CHAPTER 14

Is Earth Experiencing a Biodiversity Crisis?

Community Ecology, Ecosystem Ecology, and Conservation Biology

The Lost River sucker faces extinction . . .

... but saving the fish has angered these farmers.

Who has the right to use this lake for their survival—the farmers or the fish?

In the summer of 2001, the typically quiet, conservative community of Klamath Falls, Oregon, suddenly began seething with revolutionary passion. Anger at federal authorities was widespread and palpable; signs along Route 39 outside the city read, "Please thank the U.S. Fish and Wildlife Service for destroying the Klamath Basin's economy," and "Crime Scene . . . by the U.S. Federal Government." The residents' fury reached a boiling point in late June and July, when distraught farmers repeatedly confronted and threatened federal officials and eventually destroyed a Bureau of Reclamation facility using chainsaws, pry bars, and blowtorches.

The wrath of the people of Klamath Falls and surrounding communities was generated by the federal government's legal requirement to protect species that are recognized as in danger of extinction. In the case of the Klamath crisis, the species at risk are two fish—the Lost River sucker and the shortnose sucker. In the midst of a multiyear drought and dangerously low water levels in Upper Klamath Lake, home to these endangered fish, the U.S. Fish and Wildlife Service stopped the outflow of water from the lake in April 2001. The irrigation canals that had fed barley, potato, and alfalfa fields in the high desert of the Klamath Basin since the early 1900s suddenly went dry. Without irrigation, thousands of farmers were unable to produce crops and faced the prospect of bankruptcy, foreclosure, and loss of their livelihood.

Why should we care about the fate of such a controversial endangered species—or any endangered species?

Lost River and shortnose suckers are dull-colored fish that feed on the mucky bottoms of lakes and streams in the region. These fish have not represented a viable economic resource for humans for several decades. In contrast, the crops produced annually by irrigated fields in the region produce millions of dollars in income. Ty Kliewer, a student at Oregon State University whose family farms in the basin, summarized the feelings of many when he told his senator in 2001 that he had learned the importance of balancing mathematical and chemical equations in school. "It appears to me that the people who run the Bureau of Reclamation and the U.S. Fish and Wildlife Service slept through those classes," Kliewer said. "The solution lacks balance, and we've been left out of the equation." The Klamath crisis of 2001 was not unique; thousands of people all over the United States have had their jobs threatened or eliminated by the government's attempts to protect endangered species.

Why should the survival of one or a few species come before the needs of humans? Many biologists and environmentalists say that the Klamath Falls bumper sticker "Fish or Farmers?" misstates the dilemma. Instead, they argue, humans depend on the web of life that creates and supports natural ecosystems, and they worry that disruptions to this web may become so severe that our own survival as a species will be threatened. In this view, protecting endangered species is not about pitting fish against farmers; it is about protecting fish to ensure the survival of farmers. In this chapter, we explore the causes and consequences of the loss of biological diversity.

14.1 The Sixth Extinction

The government agencies that stopped water delivery to the Klamath Basin farmers were acting under the authority of the **Endangered Species Act (ESA)**, a law passed in 1973 with the purpose of protecting and encouraging the population growth of threatened and endangered species. Lost River and shortnose suckers were once among the most abundant fish in Upper Klamath Lake—at one time, they were harvested and canned for human consumption. Now, with populations of fewer than 500 and minimal reproduction, these fish are in danger of **extinction**, defined as the complete loss of a species. Critically imperiled species such as the Lost River and shortnose suckers are exactly the type of organisms that legislators had in mind when they enacted the ESA.

The ESA was passed because of the public's concern about the continuing erosion of **biodiversity**, the entire variety of living organisms. The fate of the whooping crane, one of only two cranes native to North America, prompted the passage of the ESA. Biologists estimate that more than 1000 whooping cranes were alive in the mid-1860s. By 1938, as a result of hunting and the loss of nesting areas, the whooping crane had disappeared from much of the continent; only two small flocks were left. By 1942, only 16 birds remained in the wild. Unfortunately, the near extinction of the whooping crane is not a unique event. Bald eagles, peregrine falcons, gray wolves, and elephant seals—once abundant species—are or recently have been pushed close to extinction as a result of human activity. Even one of the most numerous bird species on the planet, the passenger pigeon (Figure 14.1), was not safe. This species was driven to extinction in North America nearly 100 years ago by familiar causes—habitat loss and overhunting. The ESA was drafted because humans appear to be triggering an unprecedented and rapid rate of species loss.

Critics of the ESA argue that the goal of saving all species from extinction is unrealistic. After all, extinction is a natural process—the approximately 10 million species living today constitute less than 1% of the species that have ever existed—and trying to save rare species, as we have seen in the Klamath Basin, can be detrimental to humans. In the next section, we

Figure 14.1 An extinct species. Passenger pigeons were once the most common bird in North America, but they were driven to extinction by human activity.

explore the scientific questions posed by ESA critics: How does the rate of extinction today compare to the rates in the past? Is the ESA just attempting to postpone the inevitable, natural process of extinction?

Measuring Extinction Rates

If ESA critics are correct in stating that the current rate of species extinctions is "natural," then the extinction rate today should be roughly equal to the rate in previous eras. The rate of extinction in the past can be estimated by examining the fossil record.

Figure 14.2 illustrates what examinations of the fossil record tell scientists about the history of biodiversity on Earth. Since the rapid evolution of a wide variety of animal groups approximately 580 million years ago, the number of families of organisms has generally increased. However, this increase in biodiversity has not been smooth or steady. The history of life on Earth has been punctuated by five **mass extinctions**—species losses that are global in

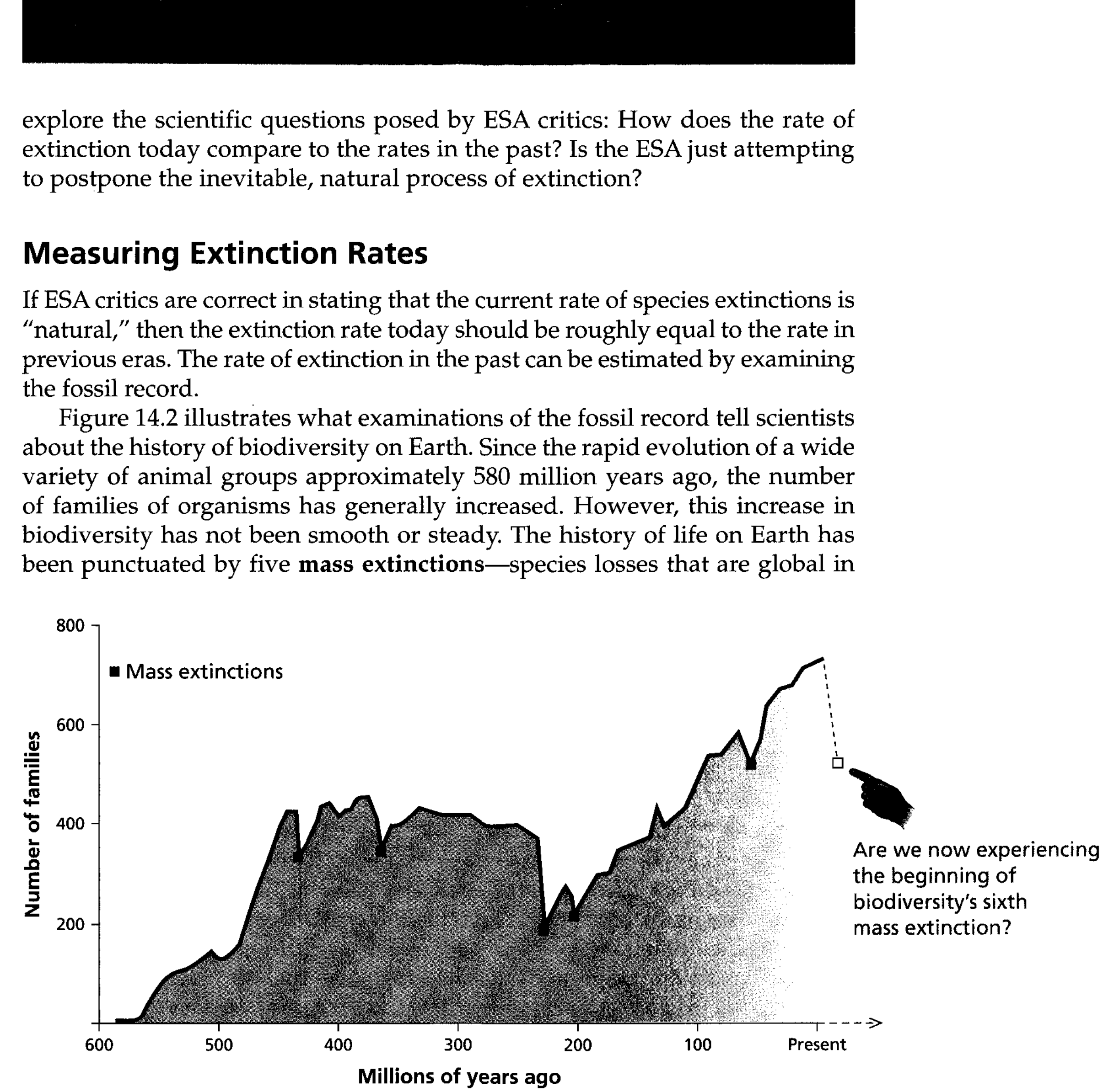


Figure 14.2 Mass extinction. This graph illustrates the general rise in biodiversity over the past 600 million years, as indicated by an increase in the number of marine families present in the fossil record. However, this rise has been punctuated by five mass extinctions (marked here with black squares), each resulting in a global decline in biodiversity. The proportion of species lost during these mass extinctions appears to be even greater than the proportion of families lost because families that were especially species-rich died out.

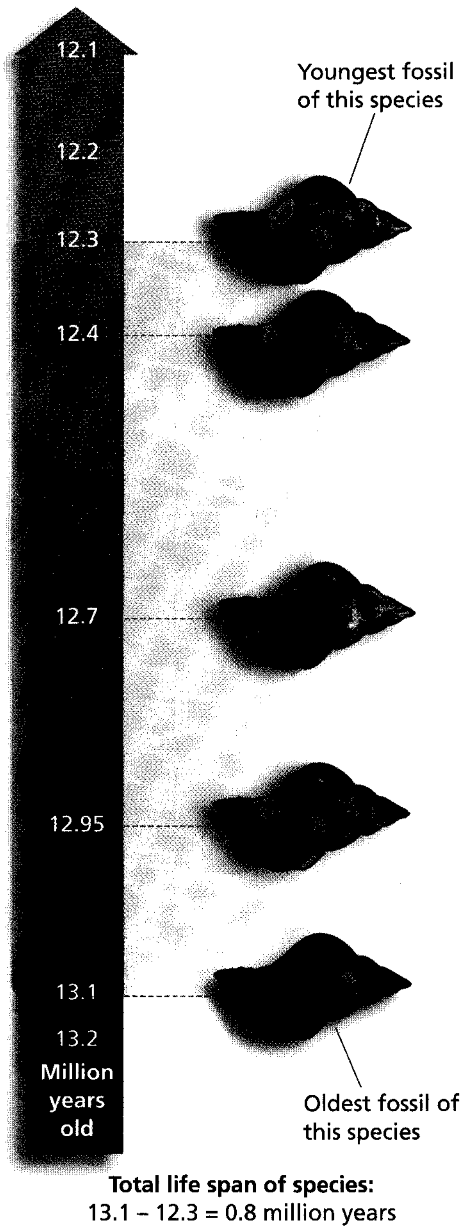


Figure 14.3 Estimating the life span of a species. Using a process called radiometric dating, the ages of these fossil shells are estimated from the age of the rocks in which they are embedded. Fossils of the same species are arranged on a timeline from oldest to youngest. The difference in age between the oldest and youngest fossil of a species is an estimate of the species' life span.

scale, affect large numbers of species, and are dramatic in impact. During mass extinctions, 20% to 50% of living families, containing 50% to 90% of all living species, were lost over the course of a few thousand to a few hundred thousand years. Past mass extinctions were probably caused by massive global changes—for instance, changes in sea levels brought about by climate fluctuations, shifts in ocean and land forms caused by continental drift, or widespread destruction and climate disruption caused by an asteroid impact. Many scientists argue that we are now seeing biodiversity's sixth mass extinction, this one caused by the massive global changes resulting from human activity.

Determining whether the current rate of extinction is unusually high requires some knowledge about the **background extinction rate**, the rate at which species are lost through the normal evolutionary process. Normal extinctions occur when a species lacks the ability to adapt to environmental change—for instance, if a species does not have the right combination of alleles to survive in a new climate condition, compete with new species for the same resources, or escape new predators. In many cases, a new species arises due to the evolution of populations of the old species. When individuals in a population possess unique traits that allow them to survive environmental changes, they will give rise to populations of descendants that display these traits. If the differences between the original population and its descendants are great enough, scientists will identify fossils of the ancestral and descendant populations as separate species. In other cases, the extinction of one species increases the resources for a population of a different species, which may adapt and change in form as it fills the now "open" role in the system. The fossil record can provide clues about the background extinction rate that results from this continual process of species turnover.

The span of geological time in which fossils of an individual species are found represents the life span of that species (Figure 14.3). Biologists have thus estimated that the "average" life span of a species is around 1 million years (although there is tremendous variation) and that the overall rate of extinction is about one species per million (0.0001%) per year. Some scientists have argued that these estimates are too low because they are based on observations of fossils, a record that may be biased toward long-lived species. However, the estimates are currently scientists' best approximation of background extinction rates.

Current rates of extinction are calculated from actual recorded extinctions. This is a challenge because extinctions are surprisingly difficult to document. The only way to conclude that a species no longer exists is to exhaustively search all areas where it is likely to have survived. In the absence of a complete search, most conservation organizations have adopted this standard: To be considered extinct, no individuals of a species must have been seen in the wild for 50 years.

A few searches for specific species give hints to the recent extinction rate. In Malaysia, a 4-year search for 266 known species of freshwater fish turned up only 122. In Africa's Lake Victoria, 200 of 300 native fish species have not been seen for years. On the Hawaiian island of Oahu, half of 41 native tree snail species have not been found, and in the Tennessee River, 44 of the 68 shallow-water mussel species are missing. Despite these results, few of the missing species in any of these searches is officially considered extinct.

The most complete records of documented extinction occur in groups of highly visible organisms, primarily mammals and birds. Since 1600, eighty-three out of an approximate 4500 identified mammal species have become extinct, while 113 of approximately 9000 known bird species have disappeared. The known extinctions of mammals and birds, spread out over the 400 years of these records, correspond to a rate of 0.005% per year. Compared to the background rate of extinctions calculated from the fossil record, the current rate of extinction is 50 times higher. If we examine the past 400 years more closely, we see that the extinction rate has actually increased since the start of this historical record (Figure 14.4) to about 0.01% per year, making the current rate 100 times higher than the calculated background rate.

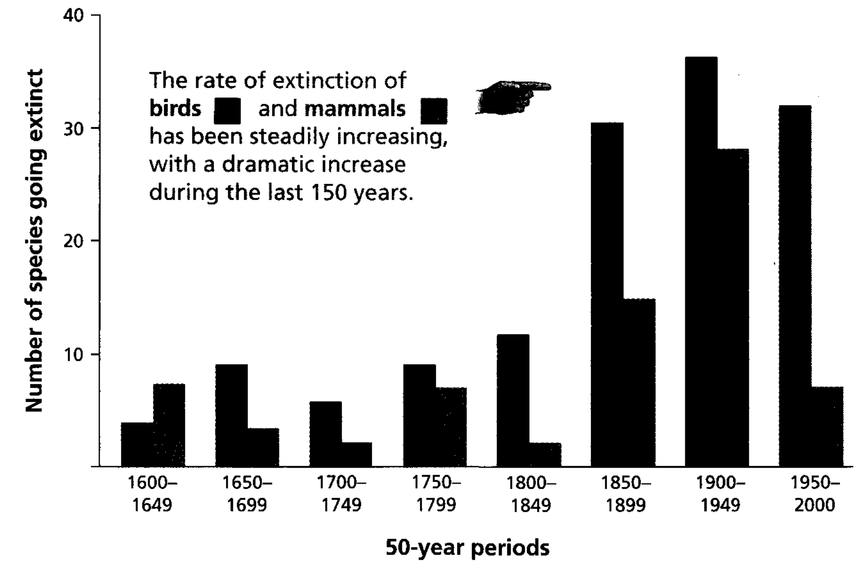


Figure 14.4 Rate of extinction. This graph illustrates the number of species of mammals and birds known to have become extinct since 1600.

In addition, there are reasons to expect that the current elevated rate of extinction will continue into the future. The World Conservation Union (known by its French acronym, IUCN), a highly respected global organization composed of and funded by states, government agencies, and nongovernmental organizations from over 140 countries, collects and coordinates data on threats to biodiversity. According to the IUCN's most recent assessment, 11% of all plants, 12% of all bird species, and 24% of all mammal species (the three best-studied groups of organisms) are in danger of extinction, and human activities on the planet pose the greatest threat to most of these species.

Habitat Loss and Food Chains

A variety of human activities can put species at risk of extinction. The most severe threats belong to one of four general categories: loss or degradation of habitat, introduction of nonnative species, overharvesting, and effects of pollution. However, these four categories are not equal; the IUCN estimates that 83% of endangered mammals, 89% of endangered birds, and 91% of endangered plants are directly threatened by damage to or destruction of the places where they live.

Habitat Destruction. The dramatic reduction in numbers of shortnose and Lost River suckers in Upper Klamath Lake is almost entirely due to human modification of these species' **habitat**, the place where they live and obtain their food, water, shelter, and space. At one time, 350,000 acres of wetlands regulated the overall quality and amount of water entering into the lake. Most of these wetlands have been drained and converted to irrigated agricultural fields now. The disruption of natural water flows into and out of the lake has interfered with sucker reproduction and has reduced the number of offspring they produce by as much as 95%.

The outright loss of habitat experienced by the Lost River and shortnose suckers is commonly called **habitat destruction**, and it is not limited to species in the more developed world (Figure 14.5). Rates of habitat destruction caused by agricultural, industrial, and residential development accelerated throughout the twentieth century as Earth's total human population more than tripled from less than 2 billion in 1900 to over 6 billion today. This trend will likely continue as the human population continues to increase and become more affluent. As the amount of natural landscape declines, the number of species supported by the habitats in these landscapes naturally also decreases.

The relationship between the size of a natural area and the number of species that it can support follows a general pattern called a **species-area curve**. A species-area curve for reptiles and amphibians on a West Indian archipelago is

Figure 14.5 Lost habitat = lost species. Lemurs are the most highly endangered primates in the world. These acrobatic animals are found only on the island of Madagascar, first settled by humans 1500 years ago. Today only 10% of natural forest remains there. Of the 48 species of lemur present on the island 2000 years ago, 16 have become extinct, and 15 are at risk of extinction.

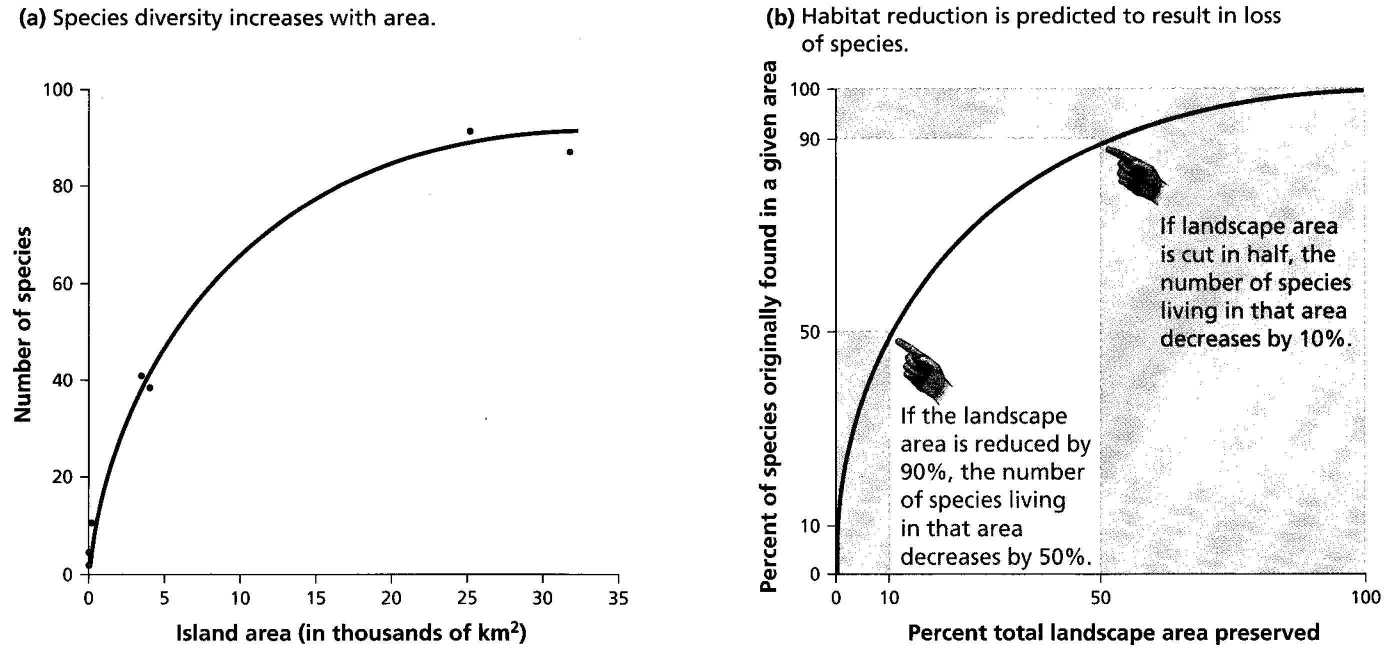


Figure 14.6 Predicting extinction caused by habitat destruction. (a) This curve demonstrates the relationship between the size of an island in the West Indies and the number of reptile and amphibian species living there. (b) We use a generalized species-area curve to roughly predict the number of extinctions in an area experiencing habitat loss.

illustrated in Figure 14.6a. Similar graphs have been generated in studies of different groups of organisms in a variety of habitats. Although the precise relationship between habitat area and number of species found in that habitat varies, the general pattern is that the number of species in an area increases rapidly as the size of the area increases, but the rate of increase slows as the area becomes very large. This rule of thumb, the approximation derived from the studies, is shown in Figure 14.6b. From the graph, we can estimate that a 90% decrease in landscape area will cut the number of species living in the remaining area by half.

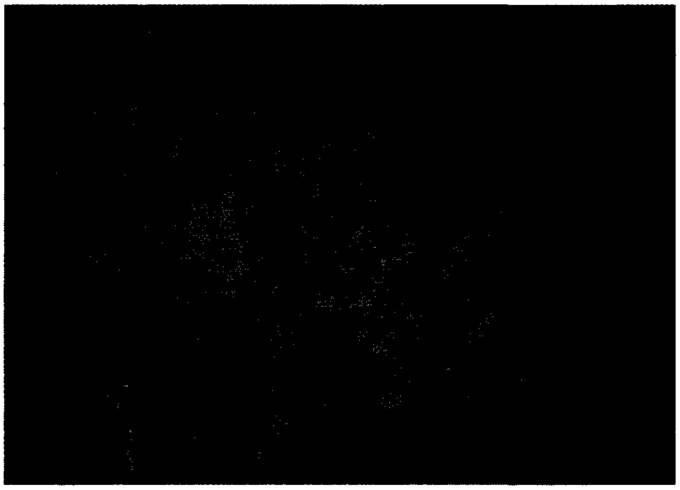
Applying species-area curves to estimate extinction rates requires that we calculate the amount of natural landscape that has been lost in recent decades—a difficult task. Most studies have focused on tropical rain forests, which cover a broad swath of land roughly 20 degrees north and south of the equator. Tropical rain forests contain, by far, the greatest number of species of any habitat type on Earth. In 1988, biologist Edward O. Wilson estimated the rate of habitat destruction in the rain forest; he calculated that about 1% of the tropical rain forest is converted to agricultural use every year. Conservatively estimating the number of species in the rain forest at 5 million, Wilson applied the generalized species-area curve and projected that nearly 20,000 to 30,000 species (about 0.5%) are lost each year due to rain forest destruction.

More modern studies using images from satellites (Figure 14.7a) indicate that approximately 20,000 square kilometers (about 7722 square miles, an area the size of Massachusetts) of rain forest are cut each year in South America's Amazon River basin. This is a rate of 2% per year, or double Wilson's estimate. At this rate of habitat destruction, tropical rain forests will be reduced to 10% of their original size within about 35 years. If we apply the species-area curve, the habitat loss translates into the extinction of about 50% of species living in the Amazonian rain forest. Most of these species are small, and most are not even known to science; but if this prediction proves accurate, the extinct species in the rain forest would include about 50,000 of all known 250,000 species of plants, 1800 of the known 9000 species of birds, and 900 of the 4500 species of mammals in the world.

Of course, habitat destruction is not limited to tropical rain forests. When all of Earth's biomes are evaluated, freshwater lakes and streams, grasslands, and temperate forests are also experiencing high levels of modification. According to the IUCN, if habitat destruction around the world continues at

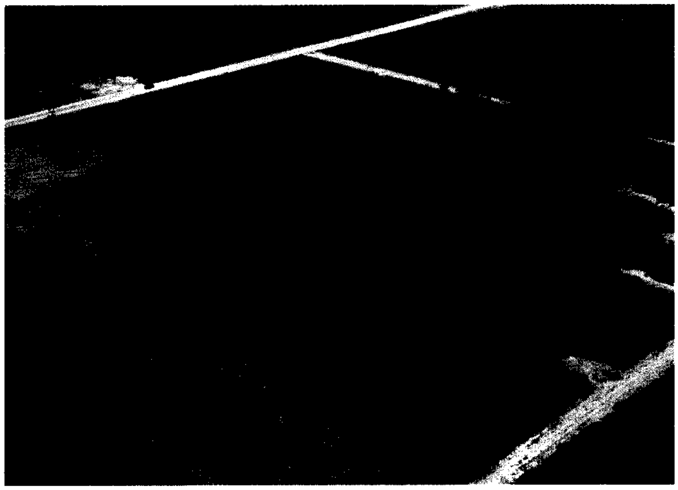
Figure 14.7 The primary causes of extinction.

(a) Habitat destruction



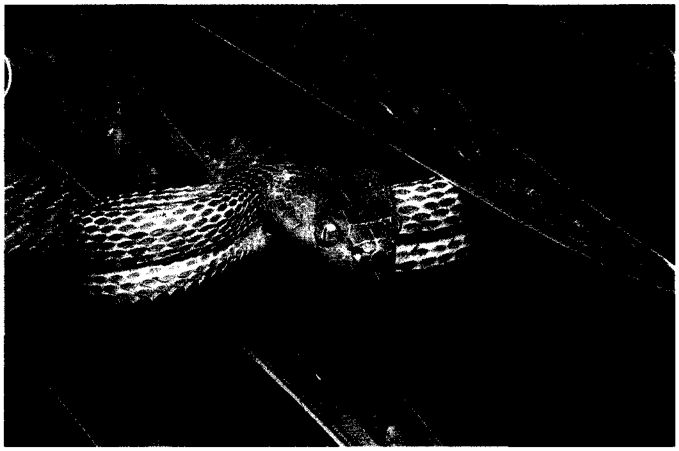
Humans are rapidly destroying tropical rain forests. This 1999 satellite photo illustrates the extent of destruction in an area of Brazilian rain forest that, until 30 years ago, contained no agricultural lands. The lighter parts of the photo are agricultural fields; the darker regions are intact forest.

(b) Habitat fragmentation



This "island" of tropical forest was created when the surrounding forest was logged. Scientists have documented hundreds of localized extinctions within fragments such as this.

(c) Introduced species

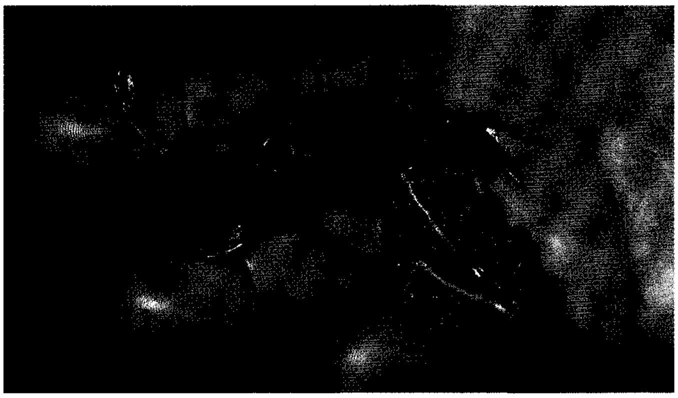


The introduced brown tree snake is responsible for the extinction of dozens of native bird species on the Pacific island of Guam.

(d) Overexploitation of species

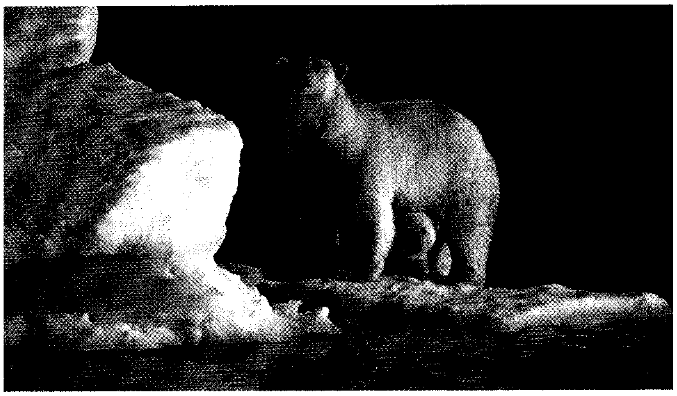
These tiger skins represent a small fraction of the illegal harvest of tigers in Asia, primarily for the Chinese market.

(e) Pollution



Pollution from herbicides appears to be responsible for the increase of deformities in frogs in the midwestern United States and may partially explain the worldwide decline in frog species.

(f) Global warming



Polar bears hunt for seals, their primary prey, from sea ice. The extent of sea ice in the Arctic Ocean has been steadily declining over the past 20 years, threatening the bears' survival.

its present rate, nearly one-fourth of *all* living species will be lost within the next 50 years.

Some critics have argued that these estimates of future extinction are too high because not all groups of species are as sensitive to habitat area as the curve in Figure 14.6b suggests. Many species may still survive and even thrive in human-modified landscapes. Other biologists contend that there are other threats to species, including habitat fragmentation, and therefore the rate of species loss is likely to be even higher than these estimates.

Habitat Fragmentation. Habitat destruction rarely results in the complete loss of a habitat type. Often what results from human activity is **habitat fragmentation**, in which large areas of intact natural habitat are subdivided (Figure 14.7b). Habitat fragmentation is especially threatening to large predators, such as grizzly bears and tigers, because of their need for large hunting areas.

Large predators require large, intact hunting areas due to a basic rule of biological systems: Energy flows in one direction within an ecological system along a **food chain**, which typically runs from the sun to **producers** (photosynthetic organisms) to the **primary consumers** that feed on them, to **secondary consumers** (predators that feed on the primary consumers), and so on. Along the way, most of the calories taken in at one **trophic level** (that is, a level of the food chain) are used to support the activities of the individuals at that level and therefore are not available for use by organisms at the next level. In other words, a substantial amount of the solar energy initially fixed by producers is dissipated—that is, given off as heat—at each level within a food web. You can see this in your own life; an average adult needs to consume between 1600 and 2400 Calories per day simply to maintain his or her current weight. The flow of energy along a food chain leads to the principle of the **trophic pyramid**, the bottom-heavy relationship between the **biomass** (total weight) of populations at each level of the chain (Figure 14.8). Habitat destruction and fragmentation can cause the lower levels of the pyramid to shrink, depriving the top predators of adequate calories for survival.

Habitat fragmentation also exposes wide-ranging predators to additional dangers. For example, grizzly bears need 200 to 2000 square kilometers of habitat to survive a Canadian winter, but the Canadian wilderness is increasingly bisected by roads built for tree harvesting. Each road represents an increased chance of grizzly-human interaction. Every interaction between grizzly bears and humans represents a greater danger to the bears than to humans. For example, of the 136 grizzlies that died in Canada's national parks between 1970 and 1995, seventeen died of natural causes and 119 were killed by humans.

The species that do remain in small fragments of habitat are more susceptible to extinction because populations in each fragment become isolated. Habitat fragmentation often makes it impossible for individuals to move from an area that has become unsuitable because of natural environmental changes to an area that is suitable. Isolated populations are also subject to genetic problems that threaten their long-term survival, as we discuss in detail later in the chapter.

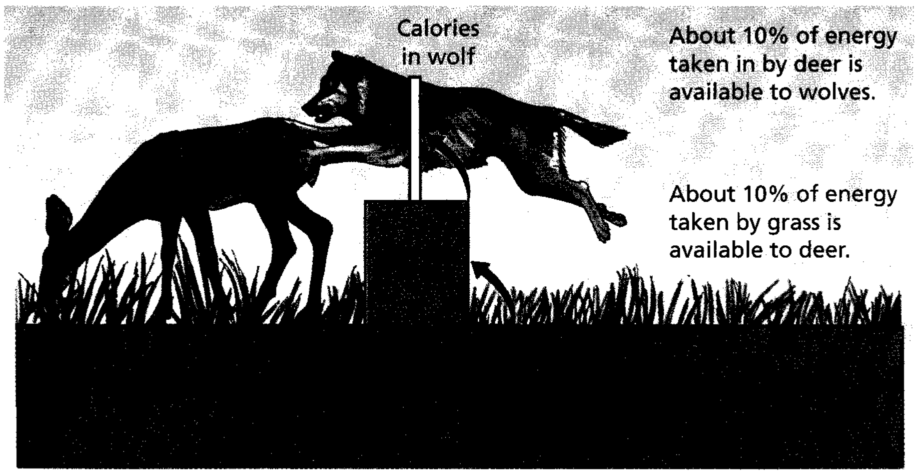


Figure 14.8 A trophic pyramid. The relationship between producers, primary consumers, and secondary consumers in a biological community is illustrated here. Because most of the energy consumed by a trophic level is used within that level for maintenance, biomass decreases as position in the food chain increases. As a result, for secondary consumers to survive, a habitat must be large enough to support large producer and primary consumer populations.

These genetic threats accrue to species whose populations are made small by other causes as well.

Other Human Causes of Extinction

According to the IUCN, the remaining threats to biodiversity posed by human activity play a role in about 40% of all cases of endangerment (Figure 14.7c–f on page 365).

Introduced Species. **Introduced species** include organisms brought by human activity to a region where they previously had never been found. Introduced species are often dangerous to native species because they have not evolved together; for instance, many birds on oceanic islands such as Hawaii and New Zealand are unable to defend themselves from introduced ground hunters. On Hawaii, one of these introduced predators, the Pacific black rat, became very adept at raiding eggs from nests and contributed to the extinction of dozens of species of honeycreepers, birds found nowhere else on Earth. Even domestic cats can take an enormous toll on wildlife when introduced into new habitats. A recent study in Wisconsin estimated that free-ranging cats in that state kill approximately 39 million birds every year.

Introduced species may also compete with native species for resources, causing populations of the native species to decline. For example, zebra mussels in the Great Lakes crowd out native mussel species as well as other organisms that filter algae from water, and the introduced vine known as kudzu shades over native trees and vines in the Southeast.

When introduced species crowd out native species, it is not only their direct competitors that suffer. Other species that rely on the struggling natives may decline as well. For example, opposum shrimp were introduced into Montana's Flathead Lake as a potential food source for game fish, primarily kokanee salmon. Unfortunately, the shrimp competed with the kokanee for the same food source, and introduction of the shrimp led to sharp declines in kokanee abundance. As a result, bald eagles that relied on kokanee populations in Flathead Lake also declined.

Humans continue to move species around the planet. As the global trade in agriculture and other goods continues to expand, the number of species introductions are likely to increase over the next century without a concerted effort to prevent them.

Overexploitation. When the rate of human destruction or use of a species outpaces its ability to reproduce, the species is subject to **overexploitation**. This often occurs when particular organisms are highly prized by humans, which is the case with animals and plants whose parts are used as medicinal therapies in some societies. For instance, three of the planet's eight tiger species have become extinct, and the remaining species are gravely endangered, in part due to the demand for their bones for their purported ability to treat arthritis and their genitals, which are erroneously believed to reverse male impotence. Popular wild-grown herbal medicines—including echinacea, the common cold remedy discussed in Chapter 1—are also at risk of overexploitation. The Pacific yew, a tree that produces the anticancer chemical taxol described in Chapter 5, faced the potential risk of extinction via overharvesting until production processes were developed to extract taxol from more common and faster-growing species of yew.

Overexploitation is also likely when an animal competes directly with humans—as in the case of the gray wolf, which was nearly exterminated in the United States by human hunters determined to protect their livestock. Species that cross international boundaries during migration or live in the world's oceans are also highly susceptible to overexploitation since it can be difficult to maintain a healthy population when no single government can regulate the total harvest. The near extinction of numerous whale species occurred in the nineteenth and early twentieth centuries due to unregulated harvest by many nations. Stocks of cod, swordfish, and tuna are now similarly threatened.

Pollution. The release of poisons, excess nutrients, and other wastes into the environment—a practice otherwise known as **pollution**—poses an additional threat to biodiversity. For example, the herbicide atrazine poses a risk to frogs and salamanders in agricultural areas of the United States; and nitrogen pollution caused by fertilizer, automobile exhaust, and industrial emissions has led to drastic declines in populations of sensitive plant species within native grasslands in Europe. Fertilizer pollution from farms in the Klamath Valley poses a risk to the shortnose and Lost River suckers. Increased levels of nitrogen and phosphorus from fertilizer that runs off into waterways have increased the growth of algae in Upper Klamath Lake; when these algae explode in numbers, the bacteria that feed on them flourish and rapidly use up the available oxygen in the water. This process of oxygen-depleting **eutrophication** results in large fish kills, not just in Upper Klamath Lake but also in rivers, ponds, and oceans that receive fertilizer runoff from farms. Eutrophication threatens dozens of fish and invertebrate species in the Gulf of Mexico, where fertilizer draining from farm fields in the midwestern United States creates a low-oxygen "dead zone" the size of New Jersey at the mouth of the Mississippi River.

Perhaps the most serious pollutant released by humans is carbon dioxide, also a principal cause of global climate change (see Chapter 4). Computer models that link predicted changes in climate to known ranges and requirements of over 1000 species indicate that 15% to 37% of these plants will face extinction in the next century as the climate changes.

While determining the exact causes for why certain species are disappearing can sometimes be difficult, the evidence just discussed suggests that ESA critics who describe modern extinction rates as "natural" are incorrect. Over the past 400 years, humans have caused the extinction of species at a rate that appears to far exceed past rates, and it is clear that human activities continue to threaten thousands of additional species around the world. Earth appears to be on the brink of a sixth mass extinction of biodiversity—and the pervasive global change causing this extinction is human activity.

Many people who feel a moral responsibility to minimize the human impact on other species continue to support actions that conserve species despite the cost. However, in addition to supporting rights for nonhuman species, there is a practical reason to prevent the sixth extinction from occurring—the loss of nonhuman species can cause human suffering as well.

14.2 The Consequences of Extinction

Concern over the loss of biodiversity is not simply a matter of an ethical concern for nonhuman life. Humans have evolved with and among the variety of species that exist on our planet, and the loss of these species often results in negative consequences for us. In addition, the fossil record illustrated in Figure 14.2 (page 361) reveals that it takes 5 to 10 million years to recover the biological diversity lost during a mass extinction. The species that replaced those lost in previous mass extinctions were also very different; for instance, after the mass extinction of the reptilian dinosaurs, mammals replaced them as the largest animals on Earth. We cannot predict what biodiversity will look like after another mass extinction. In other words, the mass extinction we may be witnessing today will have consequences felt by people in thousands of generations to come.

Loss of Resources

The Lost River and shortnose suckers were once numerous enough to support fishing and canning industries on the shores of Upper Klamath Lake. Even before the arrival of European settlers, the native people of the area relied heavily upon these fish as a mainstay of their diet. The loss of these species represents a tremendous impoverishment of wild food sources. The biological resources that are harvested directly from natural areas are numerous and diverse—for example, wood for fuel and lumber, shellfish for protein, algae for gelatins, and herbs for medicines. The loss of any of these species affects human populations economically; one estimate places the value of wild species in the United States at $87 billion a year, or about 4% of the gross domestic product.

Wild species can also provide resources for humans in the form of unique biological chemicals. One example of a natural origin for valuable chemicals is the rosy periwinkle (*Catharanthus roseus*), which evolved on the island of Madagascar and has been exported around the world as a garden plant (Figure 14.9a). In the 1950s, scientists interested in the medicinal properties of plants noted that several African populations used extracts of rosy periwinkle as a treatment for diabetes. While they did not find an effective diabetes treatment when they screened this plant, two different laboratories found that chemicals derived from it appeared to be quite effective at stopping the growth of cancer cells. These two drugs, vincristine and vinblastine, have contributed to major gains in the likelihood of survival from leukemia and Hodgkin's disease. If we are unable to screen living species due to their extinction, we will never know which ones might have provided compounds that would improve human lives. In Chapter 12, we describe a small fraction of the thousands of species that have provided valuable biochemicals to humans.

Wild relatives of plants and animals that have been domesticated, such as agricultural crops and cattle, are also important resources for humans. Genes and gene variants that have been "bred out" of domesticated species are often still found in their wild relatives. These genetic resources represent a reservoir of traits that could be reintroduced into agricultural species through breeding or genetic engineering. Agricultural scientists who are attempting to produce better strains of wheat, rice, and corn look to the wild relatives of these crops as sources of genes for pest resistance and for traits that improve yields in specific environmental conditions. For example, the Mexican teosinte species *Zea diploperennis* (Figure 14.9b), discovered in 1977, appears to be an ancestor of modern corn. This species of teosinte is resistant to several viruses that plague cultivated corn; some genes that confer this resistance have been transferred via hybridization to produce disease-resistant varieties. Additionally, there is value in preserving wild relatives of domesticated crops in their natural habitats; often the wild organisms in these communities provide the key to reducing pest damage and

(a) Rosy periwinkle (b) Teosinte, ancestor of modern corn (c) Boll weevil wasp

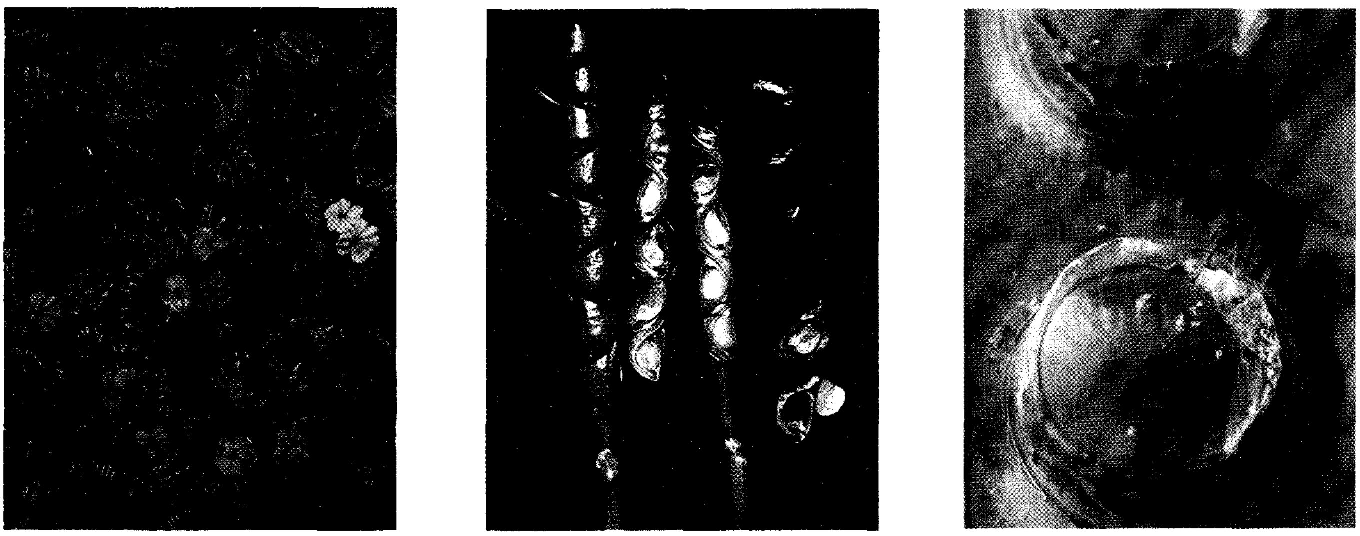


Figure 14.9 Resources from nature. (a) Anticancer drugs vincristine and vinblastine were first isolated from rosy periwinkle (*Catharanthus roseus*), a species of flower native to Madagascar. (b) Teosinte is the ancestor of modern corn, first cultivated in Central America. This species, *Zea diploperennis*, was discovered in a remote Mexican site in 1978. (c) *Catolaccus grandis* is a predator of boll weevils, which are one of the most damaging cotton pests. *C. grandis* was discovered preying on pests of wild cotton in southern Mexico.

disease on the domestic crop. For example, the wasp *Catolaccus grandis* consumes boll weevils and is used to control infestations of these pests in cotton fields (Figure 14.9c). *C. grandis* was discovered in the tropical forest of southern Mexico, where it parasitizes a similar pest in wild cotton populations. Of course, introducing an insect such as *C. grandis* into a new environment carries risk, even if the introduction is meant to reduce environmental damage. There are many examples of environmental disasters caused by introduced predators—for example, the cane toad, which was brought to Australia to control beetles in sugarcane crops but now threatens the survival of several native frog species as well as their predators, which are poisoned by the toad's skin toxins. Often, a less risky approach to reducing pest damage to crops is to preserve nearby habitats and the ecological interactions that persist there.

Disruption of Ecological Communities

Although humans receive direct benefits from thousands of species, most threatened and endangered species are probably of little or no use to people. Even the Lost River and shortnose suckers, as valuable as they once were to the

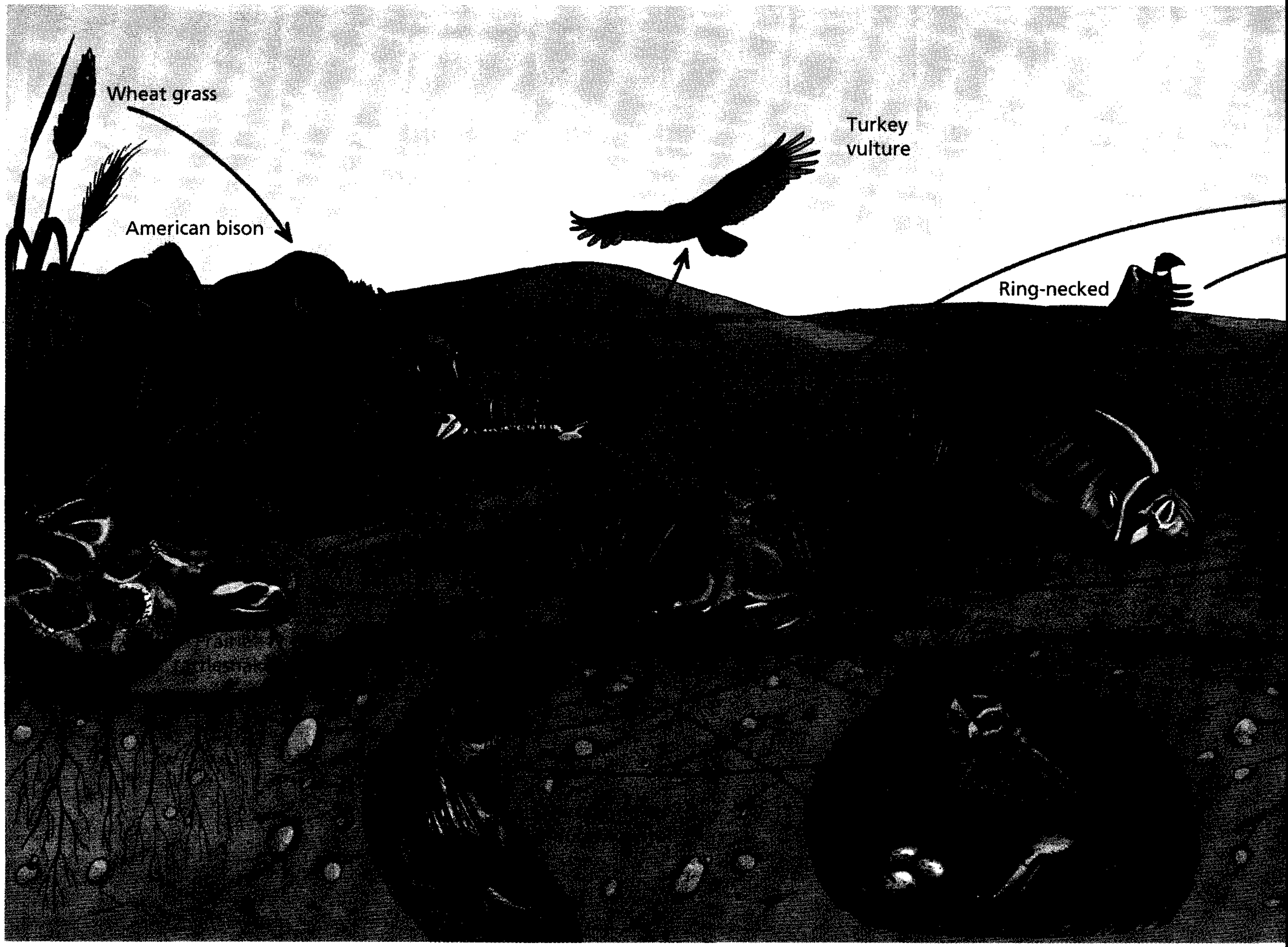
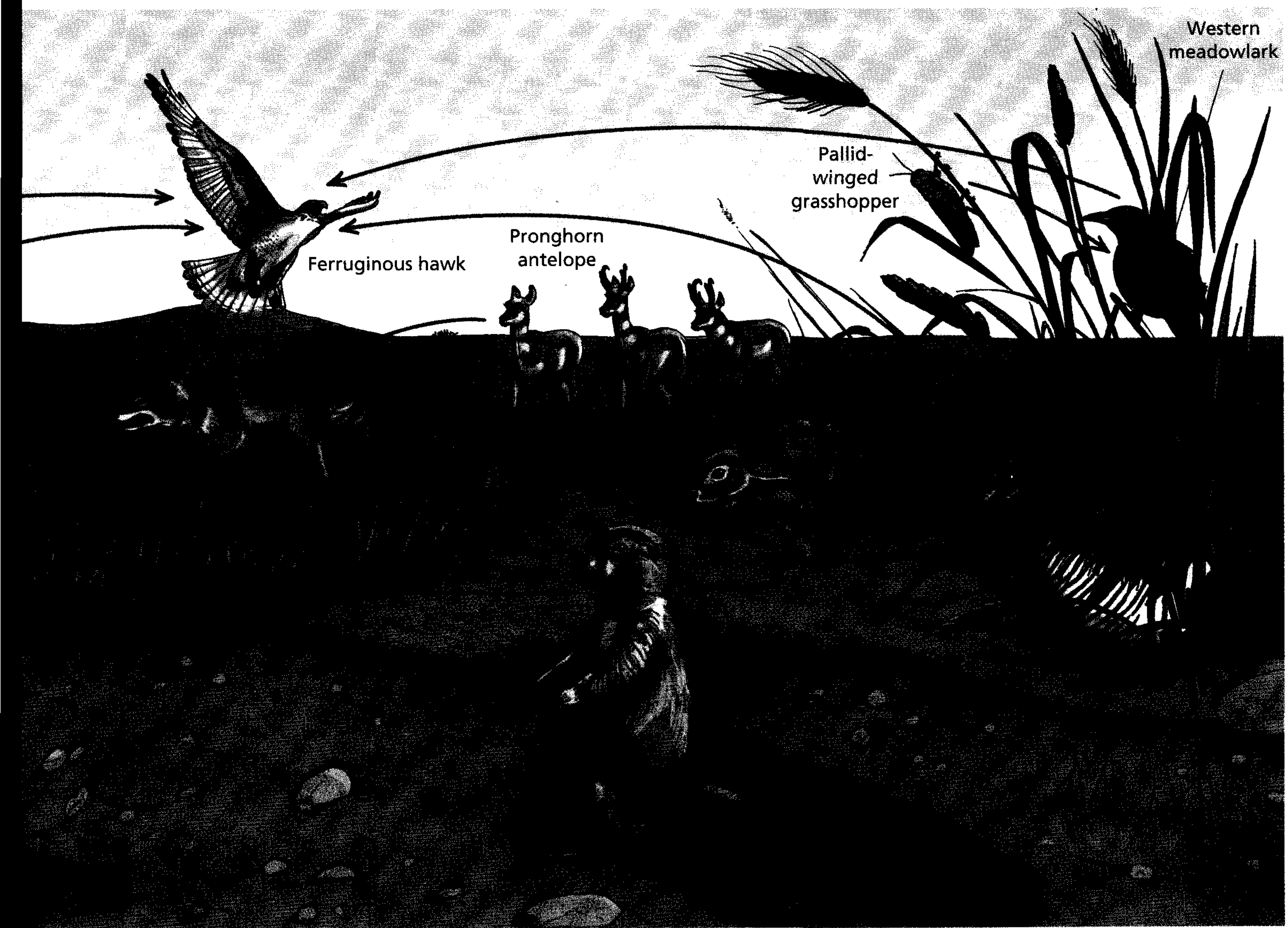


Figure 14.10 The web of life. Species are connected to each other and to their environment in various, complex ways. This drawing shows some of the important relationships among organisms and their environments in a North American prairie. Black arrows represent feeding relationships; for example, thirteen-lined ground squirrels eat wheat grass and in turn are eaten by badgers.

native people of the Klamath Basin, are not especially missed as a food source; no one has starved simply because these fish have become less common.

In reality, most species are beneficial to humans because they are connected to other species and natural processes in a biological **community**, consisting of all the organisms living together in a particular habitat area. The complex linkage among organisms in a community is often referred to as a **food web** (Figure 14.10). Because relationships between species may be based on requirements other than food, ecologists often use the phrase "web of life" to illustrate all of these interactions. As with a spider's web, any disruption in one strand of the web of life is felt by other portions of the web. Some tugs on the web cause only minor changes to the community, while others can cause the entire web to collapse. Most commonly, losses of strands in the web are felt by a small number of associated species. However, some disruptions caused by the loss of seemingly insignificant species have the potential to be felt by humans, especially when we rely on a functional community for particular products or services. Some examples of this phenomenon are described next.

Mutualism: How Bees Feed the World. An interaction between two species that benefit each other is called **mutualism**. Cleaner fish that remove and



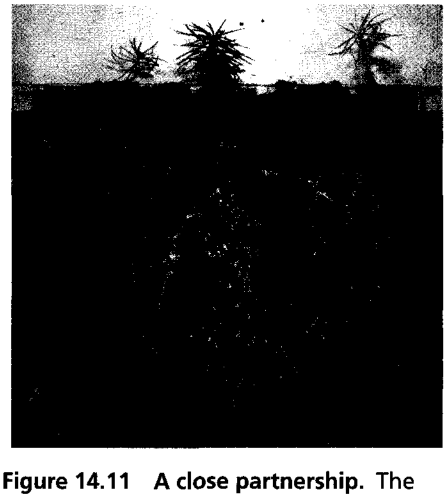


Figure 14.11 A close partnership. The relationship between plants and fungi in mycorrhizae provides benefits to both partners and is a clear example of mutualism. Most of the root-like threads in this soil are fungal hyphae.

consume parasites from the bodies of larger fish, fungi called mycorrhizae that increase the mineral absorption of plant roots while consuming the plant's sugars (Figure 14.11), and ants that find homes in the thorns of acacia trees and defend the trees from other insects are examples of mutualism. The mutualistic interaction between plants and bees is perhaps the most often described example.

Bees are the primary pollinators of many species of flowering plants; that is, they transfer sperm, in the form of pollen grains, from one flower to the female reproductive structures of another flower. The flowering plant benefits from this relationship because insect pollination increases the number and vigor of seeds that the plant produces. The bee benefits by collecting excess pollen and nectar to feed itself and its relatives in the hive (Figure 14.12).

Wild bees pollinate at least 80% of all the agricultural crops in the United States, providing a net benefit of about $8 billion. In addition, populations of wild honeybees have a major and direct impact on many more billions of dollars of agricultural production around the globe.

Unfortunately, bees have suffered dramatic declines in recent years. According to the U.S. Department of Agriculture, we are facing an "impending pollination crisis" because both wild and domesticated bees are disappearing at alarming rates. These dramatic declines are believed to result from an increased level of bee **parasites** (infectious organisms that cause disease or drain energy from their hosts), competition with the invading Africanized honeybees ("killer bees"), and habitat destruction. The extinction of these inconspicuous mutualists of crop plants would be extremely costly to humans.

Predation: How Songbirds May Save Forests. A species that survives by eating another species is typically referred to as a **predator**. The word conjures up images of some of the most dramatic animals on Earth: cheetahs, eagles, and killer whales. You might not picture wood warblers, a family of North American bird species characterized by their small size and colorful summer plumage, as predators; however, these beautiful songsters are voracious consumers of insects (Figure 14.13a). The hundreds of millions of individual warblers in the forests of North America collectively remove literally tons of insects from forest trees and shrubs every summer. Most of these insects prey on plants. By reducing the number of insects in forests, warblers reduce the damage that insects inflict on forest plants. The results of a study that excluded birds from white oak seedlings showed that the trees were about 15% smaller because of insect damage over 2 years, as compared to trees from which birds were not excluded. However, other studies have shown less dramatic benefits.

Although scientists still disagree about how important warblers and other insect-eating birds are to the survival of trees, most agree that reducing the number of forest pests increases the growth rate of the trees. Harvesting trees for paper and lumber production fuels an industry worth over $200 billion in the United

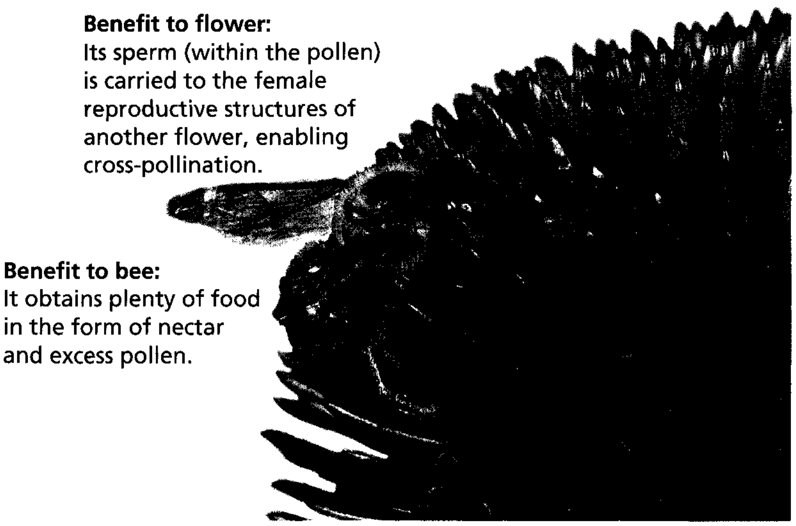


Figure 14.12 Mutualism. Honeybees transfer pollen, allowing one plant to "mate" with another plant of some distance away.

(a) Black-throated blue warbler, predator of insects.

(b) Forests suffer when insects are unchecked by predators.

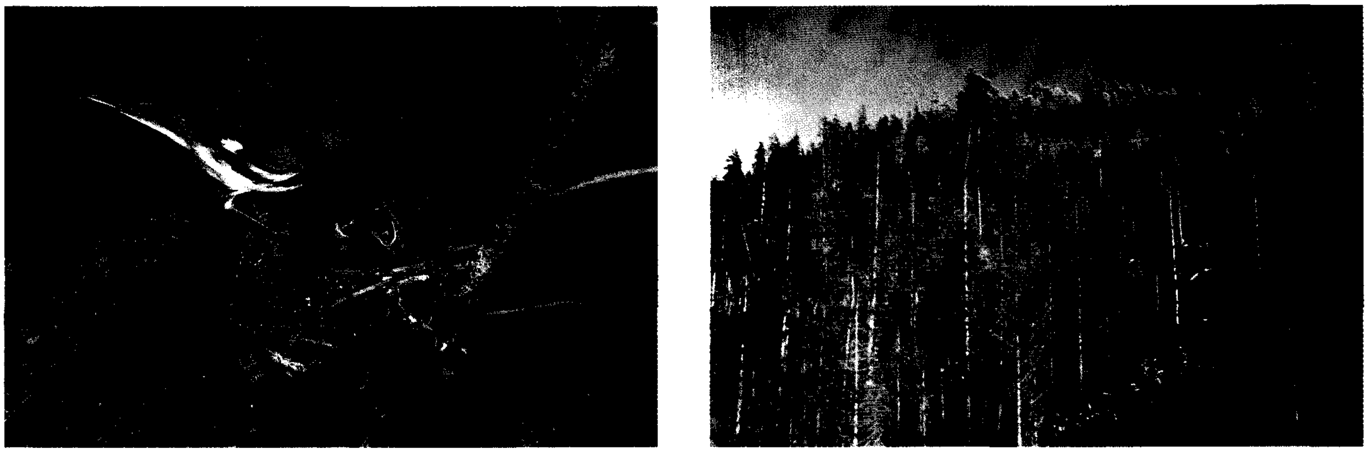


Figure 14.13 Predation. (a) The black-throated blue warbler is one of many warbler species native to North American forests. These colorful birds are among the most active predators of plant-eating insects in these forests. (b) Insects can kill many trees, as seen in this photo of a spruce budworm infestation. Warblers and other insect-eating birds probably reduce the number and severity of such insect outbreaks.

States alone. At least some of the wood harvested by the timber industry was produced only because warblers were controlling insects in forests (Figure 14.13b).

Many species of forest-inhabiting warblers appear to be experiencing declines in abundance. The loss of warbler species has several causes, including not only habitat destruction in their summer habitats in North America and their winter habitats in Central and South America but also increased predation by human-associated animals such as raccoons and house cats. Although other, less-vulnerable birds may increase in number when warblers decline, the warblers' effects on insect pest populations may not be completely replaced by less insect-dependent birds. If smaller warbler populations correspond to lower forest growth rates and higher levels of forest disease, then these tiny, beautiful birds definitely have an important effect on the human economy.

Competition: How a Deliberately Infected Chicken Could Save a Life. When two species of organisms both require the same resources for life, they will be in **competition** for the resources within a habitat. We may imagine lions and hyenas fighting over a freshly killed antelope or weeds growing in our vegetable gardens as typical examples of competition, but most competitive interactions are invisible.

In general, competition limits the size of competing populations. To determine whether two species that use similar resources are competing, we remove one from an environment. If the population of the other species increases, then the two species are competitors. One of the least visible forms of competition occurs among microorganisms. Competitive interactions among microbes may be among the most essential factors for maintaining the health of people and communities.

Salmonella enteritidis is a leading cause of food-borne illness in the United States. Between 2 million and 4 million people in this country will be infected by this bacterium in the coming year, and they will experience fever, intestinal cramps, and diarrhea as a result. In about 10% of cases, the infection results in severe illness requiring hospitalization. If it is not treated promptly, the infected individuals may die. Nearly 400 to 600 Americans die as a result of *S. enteritidis* infection every year.

Most *S. enteritidis* infections result from consuming raw or improperly cooked poultry products, especially eggs. The U.S. Centers for Disease Control estimate that as many as 1 in 50 consumers are exposed to eggs contaminated with *S. enteritidis* every year. Most of these eggs have had their shells disinfected and do not look damaged in any way; the bacteria were deposited in the egg by the hen when the egg was forming inside her. Thus, the only way to prevent *S. enteritidis* from contaminating eggs is to keep it out of hens.

A common way to control *S. enteritidis* is to feed hens antibiotics—chemicals that kill bacteria. However, like most microbes, *S. enteritidis* strains can evolve drug resistance if some members of the population contain genes that allow them to survive the effects of the antibiotic. Another way to reduce the chance of *S. enteritidis* infection in poultry is to reduce the amount of resources available for the bacteria's growth. Most *S. enteritidis* infections originate in an animal's digestive system. If another bacterial species is already monopolizing the food and available space in a hen's digestive system, then *S. enteritidis* has trouble colonizing there. Some poultry producers now intentionally infect hens' digestive systems with harmless bacteria, via a practice called **competitive exclusion**, to reduce *S. enteritidis* levels in their flocks. This technique involves feeding cultures of benign bacteria to one-day-old birds. When the harmless bacteria become established in their intestines, the chicks will be less likely to host large *S. enteritidis* populations (Figure 14.14). There is evidence that this practice is

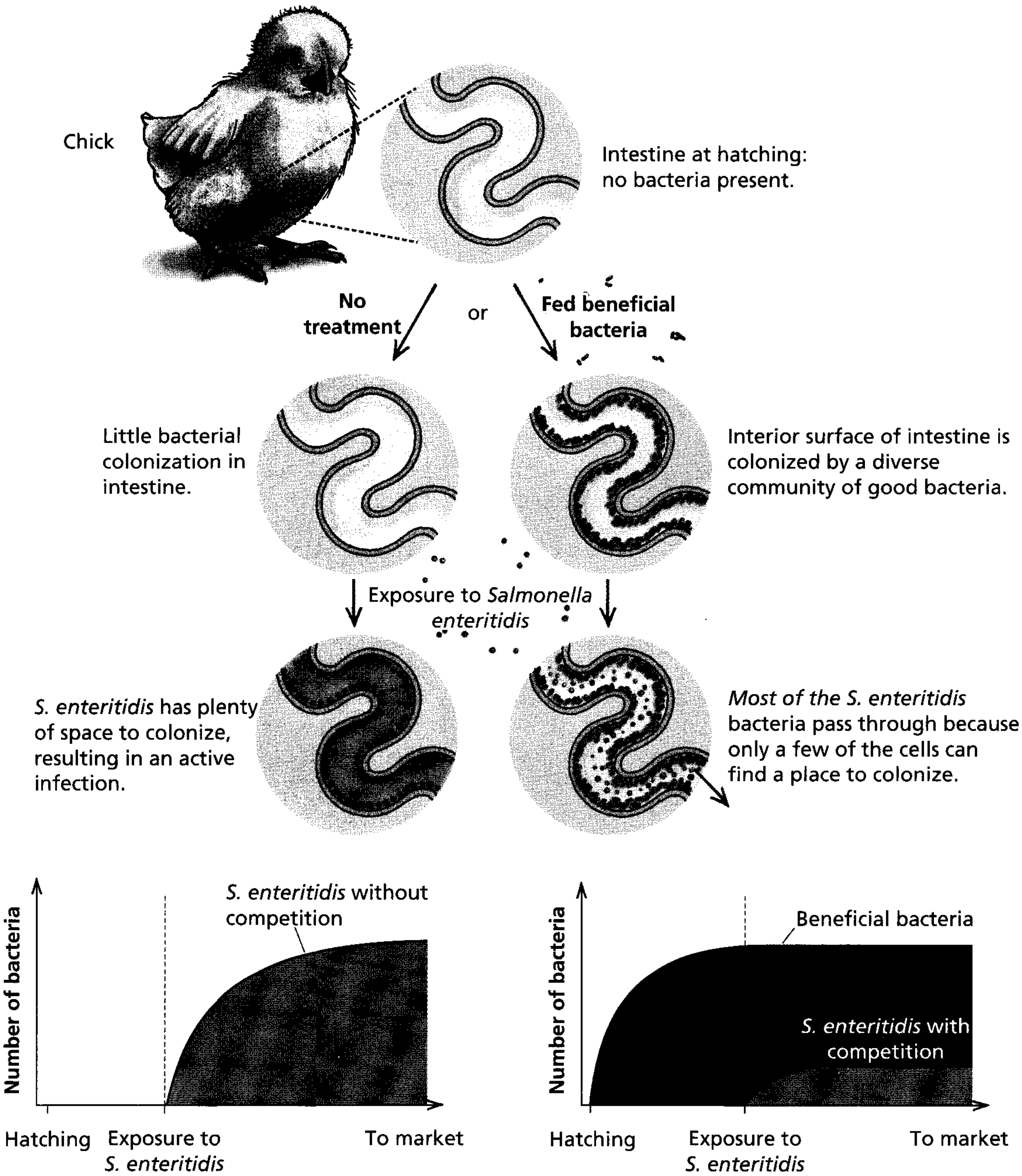


Figure 14.14 Competition. If poultry producers feed very young chicks non-disease-causing bacteria, the bacteria take up the space and nutrients in the intestine that would be used by *S. enteritidis*; thus, they will have no site to colonize and increase their population.

working; *S. enteritidis* infections in chickens have dropped by nearly 50% in the United Kingdom, where competitive exclusion in poultry is common practice.

The competitive exclusion of *S. enteritidis* in hens mirrors the role of some human-associated bacteria, such as those that normally live within our intestines and genital tracts. For instance, many women who take antibiotics for a bacterial infection will then develop vaginal yeast infections because the antibiotic kills noninfectious bacteria as well, including species in the genital tract that normally compete with yeast. Maintaining competitive interactions between larger species can be important for humans as well. For instance, in temporary ponds, the main competitors for the algae food source are mosquitoes, tadpoles, and snails. In the absence of tadpoles and snails, mosquito populations can become quite large—potentially with severe consequences since these insects may carry deadly diseases such as malaria, West Nile virus, and yellow fever. With frogs and their tadpoles increasingly endangered, this risk is a real one.

Keystone Species: How Wolves Feed Beavers. Table 14.1 summarizes the major types of ecological interactions among organisms. However, this table emphasizes the effects of each interaction on the species directly involved; it does not illustrate that many of these interactions may have multiple indirect effects. Look again at the food web pictured in Figure 14.10 on pages 370–371. None of the species in the prairie's biological community is connected to only one other species—they all eat something, and most of them are eaten by something else. You can imagine that badgers, by preying on deer mice, have a negative effect on rattlesnakes, which they compete with for these mice, and a more indirect positive effect on ground squirrels, which compete with mice for grass seeds. The existence of indirect effects of varying importance has led ecologists to hypothesize

Table 14.1 Types of species interactions and their direct effects.

Interaction	Example	Effect on Species 1	Effect on Species 2
Mutualism: Association increases the growth or population size of both species.	 1. Ants 2. Acacia tree	+ The swollen thorns of the acacia provide shelter for the ants. The acacia leaves provide "protein bodies" that the ants harvest for food.	+ Ants kill herbivorous insects and destroy competing vegetation, benefiting the acacia.
Predation and Parasitism: Consumption of one organism by another.	 1. Brown bear 2. Salmon	+ The brown bear catches the salmon and eats it, obtaining nourishment.	– The salmon does not survive.
Competition: Association causes a decrease or limitation in population size of both species.	 1. Dandelion 2. Tomato plant	– The dandelion weed does not grow as well in the presence of the tomato plant. Dandelion produces fewer seeds and fewer offspring.	– The tomato plant does not grow optimally in the presence of the weed. Tomato plant produces fewer flowers and fruit.

(a)

(b)

Figure 14.15 Keystone species. (a) The keystone in an archway helps to stabilize and maintain the arch. (b) A keystone species, such as wolves in Yellowstone National Park, help to stabilize and maintain other species in an ecosystem.

that in at least some communities, the activities of a single species can play a dramatic role in determining the composition of the system's food web. These organisms are called **keystone species** because their role in a community is analogous to the role of a keystone in an archway (Figure 14.15a). Remove the keystone, and an archway collapses; remove the keystone species, and the web of life collapses. Biologists can point to several examples of keystone species, including the population of gray wolves in Yellowstone National Park.

Gray wolves were exterminated within Yellowstone National Park by the mid-1920s because of a systematic, highly effective campaign to rid the American West of this occasional predator of livestock. However, by the 1980s, increased understanding and appreciation of these animals by the American public led to renewed interest in returning wolves to their historical homeland. In the mid-1990s, thirty-one wolves originally trapped in Canada were released into Yellowstone National Park. By the end of 2003, this number had grown to at least 301 wolves in over 30 packs, living both in the park and in surrounding public lands. During the time that wolves were extinct in the park, biologists noticed dramatic declines in populations of aspen, cottonwood, and willow trees. They attributed this decline to an increase in the consumption of these trees by elk, especially during winter when grasses become unavailable. However, just a few years after wolf reintroduction, aspen, cottonwood, and willow tree growth has rebounded in some areas of the park (Figure 14.15b). Besides the regions near active wolf dens, these areas include places on the landscape where elk have limited ability to see approaching wolves or to escape. Thus, they will stay away from these areas to avoid wolf predation. Wolves, by both reducing elk numbers and changing elk behavior, appear to be an important factor in maintaining large populations of hardwood trees in Yellowstone Park.

The rebound of aspen, cottonwood, and willow populations in Yellowstone has effects on other species as well. Beaver rely on these trees for food, and their populations appear to be growing in the park after decades of decline. Warblers, insects, and even fish that depend on shelter, food, and shade from these trees are increasing in abundance as well. Wolves in Yellowstone appear to fit the profile of a classic keystone species, one whose removal had numerous and surprising effects on biodiversity in the park. Since biologists cannot usually predict which species, if any, will act as keystones in a community, it is often impossible to know whether the rippling effects of one extinction will change that community forever.

Changed Ecosystems

As the examples in the previous section illustrate, the extinction of a single species can have sometimes surprising effects on other species in a habitat. What may be even less apparent is how the loss of seemingly insignificant species can change the environmental conditions on which the entire community depends.

Ecologists define an **ecosystem** as all of the organisms in a given area, along with their nonbiological environment. The function of an ecosystem is described in terms of the rate at which energy flows through it and the rate at which nutrients are recycled within it. The loss of some species can dramatically affect both of these ecosystem properties.

Energy Flow. In nearly all ecosystems, the primary energy source is the sun. As discussed in Chapter 4, producers convert sun energy into chemical energy during the process of photosynthesis, and the energy is passed through trophic levels making up a food chain; energy is then partitioned among trophic levels in a bottom-heavy trophic pyramid (review Figure 14.8 on page 366). The amount of sunlight reaching the surface of the Earth and the availability of water at any given location are the major determiners of both trophic pyramid structure and energy flow through it. (Chapter 15 provides a summary of how variance in sunlight and water availability leads to differences in Earth's ecosystem types.)

However, the biodiversity found in an ecosystem can also have strong effects on energy flow within it.

Studies in grasslands throughout the world have provided convincing evidence that loss of species can affect energy flow. By comparing experimental prairie "gardens" planted with the same total number of individual plants but with different numbers of species, scientists at the University of Minnesota and elsewhere have discovered that the overall plant biomass tends to be greater in more diverse gardens. This research indicates that a decline in diversity, even without a decline in habitat, may lead to less energy being made available to organisms higher on the food chain, including people who depend on wild-caught food.

Nutrient Cycling. When essential mineral nutrients for plant growth pass through a food web, they are generally not lost from the environment—hence the term **nutrient cycling**. Figure 14.16 illustrates the nitrogen nutrient cycle in a natural prairie. Nitrogen is a major component of protein, and abundant protein is essential for the proper growth and functioning of all living organisms. Nitrogen is therefore often the nutrient that places an upper limit on production in most ecosystems—more nitrogen generally leads to greater production, while areas with less available nitrogen can support fewer plants (and therefore animals).

You should note as you review Figure 14.16 that plants absorb simple molecules from the soil and incorporate them into more complex molecules. These complex molecules move through the food web with relatively minor changes until they return to the soil. Here, complex molecules are broken down into simpler ones by the action of **decomposers**, typically bacteria and fungi. Changes in the soil community can greatly affect nutrient cycling and thus the survival of certain species in ecosystems. Scientists investigating the effects of introduced earthworms that have replaced native soil communities in forests throughout the northeastern United States have observed dramatic

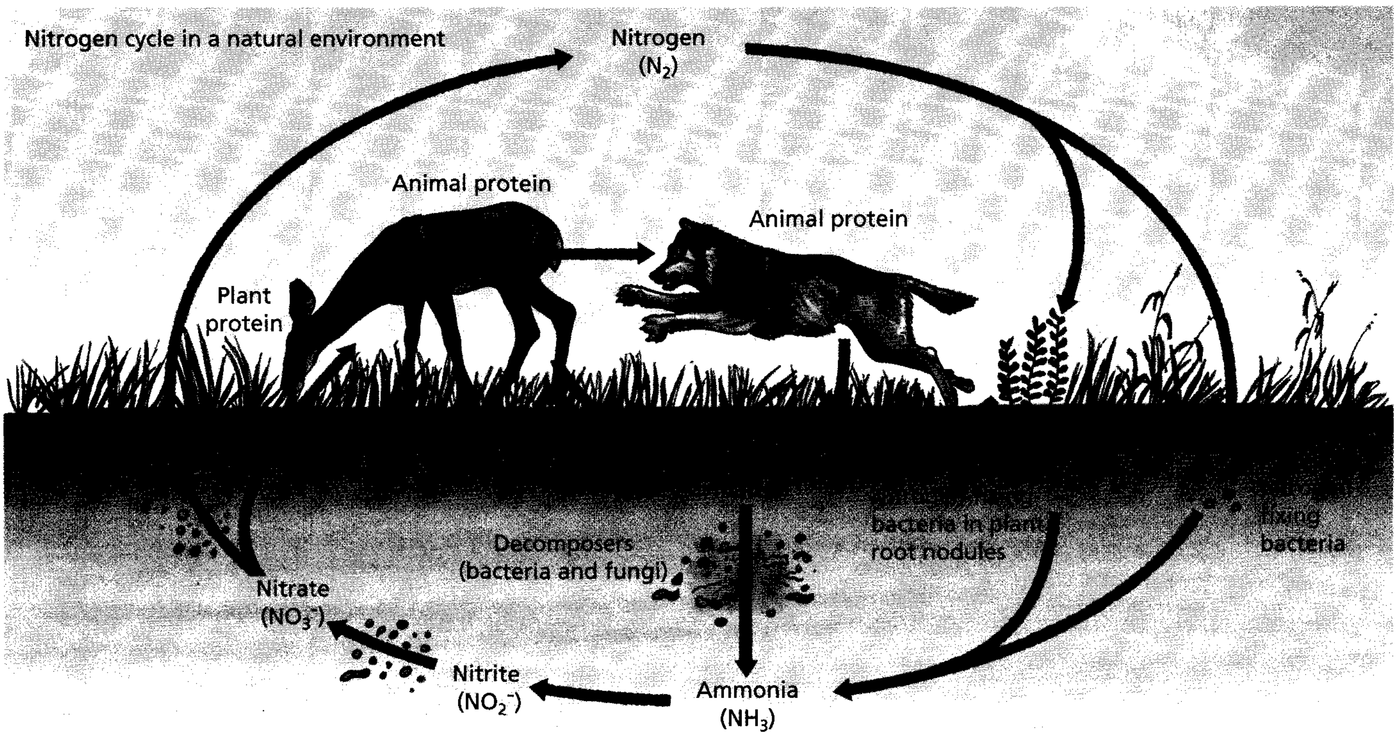


Figure 14.16 Nutrient cycling. Nutrients are recycled in an ecosystem, flowing from soil to producers to consumers and then back into the soil, where complex nutrients are decomposed into simpler forms.

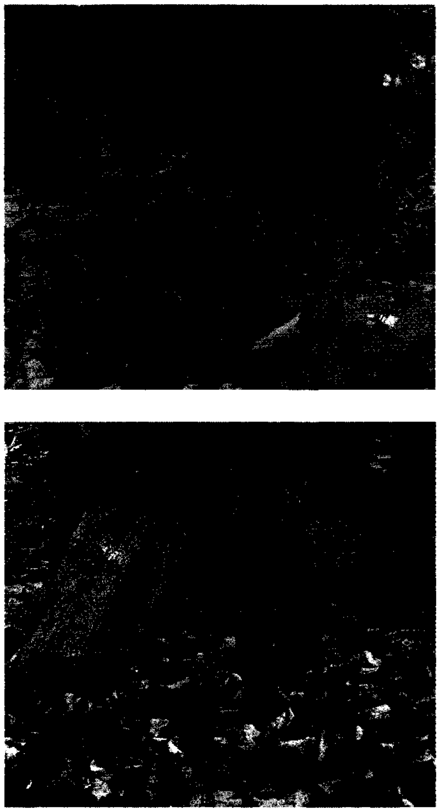


Figure 14.17 Changes in ecosystem function. In forests in northern North America, the introduction of earthworms and loss of native species have changed the plant community. Notice how barren the worm-infested forest floor, at bottom, appears, compared to the worm-free forest at top. One reason for this dramatic change may be a disruption in the native nutrient cycle.

reductions in the diversity and abundance of plants on the forest floor (Figure 14.17). These changes in the plant community may be related to the effects on nutrient cycling resulting from this change in the soil community.

The loss of biodiversity can clearly have profound effects on the health of communities and ecosystems on which humans depend. However, controversy exists over whether the current extinction may negatively affect our own psychological well-being.

Psychological Effects

Some scientists argue that the diversity of living organisms sustains humans by satisfying a deep psychological need. One of the most prominent scientists to promote this idea is Edward O. Wilson, who calls this instinctive desire to commune with nature **biophilia**.

Wilson contends that people seek natural landscapes because our distant ancestors evolved in similar landscapes (Figure 14.18). According to this hypothesis, ancient humans who had a genetic predisposition driving them to find diverse natural landscapes were more successful than those without this predisposition, since diverse areas provide a wider variety of food, shelter, and tool resources. Wilson claims that we have inherited this genetic imprint of our preagricultural past.

While there is no evidence of a gene for biophilia, there is evidence that our experience with nature has powerful psychological effects. Studies in dental clinics indicate that patients viewing landscape paintings experience a 10- to 15-point decrease in blood pressure. Patients in a Philadelphia hospital who could see trees from their windows recovered from surgery more quickly and required fewer pain medications than did patients whose views were of brick walls. Individual experiences with pets and houseplants indicate that many people derive great pleasure from the presence of nonhuman organisms. Although not conclusive, these studies and experiences are intriguing since they suggest that a continued loss of biodiversity could make life in human society less pleasant overall.

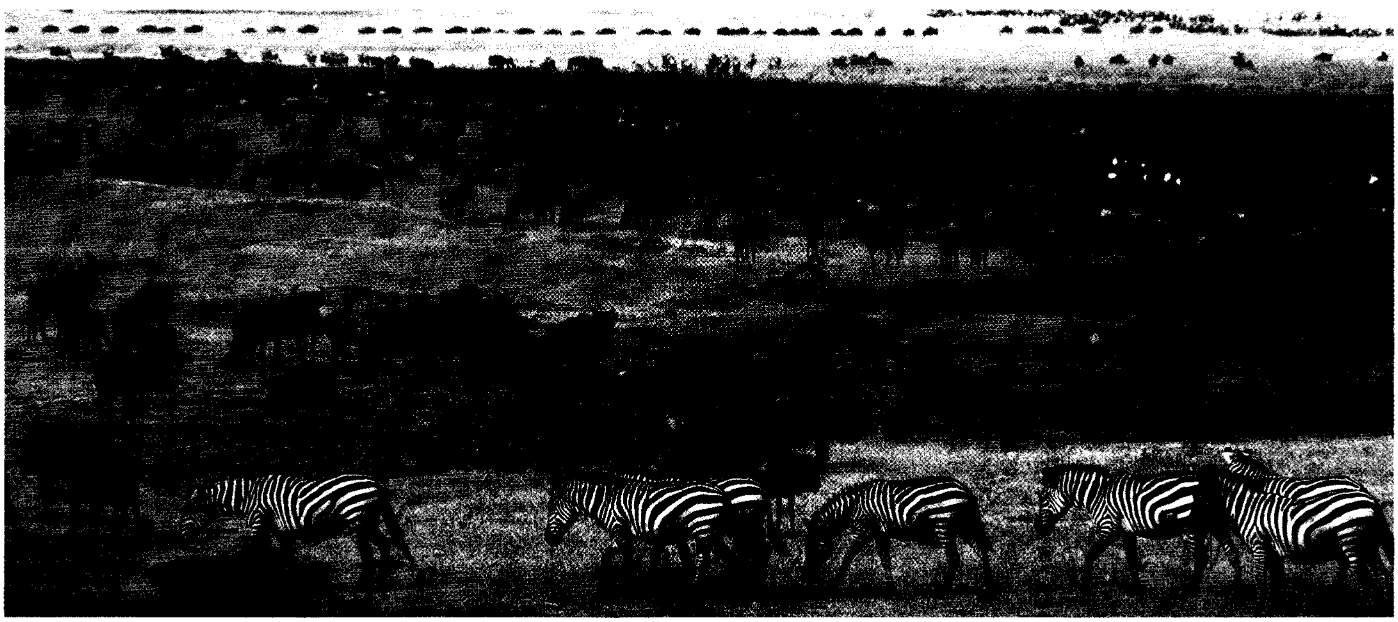


Figure 14.18 Is our appreciation of nature innate? Humans evolved in a landscape much like this one in East Africa. Some scientists argue that we have an instinctive need to immerse ourselves in the natural world.

14.3 Saving Species

So far in this chapter, we have established the possibility of a modern mass extinction occurring, and we have described the potentially serious costs of this loss of biodiversity to human populations. Since current elevated extinction rates are largely a result of human activity, reversing the trend of species loss requires mostly political and economic, rather than scientific, decisions. But what *can* science tell us about how to stop the rapid erosion of biodiversity?

Protecting Habitat

Without knowing exactly which species are closest to extinction and where they are located, the most effective way to prevent loss of species is to preserve as many habitats as possible. The same species-area curve that Wilson used to estimate the future rate of extinction also gives us hope for reducing this number. According to the curve in Figure 14.6b (page 364), species diversity declines rather slowly as habitat area declines. Thus, in theory, we can lose 50% of a habitat but still retain 90% of its species. This estimate is optimistic because habitat destruction is not the only threat to biodiversity, but the species-area curve tells us that if the rate of habitat destruction is slowed or stopped, extinction rates will slow as well.

Protecting the Greatest Number of Species. Given the growing human population, it is difficult to imagine a complete halt to habitat destruction. However, biologist Norman Myers and his collaborators have concluded that 25 biodiversity "hotspots," making up less than 2 percent of Earth's surface, contain up to 50 percent of all mammal, bird, reptile, amphibian, and plant species (Figure 14.19). Hotspots occur in areas of the globe where favorable climate conditions lead to high levels of plant production, such as rain forests, and where geological factors have resulted in the isolation of species groups, allowing them to diversify. Stopping habitat destruction in these hotspots could greatly reduce the global extinction rate. By focusing conservation efforts on hotspot areas at the greatest risk, humans can very quickly prevent the loss of a large number of species. Of course, preserving these biodiversity hotspots is not easy. It requires the concerted actions of a diverse community of nations and

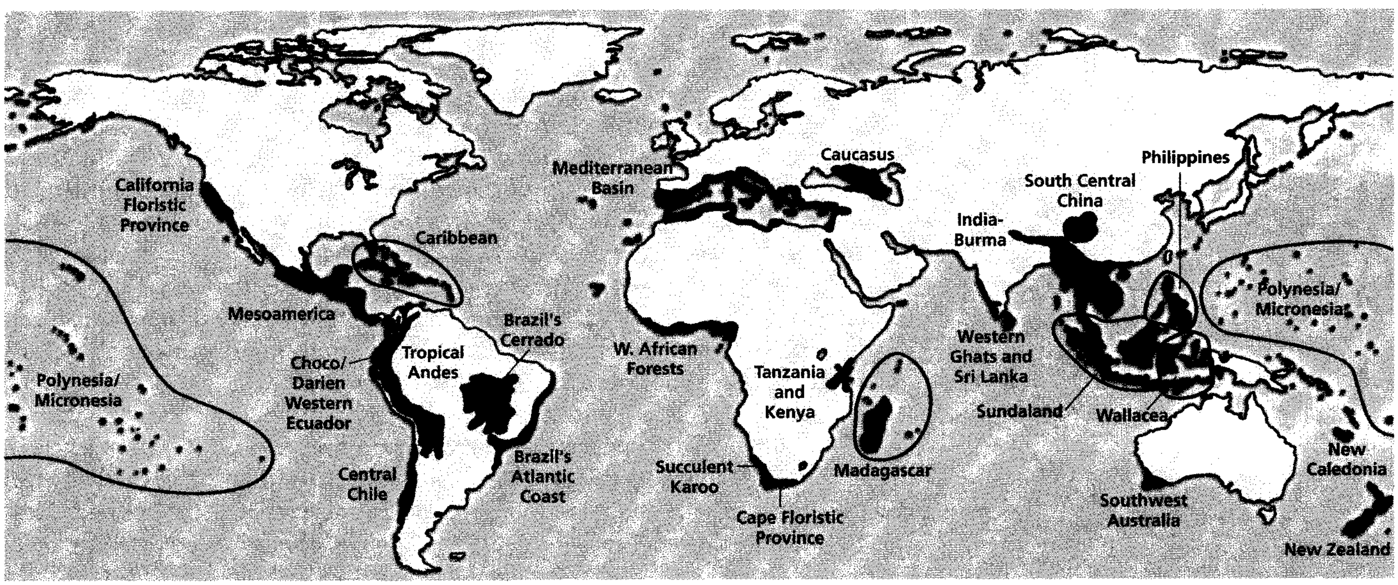


Figure 14.19 Diversity "hotspots." This map shows the locations of 25 identified biodiversity hotspots around the world. Notice how unevenly these regions of high biodiversity are distributed.

people, some of whom must also address pressing concerns of poverty, hunger, and disease. Even with habitat protection, many species in these hotspots will likely become extinct anyway for other human-mediated reasons.

In the long term, we must find ways to preserve biodiversity while including human activity in the landscape. One option is **ecotourism**, which encourages travel to natural areas in ways that conserve the environment and improve the well-being of local people. Some hotspot countries, such as Costa Rica and Kenya, have used ecotourism to preserve natural areas and provide much-needed jobs; other countries have been less successful.

While preserving hotspots may greatly reduce the total number of extinctions, this approach has its critics, who say that by promoting a strategy that focuses intensely on small areas, we risk losing large amounts of biodiversity elsewhere. These critics promote an alternative approach—identifying and protecting a wide range of ecosystem *types*—designed to preserve the greatest diversity of biodiversity rather than just the largest number of species.

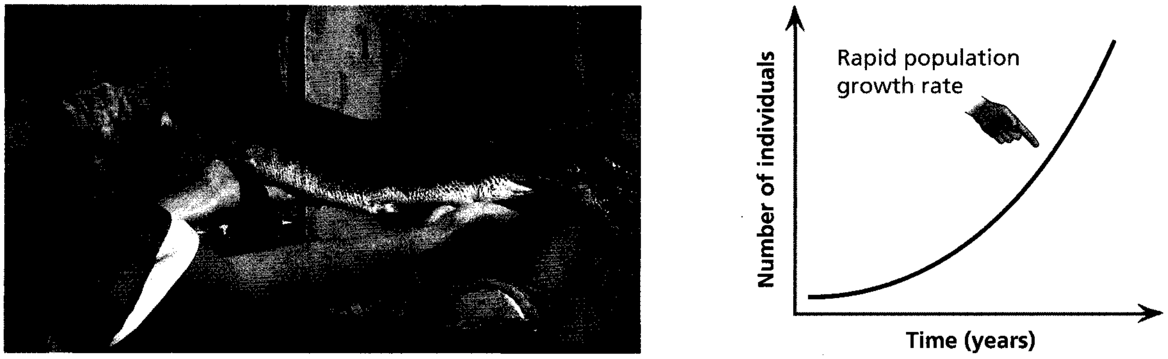
Protecting Habitat for Critically Endangered Species. Although preserving a variety of habitats ensures fewer extinctions, already endangered species require a more individualized approach. The ESA requires the U.S. Department of Interior to designate critical habitats for endangered species; that is, areas in need of protection for the survival of the species. The amount of critical habitat that becomes designated depends on political as well as biological factors. The biological part of a critical habitat designation includes conducting a study of habitat requirements for the endangered species and setting a population goal for it. The U.S. Department of Interior's critical habitat designation has to include enough area to support the recovery population. However, federal designation of a critical habitat results in the restriction of human activities that can take place there. The U.S. Department of Interior has the ability to exclude some habitats from protection if there are "sufficient economic benefits" for doing so—a decision that is in some part political.

Decreasing the Rate of Habitat Destruction. Preserving habitat is not simply the job of national governments that set aside lands in protected areas or of private conservation organizations that purchase at-risk habitats. All of us can take actions to reduce habitat destruction and stem the rate of species extinction. Conversion of land to agricultural production is a major cause of habitat destruction, and so eating lower on the food chain and reducing your consumption of meat and dairy products from animals that are fed field crops is one of the most effective actions you can take. Reducing your use of wood and paper products, and limiting your consumption of these products to those harvested sustainably (that is, in a manner that preserves the long-term health of the forest), can help slow the loss of forested land.

Other measures to decrease the rate of habitat destruction require group effort. For instance, increased financial support for developing countries and the reduction of their international debt may help slow the rate of habitat destruction. These actions allow countries to invest money in technologies that decrease their use of natural resources. Strategies that slow the rate of human population growth offer more ways to avoid mass extinction. You can participate in group conservation efforts by joining nonprofit organizations focused on these issues, writing to politicians, and educating others.

Although protecting habitat from destruction can reduce extinction rates for species on the brink of extinction—like the shortnose and Lost River suckers—preserving habitat is not enough. Populations can become so small that they can disappear, even with adequate living space. Recovery plans for both the Lost River and shortnose suckers set a short-term goal of one stable population made up of at least 500 individuals for each unique stock of suckers. To understand why at least this many individuals are required to protect the species from extinction, we need to review some of the special problems faced by small populations.

(a) Lost River sucker



(b) California condor

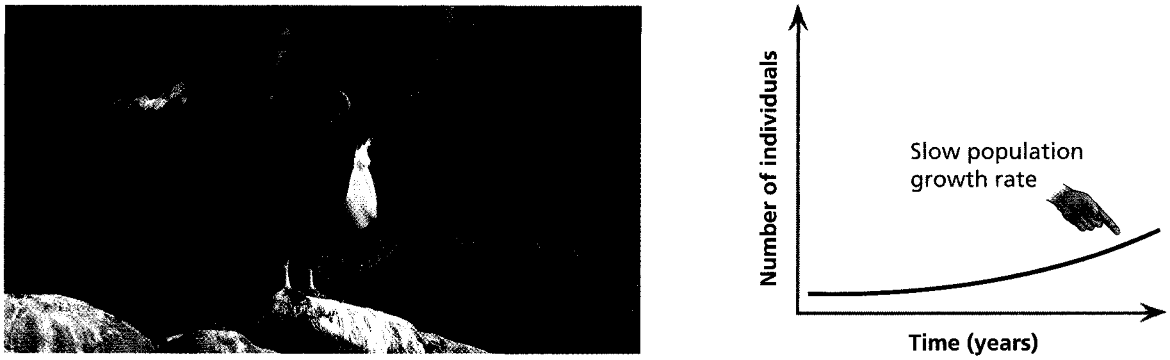


Figure 14.20 The effect of growth rate on species recovery. (a) This graph illustrates the rapid growth of a hypothetical population of quickly reproducing Lost River suckers. (b) The slow growth rate of the California condor has made the recovery of this species a long process. Today, nearly 30 years after recovery efforts began, the population of wild condors is still only in the dozens. Two wild populations of 150 condors each must be established for the bird to be removed from endangered status.

Protection from Environmental Disasters

A species' growth rate is influenced by how long the species takes to reproduce, how often it reproduces, the number of offspring produced each time, and the death rate of individuals under ideal conditions. For instance, species that reproduce slowly take longer to grow in number than do species that reproduce quickly. Thus the growth rate of an endangered species influences how rapidly that species can attain a target population size. Shortnose and Lost River suckers have relatively high growth rates and will meet their population goals quickly if the environment is ideal (Figure 14.20a). For slower-growing species, such as the California condor (Figure 14.20b), populations may take decades to recover. The rate of recovery is important because the longer a population remains small, the more it is at risk of experiencing a catastrophic environmental event that could eliminate it entirely. The story of the heath hen is a classic example of the dangers facing small populations.

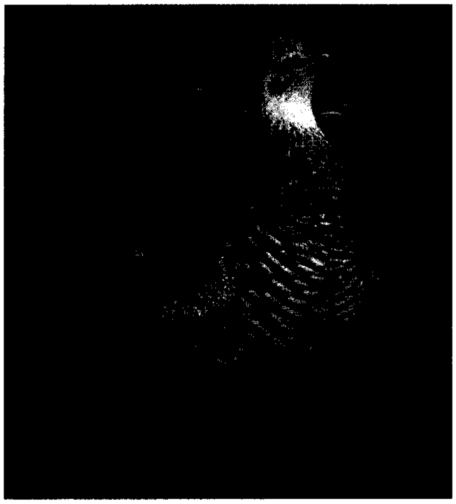


Figure 14.21 A victim of small population size. The heath hen was once abundant throughout the eastern United States. Although it was protected when its population fell to nearly 50 individuals, a series of unexpected disasters caused its extinction.

The heath hen was a small wild chicken that once ranged on the East Coast of the United States, from Maine to Virginia (Figure 14.21). In the eighteenth century, the heath hen population numbered in the hundreds of thousands of individuals, and the birds were a favorite wild meal of European settlers. Continued settlement of the eastern seaboard of the United States resulted in the loss of heath hen habitat and increased hunting, causing the rapid and dramatic decline of the birds' population. By the end of the nineteenth century, the only remaining heath hens lived on Martha's Vineyard, a 100-square-mile island off the coast of Cape Cod. Farming and settlement on the island further reduced the habitat for heath hen breeding. By 1907, only 50 heath hens were present on the island.

Recognizing the precariousness of the population, Massachusetts established a 2.5-square-mile reserve for the remaining birds on Martha's Vineyard in 1908. The establishment of this sanctuary seemed to be the solution to the heath hen's precipitous decline. By 1915, the population was recovering and had grown to nearly 2000 individuals. However, beginning in 1916, a series of disasters struck the remaining birds. First, fire destroyed much of the species' breeding habitat on the island. The following winter was long and cold, and an invasion of starving predatory goshawks from the north further reduced the heath hen population. Finally, a poultry disease brought to Martha's Vineyard in imported domestic turkeys wiped out much of the remaining population. By 1927, only 14 heath hens remained—almost all males. The last surviving member of the species was spotted for the last time on March 11, 1932.

The final causes of heath hen extinction were natural events—fire, harsh weather, predation, and disease. But it was human-caused habitat loss and human hunting that initially caused the population to become more vulnerable to these relatively common challenges. A population of 100,000 individuals can weather a disaster that kills 90% of its members but leaves 10,000 survivors; but a population of 1000 individuals will be nearly eliminated by the same circumstances. Even when human-caused losses to the heath hen population were halted, the species' survival was still extremely precarious.

Small populations of endangered species can still be protected from the fate that befell the heath hen. Having additional populations of the species at sites other than Martha's Vineyard would have nearly eliminated the risk that *all* members of the population would be exposed to the same series of environmental disasters. This is the rationale behind placing captive populations of endangered species at several different sites. For instance, captive whooping cranes are located at the U.S. National Biological Service's Patuxent Wildlife Research Center in Maryland, the International Crane Foundation in Wisconsin, the Calgary Zoo in Canada, and the Audubon Center for Endangered Species Research in New Orleans. However, if populations of endangered species remain small in number, they are subject to a more subtle but potentially equally devastating situation—the loss of genetic variability.

Protection from Loss of Genetic Diversity

A species' **genetic variability** is the sum of all of the alleles and their distribution within the species. Differences among alleles produce the variety of traits within a population. For example, the gene that determines your ABO blood type comes in three different forms, and the combination of alleles that you possess determines whether your blood type is O, A, B, or AB. Thus a population containing all three blood-type alleles contains more genetic variability for this gene than does a population with only two alleles.

The loss of genetic variability in a population is a problem for two reasons: (1) On an individual level, low genetic variability leads to low fitness; and (2) on a population level, rapid loss of genetic variability may lead to extinction.

The Importance of Individual Genetic Variability. As discussed in Chapter 10, fitness refers to an individual's ability to survive and reproduce in a given set of environmental conditions. Low individual genetic variability decreases fitness for two reasons. We can use an analogy to illustrate them. First, imagine that you could own only two jackets (Figure 14.22a). If both are blazers, then you would be well prepared to meet a potential employer. However, if you had to walk across campus to your job interview in a snowstorm, you would be pretty uncomfortable. If you own two parkas, then you will always be protected from the cold, but you would look pretty silly at a dinner party. However, if you own one warm jacket and one blazer, you are ready for slush and snow as well as a nice date. In a way, individuals experience the same advantages when they carry two different functional alleles for a gene—that is, when they are heterozygous for codominant alleles. In this case, since each allele codes for a functional protein, a heterozygous individual produces two, slightly different proteins for the same function. If the protein produced by each allele works best in different environments (for instance, if one works best at high temperatures and the other at moderate temperatures), then heterozygous individuals are able to function efficiently over a wider range of conditions than are homozygotes, who only make one version of the protein.

The second reason high individual genetic variability increases fitness is that, in many cases, one allele for a gene is **deleterious**—that is, it produces a protein that is not very functional. In our jacket analogy, a nonfunctional, deleterious allele is equivalent to a badly torn jacket. If you have this jacket and an intact one, at least you have one warm covering (Figure 14.22b). In this case, heterozygosity is valuable because a heterozygote still carries one functional copy of the gene. Often these deleterious alleles are recessive, meaning that the activity of the functional allele in a heterozygote masks the fact that a deleterious allele is present (see Chapter 6). An individual who is homozygous (carries two identical copies of a gene) for the deleterious allele will have low fitness—in our analogy, two torn jackets and nothing else. For both of these reasons, when individuals are heterozygous for many genes, (or, in our analogy, have two choices for all clothing items), the cumulative effect is often greater fitness relative to individuals who are homozygous for many genes.

In a small population, where mates are more likely to be related to each other than in a very large population simply because there are fewer mates to choose from, heterozygosity declines. When related individuals mate—known as **inbreeding**—the chance that their offspring will be homozygous for any allele is relatively high. The negative effect of homozygosity on fitness is known as **inbreeding depression**. This is seen in humans as well as in other species; numerous studies consistently show that the children of first cousins have higher mortality rates (thus lower fitness) than children of unrelated

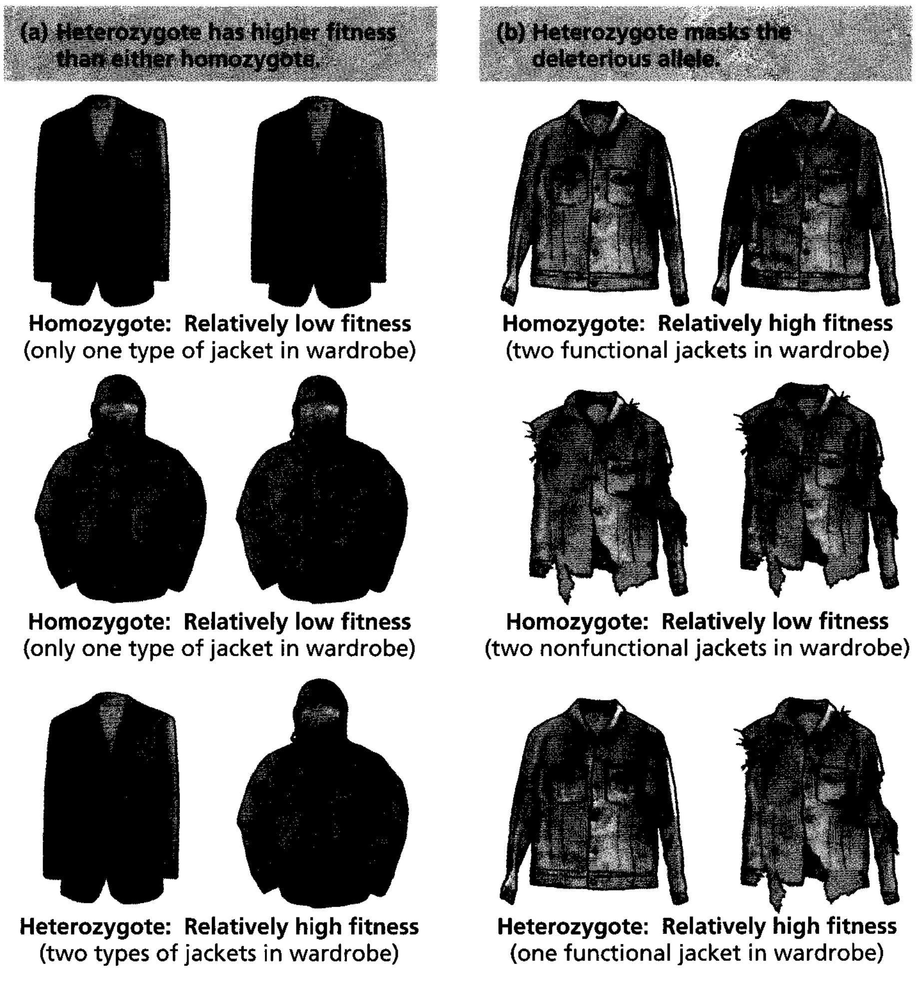


Figure 14.22 The benefits of heterozygosity. In this analogy, each jacket represents an allele. (a) Heterozygotes may be better prepared for a diversity of life experiences than homozygotes are. (b) Heterozygotes may have higher fitness than some homozygotes because certain alleles are deleterious and recessive. In this case, homozygotes for the normal allele also have higher fitness than homozygotes for the recessive allele.

parents. Because these children are the offspring of close relatives, they are more likely to have high homozygosity as compared to the children of nonrelatives. In a small population of an endangered species, low rates of survival and reproduction that are associated with high rates of inbreeding can seriously hamper a species' ability to recover from endangerment.

How Variability Is Lost via Genetic Drift. Small populations lose genetic variability because of **genetic drift**, a change in the frequency of an allele within a population that occurs simply by chance. Although in Chapter 11 we discussed genetic drift as a process for causing evolutionary change, in a small population, genetic drift can have detrimental consequences also.

Imagine a human population in which the frequency of blood-type allele A is 1%; that is, only 1 out of every 100 blood-type genes in the population is the A form (we use the symbol I^A). In a population of 20,000 individuals, we calculate the total number of I^A alleles as follows:

total number of blood-type alleles in population =

total population × 2 alleles/person

$$20{,}000 \times 2 = 40{,}000$$

total number of I^A alleles =

total number of alleles in population × frequency of allele I^A

$$40{,}000 \times 1\% = 40{,}000 \times 0.01$$

$$= 400$$

If a few of the individuals who carry the I^A allele die accidentally before they reproduce, the number of copies of the allele drops slightly in the next generation of 20,000 people—down to about 385 out of 40,000 alleles. The chance occurrences that lead to this drop result in a new allele frequency:

frequency of I^A alleles in population =

total number of I^A alleles/total number of blood-type alleles in population

$$\frac{385}{40{,}000} = 0.0096$$

$$= 0.96\%$$

The change in frequency from 1% to 0.96% is the result of genetic drift.

A change in allele frequency of 0.04% is relatively minor. Hundreds of individuals will still carry the I^A allele. It is likely that in a subsequent generation, a few individuals carrying allele I^A will have an unusually large number of offspring, thus increasing the allele's frequency within the next generation.

Now imagine the effects of genetic drift on a small population. In a population of only 200 individuals and with an I^A frequency at 1%, only 4 of the individuals in the population carry the allele. If 2 of these individuals fail to pass it on, the frequency will drop to 0.5%. Another chance occurrence in the following generation could completely eliminate the two remaining I^A alleles from the population. Thus genetic drift occurs more rapidly in small populations and is much more likely to result in the complete loss of alleles (Figure 14.23). In most populations, alleles that are lost through genetic drift have relatively small effects on fitness at the time. However, many alleles that appear to be nearly neutral with respect to fitness in one environment may have positive fitness in another environment. When this is the case, their loss may spell disaster for the entire species.

The Consequences of Low Genetic Variability in a Population. Populations with low levels of genetic variability have an insecure future for two reasons.

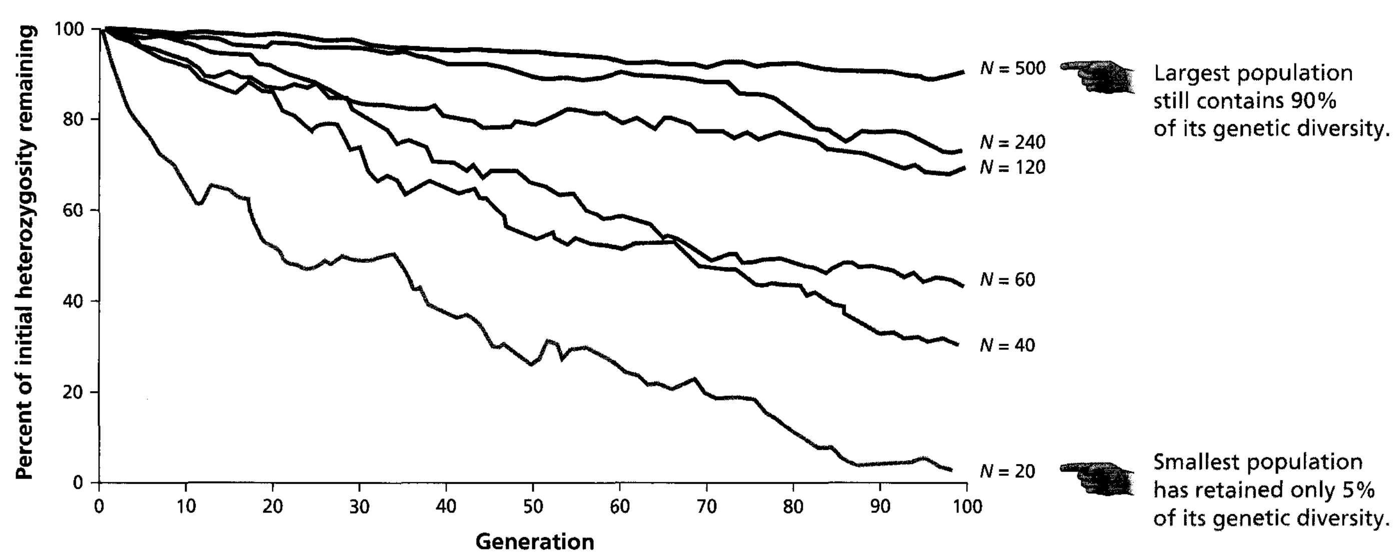


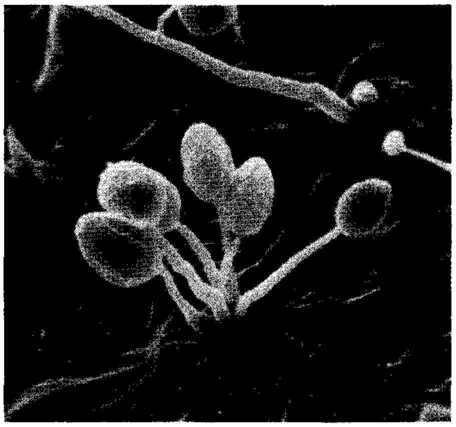
Figure 14.23 Genetic drift affects small populations more than large populations. In this graph, each line represents the average of 25 computer simulations of genetic drift for a given population size. After 100 generations, a population of 500 individuals still contains 90% of its genetic variability. In contrast, a population of 20 individuals has less than 5% of its original genetic variability.

First, when alleles are lost, the level of inbreeding depression in a population increases, which means lower reproduction and higher death rates, leading to declining populations that are susceptible to all the other problems of small populations. Second, populations with low genetic variability may be at risk of extinction because they cannot evolve in response to changes in the environment. When few alleles are available for any given gene, it is possible that no individuals in a population will possess an adaptation that allows them to survive an environmental challenge. For example, there is some evidence that individuals with type A blood are more resistant to cholera and bubonic plague than are people with type O or B blood. Therefore, possessing the I^A allele may be neutral relative to other blood-type alleles in places where these diseases are rare, but it could be an advantage where the diseases are common. If blood-type A really does protect against some infectious diseases, those individuals who carry an I^A allele will survive if a population is exposed to bubonic plague, and the population will persist. If a population has lost diversity and contains no individuals carrying the I^A allele, then it may become extinct upon exposure to bubonic plague.

As is often the case, there are some exceptions to the "rules" just described. For example, widespread hunting of northern elephant seals in the 1890s reduced the population to 20 individuals, thus probably wiping out much of the genetic variation in the species. However, elephant seal populations have rebounded to include about 150,000 individuals today. The dramatic recovery of elephant seals is apparently unusual. There are many more examples of populations that suffer because of low genetic variability. The Irish potato is perhaps the most dramatic example of this condition.

Potatoes were a staple crop of rural Irish populations until the 1850s. Although the population of Irish potatoes was high, it had remarkably low genetic variability. First, potatoes are not native to Ireland (in fact, they originated in South America), so the crop was limited to just a few varieties that were originally imported. In fact, most of the potatoes grown on the island were of one variety, called Lumper for its bumpy shape. Second, new potato plants are grown from potatoes that are produced by the previous year's plants and thus are genetically identical to their parents. This agricultural practice ensured that all of the potatoes in a given plot had identical alleles for every gene. All available evidence indicates that the genetic variability of potatoes grown in Ireland during the nineteenth century was extremely low.

(a) *Phytophthora infestans*, the protozoan that causes blight



(b) A potato plant with blight

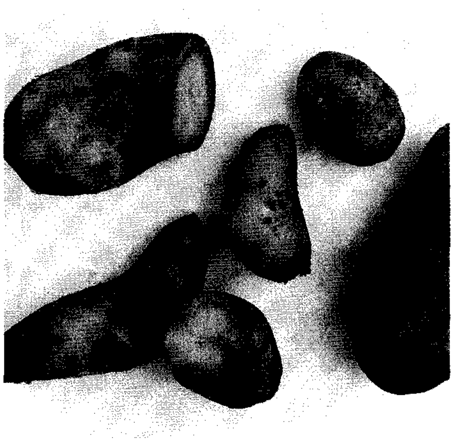


Figure 14.24 Potato blight. (a) The organism that causes late blight in potatoes, *Phytophthora infestans.* (b) Infected potato tubers.

When the organism that causes potato blight arrived in Ireland in September 1845, nearly all of the planted potatoes became infected and rotted in the fields (Figure 14.24). The few potatoes that by chance escaped the initial infection were used to plant the following year's crops. Some varieties of potatoes in South America carry alleles that allow them to resist potato blight and escape an infestation unaffected. However, apparently very few or no Irish potatoes carried these alleles; and in 1846, the entire Irish potato crop failed. Because of this failure and another in 1848, along with the ruling British government's harsh policies that inhibited distribution of food relief, nearly 1 million Irish peasants died of starvation and disease, and another 1.5 million peasants emigrated to North America.

Irish potatoes descended from a small group of plants that were missing the allele for blight resistance, so even an enormous population of these plants could not escape the catastrophe caused by this disease. Similarly, since small populations lose genetic variability rapidly through genetic drift, preventing endangered species from declining to very small population levels may be critical for avoiding a similar genetic disaster. These historical situations support the current need to preserve adequate numbers of Lost River and shortnose suckers, even at the expense of crop production in the Klamath Basin, in order to save these species from extinction.

14.4 Protecting Biodiversity Versus Meeting Human Needs

Saving the Lost River and shortnose suckers from extinction requires protecting all of the remaining fish and restoring the habitat they need for reproduction. These actions cause economic and emotional suffering for humans who make their living in the Klamath Basin. In fact, many actions necessary to save endangered species result in immediate problems for people. As pointed out earlier by the Oregon State University student, we need to balance the costs and benefits of preserving endangered species.

A provision of the Endangered Species Act allows members of a committee to weigh the relative costs and benefits of actions taken to protect endangered species. The Endangered Species Committee, which includes the U.S. Secretaries of Agriculture and the Interior as well as the Chairman of the Council of Economic Advisors, has convened a number of times for this purpose. This so-called God Squad decides if they should overrule a federal action meant to save an endangered species in order to protect the livelihoods of people. Farmers in the Klamath Basin have advocated for a God-Squad ruling on the diversion of water from Upper Klamath Lake, but history suggests that a decision is not likely to be in their favor. The Endangered Species Committee convened only four times from 1973 through 2001, and it has granted two exemptions, one of which was essentially overturned by the subsequent presidential administration.

If the debate in the Klamath Basin follows the pattern set by other ESA controversies, a political solution that causes some economic hardship while ensuring the immediate survival of the fish will prevail. Biologists working on the problem agree that the recovery goal for shortnose and Lost River suckers is high enough to ensure short-term survival (50 years), but it is not high enough to ensure both species' long-term survival (500 years). The biologists' assessment is based on computer models predicting how the population will respond to predicted environmental changes. The recovery population size of 500 is large enough to withstand environmental catastrophes in the short term, but in the long term, continued loss of genetic variability results in the extinction of populations of only 500 fish in their models.

The risk to the long-term survival of the fish helps balance the cost to the farmers of the Klamath Basin. The short-term cost to farmers was somewhat alleviated when they received federal disaster assistance to help them adjust to the loss of lake-derived irrigation water. While recent increases in rainfall have helped provide enough water for both farmers and fish and reduced the level of conflict, the federal government continues to purchase farmland from willing sellers in the Basin in order to protect and restore the fishes' habitat. The U.S. Fish and Wildlife Service hopes that this long-term solution will help provide adequate habitat for the survival of both the shortnose and Lost River suckers.

The ESA has been a successful tool for bringing species such as the peregrine falcon, American alligator, and gray wolf back from the brink of extinction, but all of these successes have come with some cost to citizens. If the solution to these and other endangered species controversies is any guide, many Americans are willing to devote tax dollars to efforts that balance the needs of people and wildlife in order to protect our natural heritage.

As with any challenge that humans face, the best strategy for preserving biodiversity is to prevent species from becoming endangered to begin with. Table 14.2 provides a list of actions that can help preserve biodiversity. Meeting this challenge requires some creativity, but it is often possible to provide for the needs of people while preserving our natural heritage. However, it will take all of us to help keep the equation in balance.

Table 14.2 Taking action to preserve biodiversity.

Objective	Why do it?	Actions
Reduce fossil fuel use. 	• Mining, drilling, and transporting fossil fuels modifies habitat and leads to pollution. • Burning fossil fuels contributes to global climate change, further degrading natural habitats.	• Buy energy-efficient vehicles and appliances. • Walk, bike, carpool, or ride the bus whenever possible. • Choose a home near school, work, or easily accessible public transportation. • Buy "clean energy" from your electric provider, if offered.
Reduce the impact of meat consumption. 	• The primary cause of habitat destruction and modification is agriculture. • Modern beef, pork, and chicken production relies on grains produced on farms. One pound of beef requires 4.8 pounds of grains, or about 25 square meters of agricultural land.	• Eat one more meat-free meal per week. • Make meat a "side-dish" instead of the main course. • Purchase grass-fed or free-range meat.
Reduce pollution. 	• Pollution kills organisms directly or can reduce their ability to survive and reproduce in an environment.	• Do not use pesticides. • Buy products produced without the use of pesticides. • Replace toxic cleaners with biodegradable, less harmful chemicals. • Consider the materials that make up the goods you purchase, and choose the least-polluting option. • Reuse or recycle materials instead of throwing them out.
Educate yourself and others. 	• Change happens most rapidly when many individuals are working for it.	• Ask manufacturers or store owners about the environmental costs of their goods. • Talk to family and friends about the choices you make. • Write to decision makers to urge action on effective measures to reduce human population growth and curb habitat destruction and species extinction.

CHAPTER REVIEW

Summary

14.1 The Sixth Extinction

- The loss of biodiversity through species extinction is exceeding historical rates by 50 to 100 times (p. 362).
- Species-area curves help us predict how many species will become extinct due to human destruction of natural habitat (pp. 363–364).
- Species at the top of the food chain are more susceptible to extinction because less energy is available for survival at higher trophic levels (p. 366).
- Additional threats of habitat fragmentation, introduced species, overexploitation, and pollution also contribute to species extinction (pp. 367–368).

Web Tutorial 14.1 Tropical Deforestation and the Species Area Curve
Web Tutorial 14.2 Habitat Destruction and Fragmentation

14.2 The Consequences of Extinction

- Species are important to us as resources, either directly as consumed products or indirectly as organisms used to provide potential medicines or genetic resources (p. 369).
- Species are members of communities; their loss as mutualists, predators, competitors, and keystone species may change a community, making it less valuable or even harmful to humans (pp. 371–376).
- Species also play a role in ecosystem function, including effects on energy flow and nutrient cycling. Changes to the biological components of an ecosystem may change its nonbiological properties as well (pp. 376–377).
- *Biodiversity may fulfill a human need to experience natural* landscapes (p. 378).

14.3 Saving Species

- If habitat protection is focused on a few well-defined biodiversity hotspots, then the number of organisms becoming extinct can be markedly reduced (p. 379).
- When species are already endangered, restoring larger populations is critical for preventing extinction (p. 380).
- Small populations are at higher risk for extinction due to environmental catastrophes (p. 381).
- Small populations are at risk when individuals have low fitness due to inbreeding and thus are less able to increase population size (p. 383).
- Genetic variability is lost in small populations because of genetic drift—the loss of alleles from a population due to chance events. Therefore, small populations may be less able to evolve in response to environmental change (p. 384).

14.4 Protecting Biodiversity Versus Meeting Human Needs

- The political process enables people to develop plans for helping endangered species recover from the brink of extinction while minimizing the negative effects of these actions on people (pp. 386–387).

Learning the Basics

1. How is the estimate of historical rates of extinction generated? What are the criticisms of these estimates?
2. Describe how habitat fragmentation endangers certain species. Which types of species do you think are most threatened by habitat fragmentation?
3. Compare and contrast the species interactions of mutualism, predation, and competition.
4. Current rates of species extinction appear to be approximately ______________ historical rates of extinction.

   A. equal to; **B.** 10 times lower than; **C.** 10 times higher than; **D.** 50 to 100 times higher than; **E.** 1000 to 10,000 times higher than
5. The relationship between the size of a natural habitat and the number of species that the habitat supports is described by a(n) ______________.

   A. habitat fragmentation measure; **B.** inbreeding depression matrix; **C.** species-area curve; **D.** overexploitation scale; **E.** ecosystem services cost
6. A mass extinction ______________.

   A. is global in scale; **B.** affects many different groups of organisms; **C.** is caused only by human activity; **D.** a and b are correct; **E.** a, b, and c are correct
7. The web of life refers to the ______________.

   A. evolutionary relationships among living organisms; **B.** connections between species in an ecosystem;

C. complicated nature of genetic variability; **D.** flow of information from parent to child; **E.** predatory effect of humans on the rest of the natural world

8. According to many scientists, the most effective way to reduce the rate of extinction is to _______________.

   A. preserve habitat, especially in highly diverse areas; **B.** focus on a single species at a time; **C.** eliminate the risk of genetic drift; **D.** produce less trash by recycling more; **E.** encourage people to rely more on agricultural products and less on wild products

9. The risks faced by small populations include _______________.

   A. erosion of genetic variability through genetic drift; **B.** decreased fitness of individuals as a result of inbreeding; **C.** increased risk of experiencing natural disasters; **D.** a and b are correct; **E.** a, b, and c are correct

10. One advantage of preserving more than one population and more than one location of an endangered species is _______________.

    A. a lower risk of extinction of the entire species if a catastrophe strikes one location; **B.** higher levels of inbreeding in each population; **C.** higher rates of genetic drift in each population; **D.** lower numbers of heterozygotes in each population; **E.** higher rates of habitat fragmentation in the different locations

Analyzing and Applying the Basics

1. Review Figure 14.6a on page 364. The graph depicts the relationship between island size and the number of amphibian and reptile species found on an island chain in the West Indies. How many species of reptiles and amphibians would you expect to find on an island that is 15,000 square kilometers in area? Imagine that humans colonize this island and dramatically modify 10,000 square kilometers of the natural habitat. What percentage of the species that were originally found on the island would you expect to become extinct?

2. Examine the web of relationships among organisms depicted in Figure 14.10 on pages 370–371. Which of the following species pairs are likely competitors? In each case, describe what they compete for.

   A. badger, jackrabbit; **B.** bison, coyote; **C.** rattlesnake, badger; **D.** ground squirrel, deer mouse; **E.** jackrabbit, prairie dog

   How could you test your hypothesis that these animals are in competition with each other?

3. The piping plover is a small shorebird that nests on beaches in North America. The plover population in the Great Lakes is endangered and consists of only about 30 breeding pairs. Imagine that you are developing a recovery plan for the piping plover in the Great Lakes. What sort of information about the bird and the risks to its survival would help you to determine the population goal for this species as well as how to reach this goal?

Connecting the Science

1. From your perspective, which of the following reasons for preserving biodiversity is most convincing? (1) Nonhuman species have roles in ecosystems and should be preserved in order to protect the ecosystems that support humans; or (2) nonhuman species have a fundamental right to existence. Explain your choice.

2. If a child asks you the following question 20 or 30 years from now, what will be your answer, and why?

   "When it became clear that humans were causing a mass extinction, what did you do about it?"