occupy the first trophic level in food webs.)

**gross primary productivity (GPP)** The total amount of photosynthetic energy that plants capture and assimilate in a given period.

## ENVIRONEWS

### Satellites Improve Biomass Estimates

To control climate warming, the international community is examining various ways to reduce carbon dioxide emissions. One possibility is for highly developed countries to offset their carbon emissions by paying developing countries in the tropics to protect their forests. (When forests are cut down or burned, much of the carbon contained in the vegetation is released into the atmosphere as carbon dioxide.) For this type of policy to work, however, we must have accurate estimates of the amount of biomass contained in the forests.

In 2009, scientists from several research teams released the first estimates of biomass in the world's tropical forests based on satellite data, considered accurate to a resolution of 1 km. Using these estimates, scientists, who continue to fine-tune their approach, can now focus on more recent trends in forest removal, even by small-scale logging operations. Thus, scientists and policymakers are gaining a more accurate understanding of how the carbon locked in biomass is changing. However, other forestry researchers stress the importance of implementing community-based monitoring programs as well, to promote the just involvement of local people in maintaining their forests.

Of course, plants respire to provide energy for their own use, and this acts as a drain on photosynthesis. Energy in plant tissues after cellular respiration has occurred is **net primary productivity (NPP)**. That is, NPP is the amount of biomass found in excess of that broken down by a plant's cellular respiration. NPP represents the rate at which this organic matter is actually incorporated into plant tissues for growth.

**et primary productivity (NPP)** Productivity after respiration losses are subtracted.

| Net Primary Productivity | | Gross Primary Productivity | | Plant Cellular Respiration |
|---|---|---|---|---|
| (plant growth per unit area per unit time) | = | (total photosynthesis per unit area per unit time) | − | (per unit area per unit time) |

Both GPP and NPP are expressed as energy per unit area per unit time (kilocalories of energy fixed by photosynthesis per square meter per year) or as dry weight (grams of carbon incorporated into tissue per square meter per year).

Only the energy represented by NPP is available as food for an ecosystem's consumers. Consumers use most of this energy for cellular respiration to contract muscles (obtaining food and avoiding predators) and to maintain and repair cells and tissues. Any energy that remains is used for growth and for the production of young, collectively called *secondary productivity*. Any environmental factor that limits an ecosystem's primary productivity—an extended drought, for example—limits secondary productivity by its consumers.

Ecosystems differ strikingly in their productivities (**Figure 3.16**). On land, tropical rainforests have the highest NPP, probably because of their abundant rainfall, warm temperatures, and intense sunlight. Tundra, with its harsh, cold winters, and deserts, with their lack of precipitation, are the least productive terrestrial ecosystems. Wetlands—swamps, marshes, and estuaries that connect terrestrial and aquatic environments—are extremely productive. The most productive aquatic ecosystems are algal beds and coral reefs. Even though the ocean is home to abundant producers, its vast size (large volume) contributes to its low NPP values. A lack of available nutrient minerals in some open ocean regions makes them extremely unproductive, equivalent to aquatic deserts. (Earth's major aquatic and terrestrial ecosystems are discussed in Chapter 6.)

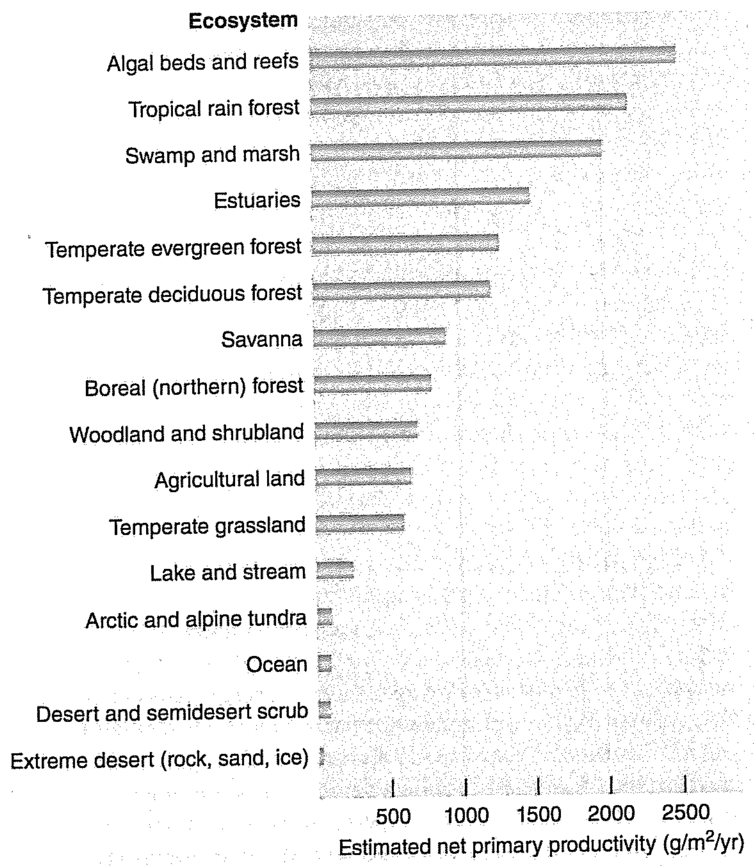



**Figure 3.16 Estimated annual net primary productivities (NPP) for selected ecosystems.** NPP is expressed as grams of dry matter per square meter per year ($g/m^2/yr$). (After R.H. Whittaker, *Communities and Ecosystems*, 2nd edition. New York: Macmillan [1975])

## HUMAN IMPACT ON NET PRIMARY PRODUCTIVITY

Humans consume far more of Earth's resources than any other of the millions of animal species. **Peter Vitousek** and colleagues at Stanford University calculated in 1986 how much of the global NPP is appropriated for the human economy and therefore not transferred to other organisms. When both direct and indirect human impacts are accounted for, Vitousek estimated that humans use 32% of the annual NPP of land-based ecosystems. This is a huge amount considering that we humans represent about 0.5% of the total biomass of all consumers on Earth.

In 2001, **Stuart Rojstaczer** and colleagues at Duke University reexamined Vitousek's groundbreaking research. Rojstaczer used contemporary data sets, many of which are satellite-based and more accurate than the data Vitousek analyzed. Rojstaczer's mean value for his conservative estimate of annual land-based NPP appropriation by humans was 32%, like Vitousek's, although Rojstaczer arrived at that number using different calculations.

In 2007, **K. Heinz Erb** at Klagenfurt University in Vienna and his colleagues plugged agricultural and forestry statistics that account for 97% of Earth's ice-free land into a computer model. Erb's model indicates that humans appropriate about 25% of Earth's land-based NPP for food, forage (for livestock), and wood.

These studies provide us with estimates, not actual values. However, the take-home message is simple: Human use of global productivity is competing with other species' energy needs. Our use of so much of the world's productivity may contribute to the loss of many species, some potentially useful to humans, through extinction. Human consumption of global NPP could become a serious threat to the planet's ability to support both its nonhuman and human occupants. If we want our planet to operate sustainably, we must share terrestrial photosynthesis products—that is, NPP—with other organisms.

*Review*

1. What is a food web?
2. How does energy flow through a food web consisting of producers, consumers, and decomposers?
3. What is a pyramid of energy?
4. What is gross primary productivity? Net primary productivity?

- **Summarize how energy flows through a food web, incorporating producers, consumers, and decomposers in your explanation.**

Energy flow through an ecosystem is linear, from the sun to producer to consumer to decomposer. Much of this energy is converted to less usable heat as the energy moves from one organism to another, as stipulated in the second law of thermodynamics. **Producers** are the photosynthetic organisms (plants, algae, and some bacteria) that are potential food resources for other organisms. **Consumers**, which feed on other organisms, are almost exclusively animals. **Decomposers** feed on the components of dead organisms and organic wastes, degrading them into simple inorganic materials that producers can then use to manufacture more organic material.

- **Describe typical pyramids of numbers, biomass, and energy.**

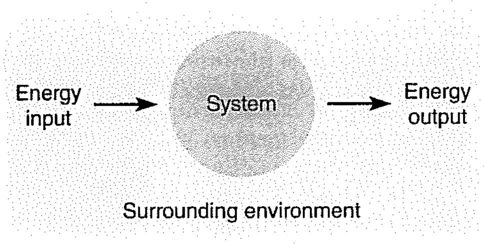
A **pyramid of numbers** shows the number of organisms at each successive trophic level. **Biomass** is a quantitative estimate of the total mass, or amount, of living material; it indicates the amount of fixed energy at a particular time. A **pyramid of biomass** illustrates the total biomass at each successive trophic level. A **pyramid of energy** illustrates the energy content of the biomass of each trophic level.

- **Distinguish between gross primary productivity and net primary productivity, and discuss human impact on the latter.**

**Gross primary productivity (GPP)** is the total amount of photosynthetic energy that plants capture and assimilate in a given period. **Net primary productivity (NPP)** is productivity after respiration losses are subtracted. Scientists have estimated that as much as 32% of the global NPP is appropriated for the human economy. Human use of global productivity is competing with other species' energy needs.

## Critical Thinking and Review Questions

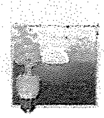
1. Draw a food web containing organisms found in a Chesapeake Bay salt marsh.
2. Describe the science of ecology. What are two questions an ecologist might explore in the Chesapeake Bay salt marsh?
3. Which scientist—a population ecologist or a landscape ecologist—would be most likely to study broad-scale environmental issues and land management problems? Explain your answer.
4. What is energy? How are the following forms of energy significant to organisms in ecosystems: (a) radiant energy, (b) mechanical energy, (c) chemical energy?
5. Give two examples of potential energy, and in each case tell how it is converted to kinetic energy.
6. Is this an example of an open system or a closed system? Explain your answer.




7. How is the first law of thermodynamics related to the movement of an automobile?
8. Give an example of a natural process in which order becomes increasingly disordered.
9. How are photosynthesis and cellular respiration related? Write the overall equations for both processes.
10. Why is the concept of a food web generally preferred over that of a food chain?
11. Could you construct a balanced ecosystem that contained only producers and consumers? Only consumers and decomposers? Only producers and decomposers? Explain the reasons for your answers.
12. Consider a simple ecosystem consisting of a shrub, a worm, a bird, and soil microbes, and identify the producer, primary consumer, secondary consumer, and decomposers. Which of these organisms photosynthesizes? Which carry out cellular respiration? Which give off heat into the surroundings?
13. Suggest a food chain with an inverted pyramid of numbers—that is, greater numbers of organisms at higher rather than at lower trophic levels.
14. Is it possible to have an inverted pyramid of energy? Why or why not?
15. Relate the pyramid of energy to the second law of thermodynamics.

**16.** What is NPP? Do humans affect the global NPP? If so, how? If not, why?

**17.** Alcohol fuels produced from corn are often considered a climate-friendly answer to our energy needs. Explain why a large-scale increase in the production of corn to provide fuel could have a negative or even catastrophic impact on ecosystems.



**18.** How do you interpret this cartoon? What sort of options is the diner considering? Relate your answer to the Food for Thought exercise which is given below.

*"I'm trying to eat lower on the food chain."*



## Food for Thought

You and a friend order lunch at a restaurant: One of you gets the house salad and the other the specialty burger. Production of the burger required far more land and farming resources than did production of the salad. Explain this difference in terms of ecological pyramids as you identify the likely steps involved in producing your respective meals. Do you consider these steps when making your dining choices?

5

# Ecosystems and Living Organisms

**Gray Wolf (*Canus lupus*).** This Yellowstone wolf, photographed near Canyon Village in 2008, is from the Molly Pack.

ray wolves originally ranged across North America from northern Mexico to Greenland, but they were trapped, poisoned, and hunted to extinction in most places. By 1960, the only wolves remaining in the lower 48 states were small populations in Minnesota.

Under the provisions of the Endangered Species Act (ESA), wolves were listed as endangered in 1974. Many scientists recommended reintroducing wolves, but this proposal was not acted on for more than two decades. Beginning in 1995, the U.S. Fish and Wildlife Service (FWS) captured a small number of gray wolves in Canada and released them into Yellowstone National Park in Wyoming. The population thrived and has increased to several hundred individuals in the Yellowstone area (see photograph).

Biologists continue to research the effects of the wolf reintroduction on the Yellowstone ecosystem. Wolves prey on elk and occasionally on mule deer, moose, and bison. In some areas of Yellowstone, hunting by wolf packs has helped reduce Yellowstone's elk population, which was at an all-time high before the wolves returned. When elk numbers are not managed properly, they overgraze their habitat, and thousands starve during hard winters.

The reduction and redistribution of Yellowstone's elk population have relieved heavy grazing pressure on aspen, willow, cottonwood, and other plants, particularly at sites where elk cannot see approaching wolves or escape from them rapidly. As a result of a more lush and varied plant composition, herbivores such as beavers and snow hares have increased in number, which in turn supports small predators such as foxes, badgers, and martens. Trout have also increased, as the more extensive willow and cottonwood help protect stream water quality and streambank integrity.

Wolf packs have reduced coyote populations, which has allowed populations of the coyotes' prey, such as ground squirrels, chipmunks, and pronghorn (coyotes prey on the fawns), to increase. Scavengers such as ravens, magpies, bald eagles, wolverines, and bears (both grizzlies and black bears) have benefited from dining on scraps from wolf kills. Researchers will continue to sort out what happens when a top predator such as the wolf is returned to its natural environment.

The reintroduction of wolves remains controversial. Nearby ranchers were against the reintroduction because their livelihood depends on livestock being safe from predators. In response to this concern, ranchers are allowed to kill wolves that attack cattle and sheep, and federal officers can remove any wolf that threatens humans or livestock. The Defenders of Wildlife, an environmental organization, is working with livestock owners to develop nonlethal ways to reduce the chances of wolves attacking livestock.

Today there are more than 5,500 wolves in the continental United States, and the gray wolf has been delisted from federal protection under the ESA. States such as Montana and Idaho now have management plants to sustain their wolf populations.

Regardless of whether an ecosystem is as large as Yellowstone National Park or as small as a roadside drainage ditch, its organisms continually interact with one another and adapt to changes in the environment. This chapter is concerned with making sense of community structure and diversity in a wide variety of populations and communities.

**In Your Own Backyard**

*Search online and find the two largest predators in your state. Is either of them endangered or threatened? Is either of them a threat to livestock or agriculture?*

## Evolution: How Populations Change over Time

LEARNING OBJECTIVES

- Define *evolution*.
- Explain the four premises of evolution by natural selection, as proposed by Charles Darwin.
- Identify the major domains and kingdoms of living organisms.

Where did the many species of plants, animals, fungi, and microorganisms in Yellowstone come from? They, like all species living today, are thought to have descended from earlier species by the process of **evolution**. The concept of evolution dates back to the time of Aristotle (384–322 B.C.E), but **Charles Darwin**, a nineteenth-century naturalist, proposed *natural selection*, the mechanism of evolution that the scientific community still accepts today. As you will see, the environment plays a crucial role in Darwin's theory of natural selection as a mechanism of evolution.

**volution** Cumulative genetic changes that occur over time in a ulation of organisms; olution explains many patterns of distribution and abundance isplayed in the natural world.

Darwin proposed that, from one generation to the next, inherited traits favorable to survival in a given environment would be preserved, whereas unfavorable ones would be eliminated. The result would be **adaptation**, evolutionary modification of a population that improves each individuals' chances of survival and reproductive success in the environment occupied by the population.

### NATURAL SELECTION

Darwin proposed the theory of evolution by **natural selection** in his monumental book *The Origin of Species by Means of Natural Selection*, published in 1859. Since then, scientists have accumulated an enormous body of observations and experiments that support Darwin's theory. Although biologists still do not agree completely on some aspects of how evolutionary changes occur, the concept of evolution by natural selection is well documented.

**natural selection** The process in which better-adapted individuals—those with a combination of genetic traits better suited to environmental conditions—are more likely to survive and reproduce, ncreasing their proportion in the population.

As a result of natural selection, the population changes over time; the frequency of favorable traits increases in successive generations, and unfavorable traits decrease or disappear. Evolution by natural selection results from four natural conditions: high reproductive capacity, heritable variation, limits on population growth, and differential reproductive success.

1. **High reproductive capacity.** Each species produces more offspring than will survive to maturity.
2. **Heritable variation.** The individuals in a population exhibit variation. Some traits improve the chances of an individual's survival (a camouflage coat, for example) and reproductive success. The variation necessary for evolution by natural selection must be inherited so that it can be passed to offspring.
3. **Limits on population growth, or a struggle for existence.** Only so much food, water, light, growing space, and so on are available to a population, and organisms compete with one another for the limited resources available to them. Other limits on population growth include predators and diseases.
4. **Differential reproductive success.** Reproduction is the key to natural selection: The best-adapted individuals reproduce most successfully, whereas less fit individuals die prematurely or produce fewer or less viable offspring. In some cases, enough changes may accumulate over time in geographically separated populations (often with slightly different environments) to produce new species.

Charles Darwin formulated his ideas on natural selection when he was a ship's naturalist on a five-year voyage around the world. During an extended stay in the Galápagos Islands off the coast of Ecuador, he studied the plants and animals of each island, including 14 species of finches. Each finch species was specialized for a particular lifestyle different from those of the other species and different from those of finches on the South American mainland. The finch species, although similar in color and overall size, exhibit remarkable variation in the shape and size of their beaks, which are used to feed on a variety of foods (**Figure 5.1**). Darwin realized that the 14 species of Galápagos finches descended from a single common ancestor—one or a small population of finches that originally colonized the Galápagos from the South American mainland. Over many generations, the surviving finch populations underwent natural selection, making them better adapted to their environments, including feeding on specific food sources. The evolution of these finches continues to be actively studied by researchers.

### MODERN SYNTHESIS

One premise on which Darwin based his theory of evolution by natural selection is that individuals transmit traits to the next generation. However, Darwin could not explain *how* this occurs or *why* individuals vary within a population. Beginning in the 1930s and 1940s, biologists combined the principles of genetics with Darwin's theory of natural selection. The result was a unified explanation of evolution known as the **modern synthesis**. In this context, *synthesis* refers to combining parts of several previous theories to form a unified whole. Today the modern synthesis includes our expanding knowledge in genetics, classification, fossils, developmental biology, and ecology.

The modern synthesis explains Darwin's observation of variation among offspring in terms of **mutation**, or changes in the nucleotide base sequence of a gene, or deoxyribonucleic acid (DNA) molecule. Mutations provide the genetic variability on which natural selection acts during evolution. Some new traits may be beneficial, whereas others may be harmful or have no effect at all. As a result of natural selection, beneficial strategies, or traits, persist in a population because such characteristics make the individuals that possess them well suited to thrive and reproduce. In contrast, characteristics that make the individuals that possess them poorly suited to their environment tend to disappear in a population.

The modern synthesis has dominated the thinking and research of many biologists. It has resulted in many new discoveries that validate evolution by natural selection. A vast body of evidence supports evolution, most of which is beyond the scope of this text.

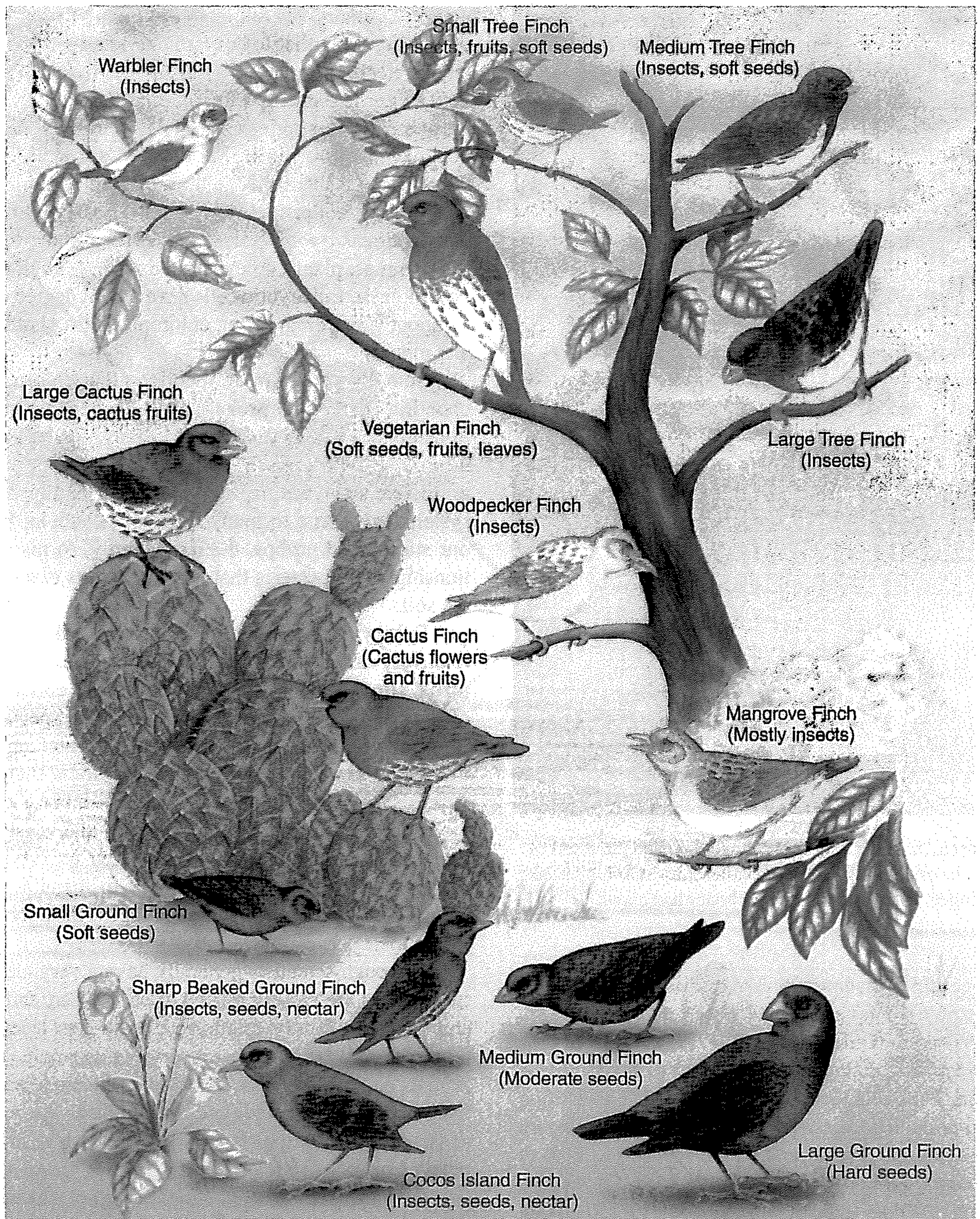
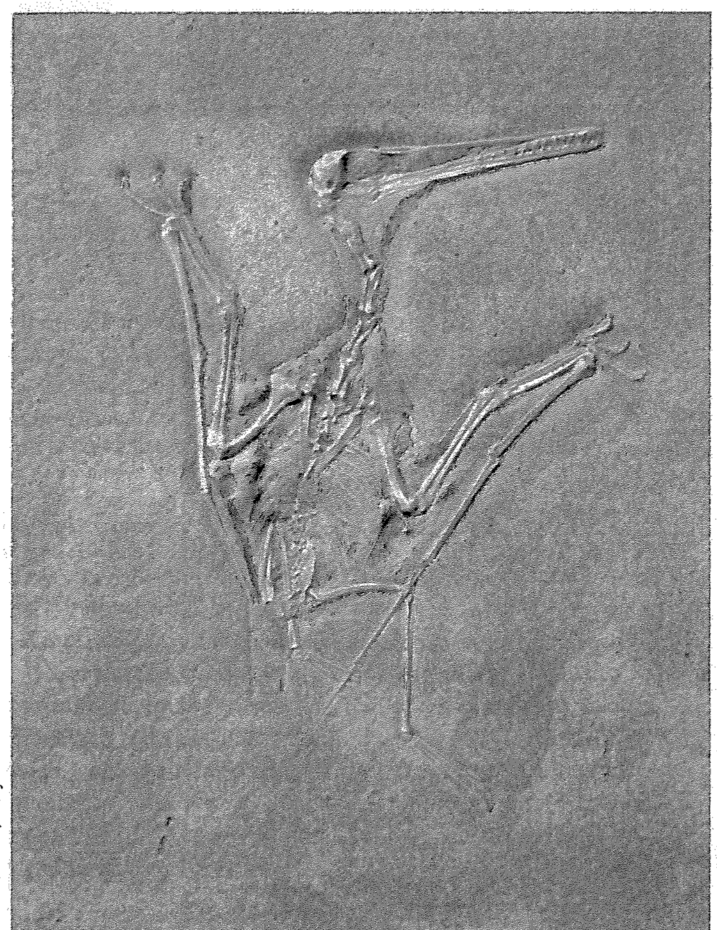



**Figure 5.1 Darwin's finches.** Note the various beak sizes and shapes, which are related to diet. Since 1973 the long-term research of Peter and Rosemary Grant and others has verified and extended Darwin's observations on the evolution of Galápagos finches by natural selection.

This evidence includes observations from biogeography (the study of the geographic locations of organisms), molecular biology, the fossil record, and underlying structural similarities (**Figure 5.2**). In addition, evolutionary hypotheses are tested experimentally.

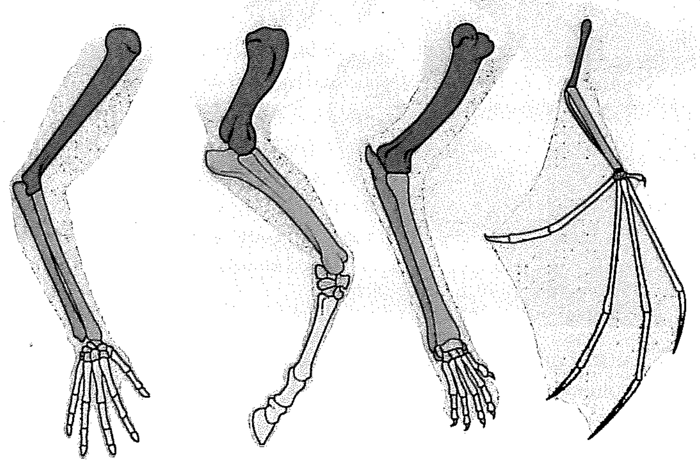
## EVOLUTION OF BIOLOGICAL DIVERSITY: THE ORGANIZATION OF LIFE

Biologists arrange organisms into logical groups to try to make sense of the remarkable diversity of life that has evolved on Earth. For hundreds of years, biologists regarded organisms as falling into two broad categories—plants and animals. With the development of microscopes, however, it became increasingly obvious that many organisms did not fit well into either the plant kingdom or the animal kingdom. For example, bacteria have a *prokaryotic* cell structure: They lack organelles enclosed by membranes, including a nucleus. This feature, which separates bacteria from all other organisms, is far more fundamental than the differences between plants and animals, which have similar cell structures. Hence, bacteria were neither plants nor animals.





(a) **A pterosaur fossil.** Note the long fourth finger bone on the fossil of this flying reptile. Pterosaur wings consisted of leathery skin supported by the elongated finger bone. The other finger bones had claws.




(b) **Similarities among organisms demonstrate how they are related.** The basic underlying similarities among these four limbs indicate that, while proportions of bones have changed in relation to each organism's way of life, the forelimbs have the same basic structure. This structural similarity strongly suggests that these animals shared a common ancestor.

**Figure 5.2 Some evidence for evolution.**

The prokaryotes fall into two groups that are sufficiently distinct from each other to be classified into two kingdoms, **Archaea** and **Bacteria** (**Figure 5.3**). The archaea frequently live in oxygen-deficient environments and are often adapted to harsh conditions; these include hot springs (like Old Faithful, at Yellowstone), salt ponds, and hydrothermal vents (see Case in Point: Life Without the Sun, in Chapter 3). The thousands of remaining kinds of prokaryotes are collectively called bacteria. The eukaryotes, organisms with *eukaryotic* cells, are classified in the four kingdoms of living things, plants, animals, protists, and fungi, all considered to be **Eukarya**. Eukaryotic cells have a high degree of internal organization, containing nuclei, chloroplasts (in photosynthetic cells), and mitochondria.

Some biologists have theorized that chloroplasts and mitochondria were once prokaryotes that began a mutualistic relationship with early eukaryotes. Many, if not most, eukaryotes continue to have relationships with prokaryotes (see discussion of mutualisms later in the chapter). Healthy human digestive systems are home to many types of beneficial bacteria. One of our staple food groups, the bean family, forms mutualistic relationships with bacteria that help the plants extract nitrogen from the soil.

Eukarya are divided into four kingdoms. Unicellular or relatively simple multicellular eukaryotes, such as algae, protozoa, slime molds, and water molds, are classified as members of the kingdom Protista. In addition, three specialized groups of multicellular organisms—fungi, plants, and animals—evolved independently from protists. The kingdoms Fungi, Plantae, and Animalia differ from one another in—among other features—their sources of nutrition. Fungi (molds and yeasts) secrete digestive enzymes into their food and then absorb the predigested nutrients. Plants use radiant energy to manufacture food molecules by photosynthesis. Animals ingest their food, then digest it inside their bodies.

Although scientists generally have a very clear idea of when two species are closely related to each other, and of the relationships within a family, relationships at higher levels, such as kingdom, are still being researched. For example, green algae are protists similar to plants but are not closely related to other protists, such as slime molds and brown algae. As our understanding of gene evolution improves, we get closer to understanding the detailed history of life on Earth.

We have seen that evolution involves changes over time to populations, so it is logical to now study organisms at the population level. Moreover, studying populations of other species provides insights into the biological principles that affect human population changes. (The human population is considered in detail in Chapters 8 and 9.)

*REVIEW*

1. How do biologists define *evolution?*
2. What are Darwin's four premises of evolution by natural selection?
3. What are the major kingdoms of life? Give an example organism from three kingdoms.

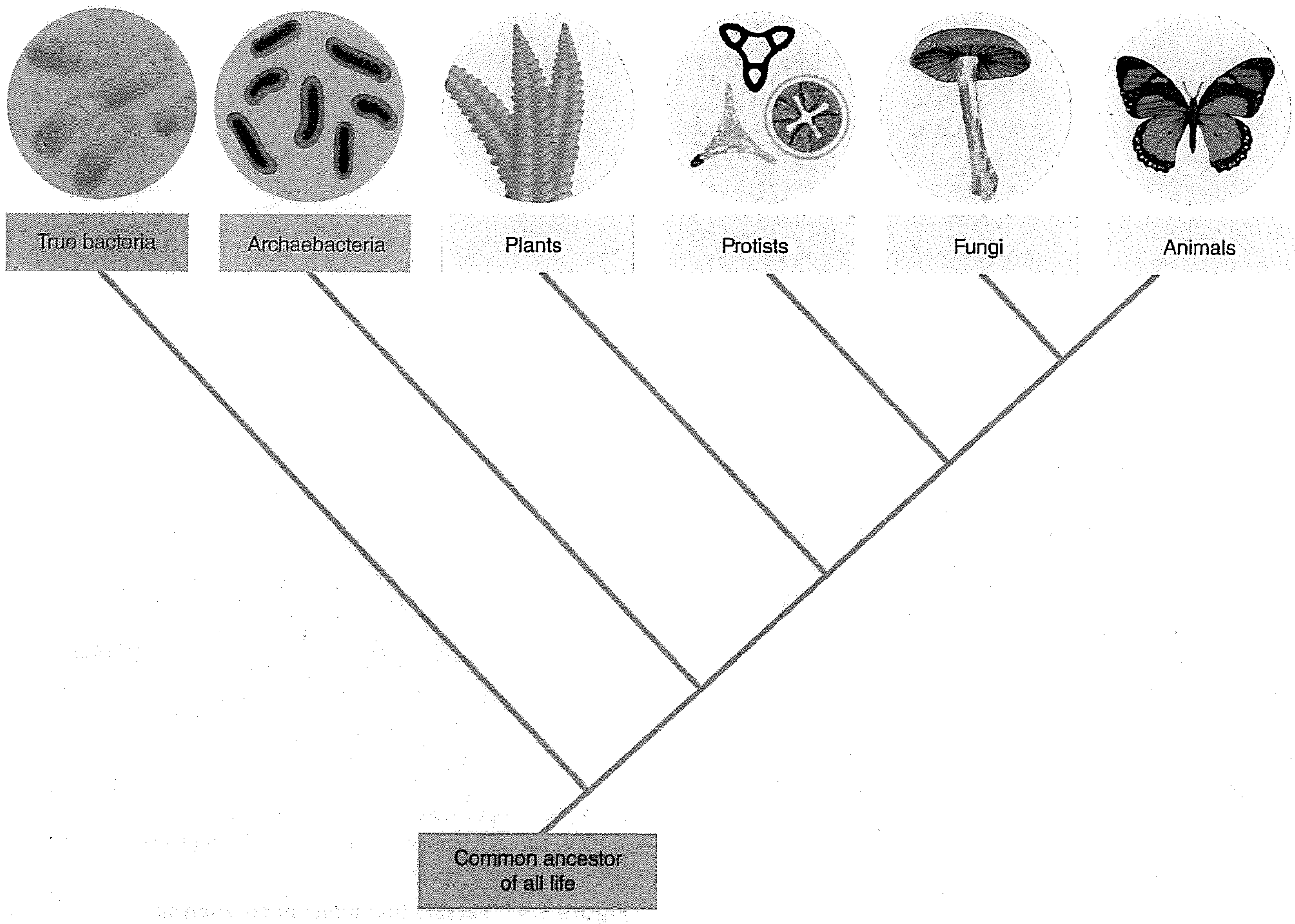



**Figure 5.3 A partial phylogeny of life forms.** To interpret this diagram, start at the bottom with the common ancestor of all life forms, and note the branch points on the way up the main (right-hand) line. The true bacteria were the first to evolve separately from other organisms, followed by the archaebacteria. Eukaryotes (plants, animals, fungi) appeared later in evolutionary history.

## Principles of Population Ecology

*LEARNING OBJECTIVES*

- Define *population*, and explain the four factors that produce changes in population size.
- Use intrinsic rate of increase, exponential population growth, and carrying capacity to explain the differences between J-shaped and S-shaped growth curves.
- Distinguish between density-dependent and density-independent factors that affect population size, and give examples of each.
- Define *survivorship*, and describe type I, type II, and type III survivorship curves.
- Define *metapopulation*, and distinguish between source and sink habitats.

Individuals of a given species that live in the same area at the same time are part of a larger organization—a **population**. Populations exhibit characteristics distinct from those of the individuals within them. Some of the features characteristic of populations but not of individuals are population density, birth and death rates, growth rates, and age structure.

**lation** A group of iduals of the same ies that live in the geographic area at ame time.

**Population ecology** is the branch of biology that deals with the numbers of a particular species found in an area and how and why those numbers change (or remain fixed) over time. Population ecologists try to determine the population processes common to all populations. They study how a population responds to its environment, such as how individuals in a population compete for food or other resources, and how predation, disease, and other environmental pressures affect the population. A population, whether of bacteria or maples or giraffes, cannot increase indefinitely because of such environmental pressures.

Additional aspects of populations important to environmental science are their reproductive success or failure (that is, extinction) and how populations affect the normal functioning of communities and ecosystems. Scientists in applied disciplines, such as forestry, agronomy (crop science), and wildlife management, must understand population ecology to effectively manage populations of economic importance, such as forest trees, field crops, game animals, and fishes. An understanding of the population dynamics of endangered species plays a key role in efforts to prevent their slide to extinction. Knowing the population dynamics of pest species helps in efforts to prevent their increase to levels that can damage crops.

## POPULATION DENSITY

By itself, the size of a population tells us relatively little. Population size is meaningful only when the boundaries of the population are defined. Consider the difference between 1000 mice in 100 hectares (250 acres) and 1000 mice in 1 kitchen. Often, a population is too large to study in its entirety. Such a population is examined by sampling a part of it and then expressing the population in terms of density. Examples include the number of dandelions per square meter of lawn, the number of water fleas per liter of pond water, and the number of cabbage aphids per square centimeter of cabbage leaf. **Population density,** then, is the number of individuals of a species per unit of area or volume at a given time.

## HOW DO POPULATIONS CHANGE IN SIZE?

Populations, whether they are sunflowers, eagles, or humans, change over time. On a global scale, this change is due to two factors: the rate at which individuals produce offspring (the birth rate) and the rate at which organisms die (the death rate) (**Figure 5.4a**). In humans, the **birth rate** *(b)* is usually expressed as the number of births per 1000 people per year, and the **death rate** *(d)* as the number of deaths per 1000 people per year.

**growth rate (*r*)** The of change of a population's size, expressed in percent per year.

The **growth rate** *(r)* of a population is equal to the birth rate (*b*) minus the death rate (*d*). Growth rate is also called **natural increase** in human populations.

$$r = b - d$$

As an example, consider a hypothetical human population of 10,000 in which there are 200 births per year (that is, by convention, 20 births per 1000 people) and 100 deaths per year (that is, 10 deaths per 1000 people).

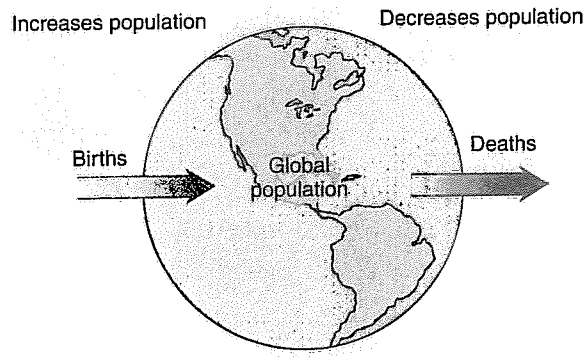
$$r = \underbrace{20/1000}_{b} - \underbrace{10/1000}_{d}$$

$$r = 0.02 - 0.01 = 0.01, \text{ or } 1\% \text{ per year}$$

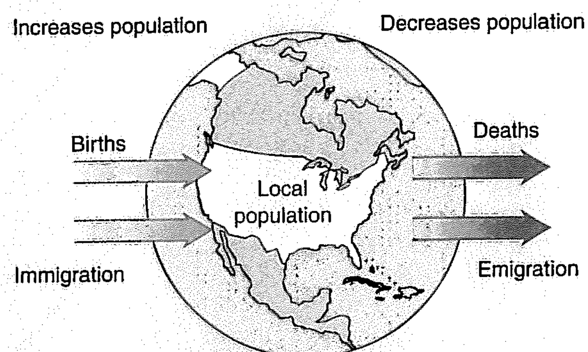
If individuals in the population are born faster than they die, *r* is a positive value, and population size increases. If individuals die faster than they are born, *r* is a negative value, and population size decreases. If *r* is equal to zero, births and deaths match, and population size is stationary despite continued reproduction and death.

In addition to birth and death rates, **dispersal**, or movement from one region or country to another, is considered when changes in populations on a local scale are examined. There are two types of dispersal: **immigration** (*i*), in which individuals enter a population and increase its size, and **emigration** (*e*), in which individuals leave a population and decrease its size. The growth rate of a local population must take into account birth rate (*b*), death rate (*d*), immigration (*i*), and emigration (*e*) (**Figure 5.4b**). The growth rate equals (the birth rate minus the death rate) plus (immigration minus emigration):

$$r = (b - d) + (i - e)$$




(a) On a global scale, the change in a population is due to the number of births and deaths.




(b) In local populations, such as the population of the United States, the number of births, deaths, immigrants, and emigrants affects population size.

**Figure 5.4 Factors that affect population size.**

For example, the growth rate of a population of 10,000 that has 100 births (by convention, 10 per 1000), 50 deaths (5 per 1000), 10 immigrants (1 per 1000), and 100 emigrants (10 per 1000) in a given year is calculated as follows:

$$r = (\underbrace{10/1000}_{b} - \underbrace{5/1000}_{d}) + (\underbrace{1/1000}_{i} - \underbrace{10/1000}_{e})$$

$$r = (0.010 - 0.005) + (0.001 - 0.010)$$

$$r = 0.005 - 0.009 = -0.004, \text{ or } -0.4\% \text{ per year}$$

Is this population increasing or decreasing in size?

## MAXIMUM POPULATION GROWTH

The maximum rate that a population could increase under ideal conditions is its **intrinsic rate of increase** (also called *biotic potential*). Different species have different intrinsic rates of increase. Several factors influence a particular species' intrinsic rate of increase. These include the age at which reproduction begins, the fraction of the life span during which an individual can reproduce, the number of reproductive periods per lifetime, and the number of offspring produced during each period of reproduction. These factors, called *life*

**intrinsic rate of increase** The exponential growth of a population that occurs when resources are not limited.

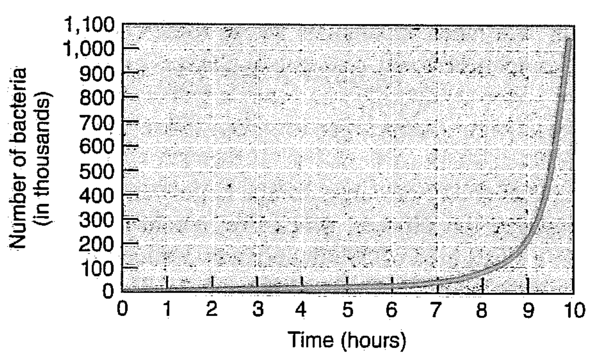
*history characteristics*, determine whether a particular species has a large or a small intrinsic rate of increase.

Generally, larger organisms, such as blue whales and elephants, have the smallest intrinsic rates of increase, whereas microorganisms have the greatest intrinsic rates of increase. Under ideal conditions (that is, an environment with unlimited resources), certain bacteria reproduce by dividing in half every 30 minutes. At this rate of growth, a single bacterium would increase to a population of more than 1 million in just 10 hours (**Figure 5.5a**), and the population from a single individual would exceed 1 billion in 15 hours! If you plot the population number versus time, the graph has a J shape characteristic of **exponential population growth** (**Figure 5.5b**). When a population grows exponentially, the larger the population gets, the faster it grows.

**exponential population growth** The :elerating population wth that occurs when imal conditions allow a constant reproductive rate over a period of time.

| Time (hours) | Number of bacteria |
|---|---|
| 0 | 1 |
| 0.5 | 2 |
| 1.0 | 4 |
| 1.5 | 8 |
| 2.0 | 16 |
| 2.5 | 32 |
| 3.0 | 64 |
| 3.5 | 128 |
| 4.0 | 256 |
| 4.5 | 512 |
| 5.0 | 1,024 |
| 5.5 | 2,048 |
| 6.0 | 4,096 |
| 6.5 | 8,192 |
| 7.0 | 16,384 |
| 7.5 | 32,768 |
| 8.0 | 65,536 |
| 8.5 | 131,072 |
| 9.0 | 262,144 |
| 9.5 | 524,288 |
| 10.0 | 1,048,576 |

(a) When bacteria divide at a constant rate, their numbers increase exponentially. This sample data set assumes a zero death rate, but exponential growth can still occur, albeit more slowly, even if some percentage of bacteria died.




(b) When these data are graphed, the curve of exponential population growth has a characteristic J shape.

**Figure 5.5 Exponential population growth.**

An everyday example of exponential growth is a savings account in which a fixed percentage of interest—say, 2%—is accumulating (i.e., compounding). Assuming you do not deposit or withdraw any money, the amount that your money grows starts increasing slowly and proceeds faster and faster over time, as the balance increases. Exponential population growth works the same way. A small population that is growing exponentially increases at a slow rate initially, but growth proceeds faster and faster as the population increases. Ecologists use the equation at the end of the chapter to predict population levels and growth rates for particular populations.

Regardless of the species, whenever the population is growing at its intrinsic rate of increase, population size plotted versus time gives a curve of the same shape. The only variable is time. A dolphin population will take longer than a bacterial population to reach a certain size (because dolphins do not reproduce as rapidly as bacteria), but both populations will always increase exponentially as long as their growth rates remain constant.

## ENVIRONMENTAL RESISTANCE AND CARRYING CAPACITY

Certain populations may exhibit exponential population growth for a short period. Exponential population growth has been experimentally demonstrated in bacterial and protist cultures and in certain insects. However, organisms cannot reproduce indefinitely at their intrinsic rates of increase because the environment sets limits, collectively called **environmental resistance**. Environmental resistance includes such unfavorable environmental conditions as the limited availability of food, water, shelter, and other essential resources (resulting in increased competition), as well as limits imposed by disease and predation.

Using the earlier example, we find that bacteria would never reproduce unchecked for an indefinite period because they would run out of food and living space, and poisonous body wastes would accumulate in their vicinity. With crowding, bacteria would become more susceptible to parasites (high population densities facilitate the spread of infectious organisms such as viruses among individuals) and predators (high population densities increase the likelihood of a predator catching an individual). As the environment deteriorates, their birth rate ($b$) would decline and their death rate ($d$) would increase. The environmental conditions might worsen to a point where $d$ would exceed $b$, and the population would decrease. The number of individuals in a population, then, is controlled by the ability of the environment to support it. As the number of individuals in a population increases, so does environmental resistance, which acts to limit population growth. Environmental resistance is an excellent example of a **negative feedback mechanism**, in which a change in some condition triggers a response that counteracts, or reverses, the changed condition.

Negative feedback acting on a rapidly growing population can eventually reduce the rate of population growth to nearly zero. This leveling out occurs at or near the **carrying capacity (*K*)**, the limit of the environment's ability to support a population. In nature, the carrying capacity is dynamic and changes in response to environmental changes, such as seasons.

**carrying capacity (*K*)** The maximum number of individuals of a given species that a particular environment can support for an indefinite period, assuming there are no changes in the environment.

An extended drought, for example, could decrease the amount of vegetation growing in an area, and this change, in turn, would lower the carrying capacity for deer and other herbivores.

**G. F. Gause**, a Russian ecologist who conducted experiments during the 1930s, grew a population of a single species, *Paramecium caudatum*, in a test tube. He supplied a limited amount of food (bacteria) daily and replenished the media occasionally to eliminate the buildup of metabolic wastes. Under these conditions, the population of *P. caudatum* increased exponentially at first, but then their growth rate declined to zero, and the population size leveled off. This characteristic population growth pattern theoretically fits most wild organisms, such as ocean fish (**Figure 5.6a**), though students of population ecology can observe many variations from this general pattern. All populations grow best when the number of individuals is high enough for ample reproductive opportunity, but small enough that shortages of resources do not impede growth.

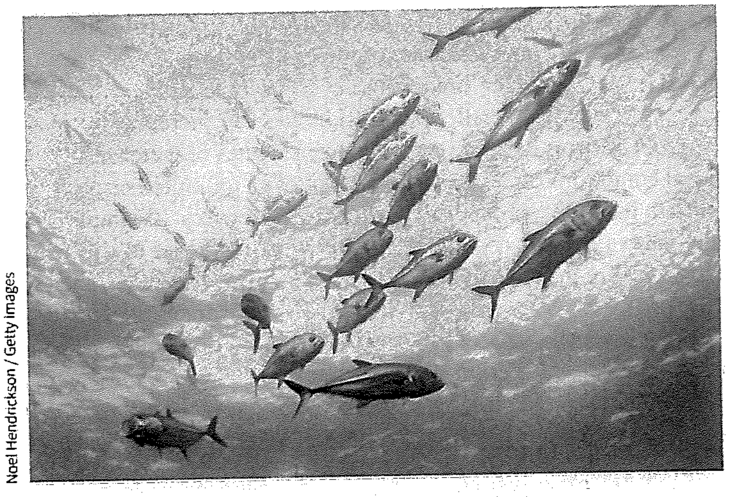
When a population affected by environmental resistance is graphed over a long period (**Figure 5.6b**), the curve has the characteristic S shape of **logistic population growth**. The curve shows an approximate exponential increase initially (note the curve's J shape at the start, when environmental resistance is low), a peak growth rate that occurs when the population is at half the carrying capacity, followed by a leveling out as the carrying capacity of the environment is approached. In logistic population growth, the rate of population growth is proportional to the amount of existing resources, and competition leads to limited population growth. Although logistic population growth is an oversimplification of how most populations change over time, it fits some populations studied in the laboratory, as well as a few studied in nature.

Successful management of either pest species or desirable species requires an understanding of logistic population growth. For example, if we know the carrying capacity of an edible fish, we can calculate the maximum **sustainable harvest** for that species, the number of fish that can be caught each year without reducing the overall population (see Equations at chapter end). This maximum sustainable fishing level will be possible when the fish population is at half the total carrying capacity and achieves its maximum population growth rate. In contrast, in pest control, keeping a pest population well below its maximum growth rate will help minimize the need for ongoing control measures. Additionally, if we work to minimize the carrying capacity for the pest, the necessity for control will be lower. For example, a kitchen that is kept clean of food scraps and dripping water will have a lower carrying capacity for mice and cockroaches. If a city manages feral cat populations by minimizing breeding (through trap-and-neuter programs), the growth rate of the feral cat population will be slower, allowing populations to be kept low more easily. The logistic population growth equation has a wide range of uses in managing both beneficial and pest organisms.

**sustainable harvest** The number of individuals that can be harvested from a population each year without reducing the total population.

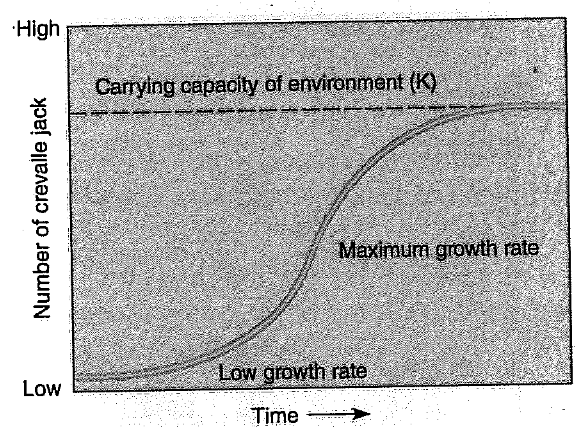
A population rarely stabilizes at $K$ (carrying capacity) as shown in Figure 5.6, but may temporarily rise higher than $K$. It will then drop back to, or below, the carrying capacity. Sometimes a population that overshoots $K$ will experience a **population crash**, an abrupt decline from high to low population density. Such an abrupt change is commonly observed in bacterial cultures, zooplankton, and other populations whose resources are exhausted. Also, $K$ is not necessarily constant, as changes in food supply, climate, or water availability can cause a habitat to have richer or poorer resources. A population crash can follow a drop in carrying capacity.

The availability of winter forage largely determines the carrying capacity for reindeer, which live in cold northern habitats. In 1910, a small herd of 26 reindeer was introduced on to one of the Pribilof Islands of Alaska (**Figure 5.7**). The herd's population increased exponentially for about 25 years until there were approximately 2000 reindeer, many more than the island could support, particularly in winter. The reindeer overgrazed the vegetation until the plant life was almost wiped out. Then, in slightly over a decade, as reindeer died from starvation, the number of



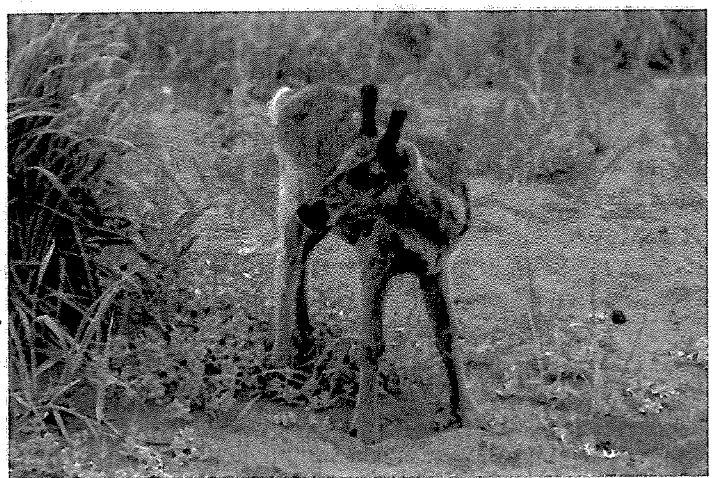
Noel Hendrickson / Getty Images

(a) A group of crevalle jack fish.

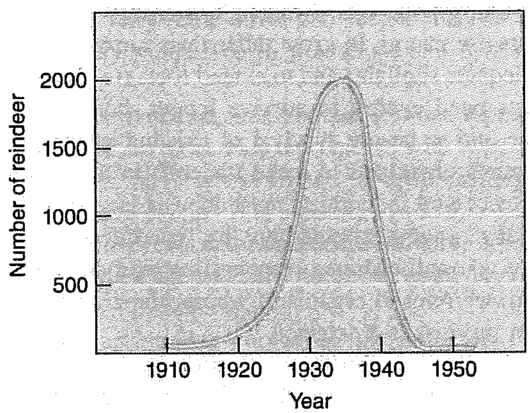



(b) Each habitat, large or small, has a carrying capacity for organisms in it. Populations typically grow slowly when their numbers are small, but growth accelerates (to the maximum growth rate) until environmental resistance (limits to food, breeding sites, habitat, etc.) force growth to slow again, leveling off as the population approaches the carrying capacity (K). Many ocean fish have been overharvested, so their populations are now at the bottom of this curve and have a low population growth rate. Sustainable fishing limits can be set at their highest when the population is at least at half of K.

**Figure 5.6 Logistic Population Growth.**



(a) A baby reindeer (*Rangifer tarandus*) on one of the Pribilof Islands in the Bering Sea, off the coast of Alaska




(b) Reindeer experienced rapid population growth followed by a sharp decline when an excess of reindeer damaged the environment. (After V.C. Scheffer. "The Rise and Fall of a Reindeer Herd." Science Month, Vol. 73, 1951)

**Figure 5.7 A population crash.**

reindeer plunged to 8, about one-third the size of the original introduced population and less than 1% of the population at its peak. Recovery of arctic and subarctic vegetation after overgrazing by reindeer takes 15 to 20 years, and during that time, the carrying capacity for reindeer is greatly reduced.

## FACTORS THAT AFFECT POPULATION SIZE

Natural mechanisms that influence population size fall into two categories, density-dependent factors and density-independent factors. These two sets of factors vary in importance from one species to another, and in most cases they probably interact simultaneously to determine the size of a population.

**Density-Dependent Factors** Certain environmental factors such as predation have a greater influence on a population when its density is greater. For example, if a pond has a dense population of frogs, predators such as waterbirds tend to congregate and eat more of the frogs than if the pond were sparsely populated by frogs. If a change in population density alters how an environmental factor affects the population, then the environmental factor is called a **density-dependent factor**. As population density increases, density-dependent factors tend to slow population growth by causing an increase in the death rate and/or a decrease in birth rate. Thus, as the population grows closer to *K*, density-dependent factors have an increasingly negative impact on the growth rate, and population growth approaches zero. Conversely, if population density declines to below *K*, density-dependent factors cause population growth to increase. Density-dependent factors therefore tend to keep a population at a relatively constant size near the carrying capacity of the environment. (Of course, the environment continually changes, and these changes continually affect the size of the carrying capacity.)

**density-dependent factor** An environmental factor whose effects on a population change as population density changes.

Predation, disease, and competition are examples of density-dependent factors. As the density of a population increases, predators are more likely to find an individual of a given prey species. When population density is high, the members of a population encounter one another more frequently, and the chance of their transmitting infectious disease organisms increases. As population density increases, so does competition for resources such as living space, food, cover, water, minerals, and sunlight. The opposite effects occur when the density of a population decreases. Predators are less likely to encounter individual prey; parasites are less likely to be transmitted from one host to another; and competition among members of the population for resources such as living space and food declines.

Most studies of density dependence are conducted in laboratory settings where all density-dependent (and density-independent) factors except one are controlled experimentally. Populations in natural settings are exposed to a complex set of variables that continually change, and it is difficult to evaluate the relative effects of a single density-dependent (or density-independent) factor.

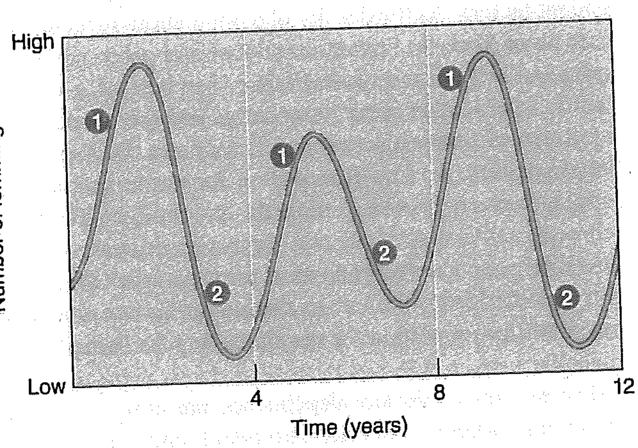
### Density Dependence and Boom-or-Bust Population Cycles

Lemmings are small rodents that live in the colder parts of the Northern Hemisphere. Lemming populations undergo dramatic increases in their population, followed by crashes over fairly regular time intervals—every three to four years (**Figure 5.8**). This cyclic fluctuation in abundance is often described as a boom-or-bust cycle. Other species such as snowshoe hares and red grouse also undergo cyclic population fluctuations.

The actual causes of such population oscillations are poorly understood, but many hypotheses involve density-dependent factors. The population density of lemming predators, such as weasels, arctic foxes, and jaegers (arctic birds that eat lemmings), may increase in response to the increasing density of prey. As more predators consume the abundant prey, the prey population declines. Another possibility is that a huge prey population overwhelms the food supply. Recent studies on lemming population cycles suggest that lemming populations crash because they eat all the vegetation in the area, not because predators eat them. It appears that prey populations may or may not be controlled by predators, whereas predator populations are most likely held in check by the availability of prey.

Tom McHugh/Science Source

(a) The brown lemming (*Lemmus trimucronatus*) lives in the arctic tundra.




(b) This hypothetical diagram shows the cyclic nature of lemming population oscillations, which are well studied but not well understood. When the population is increasing and high (labeled 1), density-dependent factors are increasingly severe; the population growth rate is dropping, and the population will soon decline. When the population is low and declining (labeled 2), density-dependent factors are relaxed; soon, the population bottoms out and then begins to increase.

**Figure 5.8 Lemming population oscillations.**

**Density-Independent Factors** **Density-independent factors** are typically abiotic. Random weather events such as a killing frost, severe blizzard, hurricane, or fire may cause extreme and irregular reductions in a population regardless of its size and thus are largely density independent.

**density-independent factor** An environmental factor that affects the size of a population but is not influenced by changes in population density.

Consider a density-independent factor that influences mosquito populations in arctic environments. These insects produce several generations per summer and achieve high population densities by the end of the season. A shortage of food is not a limiting factor for mosquitoes, nor is there any shortage of ponds in which to breed. Instead, winter puts a stop to the skyrocketing mosquito population. Not a single adult mosquito survives winter, and the entire population grows the following summer from the few eggs and hibernating larvae that survive. The timing and severity of winter weather is a density-independent factor that affects arctic mosquito populations.

## REPRODUCTIVE STRATEGIES

Each species has a lifestyle uniquely adapted to its reproductive patterns. Many years pass before a young magnolia tree flowers and produces seeds, whereas within a single season wheat grows from seed, flowers, and dies. A mating pair of black-browed albatrosses produces a single chick every year, whereas a mating pair of gray-headed albatrosses produces a single chick biennially (every other year). Biologists try to understand the adaptive consequences of these various *life history strategies*.

Since evolution involves passing genes on to the next generation, we might think that maximizing reproduction would be the best life strategy. An organism that sexually matures early, has abundant offspring, and whose offspring, in turn, survive and reproduce early and often, might seem to be the most successful organism. All of its energy is invested into reproduction, so it would seem to pass on the most genetic material. An organism with this strategy, however, could not expend any energy toward ensuring its own survival. Animals use energy to hunt for food, and plants use energy to grow taller than surrounding plants (to obtain adequate sunlight) and to extend roots (to obtain nutrients). Organisms need energy to survive longer, both to continue to reproduce and to ensure survival of existing offspring. Nature, then, requires organisms to make tradeoffs in the expenditure of energy. Successful individuals must do what is required to survive as individuals *and* as populations (by reproducing). We refer to organisms whose life strategy emphasizes reproductive success as *r* selected; we refer to organisms whose life strategy emphasizes long-term survival as *K* selected.

Populations described by ***r* selection** have traits that contribute to a high population growth rate. Recall that *r* designates the growth rate. Such organisms have a high *r* and are called *r strategists* or *r-selected species*. Small body size, early maturity, short life span, large broods, and little or no parental care are typical of many *r* strategists, which are usually opportunists found in variable, temporary, or unpredictable environments where the probability of long-term survival is low. Some of the best examples of *r* strategists are mice, insects such as mosquitoes, and common weeds such as the dandelion.

In populations described by ***K* selection**, traits maximize the chance of surviving in an environment where the number of individuals is near the carrying capacity (*K*) of the environment. These organisms, called *K strategists* or *K-selected species*, do not produce large numbers of offspring. They characteristically have long life spans with slow development, late reproduction, large body size, and low reproductive rate. Redwood trees are classified as *K* strategists. Tawny owls, elephants, and other animals that are *K* strategists typically invest in the parental care of their young. Other *K* strategists include long-lived plants, such as the century plant or the California redwood tree. *K* strategists are found in relatively constant or stable environments, where they have a high competitive ability.

## SURVIVORSHIP

Ecologists construct **life tables** for plants and animals that show the likelihood of survival for individuals at different times during their lives. Insurance companies originally developed life tables to determine how much policies should cost: Life tables show the relationship between a client's age and the likelihood the client will survive to pay enough insurance premiums to cover the cost of the policy.

**Survivorship** is the proportion of individuals surviving at each age in a given population. **Figure 5.9** is a graph of the three main survivorship curves recognized by ecologists. In type I survivorship, as exemplified by humans and elephants, the young (that is, prereproductive individuals) and those at reproductive age have a high probability of living. The probability of survival decreases more rapidly with increasing age, and deaths are concentrated later in life.

**survivorship** The probability a given individual in a population will survive to a particular age.

In type III survivorship, the probability of death is greatest early in life, and those individuals that avoid early death subsequently have a high probability of survival. In animals, type III survivorship is characteristic of many fish species and oysters. Young oysters have three free-swimming larval stages before adulthood, when they settle down and secrete a shell. These larvae are extremely vulnerable to predation, and few survive to adulthood.

In type II survivorship, intermediate between types I and III, the probability of survival does not change with age. The probability of death is likely across all age groups, resulting in a linear decline in survivorship. This constancy probably results from essentially random events that cause death with little age bias. This relationship between age and survivorship is relatively rare; some lizards have a type II survivorship.

The three survivorship curves are generalizations, and few populations exactly fit one of the three. Some species have one type of survivorship curve early in life and another type as adults. Humans' survivorship curves depend on the public health, war, and socioeconomic conditions in a given region or country.

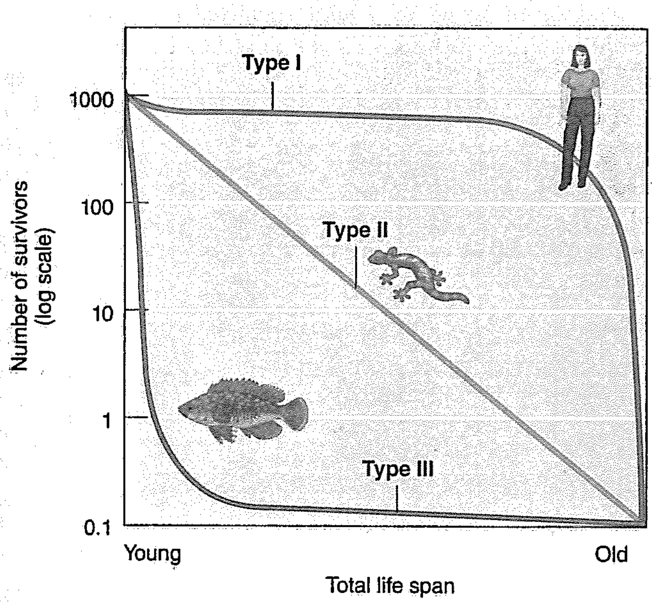



**Figure 5.9 Survivorship.** These generalized survivorship curves represent the ideal survivorships of species in which death rates are concentrated after reproduction (type I), spread evenly across age groups (type II), and greatest among the young (type III). Although humans, lizards, and fish are shown as examples of each, organisms do have a range of variability; some human populations have relatively high infant mortality, and their survivorship curves may be a hybrid of survivorship curve types.

## METAPOPULATIONS

Instead of being distributed as one large population across the landscape, many species occur as local populations in distinct habitat patches. Each local population has its own characteristic birth, death, emigration, and immigration rates. A group of local populations among which individuals occasionally *disperse* (emigrate and immigrate) is called a **metapopulation**. For example, note the three local populations that form the hemlock metapopulation on a mountain landscape in the Great Smoky Mountains (**Figure 5.10**).

**metapopulation** A set of local populations among which individuals are distributed in distinct habitat patches across a landscape.

The distribution of local populations across the landscape occurs because of local differences in elevation, temperature, amount of precipitation, soil moisture, and availability of soil minerals. Those habitats that increase the likelihood of survival and reproductive success for the individuals living there are called **source habitats**. Source populations generally have greater population densities than populations at less suitable sites, and surplus individuals in the source habitat may disperse to another habitat.

Lower-quality habitats, called **sink habitats**, are areas where the local birth rate is less than the local death rate. Without immigration from other areas, a sink population declines until extinction occurs. If a local population becomes extinct, individuals from a source habitat may recolonize the vacant habitat at a later time. Source and sink habitats, then, are linked to one another by immigration and emigration.

Metapopulations are becoming more common as humans alter the landscape by fragmenting existing habitats to accommodate

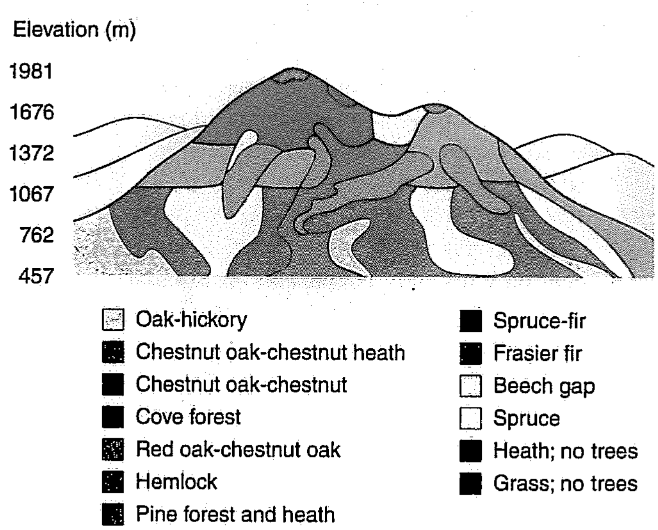



**Figure 5.10 Metapopulations.** Distribution of vegetation on a west-facing slope in Great Smoky Mountains National Park reveals the mosaic nature of landscapes. How might climate change affect these metapopulations? (Adapted from R.H. Whittaker. Vegetation of the Great Smoky Mountains. *Ecological Monographs*, Vol. 26, 1956)

roads, homes, factories, agricultural fields, and logging. As a result, the concept of metapopulations, particularly as it relates to endangered and threatened species, is an important area of study in conservation biology.

*Review*

1. What is the effect of each of the following on population size: birth rate, death rate, immigration, and emigration?
2. How do intrinsic rate of increase and carrying capacity produce the J-shaped and S-shaped population growth curves?
3. What are two examples of density-dependent factors that affect population growth? What are two examples of density-independent factors?
4. What are the three main survivorship curves?
5. How does a metapopulation differ from a local population?

## Biological Communities

*LEARNING OBJECTIVES*

- Describe the factors that contribute to an organism's ecological niche.
- Define *competition*, and relate the concepts of competitive exclusion and resource partitioning.
- Define *symbiosis*, and distinguish among mutualism, commensalism, and parasitism.
- Define *predation*, and describe the effects of natural selection on predator-prey relationships.
- Define *keystone species*, and discuss the wolf as a keystone species.

The vast assemblage of organisms that live in populations and metapopulations are organized into communities. The term *community* has a far broader sense in ecology than in everyday speech. For the biologist, a **community** is an association of different populations of organisms that live and interact in the same place at the same time.

The organisms in a community are interdependent in a variety of ways. Species compete with one another for food, water, living space, and other resources. (Used in this context, a *resource* is anything from the environment that meets a particular species' needs.) Some organisms kill and eat other organisms. Some species form intimate associations with one another, whereas other species seem only distantly connected. As discussed in Chapter 3, each organism plays one of three main roles in community life: producer, consumer, or decomposer. The unraveling of the many positive and negative, direct and indirect interactions of organisms living as a community is one of the goals of community ecologists.

Communities vary greatly in size, lack precise boundaries, and are rarely completely isolated. They interact with and influence one another in countless ways, even when the interaction is not readily apparent. Furthermore, communities are nested within one another like Russian nesting dolls—that is, communities exist within communities. A forest is a community, but so is a rotting log in that forest. Insects, plants, and fungi invade a fallen tree as it undergoes a series of decay steps (**Figure 5.11**).

Organisms exist in an abiotic (nonliving) environment that is as essential to their existence as is their biotic (living) environment. Minerals, air, water, and sunlight are just as much a part of a honeybee's environment as the flowers it pollinates and from which it takes nectar. A biological community and its abiotic environment form an **ecosystem** (Chapter 4 considered an ecosystem's abiotic environment). Ecosystems can also include biological communities managed by humans, such as farms.

### THE ECOLOGICAL NICHE

Let us consider the way of life of a given species in its community. An ecological description of a species typically includes (1) whether it is a producer, consumer, or decomposer; (2) the kinds of symbiotic associations it forms; (3) whether it is a predator and/or prey; and (4) what species it competes with. Other details are needed, however, to provide a complete picture.

Every organism is thought to have its own role, or **ecological niche**, within the structure and function of an ecosystem. An ecological niche takes into account all aspects of the organism's existence—all the physical, chemical, and biological factors an organism needs to survive, remain healthy, and reproduce. Among other things, the niche includes the local environment in which an organism lives—its **habitat**. An organism's niche also encompasses how the abiotic components of its environment, such as light, temperature, and moisture, interact with and influence it.

**ecological niche** The totality of an organism's adaptations, its use of resources, and the lifestyle to which it is fitted.

The ecological niche of an organism may be much broader potentially than it is in actuality. Put differently, an organism is potentially capable of using much more of its environment's resources or of living in a wider assortment of habitats than it actually does. The potential, idealized ecological niche of an organism is its **fundamental niche**, but various factors such as competition with other species usually exclude it from part of its fundamental niche. The lifestyle an organism actually pursues and the resources it actually uses make up its **realized niche**.

An example may clarify the distinction between fundamental and realized niches. The green anole, a lizard native to Florida and other southeastern states, perches on trees, shrubs, walls, or fences during the day and waits for insect and spider prey (**Figure 5.12a**). In the past, these little lizards were widespread in Florida. A number of years ago, a related species, the brown anole, was introduced from Cuba into southern Florida and quickly became common (**Figure 5.12b**). Suddenly green anoles became rare, apparently driven out of their habitat by competition from the slightly larger brown lizards. Careful investigation disclosed that green anoles were still around. They were, however, now confined largely to the vegetation in wetlands and to the foliated crowns of trees, where they were less obvious.

The habitat portion of the green anole's fundamental niche includes the trunks and crowns of trees, exterior house walls, and many other locations. Where they became established, brown anoles drove green anoles out from all but wetlands and tree crowns, so the green anole's realized niche became smaller as a result of competition (**Figure 5.12c, d**). Natural communities consist

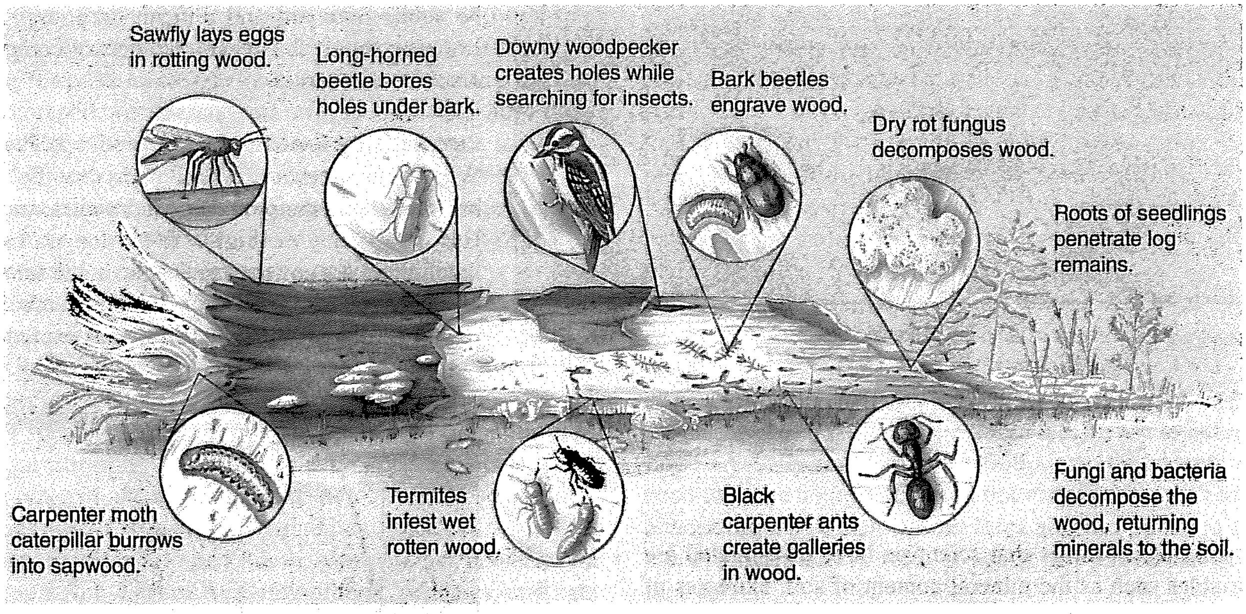
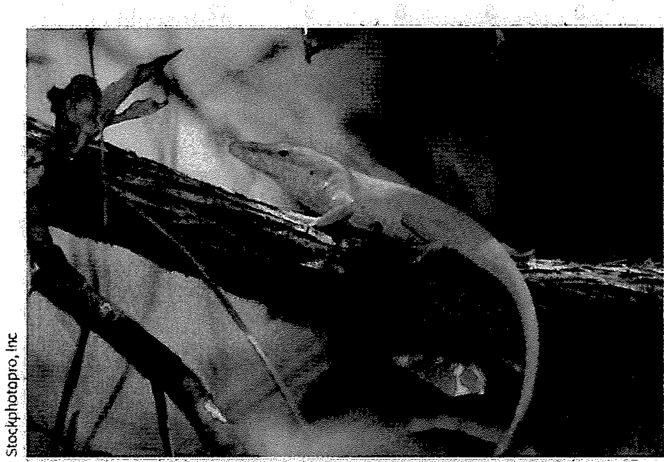
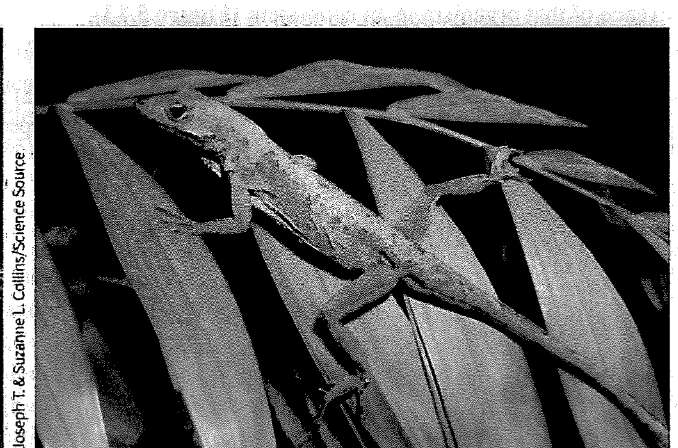


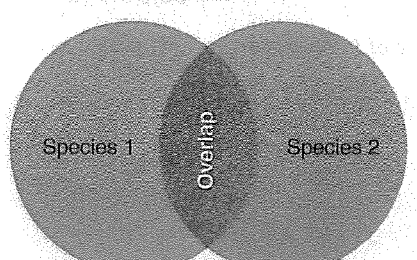

**Figure 5.11 A rotting log community.** Detritivores and decomposers consume a rotting log, which teems with a variety of bacteria, fungi, animals, and plants.



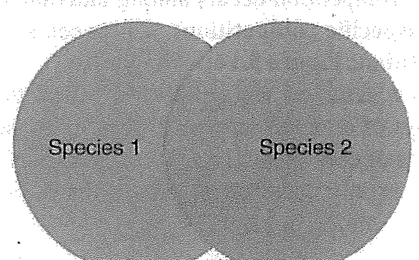

(a) The green anole (*Anolis carolinensis*) is native to Florida.




(b) The brown anole (*Anolis sagrei*) was introduced into Florida.




(c) The fundamental niches of the two lizards initially overlapped. Species 1 is the green anole, and species 2 is the brown anole.




(d) The brown anole outcompeted the green anole, restricting its niche. Note the greatly reduced area of overlap.

**Figure 5.12 Effect of competition on an organism's realized niche.**

of numerous species, many of which compete to some extent, and the interactions among species produce the realized niche of each.

A full description of an organism's niche would involve a long list of necessary and possible resources. In any habitat, only some of these resources tend to be in short supply. A fish living in a lake needs water, but water in the lake is plentiful, not usually limiting to that fish population's ability to increase. Optimal locations for spawning, however, may be limited. A necessary resource that is not abundant enough to allow easy survival or plentiful population growth is considered a **limiting resource.**

**limiting resource** Any environmental resource that, because it is scarce or at unfavorable levels, restricts the ecological niche of an organism.

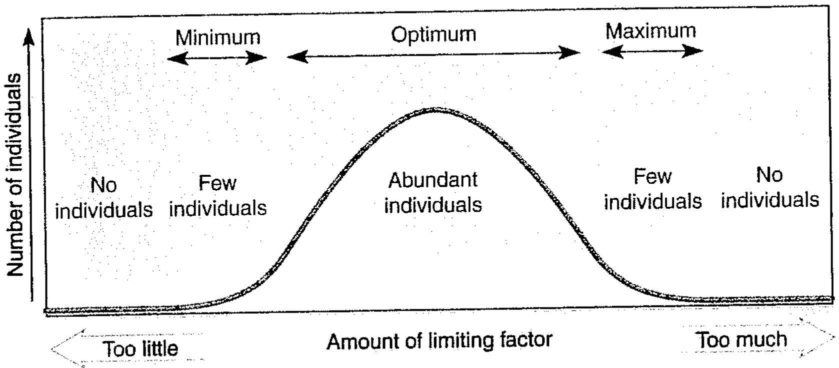



**Figure 5.13 Limiting resource.** An organism is limited by any environmental resource that exceeds its tolerance or is less than its required minimum.

Most limiting resources that scientists have investigated are simple variables such as the mineral content of soil, extremes of temperature, and amount of precipitation. Such investigations have disclosed that any resource that exceeds an organism's tolerance or is present in quantities smaller than the minimum required limits the occurrence of that organism in an ecosystem (**Figure 5.13**).

No organism exists independently of other organisms. We now consider the three main types of interactions that occur among species in an ecosystem: competition, symbiosis, and predation.

## COMPETITION

**Competition** occurs when two or more individuals attempt to use an essential common resource such as food, water, shelter, living space, or sunlight. Resources are often in limited supply in the environment, and their use by one individual decreases the amount available to others. If a tree in a dense forest grows taller than surrounding trees, it absorbs more of the incoming sunlight, and less sunlight is available for nearby trees. Competition occurs among individuals within a population (**intraspecific competition**) or between species (**interspecific competition; Figure 5.14**).

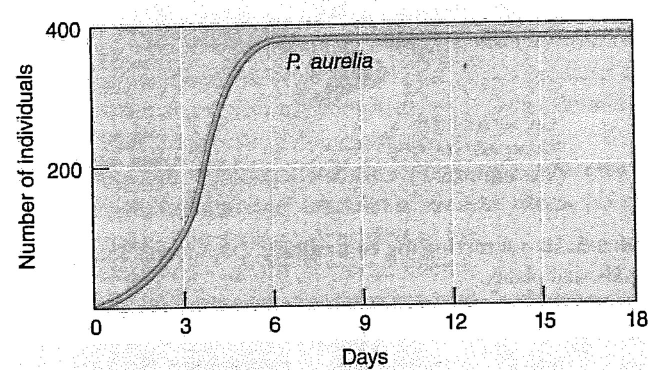
**ompetition** The interaction among organisms that vie for the same esources (such as food or living space) in an ecosystem.

Ecologists traditionally assumed that competition was the most important determinant of both the number of species found in a community and the size of each population. Today, ecologists recognize that competition is only one of many factors that affect community structure. Furthermore, competition is not always a straightforward, direct interaction. A variety of flowering plants live in a young pine forest and presumably compete with conifers for such resources as soil moisture and soil nutrient minerals. The flowers produce nectar consumed by some insect species that also prey on needle-eating insects, thereby reducing the number of insects feeding on pines. If the flowering plants were removed from the community, would the pines grow faster because they were no longer competing for necessary resources? Or would the increased presence of needle-eating insects caused by fewer omnivorous insects inhibit pine growth?

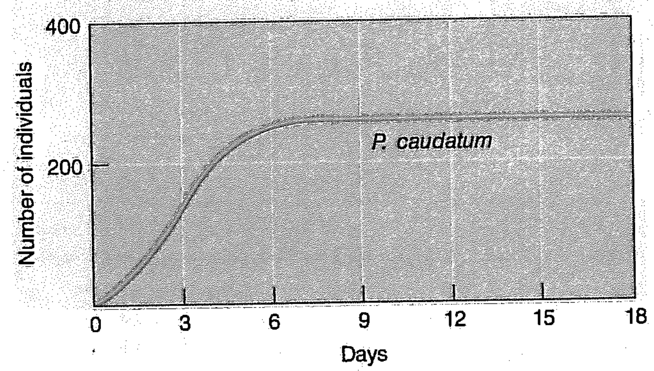
Few studies have tested the long-term effects on forest species of the removal of one competing species. Long-term effects may be subtle, indirect, and difficult to assess. They may lower or negate the negative effects of competition for resources.

### Competitive Exclusion and Resource Partitioning

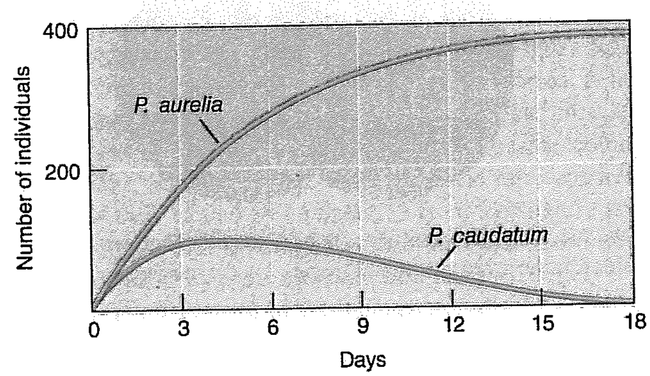
When two species are similar, as are the green and brown anoles, their fundamental niches may overlap. However, many ecologists think that no two species indefinitely occupy the same niche in the same community because **competitive exclusion** eventually occurs. In competitive exclusion, one species excludes another




(a) A population of *P. aurelia* grown in a separate culture (in a single-species environment).




(b) A population of *P. caudatum* grown in a separate culture.




(c) Populations of both species grown in a mixed culture, in competition with each other. *P. aurelia* outcompetes *P. caudatum* and drives it to extinction. (Data for graphs adapted from G.F. Gause, *The Struggle for Existence*. Baltimore: Williams & Wilkins, 1934)

**Figure 5.14 Interspecific competition.**

from a portion of a niche as a result of competition between species (interspecific competition). Although it is possible for species to compete for some necessary resource without having intense, pervasive competitive interactions, two species with absolutely identical ecological niches cannot coexist. Coexistence *can* occur if the overlap in the two species' niches is reduced. In the lizard example, direct competition between the two species was reduced as the brown anole excluded the green anole from most of its former habitat until the only places open to it were wetland vegetation and tree crowns.

Competition has adverse effects on all species that use a limited resource and may result in competitive exclusion of one or more species. Natural selection should favor those individuals of each species that avoid or at least reduce competition. In **resource partitioning,** coexisting species' realized niches differ from each other in one or more ways. Evidence of resource partitioning in animals is well documented and includes studies in tropical forests of Central and South America that demonstrate little overlap in the diets of fruit-eating birds, primates, and bats that coexist in the same habitat. Although fruits are the primary food for several hundred of these species, the wide variety of fruits available has allowed fruit eaters to specialize, thereby reducing competition.

Resource partitioning may include timing of feeding, location of feeding, nest sites, and other aspects of an organism's ecological niche. **Robert MacArthur**'s study of five North American warbler species is a classic example of resource partitioning (**Figure 5.15**).

## SYMBIOSIS

In **symbiosis**, individuals of one species usually live in or on the individuals of another species. At least one of the species—and sometimes both—uses its partner's resources. The partners of a symbiotic relationship, called **symbionts**, may benefit from, be unaffected by, or be harmed by the relationship. Examples of symbiosis occur across all of the domains and kingdoms of life.

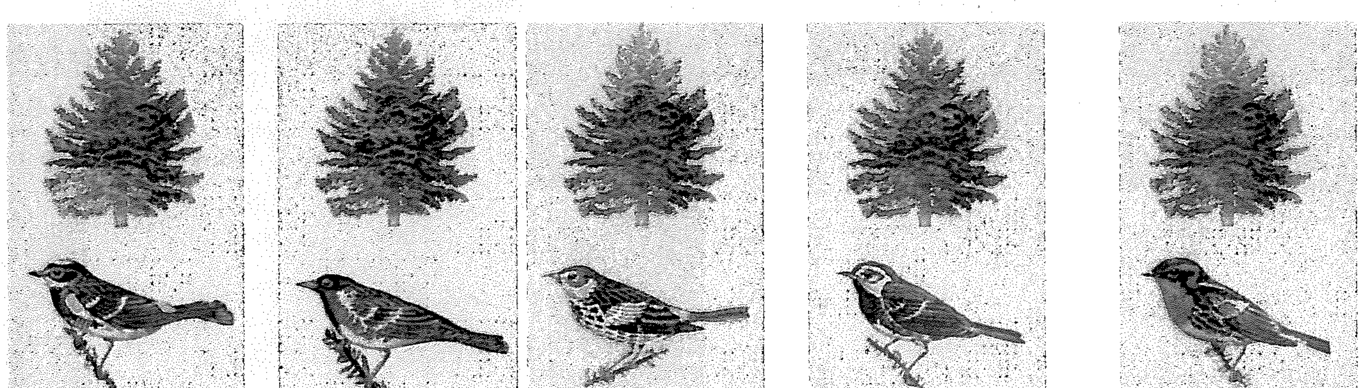
**biosis** Any intimate ationship or associa- n between members two or more species; includes mutualism, commensalism, and parasitism.

Symbiosis is the result of **coevolution**, the interdependent evolution of two interacting species. Flowering plants and their animal pollinators have a symbiotic relationship that is an excellent example of coevolution. Plants are rooted in the ground and lack the mobility that animals have when mating. Many flowering plants rely on animals to help them reproduce. Bees, beetles, birds, bats, and other animals transport the male reproductive units, called pollen grains, from one plant to another, in effect giving plants mobility. How has this come about?

During the millions of years these associations developed, flowering plants evolved in several ways to attract animal pollinators. One of the rewards for the pollinator is food—nectar (a sugary solution) and pollen. Plants often produce food precisely adapted for one type of pollinator. The nectar of bee-pollinated flowers usually contains 30% to 35% sugar, the concentration bees need to make honey. Bees will not visit flowers with lower sugar concentrations in their nectar. Bees also use pollen to make bee-bread, a nutritious mixture of nectar and pollen that bees feed to their larvae.

Plants possess a variety of ways to get the pollinator's attention, most involving colors and scents. Showy petals visually attract the pollinator, much as a neon sign or golden arches attract a hungry person to a restaurant. Insects have a well-developed sense of smell, and many insect-pollinated flowers have strong scents that are also pleasant to humans. A few specialized kinds of flowers have unpleasant odors. The carrion plant produces flowers that mimic the smell of rotting flesh. Carrion flies are attracted to these flowers while they are looking for a place to deposit their eggs, and in the process pollen is transferred.

During the time plants were evolving specialized features to attract pollinators, the animal pollinators coevolved specialized body parts and behaviors to aid pollination and to obtain nectar and pollen as a reward. Coevolution is responsible for the hairy bodies of bumblebees, which catch and hold the sticky pollen for transport from one flower to another. The long, curved beaks of certain birds, which fit into tubular, nectar-bearing flowers, are the result of coevolution (**Figure 5.16**).



(a) Yellow-rumped warbler (b) Bay-breasted warbler (c) Cape May warbler (d) Black-throated green warbler (e) Blackburnian warbler

**Figure 5.15 Resource partitioning.** In Robert MacArthur's study of five North American warbler species, the warblers' niches initially appeared identical. However, MacArthur determined that individuals of each species spend most of their feeding time in different parts (marked in brown) of the conifer trees they frequent. They also travel differently in the tree canopy, consume different combinations of insects, and nest at slightly different times. (Adapted from R.H. MacArthur, "Population Ecology of Some Warblers of Northeastern Coniferous Forests." *Ecology*, Vol. 39, 1958)

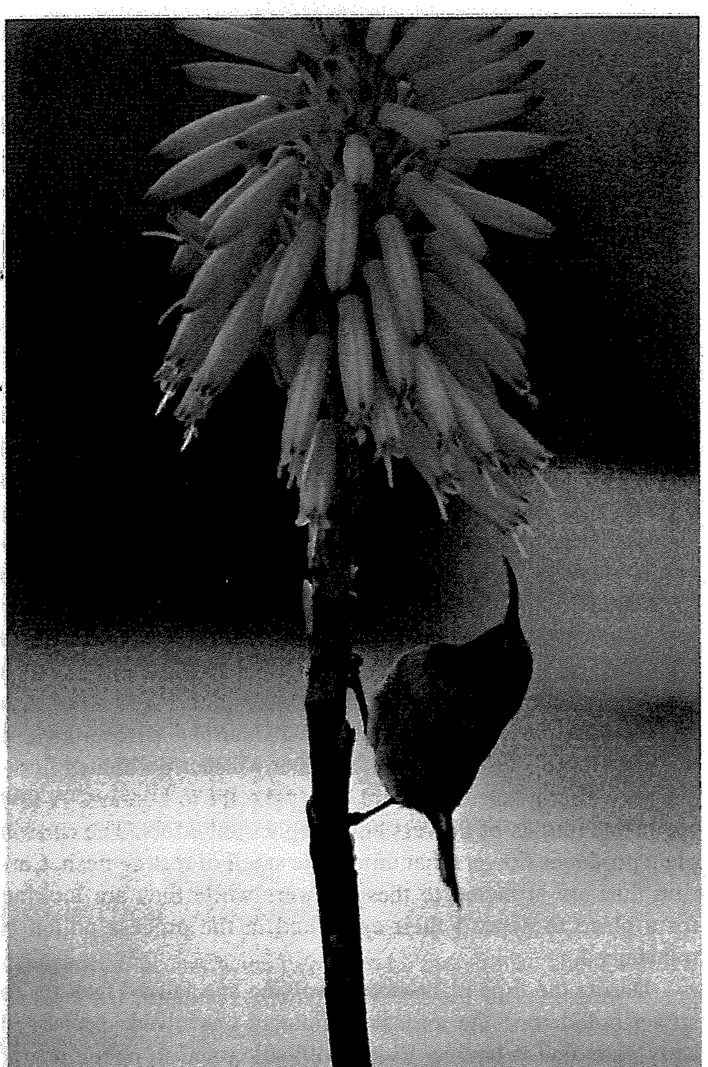



**Figure 5.16 Pollinator coevolution.** The southern double-collared Sunbird (*Cinnyrus chellybeus*) has a curved, thin beak, which perfectly fits into the aloe flower. The aloe flower's red color attracts the sunbird.

The thousands, or even millions, of symbiotic associations that result from coevolution fall into three categories: mutualism, commensalism, and parasitism.

**Mutualism** In **mutualism**, different species living in close association provide benefits to each other. The interdependent association between nitrogen-fixing bacteria of the genus *Rhizobium* and legumes (plants such as peas, beans, and clover) is an example of mutualism. Nitrogen-fixing bacteria live in nodules in the roots of legumes and supply the plants with all the nitrogen they need. The legumes supply sugar to their bacterial symbionts.

**utualism** A symbiotic relationship in which both partners benefit.

Another example of mutualism is the association between reef-building coral animals and microscopic algae. These symbiotic algae, called **zooxanthellae** (pronounced *zoh-zan-thel´ee*), live inside cells of the coral, where they photosynthesize and provide the animal with carbon and nitrogen compounds as well as oxygen. Zooxanthellae have a stimulatory effect on the growth of corals, causing calcium carbonate skeletons to form around their bodies much faster when the algae are present. The corals, in turn, supply their zooxanthellae with waste products such as ammonia, which the algae use to make nitrogen compounds for both partners.

**Mycorrhizae** (pronounced *my-kor-rye' zee*) are mutualistic associations between fungi and the roots of about 80% of all plants. The fungus, which grows around and into the root as well as into the surrounding soil, absorbs essential minerals, especially phosphorus, from the soil and provides them to the plant (**Figure 5.17**). In return, the plant provides the fungus with food produced by photosynthesis. Plants grow more vigorously in mycorrhizal relationships and better tolerate *environmental stressors* such as drought and high soil temperatures. Indeed, some plants cannot maintain themselves under natural conditions if the fungi with which they normally form mycorrhizae are not present.

Mycorrhizae are difficult to raise in experimental settings, and most crops lack mycorrhizal associations, putting them at a disadvantage compared with some weeds. Much research remains to be done on how to foster mycorrhizal associations with crop plants; this research could help reduce the need for supplemental fertilizer.

**Commensalism** **Commensalism** is an association between two different species in which one benefits and the other is unaffected. One example of commensalism is the relationship between social insects and scavengers that live with the social insects. For example, certain kinds of silverfish move along in permanent association with the marching columns of army ants and share the plentiful food caught in their raids. The army ants derive no apparent benefit or harm from the silverfish.

**Commensalism** A type of symbiosis in which one organism benefits and the other one is neither harmed nor helped.

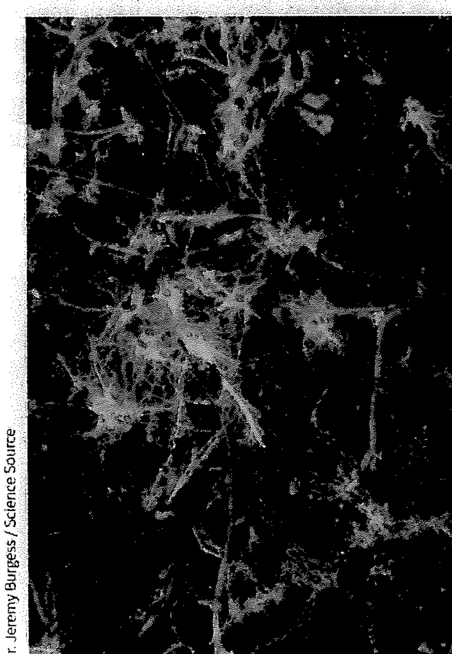



**Figure 5.17 Mutualism.** Mycorrhizae (*Scleroderma geaster*) densely surround the root of a eucalyptus tree. Eucalyptus is a highly drought-tolerant tree, perhaps because its mycorrhizae help buffer it against environmental stress; mycorrhizae obtain food from the tree.

Another example of commensalism is the relationship between a tropical tree and many **epiphytes**, smaller plants, such as mosses, orchids, bromeliads, and ferns, that live attached to the bark of the tree's branches (**Figure 5.18**). The epiphyte anchors itself to the tree but does not obtain nutrients or water directly from the tree. Its location on the tree lets it obtain adequate light, water (as rainfall dripping down the branches), and required nutrient minerals (washed out of the tree's leaves by rainfall). Thus, the epiphyte benefits from the association, whereas the tree is apparently unaffected. (Epiphytes harm their host if they block sunlight from the host's leaves. When this occurs, the relationship is not considered commensalism.)

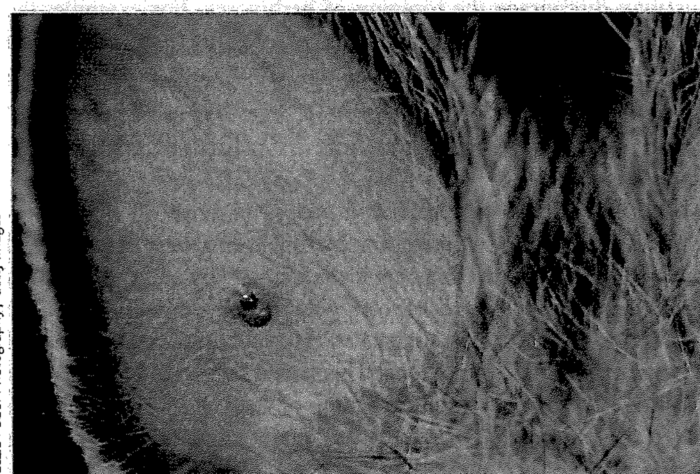
Fletcher & Baylis/Science Source

**Figure 5.18 Commensalism.** Epiphytes are small plants that grow attached to trunks or branches of trees. This orchid (*Phalaenopsis sumatrana*) grows on a tree in a montane rain forest in Malaysia.

**Parasitism** In **parasitism**, one organism, the *parasite*, obtains nourishment from another organism, its *host*. Although a parasite may weaken its host, it rarely kills it. Some parasites, such as ticks, live outside the host's body (**Figure 5.19**). Other parasites, such as tapeworms, live within the host. Parasitism is a successful lifestyle: More than 100 parasites live in or on the human species alone.

**sitism** A symbiotic onship in which one anism benefits and e other is adversely affected.

Many parasites do not cause disease. A parasite that causes disease and sometimes the death of a host is known as a **pathogen**. Crown gall disease, caused by a bacterium, occurs in many kinds of plants and results in millions of dollars' worth of damage each year to ornamental and agricultural plants. Crown gall bacteria, which live on detritus (organic debris) in the soil, enter plants through small wounds such as those caused by insects. They cause galls, or tumorlike growths, often at a plant's crown (between the stem and the roots, at or near the soil surface). Although plants seldom die from crown gall disease, they are weakened, grow more slowly, and often succumb to other pathogens.



Laszlo Podor Photography / Getty Images

**Figure 5.19 Parasitism.** Tick in a rabbit's ear.

## PREDATION

Predators kill and feed on other organisms. **Predation** includes both animals eating other animals (carnivore-herbivore interactions) and animals eating plants (herbivore-producer interactions). Predation has resulted in the coevolution of predator strategies—more efficient ways to catch prey—and prey strategies—better ways to escape the predator. An efficient predator exerts a strong selective force on its prey, and over time, the prey species may evolve some sort of countermeasure that reduces the probability of being captured. The countermeasure that the prey acquires, in turn, may act as a strong selective force on the predator.

**predation** The sumption of one pecies (the prey) by another (the predator).

Adaptations related to predator–prey interactions include predator strategies (pursuit and ambush) and prey strategies (plant defenses and animal defenses). Keep in mind as you read these descriptions that such strategies are not "chosen" by the respective predators or prey. New traits arise randomly in a population as a result of mutation, and the traits may persist under natural selection.

**Pursuit and Ambush** A gecko sights a spider and pounces on it. Orcas (killer whales), which hunt in packs, often herd salmon or tuna into a cove so that they are easier to catch (**Figure 5.20**). Any

©Lazareva / iStockphoto

**Figure 5.20 Predation.** Orcas hunting in a pack in Alaska. This cooperative behavior increases hunting success.

trait that increases hunting efficiency, such as the speed of a gecko or the intelligence of orcas, favors predators that pursue their prey. Because these carnivores must process information quickly during the pursuit of prey, their brains are generally larger, relative to body size, than those of the prey they pursue.

Ambush is another effective way to catch prey. The goldenrod spider is the same color as the white or yellow flowers in which it hides. This camouflage prevents unwary insects that visit the flower for nectar from noticing the spider until it is too late. Predators that *attract* prey are particularly effective at ambushing. For example, a diverse group of deep-sea fishes called anglerfish possess rodlike luminescent lures close to their mouths to attract prey.

**Plant Defenses against Herbivores** Plants cannot escape predators by fleeing, but they possess adaptations that protect them from being eaten. The presence of spines, thorns, tough leathery leaves, or even thick wax on leaves discourages foraging herbivores from grazing. Other plants produce an array of protective chemicals that are unpalatable or even toxic to herbivores. The active ingredients in such plants as marijuana, opium poppy, tobacco, and peyote cactus may discourage the foraging of herbivores. For example, the nicotine found in tobacco is so effective at killing insects that it is a common ingredient in many commercial insecticides. Milkweeds produce deadly alkaloids and cardiac glycosides, chemicals poisonous to all animals except for a small group of insects.

**Defensive Adaptations of Animals** Many animals, such as woodchucks, flee from predators by running to their underground burrows. Others have mechanical defenses, such as the quills of a porcupine and the shell of a pond turtle. Some animals live in groups—a herd of antelope, colony of honeybees, school of anchovies, or flock of pigeons. This social behavior decreases the likelihood of a predator catching one of them unaware; the group has many eyes, ears, and noses watching, listening, and smelling for predators.

Chemical defenses are common among animal prey. The South American poison arrow frog has poison glands in its skin. Its bright **warning coloration** prompts avoidance by experienced predators. Snakes or other animals that have tried to eat a poisonous frog do not repeat their mistake! Some insects have evolved an ability to tolerate milkweed toxins. As a result, they can eat milkweeds without being poisoned, and they accumulate the toxins in their tissues, making themselves toxic to predators (**Figure 5.21**). These insects avoid competition from other herbivorous insects because few other insects can tolerate milkweed toxins. Predators learn to avoid these insects, which are often brightly colored in combinations of red, orange, yellow, white, and black. Not coincidentally, humans use yellow, red, and black in warning signs; we intuitively understand these colors to mean: "Danger." Note that the defense a plant employs against herbivores is actually transformed into a defense herbivores use against predators.

Some animals blend into their surroundings to hide from predators. The animal's behavior often enhances such **cryptic coloration**. The pygmy sea horse resembles gorgonian coral so closely that the little sea horse was not discovered until 1970, when a zoologist found it in the coral he had placed in an aquarium (**Figure 5.22**). Evolution has preserved and accentuated such camouflage.

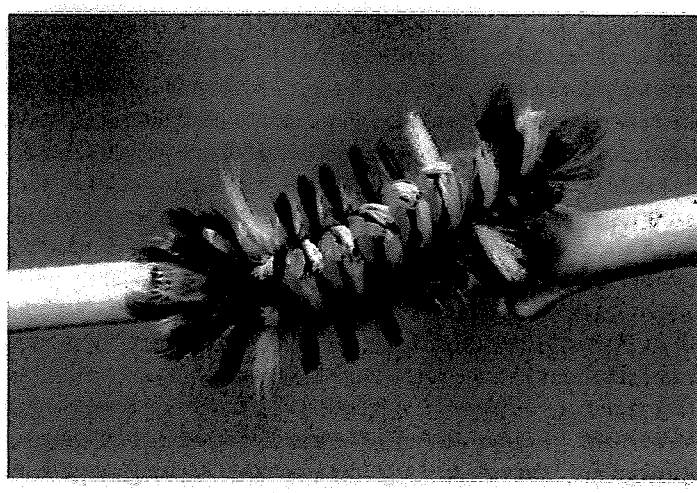



**Figure 5.21 Warning coloration.** A milkweed tussock moth caterpillar, toxic from cardiac glycosides in the milkweed it eats, avoids predation by advertising its toxicity with classic warning coloration: orange, black, and white.

## KEYSTONE SPECIES

Certain species are more crucial to the maintenance of their community than others. Such species, called **keystone species**, are vital in determining the nature and structure of the entire ecosystem—that is, its species composition and its ecosystem functioning. The fact that other species depend on or are greatly affected by the keystone species is revealed when the keystone species is removed. Keystone species are usually not the most abundant species in the ecosystem.

**keystone species** A species, often a predator, that exerts a profound influence on a community in excess of that expected by its relative abundance.

Identifying and protecting keystone species are crucial goals of conservation biologists because if a keystone species disappears from an ecosystem, many other organisms in that ecosystem may become more common, rare, or even disappear. One example of a keystone species is a top predator such as the gray wolf, which was discussed in the chapter introduction. Where wolves were hunted to extinction, the populations of deer, elk, and other herbivores increased explosively. As these herbivores overgrazed the vegetation, many plant species that could not tolerate such grazing pressure disappeared. Many smaller animals such as insects were lost from the ecosystem because the plants that they depended on for food were now less abundant. Thus, the disappearance of the wolf resulted in an ecosystem with considerably less biological diversity.

To date, few long-term studies have identified keystone species and determined the nature and magnitude of their effects on the ecosystems they inhabit. Additional studies are urgently

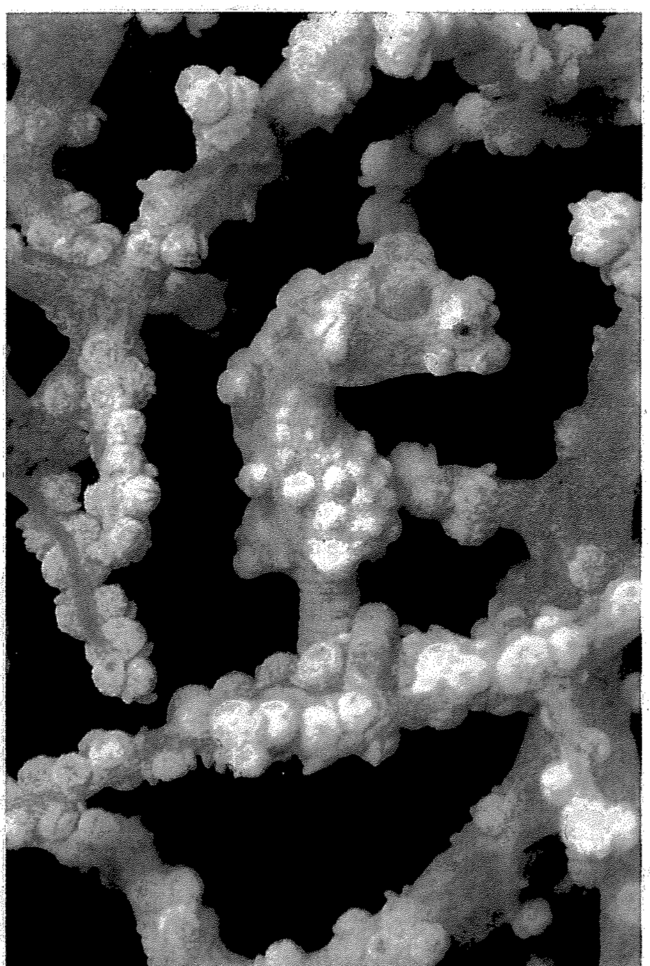

Gerald Nowak/Stockphotopro, Inc

**Figure 5.22 Cryptic coloration.** Pygmy sea horses (*Hippocampus bargibanti*), about the size of small fingernails, are virtually invisible in and around gorgonian coral (*Muricella*).

needed to provide concrete information about the importance of keystone species in conservation biology.

*REVIEW*

1. What is an ecological niche?
2. What is the principle of competitive exclusion? Of resource partitioning?
3. What is symbiosis? What are the three kinds of symbiosis?
4. Describe how evolution has affected predator–prey relationships.
5. What is a keystone species? Why do we consider the wolf a keystone species?

## Species Richness in a Community

*LEARNING OBJECTIVES*

- Describe factors associated with high species richness.
- Give several examples of ecosystem services.

**Species richness** varies greatly from one community to another. Tropical rain forests and coral reefs are examples of communities with extremely high species richness. In contrast, geographically isolated islands and mountaintops exhibit low species richness. What determines the number of species in a community? Several factors appear to be significant: the abundance of potential ecological niches, closeness to the margins of adjacent communities, geographic isolation, dominance of one species over others, habitat stress, and geologic history.

**species richness** The number of species in a community.

Species richness is related to the abundance of potential ecological niches. An already-complex community offers a greater variety of potential ecological niches than does a simple community. For example, in a study of chaparral habitats (shrubby and woody areas) in California, those with structurally complex vegetation provided birds with more kinds of food and hiding places than communities with low structural complexity (**Figure 5.23**).

Species richness is usually greater at the margins of adjacent communities than in their centers. This richness exists because an **ecotone**—a transitional zone where two or more communities meet—contains all or most of the ecological niches of the adjacent communities as well as some niches unique to the ecotone.

Species richness is inversely related to the geographic isolation of a community. Isolated island communities are much less diverse than communities in similar environments found on continents. This lack of diversity is partly the result of the difficulty many species have in reaching and successfully colonizing the island. Sometimes species become locally extinct as a result of random events, and in isolated environments such as islands or mountaintops, extinct species are not readily replaced. Isolated areas are often small and possess fewer potential ecological niches.

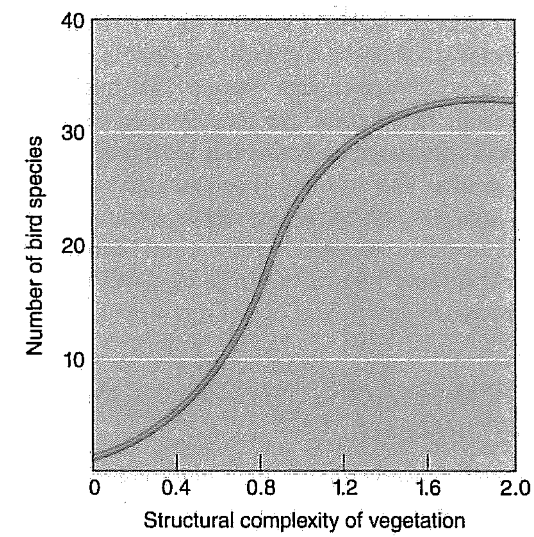



**Figure 5.23 Effect of community complexity on species richness.** As the structural complexity of chaparral vegetation in California increases, the species richness of birds in that habitat increases. (After M.L. Cody and J.M. Diamond, eds., *Ecology and Evolution of Communities*. Harvard University, Cambridge, 1975)

Species richness is reduced when any one species occupies a position of dominance within a community because it may appropriate a disproportionate share of available resources, thus crowding out other species. Ecologist **James H. Brown** and colleagues of the University of New Mexico have studied species competition and diversity in long-term experiments conducted since 1977 in the Chihuahuan Desert of southeastern Arizona. In one experiment, the scientists enclosed their study areas with fencing and then cut holes in the fencing to allow smaller rodents to come and go but to exclude the larger kangaroo rats. The removal of three dominant species, all kangaroo rats, from several plots resulted in an increased diversity of other rodent species. This increase was attributed to less competition for food and to an altered habitat because the abundance of grass species increased dramatically after the removal of the kangaroo rats.

Generally, species richness is inversely related to the environmental stress of a habitat. Only those species capable of tolerating extreme environmental conditions can live in an environmentally stressed community. The species richness of a highly polluted stream is low compared to that of a nearby pristine stream. Similarly, the species richness of high-latitude (farther from the equator) communities exposed to harsh climates is less than that of lower-latitude (closer to the equator) communities with milder climates. Although the equatorial countries of Colombia, Ecuador, and Peru occupy only 2% of Earth's land, they contain 45,000 native plant species. The continental United States and Canada, with a significantly larger land area, possess a total of 19,000 native plant species. Ecuador alone contains more than 1300 native bird species, twice as many as the United States and Canada combined.

Geologic history greatly affects species richness. Tropical rain forests are probably old, stable communities that have undergone few climate changes in Earth's entire history. During this time, myriad species evolved in tropical rain forests, having experienced few or no abrupt climate changes that might have led to their extinction. In contrast, glaciers have repeatedly modified temperate and arctic regions during Earth's history, as the climate alternately cooled and warmed. For example, an area recently vacated by glaciers will have low species richness because few species will have had a chance to enter it and become established. Scientists expect that future climate change will negatively alter species richness.

## SPECIES RICHNESS, ECOSYSTEM SERVICES, AND COMMUNITY STABILITY

Ecologists and conservationists have long debated whether the extinction of species threatens the normal functioning and stability of ecosystems. This question is of great practical concern because ecosystems supply human societies with many environmental benefits (**Table 5.1**). Conservationists maintain that ecosystems with greater species richness better supply such **ecosystem services** than ecosystems with lower species richness.

**ecosystem services** Important environmental benefits that ecosystems provide to people; include clean air to breathe, clean water to drink, and fertile soil in which to grow crops.

**Table 5.1 Ecosystem Services**

| *Ecosystem* | *Services Provided by Ecosystem* |
|---|---|
| Forests | • Purify air and water<br>• Produce and maintain soil<br>• Absorb carbon dioxide (carbon storage)<br>• Provide wildlife habitat<br>• Provide humans with wood and recreation |
| Freshwater systems (rivers and streams, lakes, and groundwater) | • Moderate water flow and mitigate floods<br>• Dilute and remove pollutants<br>• Provide wildlife habitat<br>• Provide humans with drinking and irrigation water<br>• Provide transportation corridors<br>• Generate electricity<br>• Offer recreation |
| Grasslands | • Purify air and water<br>• Produce and maintain soil<br>• Absorb carbon dioxide (carbon storage)<br>• Provide wildlife habitat<br>• Provide humans with livestock and recreation |
| Coasts | • Provide a buffer against storms<br>• Dilute and remove pollutants<br>• Provide wildlife habitat, including food and shelter for young marine species<br>• Provide humans with food, harbors, transportation routes, and recreation |
| Sustainable agricultural ecosystems | • Produce and maintain soil<br>• Absorb carbon dioxide (carbon storage)<br>• Provide wildlife habitat for birds, insect pollinators, and soil organisms<br>• Provide humans with food and fiber crops |

Adapted from p. 527 of *Climate Change Impacts in the United States*, a report of the National Assessment Synthesis Team, U.S. Global Change Research Program, Cambridge University Press [2001].

Traditionally, most ecologists assumed that **community stability**—the absence of change—is a consequence of community complexity. Stability is the result of resistance and resilience. *Resistance* is the ability of a community to withstand environmental *disturbances*, natural or human events that disrupt a community. *Resilience* is the ability of a community to recover quickly to its former state following an environmental disturbance. A community with considerable species richness may function better—that is, have more resistance and resilience—than a community with less species richness. One reason why organic farmers typically grow a wide variety of crop species is that species richness reduces the risk of crop predation and the impact of any environmental disturbance, such as an early frost or hailstorm.

According to this view, the greater the species richness, the less critically important any single species should be. With many possible interactions within the community, any single disturbance is less likely to disrupt enough components of the system to make a significant difference in its functioning. Evidence for this hypothesis includes the fact that destructive outbreaks of pests are more common in cultivated fields, which are low-diversity communities, than in natural communities with greater species richness.

Ongoing studies by **David Tilman** of the University of Minnesota and **John Downing** of the University of Iowa have strengthened the link between species richness and community stability. In their initial study, they established and monitored 207 plots of Minnesota grasslands for seven years. During the study, Minnesota's worst drought in 50 years occurred (1987–1988). The biologists found that those plots with the greatest number of plant species lost less ground cover and recovered faster than did species-poor plots. Further research supported these conclusions and showed a similar effect of species richness on community stability during nondrought years. Similar work at grassland sites in Europe also supports the link between species richness and ecosystem functioning. Sustainable agricultural ecosystems, however, are human-made and therefore inherently different from other ecosystems. Sustainable agriculture is discussed further in Chapter 18.

*CASE IN POINT*

## GARDENS AS ECOSYSTEMS

A suburban or urban garden is a community that supports both humans and wildlife. Of course, vegetables in a garden provide food for both people and insect pests. Spaces between garden plants offer niches where weeds (classic *r*-selected species) can grow, and while some of these weeds compete with garden plants for light, nutrients, and water, other weeds, like purslane (*Portulacca oleracea*), are themselves nutritious food plants for people. A gardener can control weeds with mulch, which makes light a limiting resource for germinating weed seeds. The gardener leaves spaces between vegetable plants to prevent excessive intraspecific competition. Flowers of many herbs and weeds offer food, in the form of pollen and nectar, for adult parasitic wasps, who then provide pest control as an ecosystem service, by laying eggs in caterpillars such as tomato hornworm (*Manduca quinquemaculata*).

While some birds, such as crows, are garden pests, bluebirds, mockingbirds, and other songbirds also help control insect pests through predation. Soil in a garden contains abiotic minerals, as well as bacteria, earthworms, nematodes, fungi, viruses, and insects—each of which may be either a pest or beneficial species from the gardener's perspective. The population density of each species depends on density-dependent factors (available nutrients and water) and density-independent factors (killing frosts). The gardener who monitors pest populations and keeps them well below their maximum growth rates, using natural predators and parasites, will lose less produce.

The gardener relies on mutualisms: between rhizobium bacteria and bean plants to help add nitrogen to the soil, and between honeybees and flowering plants to ensure good harvests of tomatoes and peppers and eggplant. The gardener may impose a type of resource partitioning by planting a wide variety of plants in the garden, from root crops and low-growing greens to bushy tomatoes and tall stalks of corn (**Figure 5.24**). This species richness also helps reduce the effects of environmental stress, such as drought, since different garden plants will demand water at different times in the growing season. ■

Andy Ryan / Getty Images

**Figure 5.24 A Garden Ecosystem.** A gardener with her harvest of carrots. Note the varied plant heights and the dense growth of a variety of vegetables.

*REVIEW*

1. What are two determinants of species richness? Give an example of each.
2. What are ecosystem services? Describe some ecosystem services a forest provides.

## Community Development

*LEARNING OBJECTIVE*

- Define *ecological succession*, and distinguish between primary and secondary succession.

A community develops gradually, through a sequence of species. The process of community development over time, which involves species in one stage being replaced by different species, is called **ecological succession** or, simply, **succession**. Certain organisms that initially colonize an area are replaced over time by others, which themselves are replaced much later by still others.

The actual mechanisms that underlie succession are not clear. In some cases, an earlier species modifies the environment in some way, thereby making it more suitable for a later species to colonize. Often, succession begins with *r*-selected species, which reproduce quickly. These are later replaced, through competition, with *K*-selected species, which grow more slowly and grow larger.

Ecologists initially thought that succession inevitably led to a stable and persistent community, such as a forest, called a *climax community*. But more recently, the traditional view has fallen out of favor. The apparent stability of a "climax" forest is probably the result of how long trees live relative to the human life span. Mature "climax" communities are not in a state of permanent stability but, rather, in a state of continual disturbance. Over time, a mature forest community changes in species composition and in the relative abundance of each species, despite its overall uniform appearance.

Ecological succession is usually described in terms of the changes in the species composition of the plants growing in an area, although each stage of succession may have its own characteristic kinds of animals and other organisms. The time involved in ecological succession is on the scale of tens, hundreds, or thousands of years, not the millions of years involved in the evolutionary time scale.

## PRIMARY SUCCESSION

**Primary succession** is ecological succession that begins in an environment that has not been inhabited before. No soil exists when primary succession begins. Bare rock surfaces, such as recently formed volcanic lava and rock scraped clean by glaciers, and sand dunes are examples of sites where primary succession may take place (**Figure 5.25**).

**primary succession** The change in species composition over time in a previously uninhabited environment.

**Primary Succession on Bare Rock** Although the details vary from one site to another, on bare rock, lichens are often the most important element in the **pioneer** community—the initial community that develops during primary succession. Lichens secrete acids that help break the rock apart, beginning the process of soil formation. Over time, mosses and drought-resistant ferns may replace the lichen community, followed in turn by tough grasses and herbs. Once enough soil accumulates, grasses and herbs may be replaced by low shrubs, which in turn would be replaced by forest trees in several distinct stages. Primary succession on bare rock from a pioneer community to a forest community often occurs in this sequence: lichens → mosses → grasses → shrubs → trees.

**Primary Succession on Sand Dunes** Some lake and ocean shores have extensive sand dunes deposited by wind and water. At first, these dunes are blown about by the wind. The sand dune environment is severe, with high temperatures during the day and low temperatures at night. The sand is also deficient in certain nutrient minerals needed by plants. As a result, few plants can tolerate the environmental conditions of a sand dune.

**Henry Cowles** developed the concept of succession in the 1880s when he studied succession on sand dunes around the shores

Martin Shields / Science Source

(a) After the glacier's retreat, lichens initially colonize bare gravel, followed by mosses and small shrubs.

Charles D. Winters / Science Source

(b) At a later time, dwarf trees and shrubs colonize the area (background).

Martin Shields/Science Source

(c) Still later, spruces dominate the community.

**Figure 5.25 Primary succession on glacial moraine.** During the past 200 years, glaciers have retreated in Glacier Bay, Alaska. Although these photos were not taken in the same location, they show some of the stages of primary succession on glacial moraine (rocks, gravel, and sand deposited by a glacier). How might climate change be influencing glacial moraine ecosystems?

of Lake Michigan, which has been gradually shrinking since the last ice age. The shrinking lake exposed new sand dunes that displayed a series of stages in the colonization of the land.

Grasses are common pioneer plants on sand dunes around the Great Lakes. As the grasses extend over the surface of a dune, their roots hold it in place, helping to stabilize it. At this point, mat-forming shrubs may invade, further stabilizing the dune. Later, shrubs are replaced by poplars (cottonwoods), which years later are replaced by pines and finally by oaks. Soil fertility remains low, and as a result, other forest trees rarely replace oaks. A summary of how primary succession on sand dunes around the Great Lakes might proceed is in this sequence: grasses → shrubs → poplars (cottonwoods) → pine trees → oak trees.

## SECONDARY SUCCESSION

**Secondary succession** is ecological succession that begins in an environment following destruction of all or part of an earlier community. Clear-cut forests, open areas caused by a forest fire, and abandoned farmland are common examples of sites where secondary succession occurs. Farmers routinely create spaces for secondary succession when they plow land to prepare for crop planting.

**condary succession** he change in species composition that kes place after some ırbance destroys the sting vegetation; soil is already present.

During the summer of 1988, wildfires burned approximately one-third of Yellowstone National Park. This natural disaster provided a chance for biologists to study secondary succession in areas that were once forests. After the fires, ash covered the forest floor, and most of the trees, though standing, were charred and dead. Secondary succession in Yellowstone has occurred rapidly. Less than one year later, trout lily and other herbs had sprouted and covered much of the ground. Ten years after the fires, a young forest of knee-high to shoulder-high lodgepole pines dominated the area, and Douglas fir seedlings were also present. Biologists continue to monitor the changes in Yellowstone as secondary succession proceeds.

**Old Field Succession** Biologists have extensively studied secondary succession on abandoned farmland. It takes more than 100 years for secondary succession to occur at a single site, but a single researcher can study old field succession in its entirety by observing different sites in the same area that have been undergoing succession for different amounts of time. The biologist may examine county tax records to determine when each field was abandoned.

A predictable succession of communities colonizes abandoned farmland in North Carolina (**Figure 5.26**). The first year after cultivation ceases, an annual plant, crabgrass, dominates. During the second year, horseweed, a larger plant that outgrows crabgrass, is the dominant species. Horseweed does not dominate for more than one year because decaying horseweed roots inhibit the growth of young horseweed seedlings. In addition, horseweed does not compete well with other plants that become established in the third year. During the third year after the last cultivation, other weeds—broomsedge, ragweed, and aster—become established. Typically, broomsedge outcompetes aster because broomsedge is drought-tolerant, whereas aster is not.

In years 5 to 15, the dominant plants in an abandoned field are pines such as shortleaf pine and loblolly pine. Through the buildup of soil litter, such as pine needles and branches, pines produce conditions that cause the earlier dominant plants to decline in importance. Over the next century or so, pines give up their dominance to hardwoods such as oaks. The replacement of pines by oaks depends primarily on the environmental changes produced by the pines. The pine litter causes soil changes, such as an increase in water-holding capacity, which young oak seedlings need to become established. In addition, hardwood seedlings are more tolerant of shade than are young pine seedlings. Secondary succession on abandoned farmland in the southeastern United States proceeds in this sequence: crabgrass → horseweed → broomsedge and other weeds → pine trees → hardwood trees.

### ENVIRONEWS

#### Update on Honeybee Die-Offs

Bees in the United States are necessary for the pollination of about 90 commercial crops, such as nuts, fruits, and vegetables. Since 2006, many U.S. beekeeping operations have experienced 30% to 90% losses in their bee colonies. The cause of these sudden declines in the adult bee population, known as colony collapse disorder (CCD), was a mystery. No dead bees have been found in or near the colony, so performing autopsies on dead bees has been impossible. Researchers initially investigated many potential causes of CCD, from parasites to bad weather, and some evidence indicated that more than one factor could be interacting.

In 2010 entomologists reported a link between CCD and two parasites, a virus and a fungus. When the virus is present but not the fungus, some bees get sick but the colony as a whole does not collapse. Similarly, when the fungus is present but not the virus, the honeybee population does not collapse. But if the two parasites are present together in the same colony, the result is usually complete devastation. Some pesticides, used in both lawn care and agriculture—to control grubs, which eat grass roots— are also suspected of weakening honeybee navigation and immune systems. Grubs can instead be controlled with nontoxic biological control products, and minimized by cultivating lawns with clover and other low-growing broadleaf plants in combination with grasses.

### REVIEW

1. What is ecological succession?
2. How do primary and secondary succession differ?

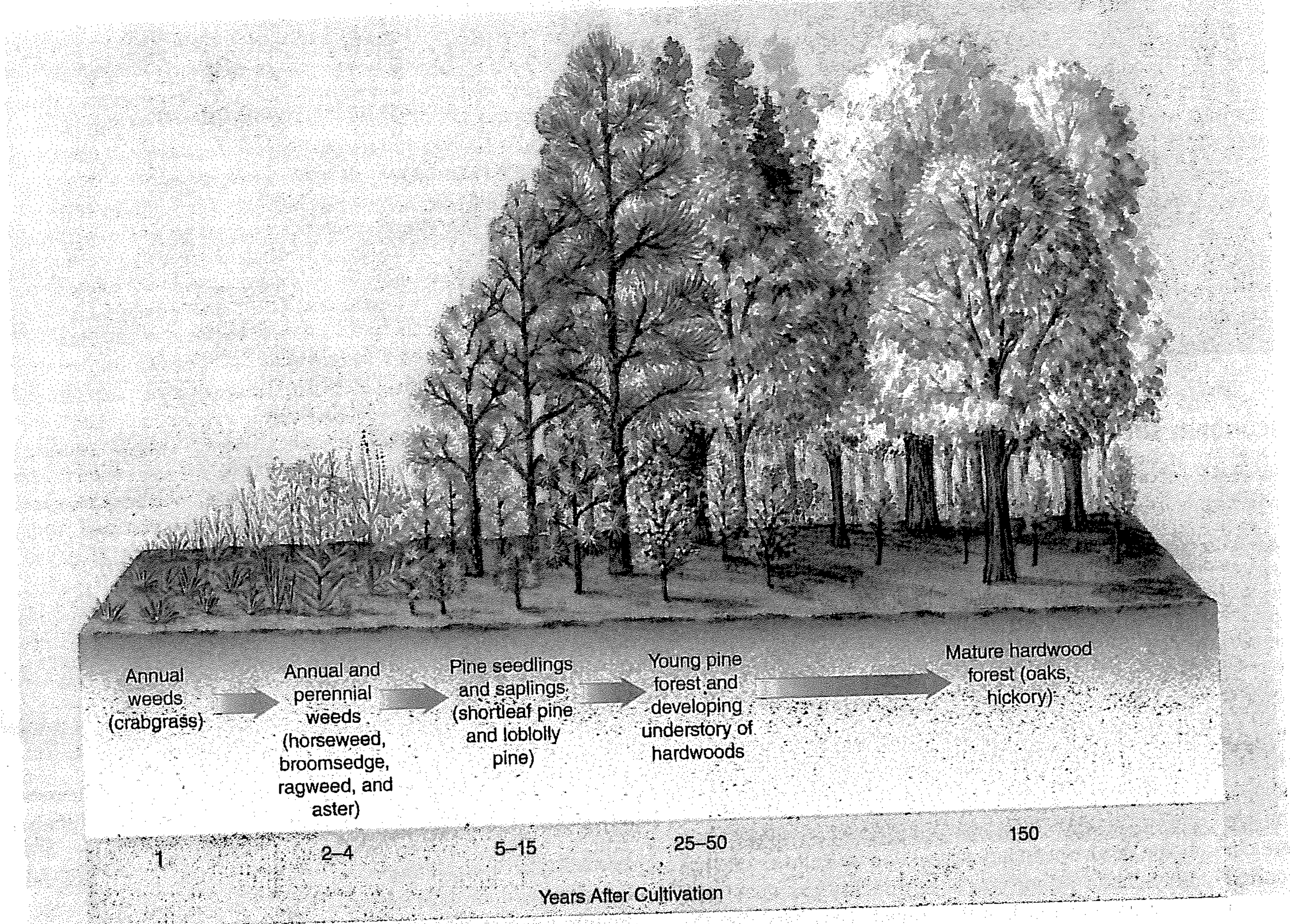



**Figure 5.26 Secondary succession on an abandoned field in North Carolina.**

## REVIEW OF LEARNING OBJECTIVES WITH SELECTED KEY TERMS

- **Define *evolution*.**

**Evolution** is cumulative genetic changes that occur over time in a population of organisms; evolution explains many patterns observed in the natural world.

- **Explain the four premises of evolution by natural selection as proposed by Charles Darwin.**

**Natural selection** is the process in which better-adapted individuals—those with a combination of genetic traits better suited to environmental conditions—are more likely to survive and reproduce, increasing their proportion in the population. Natural selection, as envisioned by **Charles Darwin**, has four premises:

1. Each species produces more offspring than will survive to maturity.
2. The individuals in a population exhibit heritable variation in their traits.
3. Organisms compete with one another for the resources needed to survive.
4. Those individuals with the most favorable combination of traits are most likely to survive and reproduce, passing their genetic characters on to the next generation.

- **Identify the major groups of living organisms.**

Organisms are classified into six major groups: Archaea, Bacteria, Protista (algae, protozoa, slime molds, and water molds), Fungi (molds and yeasts), Plantae, and Animalia.

- **Define *population*, and explain the four factors that produce changes in population size.**

A **population** is a group of individuals of the same species that live in the same geographic area at the same time. **Growth rate** ($r$) is the rate of change of a population's size, expressed in percent per year. On a global scale (when **dispersal** is not a factor), growth rate ($r$) is due to **birth rate** ($b$) and **death rate** ($d$): $r = b - d$. **Emigration** ($e$), the number of individuals leaving an area, and **immigration** ($i$), the number of individuals entering an area, affect a local population's size and growth rate. For a local population (where dispersal is a factor), $r = (b - d) + (i - e)$.

- **Use intrinsic rate of increase, exponential population growth, and carrying capacity to explain the differences between J-shaped and S-shaped growth curves.**

**Intrinsic rate of increase** is the exponential growth of a population that occurs under ideal conditions. **Exponential population growth** is the accelerating population growth that occurs when optimal conditions allow a constant reproductive rate over a period of time. The **carrying capacity** ($K$) is the maximum number of individuals of a given species that a particular environment can support for an indefinite period, assuming there are no changes in the environment. Although populations with a constant reproductive rate exhibit exponential population growth for limited periods (the J curve), eventually the growth rate decreases to around zero or becomes negative. The S curve shows an initial lag phase (when the population is small), followed by an exponential phase, followed by a leveling phase as the carrying capacity of the environment is reached.

- **Distinguish between density-dependent and density-independent factors that affect population size, and give examples of each.**

A **density-dependent factor** is an environmental factor whose effects on a population change as population density changes. Predation, disease, and competition are examples. A **density-independent factor** is an environmental factor that affects the size of a population but is not influenced by changes in population density. Hurricanes and fires are examples.

- **Define *survivorship,* and describe type I, type II, and type III survivorship curves.**

**Survivorship** is the probability that a given individual in a population will survive to a particular age. There are three general types of survivorship curves. In type I survivorship, death is greatest in old age. In type III survivorship, death is greatest among the young. In type II survivorship, death is spread evenly across all age groups.

- **Define *metapopulation,* and distinguish between source and sink habitats.**

Many species exist as a **metapopulation**, a set of local populations among which individuals are distributed in distinct habitat patches across a landscape. **Source habitats** are preferred sites where local reproductive success is greater than local mortality. **Sink habitats** are lower-quality habitats where individuals may suffer death or, if they survive, poor reproductive success.

- **Describe the factors that contribute to an organism's ecological niche.**

An organism's **ecological niche** is the totality of its adaptations, its use of resources, and the lifestyle to which it is fitted. The ecological niche is the organism's place and role in a complex biotic and abiotic system.

- **Define *competition,* and relate the concepts of competitive exclusion and resource partitioning.**

**Competition** is the interaction among organisms that vie for the same resources (such as food or living space) in an ecosystem. Many ecologists think two species cannot occupy the same niche in the same community for an indefinite period. In **competitive exclusion**, one species excludes another as a result of competition for limited resources. Some species reduce competition by **resource partitioning**, in which they use resources differently.

- **Define *symbiosis,* and distinguish among mutualism, commensalism, and parasitism.**

**Symbiosis** is any intimate relationship or association between members of two or more species. **Mutualism** is a symbiotic relationship in which both partners benefit. **Commensalism** is a type of symbiosis in which one organism benefits and the other one is neither harmed nor helped. **Parasitism** is a symbiotic relationship in which one organism benefits and the other is adversely affected.

- **Define *predation,* and describe the effects of natural selection on predator–prey relationships.**

**Predation** is the consumption of one species (the prey) by another (the predator). During **coevolution** between predator and prey, the predator evolves more efficient ways to catch prey, and the prey evolves better ways to escape the predator.

- **Define *keystone species,* and discuss the wolf as a keystone species.**

A **keystone species** is a species, often a predator, that exerts a profound influence on a community in excess of that expected by its relative abundance. One example of a keystone species is the gray wolf. Where wolves were hunted to extinction, the populations of deer, elk, and other herbivores increased. As these herbivores overgrazed the vegetation, many plant species disappeared. Many smaller animals such as insects and trout decreased because the plants they depended on for food were now less abundant. Thus, the disappearance of the wolf resulted in an ecosystem with considerably less biological diversity.

- **Describe factors associated with high species richness.**

**Species richness**, the number of species in a community, is often great when there are many potential ecological niches, when the area is at the margins of adjacent communities, when the community is not isolated or severely stressed, when one species does not dominate others, and when communities have a long geologic history.

- **Give several examples of ecosystem services.**

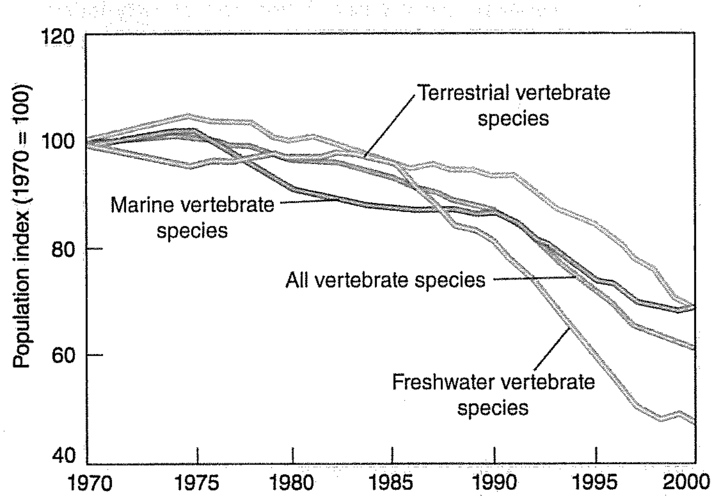
**Ecosystem services**, important environmental benefits that ecosystems provide to people, include clean air to breathe, clean water to drink, and fertile soil in which to grow crops.

- **Define *ecological succession,* and distinguish between primary and secondary succession.**

**Ecological succession** is the orderly replacement of one community by another. **Primary succession** is the change in species composition over time in a previously uninhabited environment. **Secondary succession** is the change in species composition that takes place after some disturbance destroys the existing vegetation; soil is already present.

## Critical Thinking and Review Questions

1. Charles Darwin once said, "It is not the strongest of the species that survive, nor the most intelligent, but the ones most responsive to change." How does this statement relate to the definition of *evolution*?
2. During mating season, male giraffes slam their necks together in fighting bouts to determine which male is stronger and can mate with females. Explain how long necks may have evolved under this scenario, using Darwin's theory of evolution by natural selection.
3. How do the Eukarya and Prokarya differ?
4. How are the following factors related in determining population growth: birth rate, death rate, immigration, and emigration?
5. Draw a graph to represent the long-term growth of a population of bacteria cultured in a test tube containing a nutrient medium that is replenished. Now draw a graph to represent the growth of bacteria in a test tube when the nutrient medium is not replenished. Explain the difference.
6. Which of the following are density-dependent factors: a hurricane, disease, or competition? Why?
7. How do survivorship curves relate to *r* selection and *K* selection in animals?
8. What is the difference between a source habitat and a sink habitat in terms of birth rates and death rates?
9. What is an organism's ecological niche, and why is a realized niche usually narrower, or more restricted, than a fundamental niche?
10. What portion of humans' fundamental niche are we occupying today? Do you think our realized niche has changed over the past 200 years? Why or why not?
11. What is the most likely limiting resource for plants and animals in deserts? How are limiting resources related to competition? Explain your answers.
12. What type of symbiotic relationship—mutualism, commensalism, or predation—do you think exists between the pygmy sea horse and the gorgonian coral pictured in Figure 5.22? Explain your answer.
13. How is predation related to the concept of energy flow through ecosystems (covered in Chapter 3)?
14. Some biologists think that protecting keystone species would help preserve biological diversity in an ecosystem. Explain.
15. Why does species richness vary from one community to another?
16. What kinds of ecosystem services does a forest provide?
17. Describe an example of secondary succession. Begin your description with the specific disturbance that preceded it.
18. Draw a diagram of three concentric circles and label the circles to show the relationships among species, ecosystems, and communities. If you were adding symbiosis, predation, and competition to the simple system you have depicted, in which circle(s) would you place them?
19. Study the graph and determine the overall trend in biological diversity of vertebrate species from 1970 to 2000. Sociobiologist E. O. Wilson says that the five forces responsible for this trend are habitat loss, invasive species, pollution, human population growth, and overconsumption. How do each of these forces relate to energy use and/or climate change?




Adapted from Millennium Ecosystem Assessment. *Ecosystems and Human Well-Being: Biodiversity Synthesis*. Washington, D.C.: World Resources Institute [2005]

## Food for Thought

### Weed Ecology

Weeds, typically pioneer, *r*-selected species, grow quickly and reproduce abundantly.

In agriculture, weeds can interfere with food production. Understanding ecosystems can help farmers manage weeds more effectively. By fostering healthy soils, farmers encourage bacteria, fungi, and insect populations that might consume weed seeds as food. If water is a limiting resource, the farmer might irrigate crops only in the crop row, not allowing weeds between rows to access the water. When we understand weeds as pioneer species, how can we use this knowledge to help us manage weeds in gardens?

## Exponential and Logistic Population Growth: Equations

Under exponential population growth, the number of individuals (N) in the population at any single time, t, can be reflected by equation 1:

$$(1)\ N_t = N_o * e^{rt}$$

In this equation $N_t$ represents the population at time t, $N_o$ represents the starting population, e is the base of the natural logarithm (~2.718), r is the natural growth rate of the population, and t is the time since the start of growth.

At any given moment, a student can calculate how much the population will increase in the next time interval. The increase in population can be calculated with equation 2:

$$(2)\ dN/dt = r * N$$

In this equation, dN/dt represents the number of individuals added to the population at any time. In the table of bacterial growth above, r = 1, which means that the population doubles in every time interval.

Although the equation for the logistic growth curve is more complex than the equation for exponential growth, a student can still easily calculate, using equation 3, the predicted growth in population, for any population level, N:

$$(3)\ dN/dt = r * N * (1 - N/K)$$

One way to think about this equation is to note that, as in equation 2, the change in population is proportional to the population level at that moment, N, and to the rate of population growth, r, but is reduced when the population, N, is close to the carrying capacity, K. If N is large, (1-N/K) will be close to zero; if N exceeds K, 1-N/K will become negative, meaning that the population will decrease. But, if N is small, 1-N/K is close to 1, and the population will grow similarly to the exponential growth pattern, at least until the population, N, gets closer to the carrying capacity (K).