The plant known as the Dung of the Devil, discovered as a treatment for the Spanish flu of 1918, may also be a remedy for the H1N1 virus. *(Rstudio/Alamy)* chapter 5

Evolution of Biodiversity

The Dung of the Devil

From 1918 to 1920, the world experienced a flu outbreak of unprecedented scale. Known as the Spanish flu, the disease had a devastating effect. Mortality estimates from that time vary, but somewhere between 20 million and 100 million people died worldwide, including more than 600,000 people in the United States. During the height of the outbreak, reports stated that some people in China had found the roots of a particular plant beneficial in fighting the flu. The plant (*Ferula assafoetida*) had a pleasant smell when cooked, but the raw sap from the roots had a foul smell that inspired the plant's common name, the Dung of the Devil.

The Dung of the Devil story does not end in 1920. It turns out that Spanish flu was caused by an H1N1 virus that is closely related to the H1N1 virus that caused the worldwide "swine flu" outbreak of 2009–2010. Scientists in China recalled that people had used the plant to fight the Spanish flu 80 years ago, so they decided to explore its potential to combat the modern H1N1 flu virus. They found that extracts from the plant had strong antiviral properties, stronger even than those of contemporary antiviral drugs. Thus the Dung of the Devil has the potential to produce a new pharmaceutical drug to fight future H1N1 flu epidemics.

> The Dung of the Devil has the potential to produce a new pharmaceutical drug to fight future H1N1 flu epidemics.

The Dung of the Devil is just one of the organisms from which humans have extracted life-saving drugs. Willow trees from temperate forests were the original source of salicylic acid, from which aspirin is derived. More recently, wild plants have provided several important medicines for treating a variety of cancers. For example, the rosy periwinkle (*Catharanthus roseus*), found only in the tropical forests of Madagascar, is the source of two drugs used to treat childhood leukemia and Hodgkin's disease. The mayapple (*Podophyllum peltatum*), a common herb of the eastern United States, is the source of two other anticancer drugs. Many new medicines, including anti-inflammatory, antiviral, and antitumor drugs, have come from a variety of invertebrate animals that inhabit coral reefs, including sponges, corals, and sea squirts. Of the most promising current candidates for new drugs, 70 percent were first discovered in plants, animals, and microbes. Unfortunately, many species that are either known or suspected sources of drugs are being lost to deforestation, agriculture, and other human activities. At the same time, indigenous people with knowledge about medicinal uses of the natural drugs in their environment are being forced to relocate, and their knowledge may soon be lost.

Only a small fraction of the millions of species on Earth has been screened for useful drugs. It is likely that many more medicines could be found in living organisms. The continual discovery of new drugs in organisms around the world, including the Dung of the Devil, makes yet another convincing argument for conserving Earth's biodiversity.

Sources:
C. L. Lee et al., Influenza A (H1N1) antiviral and cytotoxic agents from *Ferula assafoetida, Journal of Natural Products* 72 (2009): 1568–1572; D. Newman and G. M. Cragg, Natural products as sources of new drugs over the last 25 years, *Journal of Natural Products* 70 (2007): 461–477.

The use of plants for drugs that can help humans fight diseases is just one of many reasons that we want to protect the biodiversity of the planet. In general, biodiversity is an important indicator of environmental health, so a rapid decline of biodiversity in an ecosystem indicates that it is under stress. The biodiversity on Earth today is the result of evolution and extinction. Knowledge of these processes helps us to understand past and present environmental changes and their effects. In this chapter, we will examine how scientists quantify biodiversity and then look at how the process of evolution creates biodiversity. We will also examine the processes of speciation and extinction and the ways species have evolved unique ways of life that affect the abiotic and biotic conditions under which they can live.

module

14

The Biodiversity of Earth

As you will recall from Chapter 1, we can think about biodiversity at three different scales (see Figure 2.1 on page 9). Within a given region, for example, the variety of ecosystems is a measure of ecosystem diversity. Within a given ecosystem, the variety of species constitutes species diversity. Within a given species, we can think about the variety of genes as a measure of genetic diversity. Every individual organism is distinguished from every other organism, at the most basic level, by the differences in the information coded by their genes. Because genes form the blueprint for an organism's traits, the diversity of genes on Earth ultimately helps determine the species diversity and ecosystem diversity on Earth. In other words, all three scales of biodiversity contribute to the overall biodiversity of the planet. In this module, we will examine how we estimate the number of species on Earth and how scientists quantify biodiversity. We will then examine how scientists illustrate the relatedness among species.

Learning Objectives

After reading this module you should be able to

- understand how we estimate the number of species living on Earth.
- quantify biodiversity.
- describe patterns of relatedness among species using a phylogeny.

It is difficult to estimate the number of species on Earth

A short walk through the woods, a corner lot, or a city park makes one thing clear: Life comes in many forms. A small plot of untended land or a tiny pond contains dozens, perhaps hundreds, of different kinds of plants and animals visible to the naked eye as well as thousands of different kinds of microscopic organisms. In contrast, a carefully tended lawn or a commercial timber plantation usually supports only a few types of grasses or trees (FIGURE 14.1). The total number of organisms in the plantation or lawn may be the same as the number in the pond or in the untended plot, but the number of species will be far smaller.

Recall from Chapter 1 that a species is defined as a group of organisms that is distinct from other such

(a) (b)

FIGURE 14.1 Species diversity and ecosystems. (a) Natural forests contain a high diversity of tree species. (b) In forest plantations, in which a single tree species has been planted for lumber and paper products, species diversity is low. *(a: Ron and Patty Thomas/Getty Images; b: Brent Waltermire/Alamy)*

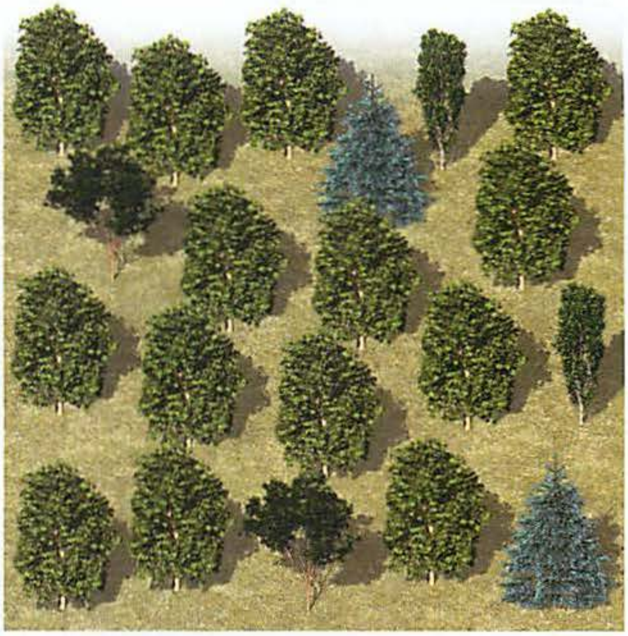
groups in terms of size, shape, behavior, or biochemical properties, and that can interbreed with other individuals in its group to produce viable offspring. This last requirement is important because sometimes individuals from different species can mate, but they do not produce offspring that survive.

The number of species in any given place is the most common measure of biodiversity, but estimating the total number of species on Earth is a challenge. Many species are easy to find, such as the birds or small mammals you might see in your neighborhood. Others are not so easy to find. Some species are active only at night, live in inaccessible locations such as the deep ocean, or cannot be seen without a microscope. To date, scientists have named approximately 2 million species, which means the total must be larger than that.

The insects represent a group that contains more species than most other groups, so scientists reason that if we could get a good estimate for the number of insect species in the world, we would have a much better sense of the total number of species. In one study, researchers fumigated the canopies of a single tree species in the tropical rainforest and then collected all the dead insects that fell from the trees onto a tarp on the ground. From this collection of dead insects, they counted the number of beetle species that fed on only the one tree species they fumigated. By multiplying this number of beetle species by the total number of tropical tree species, they estimated that in the tropics there were perhaps 8 million species of beetles that feed on a single species of tree. Because beetles make up about 40 percent of all insect species, and because insect species in the forest canopy tend to be about twice as numerous as insect species on the forest floor, the researchers suggested that a reasonable estimate for the total number of tropical insect species might be 30 million. More recent work has indicated that this number is probably too high. Current estimates for the total number of species on Earth range between 5 million and 100 million, but most scientists estimate that there are about 10 million species.

We can measure biodiversity in terms of species richness and evenness

Because species are not uniformly distributed, the number of species on Earth is not a useful indicator of how many species live in a particular location. Often we desire to know the number of species at a given location to determine whether a region is being affected by



Community 1
A: 25% B: 25% C: 25% D: 25%

Community 2
A: 70% B: 10% C: 10% D: 10%

FIGURE 14.2 Measures of species diversity. Species richness and species evenness are two different measures of species diversity. Although both communities contain the same number of species, community 1 has a more even distribution of species and is therefore more diverse than community 2.

human activities. To measure species diversity at local or regional scales, scientists have developed two measures: *species richness* and *species evenness*.

The number of species in a given area, such as a pond, the canopy of a tree, or a plot of grassland, is known as **species richness.** Species richness is used to give an approximate sense of the biodiversity of a particular place. However, we may also want to know the **species evenness,** which is the relative proportion of individuals within the different species in a location. Species evenness tells us whether a particular ecosystem is numerically dominated by one species or whether all of its species have similar abundances. An ecosystem has high species evenness if its species are all represented by similar numbers of individuals. An ecosystem has low species evenness if one species is represented by many individuals whereas other species are represented by only a few individuals. In this case, there is effectively less diversity.

Scientists evaluating the biodiversity of an area must often look at both species richness and species evenness. Consider the two forest communities, community 1 and community 2, shown in FIGURE 14.2. Both forests contain 20 trees that are distributed among four species. In community 1, each species is represented by 5 individuals. In community 2, one species is represented by 14 individuals and each of the other three species is represented by 2 individuals. Although the species richness of the two forests is identical, the four species are more evenly represented in community 1. That forest therefore has greater species evenness and is considered to be more diverse.

Because species richness or evenness often declines after a human disturbance, knowing the species richness and species evenness of an ecosystem gives environmental scientists a baseline they can use to determine how much that ecosystem has changed. "Do the Math: Measuring Species Diversity" on page 108 demonstrates one common way of calculating species diversity.

The evolutionary relationship among species can be illustrated using a phylogeny

Scientists organize species into categories that indicate how closely related they are to one another. The branching pattern of evolutionary relationships is called

Species richness The number of species in a given area.

Species evenness The relative proportion of individuals within the different species in a given area.

do the **math**

Measuring Species Diversity

Environmental scientists are often interested in evaluating both species richness and species evenness, so they have come up with indices of species diversity that take both measures into account. One commonly used index is Shannon's index of diversity. To calculate this index, we must know the total number of species in a community (n) and, for each species, the proportion of the individuals in the community that represent that species (p_i). Once we have this information, we can calculate Shannon's index (H) by taking the product of each proportion (p_i) and its natural logarithm [ln (p_i)] and then summing these products, as indicated by the summation symbol (Σ):

$$H = -\sum_{i=1}^{n} p_i \ln(p_i)$$

The minus sign makes the index a positive number. Higher values of H indicate higher diversity.

Imagine a community of 100 individuals that are evenly divided among four species, so that the proportions (p_i) of the species all equal 0.25. We can calculate Shannon's index as follows:

$$H = -[(0.25 \times \ln 0.25) + (0.25 \times \ln 0.25) + (0.25 \times \ln 0.25) \times (0.25 \times \ln 0.25)]$$
$$H = -[(-0.35) + (-0.35) + (-0.35) + (-0.35)]$$
$$H = 1.40$$

Now imagine another community of 100 individuals that also contains four species, but in which one species is represented by 94 individuals and the other three species are each represented by 2 individuals. We can calculate Shannon's index to see how this difference in species evenness affects the value of the index:

$$H = -[(0.94 \times \ln 0.94) + (0.02 \times \ln 0.02) + (0.02 \times \ln 0.02) + (0.02 \times \ln 0.02)]$$
$$H = -[(-0.06) + (-0.08) + (-0.08) + (-0.08)]$$
$$H = 0.30$$

Because this value of H is lower than the value we calculated for the first community, we can conclude that the second community has lower diversity. Note that the total number of individuals does not affect Shannon's index of diversity; only the number of species and the proportion of individuals within each species matter.

Your Turn Imagine a third community of 100 individuals in which those individuals are distributed evenly among all the species, but there are only two species, not four. Calculate Shannon's index to see how this difference in species richness affects the value of the index.

a **phylogeny.** Phylogenies can be described with a diagram like the one shown in FIGURE 14.3, called a phylogenetic tree.

Phylogeny The branching pattern of evolutionary relationships.

The relatedness of the species in a phylogeny is determined by similarity of traits: The more similar the traits of two species, the more closely related the two species are assumed to be. Historically, scientists used mostly morphological traits, including a large number of bone measurements, to measure similarity. Today, scientists base phylogenies on a variety of characteristics, including morphology, behavior, and genetics.

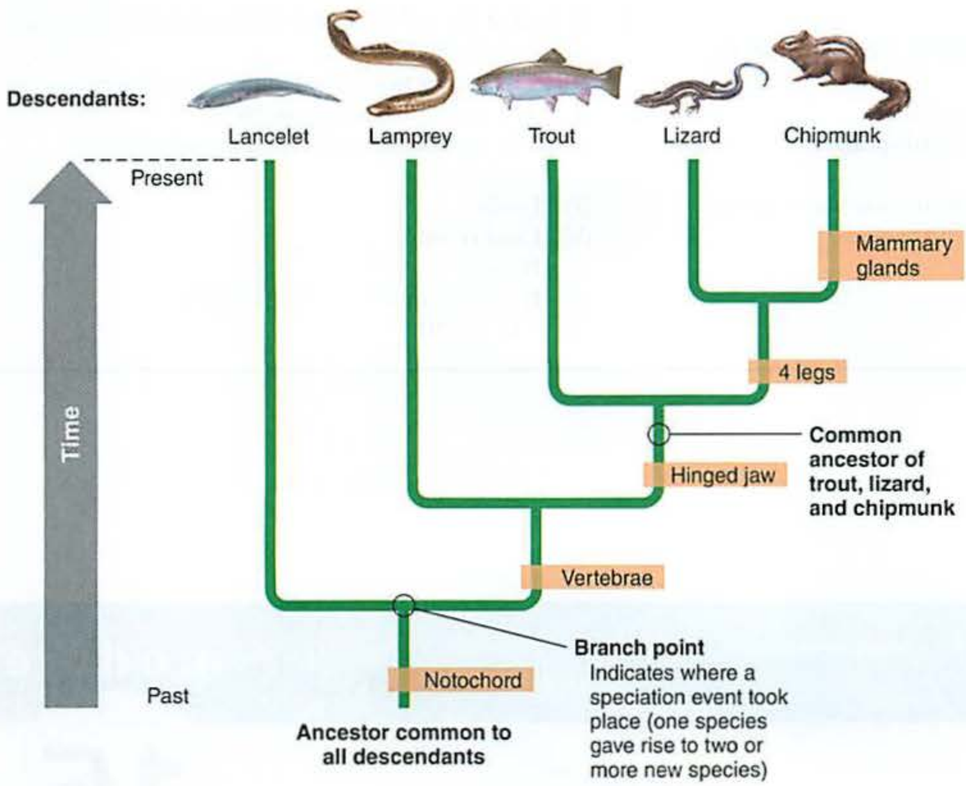


FIGURE 14.3 A phylogenetic tree. Phylogenies are based on the similarity of traits among species. Scientists can assemble phylogenetic trees that indicate how different groups of organisms are related and show where speciation events have occurred. The brown boxes indicate when major morphological changes evolved over evolutionary time.

module

14

REVIEW

In this module, we learned that scientists are not able to determine the exact number of species on Earth. Most estimates agree on approximately 10 million species, of which we have identified approximately 2 million. We saw that biodiversity can be quantified in terms of species richness and evenness. Species can be arranged on a phylogenetic tree that illustrates the evolutionary steps that gave rise to current species. In the next module, we will examine how evolution has produced such a large diversity of species.

Module 14 AP® Review Questions

1. How many species are estimated to exist on Earth?
   (a) 2 million
   (b) 8 million
   (c) 10 million
   (d) 30 million
   (e) 100 million

2. Two savanna communities both contain 15 plant species. In community A, each of the 15 species is represented by 20 individuals. In community B, 10 of the species are each represented by 12 individuals; the remaining 5 species are each represented by 3 individuals. Which statement best describes the two communities?
   (a) Community A has the same biodiversity as community B.
   (b) Both communities have the same species evenness.
   (c) Community B has a higher species richness.
   (d) Community A has a higher species evenness.
   (e) Community B has a lower species richness.

3. Phylogeny is
   (a) the number of evolutionarily related species in an ecosystem.
   (b) the study of morphological traits.
   (c) the branching pattern of evolutionary relationships.
   (d) the process of evolution that creates new species.
   (e) the genetic biodiversity of a species.

4. Which of the following is used to calculate Shannon's index of diversity?
   I. The proportion of individuals in each species
   II. The total number of species
   III. The number of individuals in each species

   (a) I only
   (b) I and II only
   (c) II only
   (d) II and III only
   (e) I, II, and III

module

15

How Evolution Creates Biodiversity

We have seen the importance of biodiversity. In this module we will look at the processes of *evolution*, which is the source of biodiversity. Because the evolution of biodiversity depends on genetic diversity, we will examine how genetic diversity is created. We begin by exploring the sources of genetic variation and then consider how humans and the natural world select from this variation to favor particular individuals that go on to reproduce in the next generation. Finally, we will examine how several random processes can also cause evolution.

Learning Objectives

After reading this module you should be able to

- identify the processes that cause genetic diversity.
- explain how evolution can occur through artificial selection.
- explain how evolution can occur through natural selection.
- explain how evolution can occur through random processes.

Genetic diversity is created through mutation and recombination

Earth's biodiversity is the product of **evolution,** which can be defined as a change in the genetic composition of a population over time. Evolution can occur at multiple levels. Evolution below the species level, such as the evolution of different varieties of apples or potatoes, is called **microevolution.** In contrast, when genetic changes give rise to new species, or to new genera, families, classes, or phyla—larger categories of organisms into which species are organized—we call the process **macroevolution.** Among these many levels of macroevolution, the term speciation is restricted to the evolution of new species.

To understand how genetic diversity is created, we first need to understand *genes*. **Genes** are physical locations on chromosomes within each cell of an organism. A given gene has DNA that codes for a particular trait, such as body size, but the DNA can take different forms known as alleles. An organism's genes determine the range of possible traits (physical or behavioral characteristics) that it can pass down to its offspring. The complete set of genes in an individual is called its **genotype.** In this section, we will discuss how genotypes help to determine the traits of individuals and the two processes that can create genetic diversity in a population: *mutation* and *recombination*.

Genotypes versus Phenotypes

An individual's genotype serves as the blueprint for the complete set of traits that organism may potentially possess. An individual's **phenotype** is the actual set of traits expressed in that individual. Among these traits are the individual's anatomy, physiology, and behavior. The color of your eyes, for example, is your phenotype, whereas the genes that code for eye color are a part of your genotype. Changes in genotypes can produce important changes in phenotypes.

In some cases, an individual's phenotype is determined almost entirely by genes. For instance, a person who inherits the genes for brown eyes will have brown eyes, regardless of where that person lives. Most phenotypes, however, are the product of an individual's environment as well as its genotype. For example, in many turtle and crocodile species, the temperature of eggs during incubation determines whether the offspring will hatch as males or females. The water flea, a tiny animal that lives in ponds and lakes, offers another interesting example. The body shape of the water flea depends on whether or not a young individual smells predators in its environment (FIGURE 15.1). If predators are absent, the water flea develops a relatively small head and tail spine. If predators are present, however, the water flea develops a much larger head and a long tail spine. Although the larger head and longer tail spine help prevent the water flea from being eaten, they come at the cost of slower reproduction. Therefore, it is beneficial that the water flea not produce these defenses unless they are needed. By being able to respond to changing environmental conditions, organisms such as the water flea can improve their ability to survive and reproduce in any environment.

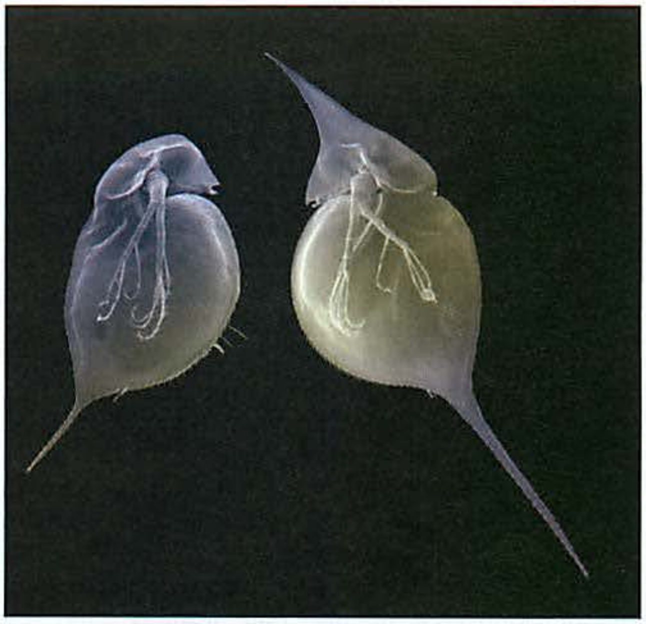


FIGURE 15.1 Environmental effects on phenotype. Water fleas raised in the absence of predators produce relatively small heads and short tail spines (left), whereas individuals raised in the presence of predators produce relatively large heads and long tail spines (right). *(Christian Laforsch/Science Photo Library/Photo Researchers)*

Evolution A change in the genetic composition of a population over time.

Microevolution Evolution below the species level.

Macroevolution Evolution that gives rise to new species, genera, families, classes, or phyla.

Gene A physical location on the chromosomes within each cell of an organism.

Genotype The complete set of genes in an individual.

Phenotype A set of traits expressed by an individual.

Mutation

DNA is copied millions of times during an organism's lifetime as cells grow and divide. An occasional mistake in the copying process produces a random change in the genetic code, which is known as a **mutation.** Environmental factors, such as ultraviolet radiation from the Sun, can also cause mutations. When mutations occur in cells responsible for reproduction, such as the eggs and sperm of animals, those mutations can be passed on to the next generation.

Most mutations are detrimental, and many cause the offspring that carry them to die while they are embryos. The effects of some mutations are less severe, but can still be detrimental. For example, some dusky-headed conures (*Aratinga weddellii*) have a mutation that makes these normally green-feathered parrots produce feathers that appear to be blue (**FIGURE 15.2**). In the wild, individuals with this mutation have a poor chance of survival because blue feathers stand out against the green vegetation and make them conspicuous to predators.

Sometimes a mutation improves an organism's chances of survival or reproduction. If such a mutation is passed along to the next generation, it adds new genetic diversity to the population. Some mosquitoes, for example, possess a mutation that makes them less vulnerable to insecticides. In areas that are sprayed with insecticides, this mutation improves an individual mosquito's chance of surviving and reproducing.

Recombination

Genetic diversity can also be created through *recombination*. In plants and animals, genetic **recombination** occurs as chromosomes are duplicated during reproductive cell division and a piece of one chromosome breaks off and attaches to another chromosome. This process does not create new genes, but it does bring together new combinations of alleles on a chromosome and can therefore produce novel traits. For example, the human immune system must battle a large variety of viruses and bacteria that regularly attempt to invade the body. Recombination allows new allele combinations to come together, and this provides new immune defenses that may prove to be effective against the invading organisms.

Mutation A random change in the genetic code produced by a mistake in the copying process.

Recombination The genetic process by which one chromosome breaks off and attaches to another chromosome during reproductive cell division.

Evolution by artificial selection The process in which humans determine which individuals breed, typically with a preconceived set of traits in mind.

FIGURE 15.2 Mutations. A mutation in the genetic code of the dusky-headed conure causes these normally green-feathered parrots to develop feathers that appear blue. In nature the mutation makes individuals more conspicuous and prone to predation. *(Howard Voren at www.Voren.com)*

Evolution can occur through artificial selection

Evolution occurs in three primary ways: *artificial selection, natural selection,* and *random processes*. In this section we will look at artificial selection.

Humans have long influenced evolution by breeding plants and animals for desirable traits. For example, all breeds of domesticated dogs belong to the same species as the gray wolf (*Canis lupus*), yet dogs exist in an amazing variety of sizes and shapes, ranging from toy poodles to Siberian huskies. **FIGURE 15.3** shows the phylogenetic relationships among the wolf and different breeds of domestic dogs that were bred from the wolf by humans. Beginning with the domestication of wolves, dog breeders have selectively bred individuals that had particular qualities they desired, including body size, body shape, and coat color. After many generations of breeding, the selected traits became more and more exaggerated until breeders felt satisfied that the desired characteristics of a new dog breed had been achieved. As a result of this carefully controlled breeding, we have a tremendous variety of dog sizes, shapes, and colors today. Yet dogs remain a single species: All dog breeds can still mate with one another and produce viable offspring.

When humans determine which individuals to breed, typically with a preconceived set of traits in mind, we call the process **evolution by artificial selection.** Artificial selection has produced numerous breeds of horses, cattle, sheep, pigs, and chickens with traits that humans find useful or aesthetically pleasing. Most of our modern agricultural crops are also the result of many years of careful breeding. For example, starting with a single species of wild mustard, *Brassica oleracea*, plant breeders have produced a variety of food

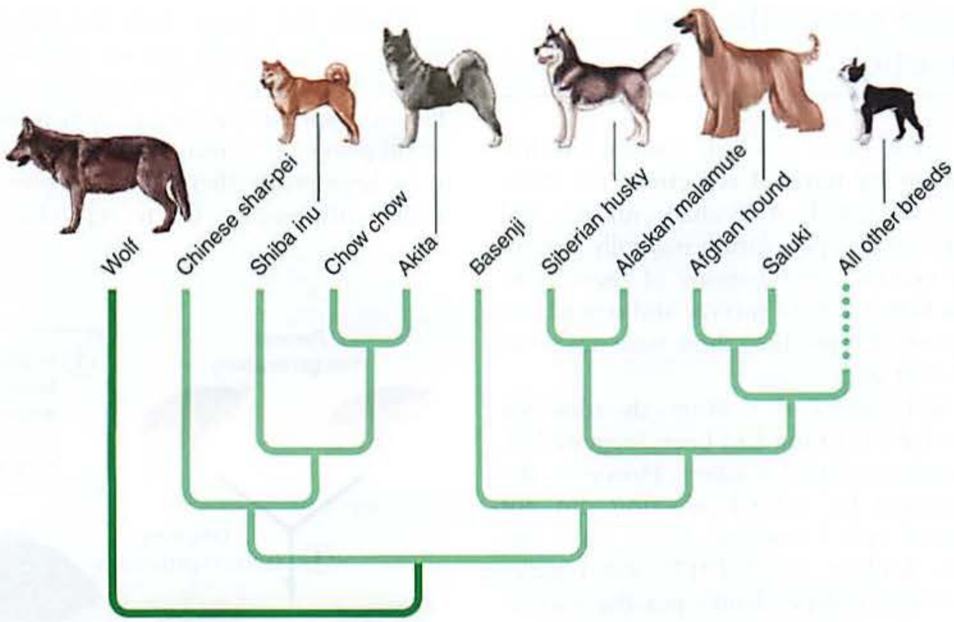


FIGURE 15.3 Artificial selection on animals. The diversity of domesticated dog breeds is the result of artificial selection on wolves. The wolf is the ancestor of the various breeds of dogs. It is illustrated at the same level as the dogs in this phylogeny because it is a species that is still alive today. *(Data from H. G. Parker et al., Science 304 (2004): 1160–1164.)*

crops, including cabbage, cauliflower, broccoli, Brussels sprouts, kale, and kohlrabi, shown in FIGURE 15.4.

As useful as artificial selection has been to humans, it can also produce a number of unintended results. For example, farmers often use herbicides to kill weeds. However, as we cover larger and larger areas with herbicides, there is an increasing chance that at least one weed will possess a mutation that allows it to survive the herbicide application. If that one mutant plant passes on its herbicide resistance to its offspring, we will have artificially selected for herbicide resistance in that weed. This process is occurring in many parts of the world where increased use of the popular herbicide Roundup (chemical name: glyphosate) has led to the evolution of several species of Roundup-resistant weeds. A similar process has occurred in hospitals, where the use of antibiotics and antibacterial cleaners has caused artificial selection of harmful drug-resistant bacteria. These examples underscore the importance of understanding the mechanisms of evolution and the ways in which humans can either purposefully or inadvertently direct the evolution of organisms.

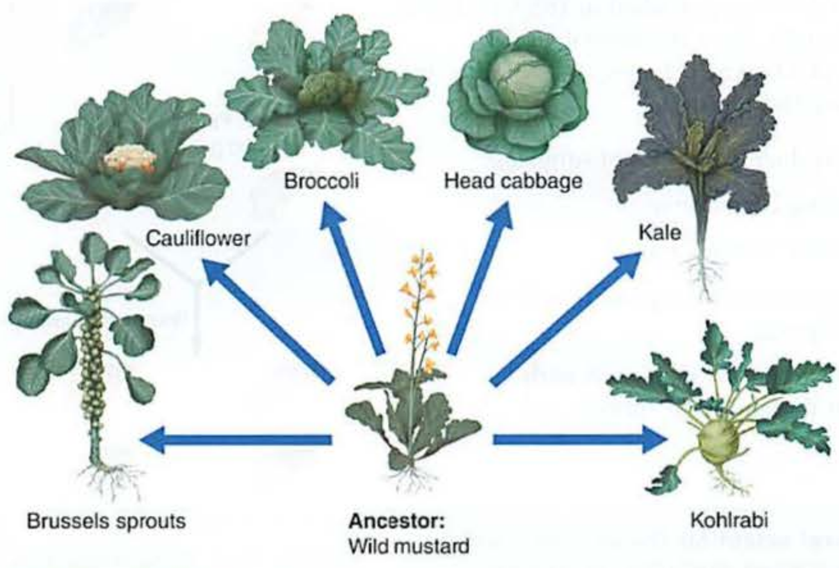


FIGURE 15.4 Artificial selection on plants. Plant breeders have produced a wide range of edible plants from a single species of wild mustard.

Evolution can occur through natural selection

Evolution also takes place through natural mechanisms. In **evolution by natural selection,** the environment determines which individuals survive and reproduce. Members of a population naturally vary in their traits, and certain combinations of those traits make individuals better able to survive and reproduce. As a result, the genes that produce those traits are more common in the next generation.

Prior to the mid-nineteenth century, the idea that species could evolve over time had been suggested by a number of scientists and philosophers. However, the concept of evolution by natural selection did not become synthesized into a unifying theory until two scientists, Alfred Wallace (1823–1913) and Charles Darwin (1809–1882), independently put the various pieces together.

Of the two scientists, Charles Darwin is perhaps the better known. At age 22, he became the naturalist on board HMS *Beagle,* a British survey ship that sailed around the world from 1831 to 1836. During his journey, Darwin made many observations of trait variation across a tremendous variety of species. In addition to observing living organisms, he found fossil evidence of a large number of extinct species. He also recognized that organisms produce many more offspring than are needed to replace the parents, and that most of these offspring do not survive. Darwin questioned why, out of all the species that had once existed on Earth, only a small fraction had survived. Similarly, he wondered why, among all the offspring produced in a population in a given year, only a small fraction survived to the next year. During the decades following his voyage, he developed his ideas into a robust theory. His *On the Origin of Species by Means of Natural Selection,* published in 1859, changed the way people thought about the natural world.

The key ideas of Darwin's theory of evolution by natural selection are the following:

- Individuals produce an excess of offspring.
- Not all offspring can survive.
- Individuals differ in their traits.
- Differences in traits can be passed on from parents to offspring.
- Differences in traits are associated with differences in the ability to survive and reproduce.

Evolution by natural selection The process in which the environment determines which individuals survive and reproduce.

FIGURE 15.5 shows how this process works using the example of body size in a group of crustaceans known as amphipods. We can begin with parents producing offspring that vary in their body size. The largest offspring are consumed by fish because fish prefer to eat large prey rather than small prey. As a result, the smaller offspring are left to reproduce. Because body

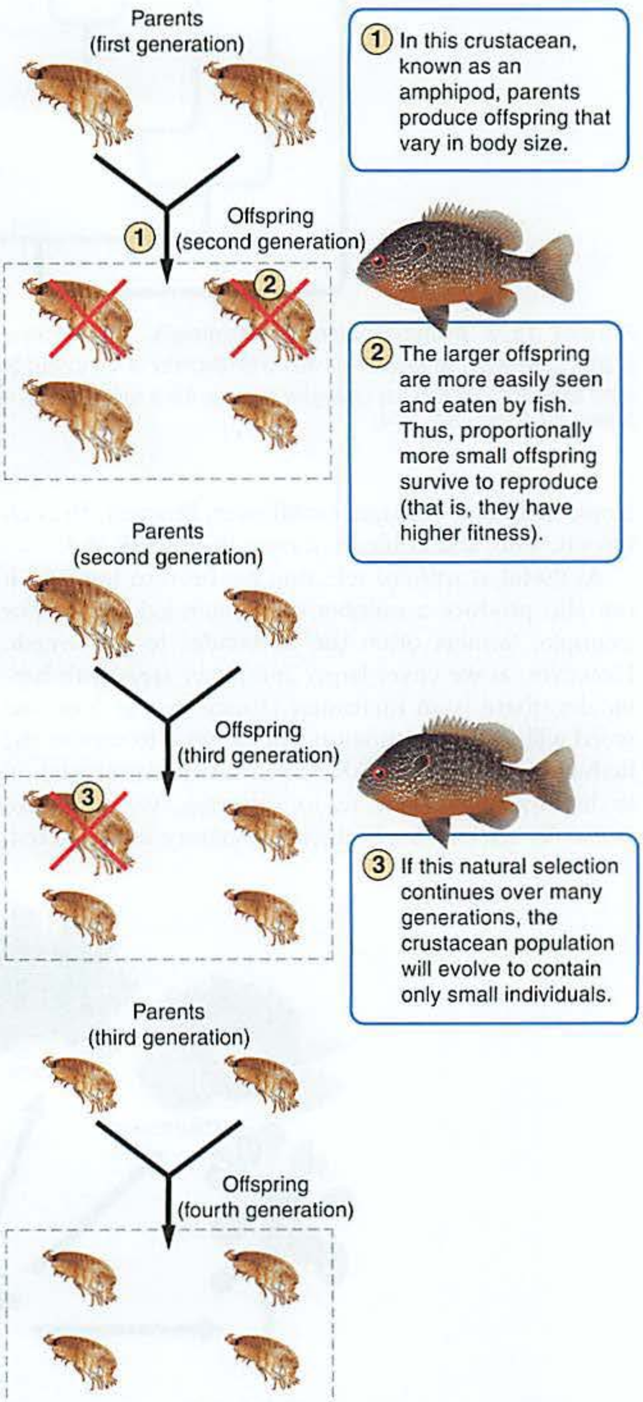


FIGURE 15.5 Natural selection. All species produce an excess number of offspring. Only those offspring with the fittest genotypes will pass on their genes to the next generation.

size is, in part, determined by an individual's genes, the next generation of amphipods will be smaller. This process can continue over many generations and over time the fish will cause the evolution of smaller body sizes in amphipods.

Both artificial and natural selection begin with the requirement that individuals vary in their traits and that these variations are capable of being passed on to the next generation. In both cases, parents produce more offspring than necessary to replace themselves, and some of these offspring either do not survive or do not reproduce. But in the case of artificial selection, humans decide which individuals will breed, based on those individuals that possess the traits that tend toward some predetermined goal, such as a curly coat or large size. Natural selection does not select for specific traits that tend toward some predetermined goal. Rather, natural selection favors any combination of traits that improves an individual's **fitness**—its ability to survive and reproduce, as we saw in the case of the smallest amphipods surviving predation by fish. Traits that improve an individual's fitness are called **adaptations.**

Natural selection can favor multiple solutions to a particular environmental challenge, as long as each solution improves an individual's ability to survive and reproduce. For example, while all plants living in the desert face the challenge of low water availability in the soil, different species have evolved different solutions to this common challenge. Some species have evolved large taproots to draw water from deep in the soil. Other species have evolved the ability to store excess water during infrequent rains. Still other species have evolved waxy or hairy leaf surfaces that reduce water loss. Each of these very different adaptations allows the plants to survive and reproduce in a desert environment (FIGURE 15.6).

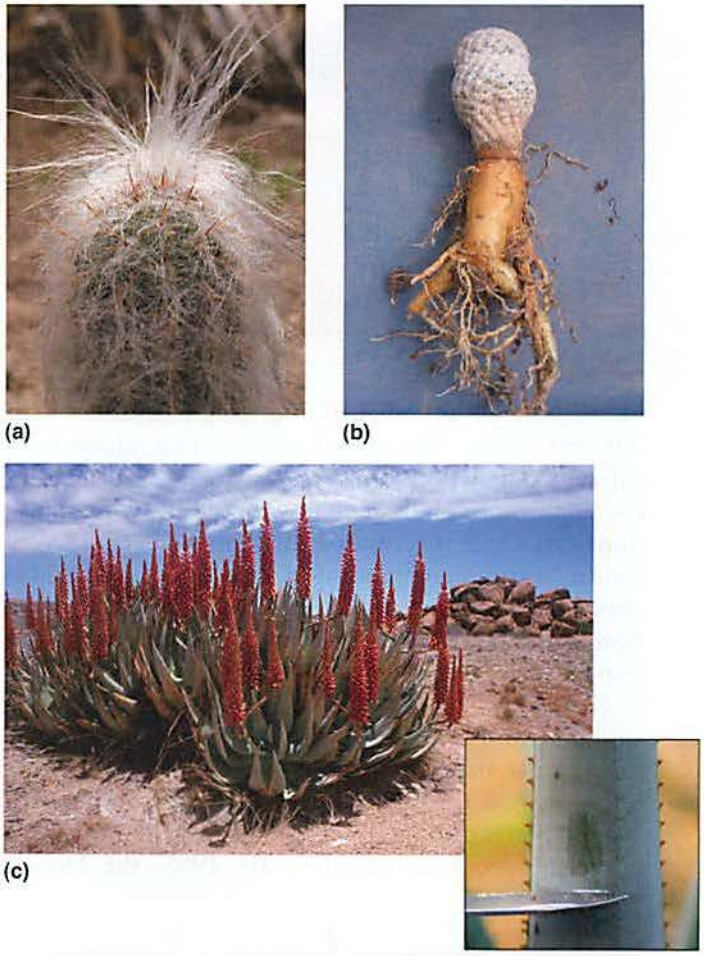


FIGURE 15.6 Adaptations. Desert plants have evolved several different adaptations to their desert environment. (a) The wedgeleaf draba (*Draba cuneifolia*) has leaf hairs that reduce water loss. (b) The Leuchtenbergia cactus (*Leuchtenbergia principis*) has a large taproot to draw water from deep in the soil. (c) The waxy outer layers of *Aloe vera* reduce water loss. (Inset) Close-up of waxy layer on an aloe that has been scraped with a knife. *(a: FPI/Alamy; b: Ian Nartowicz; c: Mark Hannaford/JWL/Aurora Photos; inset: Lee Wilcox)*

Evolution can also occur through random processes

Artificial and natural selection are important mechanisms of evolution, but evolution can also occur by random, or nonadaptive, processes. In these cases, the genetic composition of a population changes over time, but the changes are not related to differences in fitness among individuals. There are five random processes: *mutation, gene flow, genetic drift, bottleneck effects,* and *founder effects.*

Mutation

If a random mutation is not lethal, it can add to the genetic variation of a population. As shown in FIGURE 15.7, the larger the population, the more opportunities there will be for mutations to appear within it. As the number of mutations accumulates in the population over time, evolution occurs.

Gene flow

Gene flow is the process by which individuals move from one population to another and thereby alter the genetic composition of both populations. Populations

Fitness An individual's ability to survive and reproduce.

Adaptation A trait that improves an individual's fitness.

Gene flow The process by which individuals move from one population to another and thereby alter the genetic composition of both populations.

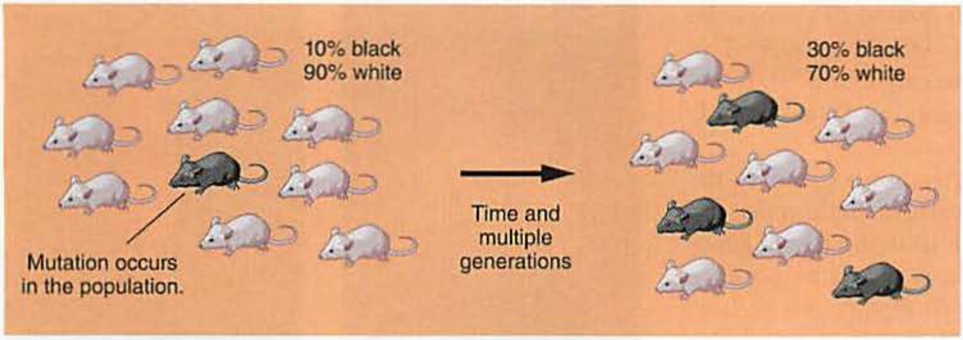


FIGURE 15.7 Evolution by mutation. A mutation can arise in a population and, if it is not lost, it may increase in frequency over time.

can experience an influx of migrating individuals with different alleles. The arrival of these individuals from adjacent populations alters the frequency of alleles in the population. High gene flow between two populations can cause the two populations to become very similar in genetic composition. In a population that is experiencing natural or artificial selection, high gene flow from outside can prevent the population from responding to selection.

Gene flow can be helpful in bringing in genetic variation to a population that lacks it. For example, the Florida panther is a subspecies of panther that once roamed throughout much of the southeastern United States and likely experienced gene flow with other subspecies of panthers. By 1995, the Florida panther only lived in southern Florida, occupying only 5 percent of its original habitat. Moreover, the number of panthers declined to only about 30 individuals, and because the Florida subspecies was isolated from other subspecies, it did not experience gene flow. As a result, shown in **FIGURE 15.8**, the small population had low genetic variation and the remaining individuals became very inbred. Being inbred causes individuals to express homozygous, harmful alleles. In the case of the panthers, these deleterious alleles caused a high prevalence of kinked tails, heart defects, and low sperm counts. In response, the U.S. Fish and Wildlife Service captured eight panthers from the Texas subspecies and introduced them to Florida with the hope that this gene flow

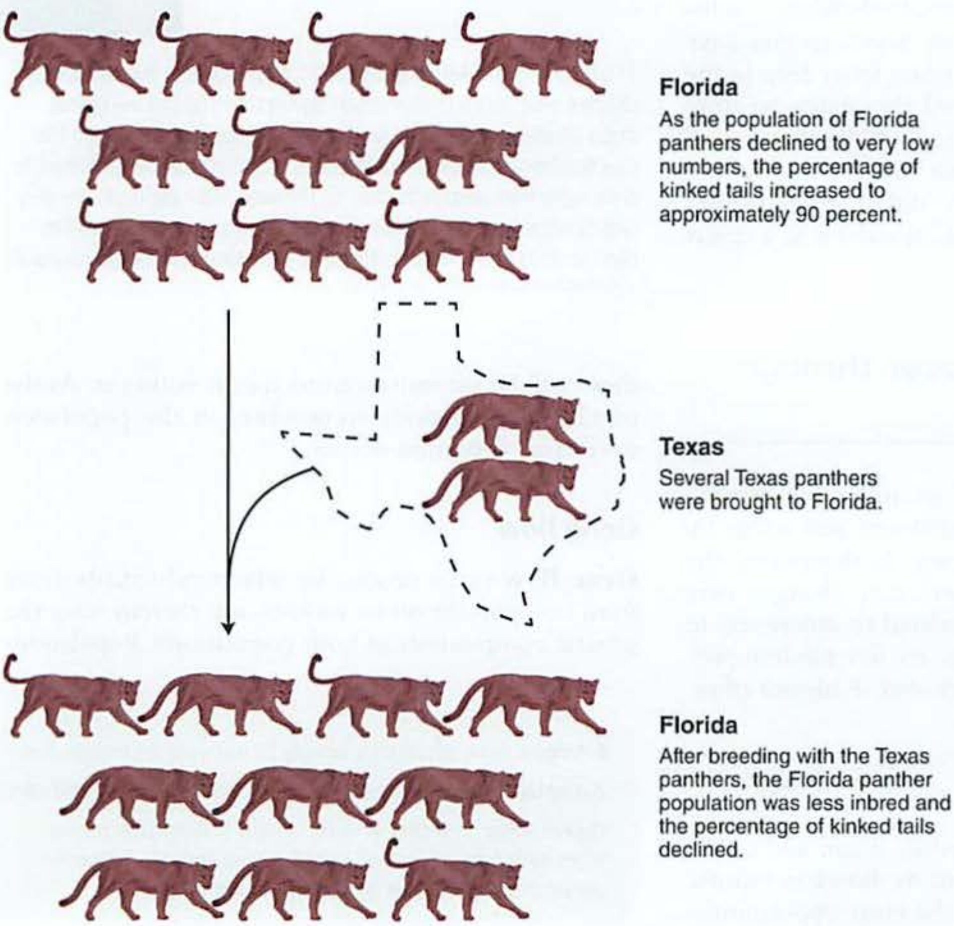


FIGURE 15.8 Evolution by gene flow. As the Florida panther declined in population size, the animals experienced low genetic variation and showed signs of inbreeding, which lead to kinky tails, heart defects, and low sperm counts. With the introduction of eight panthers from Texas, the Florida population experienced a decline in the prevalence of defects and a growth in population from 30 to 160 individuals.

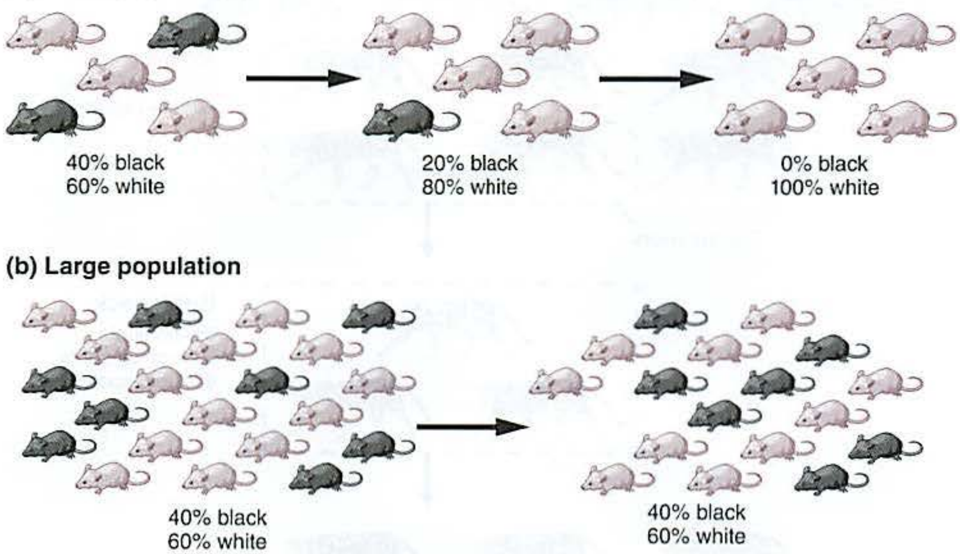


FIGURE 15.9 Evolution by genetic drift. (a) In a small population, some less-common genotypes can be lost by chance as random mating among a small number of individuals can result in the less-common genotype not mating. As a result, the genetic composition can change over time. (b) In a large population, it is more difficult for the less-common genotypes to be lost by chance because the absolute number of these individuals is large. As a result, the genetic composition tends to remain the same over time in larger populations.

would increase the genetic variation and allow the population to grow. By 2011, the prevalence of defects previously seen from inbreeding had declined and the Florida panther population had increased to 160 individuals.

Genetic Drift

Genetic drift is a change in the genetic composition of a population over time as a result of random mating. Like mutation and gene flow, genetic drift is a nonadaptive, random process. It can have a particularly important role in altering the genetic composition of small populations, as illustrated in FIGURE 15.9. In small populations, shown in Figure 15.9a, random mating among individuals can eliminate some of the rare individuals simply because they did not find a mate in a given year. For example, imagine a small population of five animals, in which two individuals carry genes that produce black hair and three individuals carry genes that produce white hair. If, by chance, the individuals that carry the genes for black hair fail to find a mate, those genes will not be passed on. The next generation will be entirely white-haired, and the black-haired phenotype will be lost. In this case, the genetic composition of the population has changed, and the population has therefore evolved. The cause underlying this evolution is random; the failure to find a mate has nothing to do with hair color. In contrast, a large population that has the same proportion of black-haired mice, shown in Figure 15.9b, has a greater absolute number of mice. As a result, it is less likely that random mating events will cause all of the black-haired mice to not find a mate, so their genes are passed on to the next generation and genetic drift is less likely to occur.

Bottleneck Effect

A drastic reduction in the size of a population that reduces genetic variation—known as a **bottleneck effect**—is another random process that can change a population's genetic composition. A population might experience a drastic reduction in its numbers for many reasons, including habitat loss, a natural disaster, harvesting by humans, or changes in the environment. FIGURE 15.10 illustrates the bottleneck effect using the example of cheetahs and spots. When the size of a population is reduced, the amount of genetic variation that can be present in the population is also reduced. With fewer individuals there are fewer unique genotypes remaining in the population.

Low genetic variation in a population can cause several problems, including increased risk of disease and low fertility. In addition, species that have been through a population bottleneck are often less able to adapt to future changes in their environment. In some cases, once a species has been forced through a bottleneck, the

Genetic drift A change in the genetic composition of a population over time as a result of random mating.

Bottleneck effect A reduction in the genetic diversity of a population caused by a reduction in its size.

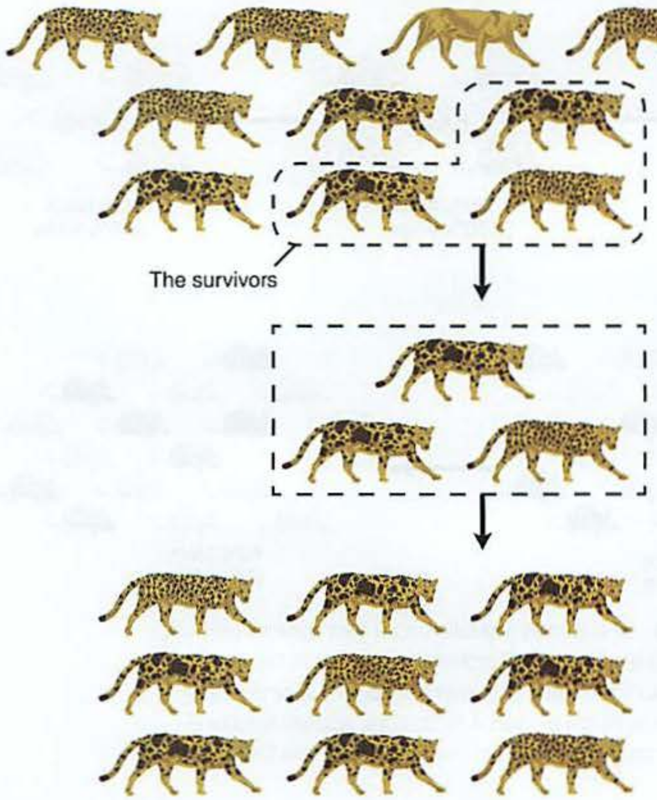


FIGURE 15.10 Evolution by the bottleneck effect. If a population experiences a drastic decrease in size (goes through a "bottleneck"), some genotypes will be lost, and the genetic composition of the survivors will differ from the composition of the original group.

resulting low genetic diversity causes it to decline to **extinction,** which occurs when the last member of a species dies. Such declines are thought to be occurring in a number of species today. The cheetah, for example, has relatively little genetic variation due to a bottleneck that appears to have occurred 10,000 years ago.

Founder Effect

Imagine that a few individuals of a particular bird species happen to be blown off their usual migration route and land on a hospitable oceanic island, as illustrated in FIGURE 15.11. These two individuals will have been drawn at random from the mainland population, and the genotypes they possess are only a subset of those in the original mainland population. These colonizing individuals, or founders, will give rise to an island population that has a genetic composition very different from that of the original mainland population. A change in the genetic composition of a population as a result of descending from a small number of colonizing individuals is known as the **founder effect.** Like mutation, genetic drift, and the bottleneck effect, the founder effect is a random process that is not based on differences in fitness.

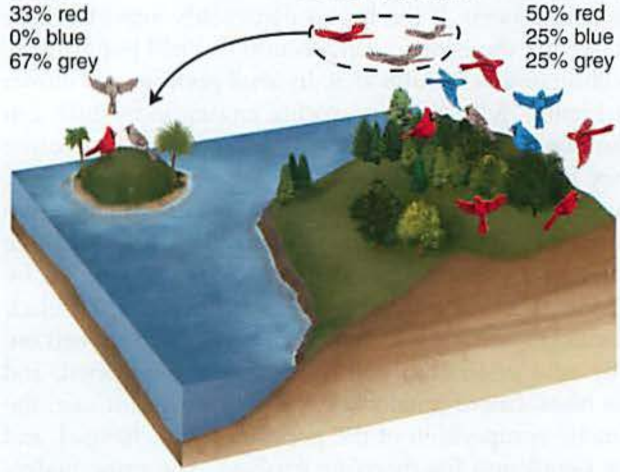


FIGURE 15.11 Evolution by the founder effect. If a few individuals from a mainland population colonize an island, the genotypes on the island will represent only a subset of the genotypes present in the mainland population. As with the bottleneck effect, some genotypes will not be present in the new population.

Extinction The death of the last member of a species.

Founder effect A change in the genetic composition of a population as a result of descending from a small number of colonizing individuals.

We can see an example of the founder effect in the Amish communities of Pennsylvania. The Amish population was founded by a relatively small number of individuals—about 200 people from Germany. This group happened to carry a mutation for Ellis-van Creveld syndrome, a condition that causes a variety of malformations including extra fingers. The mutation is rare in humans around the world, but by chance the frequency of the mutation was higher in the early Amish colonists and has remained higher because the population is an isolated group with little gene flow from outside its community.

module

15

REVIEW

In this module, we learned that genetic variation helps to determine the traits that individuals express. We also learned that artificial selection, natural selection, and random processes can all cause the evolution of populations. In the next module, we will examine how these evolutionary processes can cause the evolution of new species, which increases biodiversity, and how environmental change that is too rapid for selection can result in extinctions that cause declines in biodiversity.

Module 15 AP® Review Questions

1. Which evolutionary effect results in reduced genetic variation in a community?
   (a) Natural selection
   (b) The founder effect
   (c) Artificial selection
   (d) Gene flow
   (e) Mutation

2. A phenotype is
   (a) an adaptation that creates a new species.
   (b) the genes of a particular individual.
   (c) a result of genetic recombination.
   (d) the set of traits expressed in an individual.
   (e) a genetic mutation passed from parent to offspring.

3. Which of the following processes create genetic diversity in a population?
   I. Mutation
   II. Allele division
   III. Recombination

   (a) I only
   (b) I and II only
   (c) I and III only
   (d) II and III only
   (e) I, II, and III

4. Evolved resistance to a pesticide is an example of
   (a) a nonadaptive process.
   (b) the bottleneck effect.
   (c) natural selection.
   (d) artificial selection.
   (e) range of tolerance.

5. Which is the best definition of an adaptation?
   (a) A mutation that creates a new species
   (b) A trait that improves an individual's fitness
   (c) A trait that is passed on to the next generation
   (d) A trait that has no effect on an individual's fitness
   (e) A trait created by natural selection

6. The change in the genetic composition of a population over time due to random mating is called
   (a) the bottleneck effect.
   (b) gene flow.
   (c) genetic drift.
   (d) mutation.
   (e) phenotype adaption.

7. In a particular zoo the population of spider monkeys has a higher proportion of individuals with light golden brown fur than spider monkeys in the wild. If the monkeys were recently captured from the wild and if fur color is largely determined by genetics, what evolutionary process is at work?
   (a) The founder effect
   (b) The bottleneck effect
   (c) Microevolution
   (d) Artificial selection
   (e) Genetic drift

module

16

Speciation and the Pace of Evolution

Over time, speciation has given rise to the millions of species present on Earth today. Beyond determining how many species exist, environmental scientists are also interested in understanding how quickly existing species can change, how quickly new species can evolve, and how quickly species can go extinct. In this section we will examine the processes that produce new species and the factors that determine how rapidly species can evolve in response to changes in the environment.

Learning Objectives

After reading this module you should be able to

- explain the processes of allopatric and sympatric speciation.
- understand the factors that affect the pace of evolution.

Speciation can be allopatric or sympatric

Microevolution is happening all around us, from the breeding of agricultural crops, to the unintentional evolution of drug-resistant bacteria in hospitals, to the bottleneck that reduced genetic variation in the cheetah. But how do we move from the evolution of genetically distinct populations of a species to the evolution of genetically distinct species? That is, how do we move from microevolution to macroevolution?

Geographic isolation Physical separation of a group of individuals from others of the same species.

Allopatric speciation The process of speciation that occurs with geographic isolation.

Two common processes are *allopatric speciation* and *sympatric speciation*.

Allopatric speciation

One common way in which evolution creates new species is through **geographic isolation,** which means the physical separation of a group of individuals from others of the same species. The process of speciation that occurs with geographic isolation is known as **allopatric speciation** (from the Greek *allos,* meaning "other," and *patris,* meaning "fatherland"). As shown in FIGURE 16.1, geographic isolation can occur when a subset of individuals from a larger population colonizes a new area of habitat that is physically separated from that larger population. For example, a single large population of field mice might be split into two smaller populations as geographic barriers change over time. For example, a river might change course and divide a

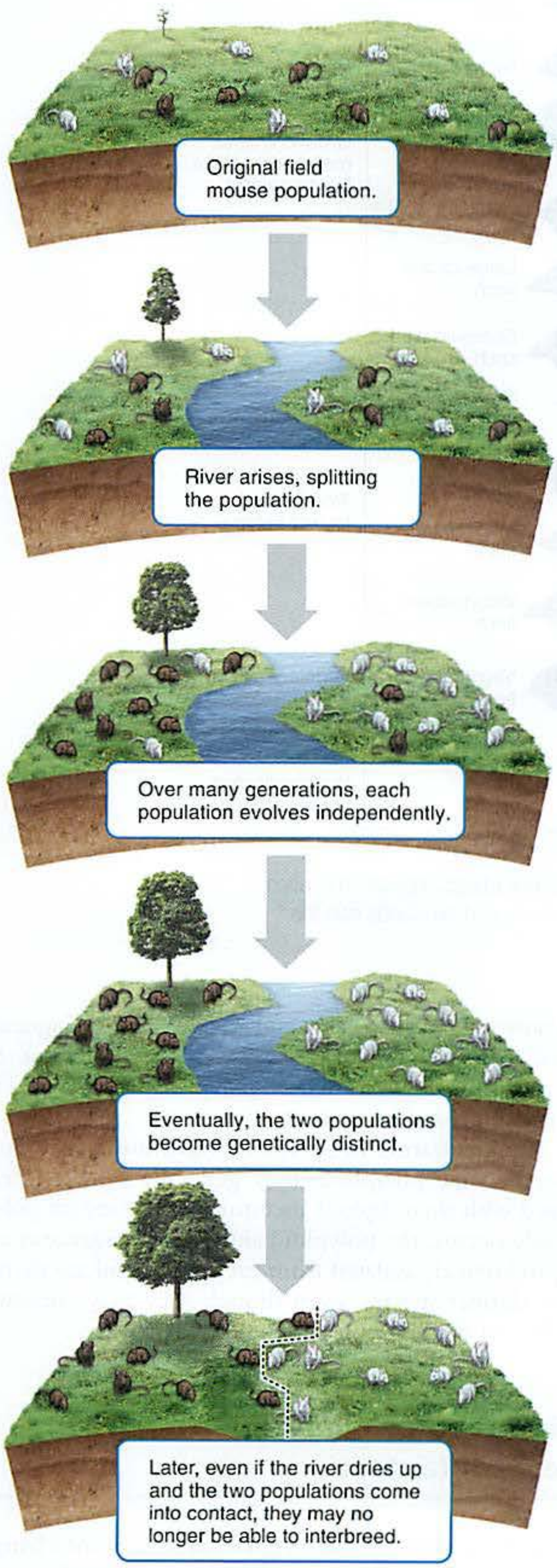


FIGURE 16.1 Allopatric speciation. Geographic barriers can split populations. Natural selection may favor different traits in the environment of each isolated population, resulting in different adaptations. Over time, the two populations may become so genetically distinct that they are no longer capable of interbreeding.

large prairie into two halves, a large lake might split into two smaller lakes, or a new mountain range could rise. In such cases, the genetic composition of the isolated populations might diverge over time, either because of random processes or because natural selection favors different adaptations on each side of the barrier.

If the two separated habitats differ in environmental conditions, such as temperature, precipitation, or the occurrence of predators, natural selection will favor different phenotypes in each of the habitats. If individuals cannot move between the populations, then over time the two geographically isolated populations will continue to become more and more genetically distinct. Eventually, the two populations will be separated not only by geographic isolation but also by **reproductive isolation,** which means the two populations of a species have evolved separately to the point that they can no longer interbreed and produce viable offspring. At this point, the two populations will have become distinct species.

Allopatric speciation is thought to be responsible for the diversity of the group of birds known as Darwin's finches. When Charles Darwin visited the Galápagos Islands, located just west of Ecuador, he noted a large variety of finch species, each of which seemed to live in different habitats or to eat different foods. Research on these birds has demonstrated that they all share a common ancestor that colonized the islands from the mainland long ago. FIGURE 16.2 is a phylogenetic tree for these finches. Over a few million years, as Darwin discovered, the finches that were geographically isolated on different islands became genetically distinct and eventually became reproductively isolated.

Sympatric Speciation

Allopatric speciation is thought to be the most common way in which evolution generates new species. However, it is not the only way. **Sympatric speciation** is the evolution of one species into two species without geographic isolation. It usually happens through a process known as polyploidy. Most organisms are diploid: They have two sets of chromosomes. In polyploidy, the number of chromosomes increases to three, four, or even six sets. Such increases can occur during the division of reproductive cells, either accidentally in nature or as a result of deliberate human actions. Plant breeders, for example, have found several ways to interrupt the normal cell division process. Polyploid organisms include some species of snails and salamanders, 15 percent of

Reproductive isolation The result of two populations within a species evolving separately to the point that they can no longer interbreed and produce viable offspring.

Sympatric speciation The evolution of one species into two, without geographic isolation.

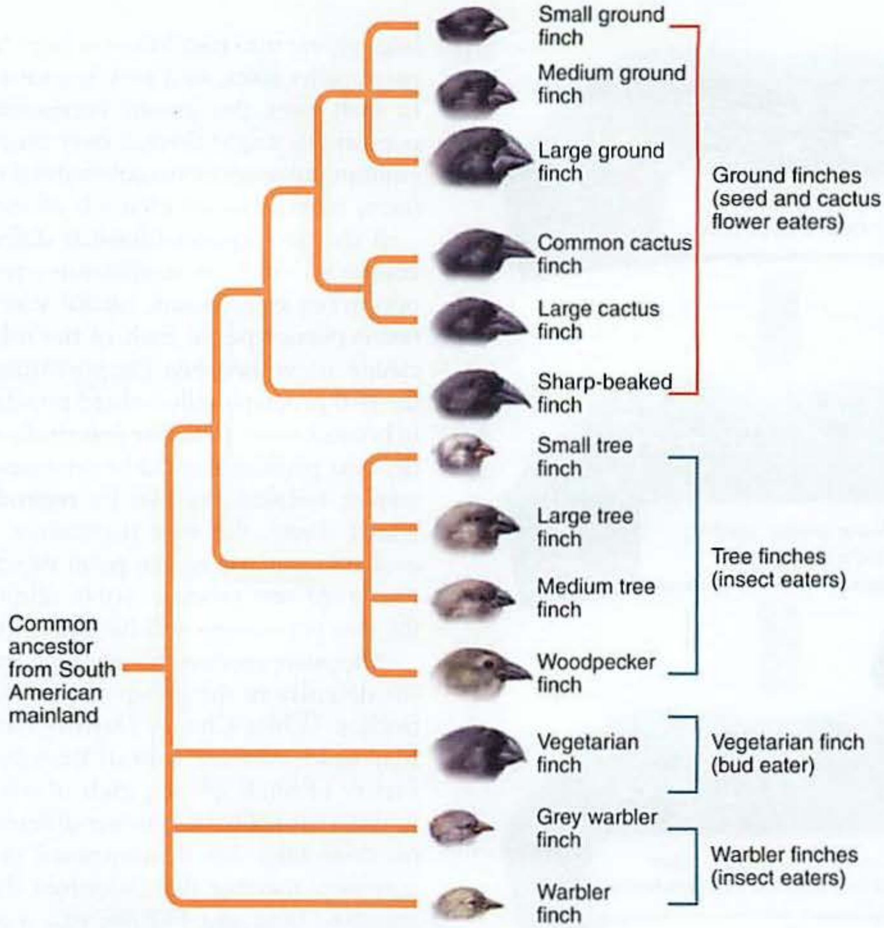


FIGURE 16.2 Allopatric speciation of Darwin's finches. In the Galápagos Islands, allopatric speciation has led to a large variety of finch species, all descended from a single species that colonized the islands from the South American mainland.

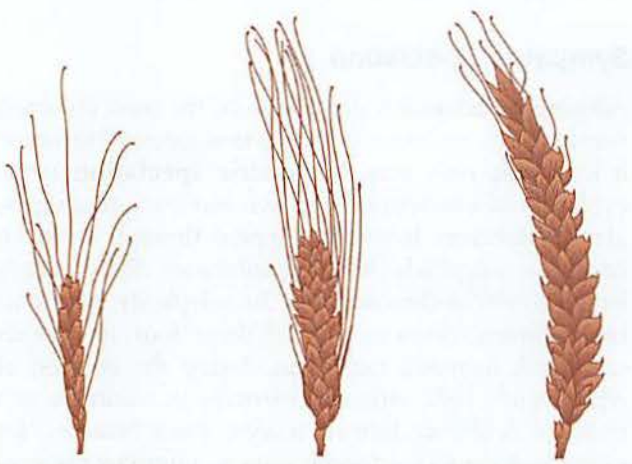


FIGURE 16.3 Sympatric speciation. Flowering plants such as wheat commonly form new species through the process of polyploidy, an increase in the number of sets of chromosomes beyond the normal two sets. (a) The ancestral einkorn wheat (*Triticum boeoticum*) has two sets of chromosomes and produces small seeds. (b) Durum wheat (*Triticum durum*), which is used to make pasta, was bred to have four sets of chromosomes and produces medium-sized seeds. (c) Common wheat (*Triticum aestivum*), which is used mostly for bread, was bred to have six sets of chromosomes and produces the largest seeds.
(After http://zr.molbiol.ru/poaceae_znachenije.html)

all flowering plant species, and a wide variety of agricultural crops such as bananas, strawberries, and wheat. As FIGURE 16.3 shows for wheat, polyploidy often results in larger plants and larger fruits.

The key feature of polyploid organisms is that once they become polyploid, they generally cannot interbreed with their diploid ancestors. At the instant polyploidy occurs, the polyploid and diploid organisms are reproductively isolated from each other and are therefore distinct species, even though they may continue to live in the same place.

The pace of evolution depends on several factors

How long does evolution take? A significant change in a species' genotype and phenotype, such as an adaptation to a completely different food source, can take anywhere from hundreds to millions of years. In this section, we will consider examples of rapid evolution by natural selection and very rapid evolution by artificial selection.

FIGURE 16.4 Rapid evolution. The cichlid fishes of Lake Tanganyika have evolved approximately 200 distinct and colorful species in the relatively short period since the lake formed in eastern Africa. The location where each species can be found in the lake is indicated by a corresponding black dot on the map. *(After http://www.uni-graz.at/~sefck/)*

Rapid Evolution by Natural Selection

Sometimes evolution can occur rapidly, as in the case of the cichlid fishes of Lake Tanganyika, one of the African Great Lakes. You can see a variety of these species in FIGURE 16.4. Evidence indicates that the roughly 200 different species of cichlids in the lake evolved from a single ancestral species over a period of several million years. During this period, some cichlid species specialized to become insect eaters and others to become fish eaters, while still others evolved to eat invertebrates such as snails and clams.

Although the cichlids of Lake Tanganyika evolved quickly in evolutionary terms, the pupfishes of the Death Valley region of California and Nevada evolved even more rapidly. In the 20,000 to 30,000 years since the large lakes of the region were reduced to isolated springs, several species of pupfish have evolved.

The ability of a species to survive an environmental change depends greatly on how quickly it evolves the adaptations needed to thrive and reproduce under the new conditions. If a species cannot adapt quickly enough, it will go extinct. This can happen when the rate of environmental change is faster than the rate at which evolution can respond. Slow rates of evolution can occur when a population has long generation times or when a population contains low genetic variation on which natural selection can act.

Very Rapid Evolution by Artificial Selection

The pace of evolution by artificial selection can be incredibly fast. Such rapid evolution is occurring in many species of commercially harvested fish, including the Atlantic cod (*Gadus morhua*). Intensive fishing over several decades has targeted the largest adults, selectively removing most of those individuals from the population and, therefore, also removing the genes that produce large adults. Because larger fish tend to reach sexual maturity later, the genes that code for a later onset of sexual maturity have also been removed. As a result, after just a few decades of intensive fishing, the Atlantic cod population has evolved to reach reproductive maturity at a smaller size and a younger age. This evolution of shorter generation times also means that the cod may be able to evolve even faster in the future.

Evolution occurs even more rapidly in populations of *genetically modified organisms*. Using genetic engineering techniques, scientists can now copy genes from a species with some desirable trait, such as rapid growth or disease resistance. Scientists can insert these genes into other species of plants, animals, or microbes to produce **genetically modified organisms (GMO).** When those organisms reproduce, they pass on the inserted genes to their offspring. For example, scientists have found that a soil bacterium (*Bacillus thuringiensis*) naturally produces an insecticide as a defense against being consumed by insects in the soil. Plant breeders have identified the bacterial genes that are responsible for making the insecticide, copied those genes, and inserted them into the genomes of crop plants. Such crops can now naturally produce their own insecticide, which makes them less attractive to insect herbivores. Common examples include Bt-corn and Bt-cotton, so named because they contain genes from soil bacterium. As you might guess, inserting genes into an organism is a much faster way to produce desired traits than traditional plant and animal breeding, which can only select from the naturally available variation in a population.

Genetically modified organism (GMO) An organism produced by copying genes from a species with a desirable trait and inserting them into another species.

module

16

REVIEW

In this module, we learned that species evolve through the mechanisms of allopatric and sympatric speciation. We also saw that there are a number of factors that can affect the pace of evolution including how quickly the environment changes, how much genetic variation exists in the population, the size of the population, and the generation time of the species. In the next module, we will examine how the evolution of species affects where they live and how they make their living.

Module 16 AP® Review Questions

1. Which of the following contribute to allopatric speciation?
   I. Genetic convergence over time
   II. Geographic isolation
   III. Reproductive isolation

   (a) I and II only
   (b) I and III only
   (c) II only
   (d) II and III only
   (e) I, II, and III

2. Which of the following is often a cause of sympatric speciation?
   (a) Polyploidy
   (b) Geographic separation
   (c) Macroevolution
   (d) Artificial selection
   (e) Genetic modification

3. Which of the following would cause the most-rapid evolution?
   (a) Environmental change
   (b) Artificial selection
   (c) Geographic isolation
   (d) Recombination
   (e) Natural selection

4. The Bt-cotton is an example of
   (a) evolution through geographic isolation.
   (b) evolution through polyploidy.
   (c) evolution through genetic modification.
   (d) evolution through natural selection.
   (e) macroevolution.

module

17

Evolution of Niches and Species Distributions

Because evolution alters the traits that species express and because different traits perform well in some environments but not in others, the evolution of species affects where species are able to live on Earth. As environments have changed over millions of years, species have responded by altering their

distributions. This response also suggests that environmental changes in the future will continue to affect the distributions of species. Species that can move easily will likely persist whereas species that cannot adjust or move will likely go extinct.

Learning Objectives

After reading this module you should be able to

- explain the difference between a fundamental and a realized niche.
- describe how environmental change can alter species distributions.
- discuss how environmental change can cause species extinctions.

Every species has a niche

Every species has an optimal environment in which it performs particularly well. All species have a **range of tolerance,** or limits to the abiotic conditions they can tolerate, such as extremes of temperature, humidity, salinity, and pH. FIGURE 17.1 illustrates this concept using one environmental factor—temperature. As conditions move further away from the ideal, individuals may be able to survive, and perhaps even to grow, but not be able to reproduce. As conditions continue to move away from the ideal, individuals can only survive. If conditions move beyond the range of tolerance, individuals will die. Because the combination of abiotic conditions in a particular environment fundamentally determines whether a species can persist there, the suite of abiotic conditions under which a species can survive, grow, and reproduce is the **fundamental niche** of the species.

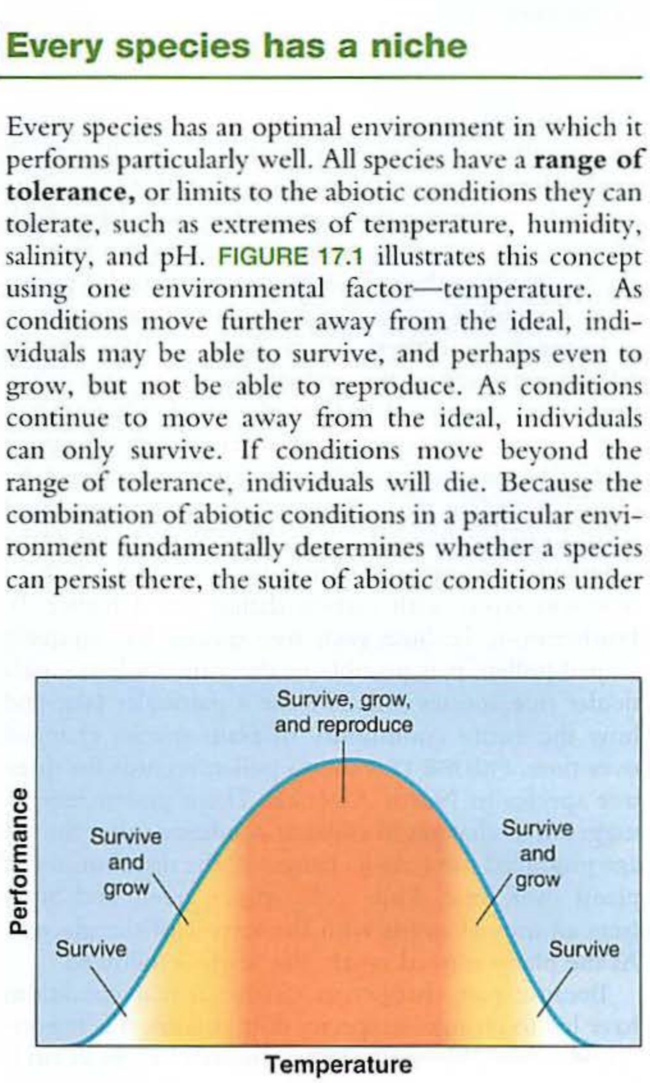


FIGURE 17.1 Range of tolerance. All species have an ideal range of abiotic conditions, such as temperature, under which their members can survive, grow, and reproduce. Under more extreme conditions, their ability to perform these essential functions declines.

The fundamental niche establishes the abiotic limits for the persistence of a species. However, biotic factors can further limit the locations where a species can live. Common biotic limitations include the presence of competitors, predators, and diseases. For example, even if abiotic conditions are favorable for a plant species in a particular location, other plant species may be better competitors for water and soil nutrients. Those competitors might prevent the species from growing in that environment. Similarly, even if a small rodent can tolerate the temperature and humidity of a tropical forest, a deadly rodent disease might prevent the species from persisting in the forest. Therefore, biotic factors further narrow the fundamental niche that a species actually uses. The range of abiotic and biotic conditions under which a species actually lives is called its **realized niche.** Once we determine what contributes to the realized niche of a species, we have a better understanding of the **distribution** of the species, or the areas of the world in which the species lives.

Range of tolerance The limits to the abiotic conditions that a species can tolerate.

Fundamental niche The suite of abiotic conditions under which a species can survive, grow, and reproduce.

Realized niche The range of abiotic and biotic conditions under which a species actually lives.

Distribution Areas of the world in which a species lives.

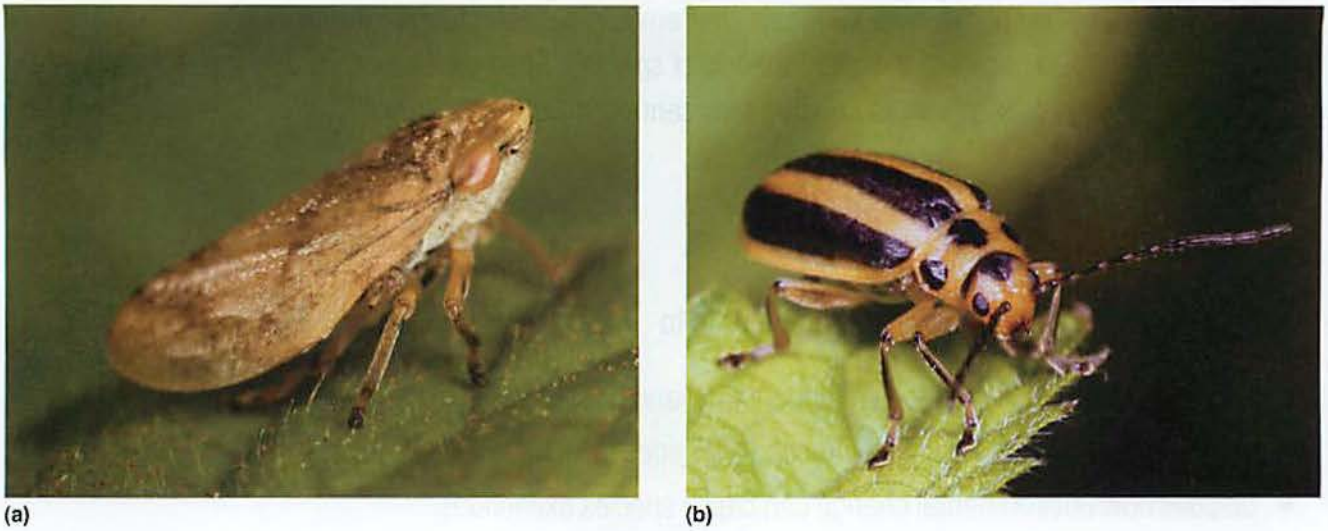


FIGURE 17.2 Generalists and specialists. (a) Some organisms, such as this meadow spittlebug, are niche generalists that have broad diets and wide habitat preferences. (b) Other organisms, such as this skeletonizing leaf beetle, are niche specialists with narrow diets and highly specific habitat preferences.
(a: Ray Wilson/Alamy; b: © Bo Zaremba 2009)

When we examine the realized niches of species in nature, we see that some species, known as **niche generalists,** can live under a very wide range of abiotic or biotic conditions. For example, some insects, such as the meadow spittlebug (*Philaenus spumarius*) (FIGURE 17.2a), feed on numerous plant species and can live in different habitats. Other species, known as **niche specialists,** are specialized to live under a very narrow range of conditions or feed on a small group of species. For example, the skeletonizing leaf beetle (*Trirhabda virgata*) (Figure 17.2b) feeds on only a single species or genus of plant. Niche specialists can persist quite well when environmental conditions remain relatively constant, but they are more vulnerable to extinction if conditions change because the loss of a favored habitat or food source leaves them with few alternatives for survival. In contrast, niche generalists should fare better under changing conditions because they have a number of alternative habitats and food sources available.

Environmental change can alter the distribution of species

Because species are adapted to particular environmental conditions, we would expect that changes in environmental conditions would alter the distribution of species on Earth. For example, scientists have found evidence for the relationship between environmental change and species distribution in layers of sediments that have accumulated over time at the bottom of modern lakes. Each sediment layer contains pollen from plants that lived in the region when the sediments were deposited. In some cases, this pollen record goes back thousands of years.

In much of northern North America, lakes formed 12,000 years ago at the end of the last ice age when temperatures warmed and the glaciers slowly retreated to the north. The retreating glaciers left behind a great deal of barren land, which was quickly colonized by plants, including trees. Some of the pollen produced by these trees fell into lakes and was buried in the lake sediments. Scientists can measure the ages of these sediment layers with carbon dating (see Chapter 2). Furthermore, because each tree species has uniquely shaped pollen, it is possible to determine when a particular tree species arrived near a particular lake and how the entire community of plant species changed over time. FIGURE 17.3 shows pollen records for three tree species in North America. These pollen records suggest that changes in climatic conditions after the ice age produced substantial changes in the distributions of plants over time. Pine trees, spruce trees, and birch trees all moved north with the retreat of the glaciers. As the plants moved north, the animals followed.

Because past changes in environmental conditions have led to changes in species distributions, it is reasonable to ask whether current and future changes in environmental conditions might also cause changes in species distributions. For example, as the global climate warms, some areas of the world are expected to receive less precipitation, while other areas are predicted to receive more. If our predictions of future environmental

Niche generalist A species that can live under a wide range of abiotic or biotic conditions.

Niche specialist A species that is specialized to live in a specific habitat or to feed on a small group of species.

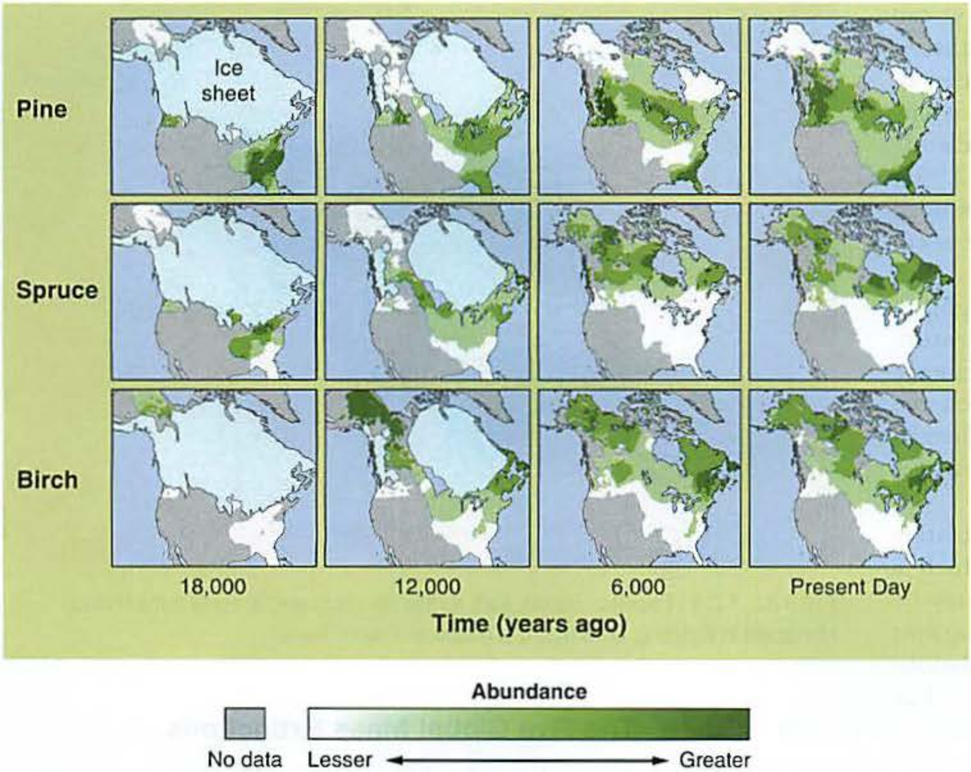


FIGURE 17.3 Changes in tree species distributions over time. Pollen recovered from lake sediments indicates that plant species moved north as temperatures warmed following the retreat of the glaciers, beginning about 12,000 years ago. Areas shown in color or white were sampled for pollen, whereas areas shown in gray were not sampled. *(Data from http://veimages.gsfc.nasa.gov//3453/boreal_model.gif)*

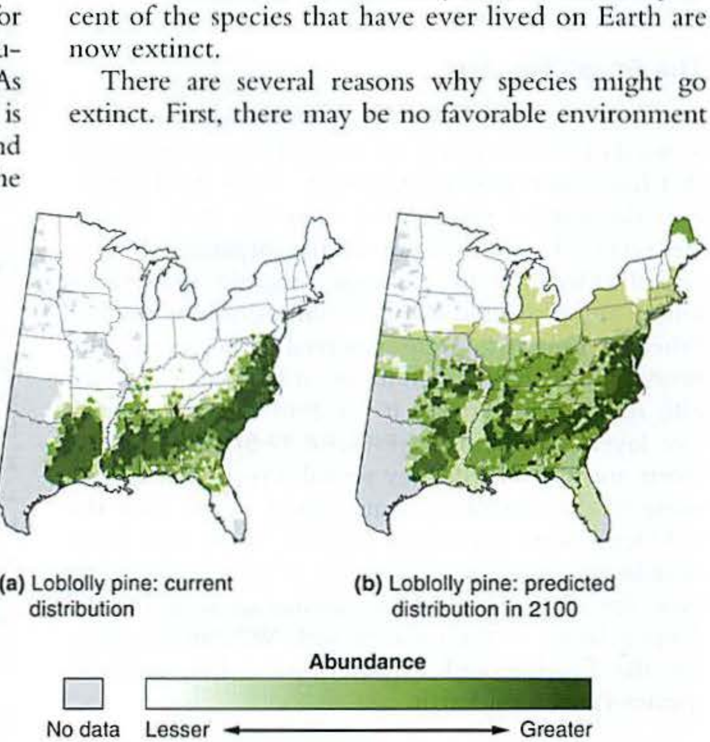
changes are correct, and if we have a good understanding of the niche requirements of many species, we should be able to predict how the distribution of species will change in the future. North American trees, for example, are expected to have more northerly distributions with future increases in global temperatures. As FIGURE 17.4 shows, the loblolly pine (*Pinus taeda*) is expected to move from its far southern distribution and become common throughout the eastern half of the United States.

Species vary in their ability to move physically across the landscape as the environment changes. Some species are highly mobile at particular life stages: Adult birds and wind-dispersed seeds, for example, move across the landscape easily. Other organisms, such as the desert tortoise (*Gopherus agassizii*), are slow movers. Furthermore, the movements of many species may be impeded by obstacles built by humans, including roads and dams. It remains unclear how species that face these challenges will shift their distributions as global climate change occurs.

Environmental change can cause species extinctions

If environmental conditions change, species that cannot adapt to the changes or move to more favorable environments will eventually go extinct. The average life span of a species appears to be only between about 1 million to 10 million years. In fact, 99 percent of the species that have ever lived on Earth are now extinct.

There are several reasons why species might go extinct. First, there may be no favorable environment



(a) Loblolly pine: current distribution

(b) Loblolly pine: predicted distribution in 2100

FIGURE 17.4 Predicting future species distributions. Based on our knowledge of the niche requirements of the loblolly pine tree, we can predict how the distributions might change as a result of future changes in environmental conditions. *(After http://www.fs.fed.us/ne/delaware/atlas/web_atlas.html#)*

close enough to which they can move. For example, on the southwest coast of Australia is a small area of land that experiences a current climate that supports a woodland/shrubland biome (see Figure 12.9 on page 128). This biome is surrounded by a large desert biome to the north and east and an ocean to the south and west. If scientists are right in predicting that the coming century will bring a hotter and drier climate to southwestern Australia, then the unique species of plants that live in this small biome will have nowhere to go where they can survive.

Even if there is an alternative favorable environment to which a species can move, it may already be occupied by other species against which the moving populations cannot successfully compete. For example, the predicted northern movement of the loblolly pine, shown in Figure 17.4b, might not happen if another pine tree species in the northern United States is a better competitor and prevents the loblolly pine from surviving in that area. Finally, an environmental change may occur so rapidly that the species does not have time to evolve new adaptations.

FIGURE 17.5 Fossils. Fossils, such as this fish discovered in Fossil Butte National Monument in Wyoming, are a record of evolution. *(David R. Frazier)*

The Fossil Record

Much of what we know about the evolution of life is based on fossils, which are the remains of organisms that have been preserved in rock. Most dead organisms decompose rapidly; the elements they contain are recycled and nothing of the organism is preserved. Occasionally, though, organic material is buried and protected from decomposition by mud or other sediments. That material may eventually become fossilized, which means it has been hardened into rocklike material as it was buried under successive layers of sediment (FIGURE 17.5). When these layers are uncovered, they reveal a record of at least some of the organisms that existed at the time the sediments were deposited. Because of the way layers of sediment are deposited on top of one another over time, the oldest fossilized organisms are found in the deepest layers of the fossil record. We can therefore use the fossil record to determine when different species existed on Earth.

Mass extinction A large extinction of species in a relatively short period of time.

The Five Global Mass Extinctions

Throughout Earth's history, individual species have evolved and gone extinct at random intervals. The fossil record has revealed five periods of global **mass extinction,** in which large numbers of species went extinct over relatively short periods of time. The times of these mass extinctions are shown in FIGURE 17.6. Note that because species are not always easy to discriminate in the fossil record, scientists count the number of genera, rather than species, that once roamed Earth but are now extinct.

The greatest mass extinction on record took place 251 million years ago when roughly 90 percent of marine species and 70 percent of land vertebrates went extinct. The cause of this mass extinction is not known.

A better-known mass extinction occurred at the end of the Cretaceous period (65 million years ago), when roughly one-half of Earth's species, including the dinosaurs, went extinct. The cause of this mass extinction has been the subject of great debate, but there is now a near-consensus that a large meteorite struck Earth and produced a dust cloud that circled the planet and blocked incoming solar radiation. This resulted in an almost complete halt to photosynthesis, and thus an almost total lack of food at the bottom of the food chain. Among the few species that survived was a small squirrel-sized primate that was the ancestor of humans.

Many scientists view extinctions as the ultimate result of change in the environment. Environmental scientists can learn about the potential effects of both large and small environmental changes by studying historic environmental changes and applying the lessons learned to help predict the effects of the environmental changes that are taking place on Earth today.

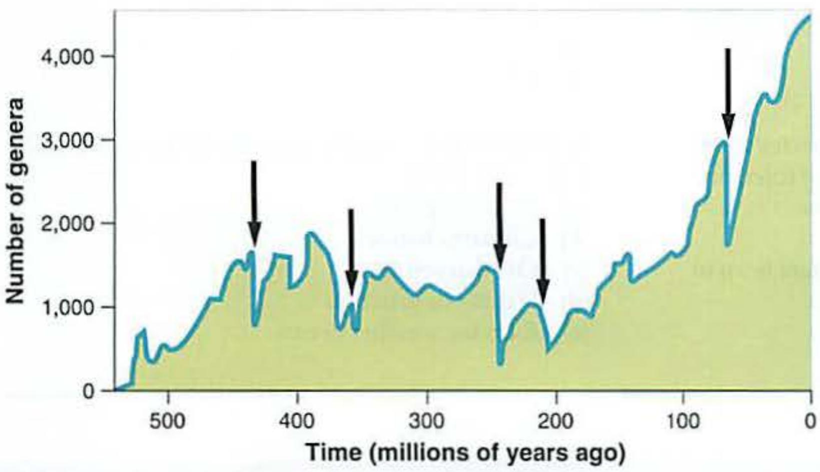


FIGURE 17.6 Mass extinctions. Five global mass extinction events have occurred since the evolution of complex life roughly 500 million years ago. *(Data from GreenSpirit, http://www.greenspirit.org.uk/resources/TimeLines.jpg)*

The Sixth Mass Extinction

During the last 2 decades, scientists have reached a consensus that we are currently experiencing a sixth global mass extinction of a magnitude within the range of the previous five mass extinctions. Estimates of extinction rates vary widely, ranging from 2 percent to as many as 25 percent of species going extinct by 2020. However, in contrast to some previous mass extinctions, there is agreement among scientists that the current mass extinction has human causes. These wide-ranging causes include habitat destruction, overharvesting, introductions of invasive species, climate change, and emerging diseases. We will examine all of these factors in detail in Chapters 18 and 19.

Because much of the current environmental change caused by human activities is both dramatic and sudden, environmental scientists contend that many species may not be able to move or adapt in time to avoid extinction.

The recovery of biodiversity from earlier mass extinctions took about 10 million years, an unthinkably long time from a human perspective. Recovery from the present mass extinction could take just as long—500,000 human generations. Much of the current debate among environmental scientists and government officials centers on the true magnitude of this crisis and on the costs of reducing the human impact on extinction rates.

module 17 REVIEW

In this module, we learned that species differ in their tolerance to abiotic conditions and that the range of abiotic and biotic conditions that allow survival, growth, and reproduction all help to determine where a species can live. Past changes in environmental conditions have altered species distributions and caused extinctions. Future environmental changes are expected to have similar effects.

Module 17 AP® Review Questions

1. The abiotic conditions under which a species can survive and reproduce is called its
   (a) range of tolerance.
   (b) realized niche.
   (c) range of persistence.
   (d) environmental distribution.
   (e) fundamental niche.

2. Which would be expected for a niche specialist?
   (a) A large distribution
   (b) Many food sources
   (c) A narrow fundamental niche
   (d) Adaptability to changing conditions
   (e) No difference between its realized and fundamental niche

3. Which of the following will NOT affect the distribution of a species?
   (a) A localized disease
   (b) Climate change
   (c) A change in the distribution of the species' food
   (d) A new food source outside its range of tolerance
   (e) The introduction of a predator species

4. How many mass extinction events have there been in Earth's history?
   (a) 2
   (b) 4
   (c) 5
   (d) 7
   (e) 12

5. Which is NOT a significant cause of the current mass extinction event?
   (a) Invasive species
   (b) Climate change
   (c) Overharvesting
   (d) Habitat destruction
   (e) Extreme weather events

working toward **sustainability**

Protecting the Oceans When They Cannot Be Bought

For over 50 years, The Nature Conservancy (TNC) has protected biodiversity by using a simple strategy: Buy it. The Conservancy uses grants and donations to purchase privately owned natural areas or to buy development rights to those areas. TNC owns over 0.8 million hectares (2 million acres) of land and has protected over 46 million hectares (115 million acres) of land by buying development rights. As a nonprofit, nongovernmental organization, TNC has great flexibility to use innovative conservation and restoration techniques on natural areas in its possession.

TNC focuses its efforts on areas containing rare species or that have high biodiversity, including the Florida Keys in southern Florida and Santa Cruz Island in California. Recently, it has set its sights on the oceans, including coastal marine ecosystems. Coastal ecosystems have experienced steep declines in the populations of many fish and shellfish, including oysters, clams, and mussels, due to a combination of overharvesting and pollution. By preserving these coastal ecosystems, TNC hopes to create reserves that will serve as breeding grounds for declining populations of overharvested species. In this way, protecting a relatively small area of ocean will benefit much larger unprotected areas, and even benefit the very industries that have led to the population declines.

Shellfish are particularly valuable in many coastal ecosystems because they are filter feeders: They remove tiny organisms, including algae, from large quantities of water, cleaning the water in the process. However, shellfish worldwide have been harvested unsustainably, leading to a cascade of effects throughout many coastal regions. For example, oyster populations in the Chesapeake Bay were once sufficient to filter the water of the entire bay in 3 to 6 days. Now there are so few oysters that it would take a year for them to filter the same amount of water. As a result, the bay has become much murkier, and excessive algae have led to lowered oxygen levels that make the bay less hospitable to fish.

Conserving marine ecosystems is particularly challenging because private ownership is rare. State and

Buying the oceans. Because the ocean floor cannot be privately owned, The Nature Conservancy has implemented a plan to lease the harvesting rights to imperiled areas and then either not harvest shellfish in the area or harvest in a sustainable way. *(Arkady Chubykin /iStockphoto.com)* federal governments generally do not sell areas of the ocean. Instead, they have allowed industries to lease the harvesting or exploitation rights to marine resources such as oil, shellfish, and physical space for marinas and aquaculture. So how can a conservation group protect coastal ecosystems if it cannot buy an area of the ocean? The Nature Conservancy's strategy is to purchase harvesting and exploitation rights and use them as a conservation tool. In some cases, TNC will not harvest any shellfish in order to allow the populations to rebound. In many cases, the leases require at least some harvesting, and TNC hopes to demonstrate sustainable management practices that will serve as an example of how shellfish harvests can be conducted while restoring the shellfish beds.

In 2002, TNC acquired the rights to 4,650 ha (11,500 acres) of oyster beds in New York's Great South Bay, along the southern shore of Long Island. These rights, which were donated to TNC by the Blue Fields Oyster Company, were valued at $2 million. TNC developed restoration strategies and in 2010 reported that populations of shellfish were starting to show signs of recovery. After the oyster populations have rebounded, TNC hopes to engage in sustainable harvesting over part of this area and conduct research in the rest of it. TNC has similar projects under way off the coasts of Virginia, North Carolina, and Washington State. In California, TNC has purchased trawling permits and, by allowing them to go unused, has secured a no-trawl area the size of Connecticut. By 2009, TNC had accumulated the rights to 10,000 ha (25,000 acres) of marine fisheries along the coasts of the United States. In the future, it hopes to lease these permits to other harvesters of fish and shellfish that will use sustainable practices.

TNC has recently expanded its efforts in California, where it buys not only fishing leases but even fishing boats. It then hires the former fishermen to fish in a more sustainable manner. For example, TNC has its fisherman post any information about areas of the ocean where they accidentally catch protected species, which helps other fishing boats avoid these areas. One result is that the amount of unintended species caught, known as "bycatch," has declined from between 15 to 20 percent to only 1 percent. In making these changes, TNC has found effective ways to continue the tradition of fishing that provides jobs to the local communities while working to ensure that the fish populations persist long into the future.

Critical Thinking Questions

1. What are the advantages of working to increase fish populations by leasing areas of the ocean and banning fishing in those areas versus leasing areas and working with local commercial fishing boats to change fishing practices?
2. What are some of the challenges in getting commercial fishing operations to change their practices?

References

The Nature Conservancy. 2002. *Leasing and Restoration of Submerged Lands: Strategies for Community-Based, Watershed-Scale Conservation.*

The Nature Conservancy. 2006. *Annual Report.* http://www.nature.org/aboutus/annualreport/file/annualreport2008.pdf.

Partnership Preserves Livelihoods and Fish Stocks. *New York Times,* November 27, 2011. http://www.nytimes.com/2011/11/28/science/earth/nature-conservancy-partners-with-california-fishermen.html?_r=0.

chapter 5 REVIEW

In this chapter, we have learned about the biodiversity of Earth, how this biodiversity came to be, and how environmental changes can cause it to decline. The estimated number of species on Earth varies widely, but many scientists agree on approximately 10 million. In any given location, we can quantify the diversity of species in terms of both species richness and species evenness. The diversity that exists came about through the process of evolution. We can view patterns of evolution by placing species on a phylogeny. Evolution occurs when there are changes in the genetic composition of a population. This can happen through artificial selection, natural selection, or random processes. The species that evolve through these processes each have a niche that helps to determine their geographic distributions. Historic changes in the environment have altered species distributions and caused many species to go extinct; current and future environmental changes are expected to have similar effects.

Key Terms

Species richness	Evolution by artificial selection	Reproductive isolation
Species evenness	Evolution by natural selection	Sympatric speciation
Phylogeny	Fitness	Genetically modified organism
Evolution	Adaptation	Range of tolerance
Microevolution	Gene flow	Fundamental niche
Macroevolution	Genetic drift	Realized niche
Gene	Bottleneck effect	Distribution
Genotype	Extinction	Niche generalist
Phenotype	Founder effect	Niche specialist
Mutation	Geographic isolation	Mass extinction
Recombination	Allopatric speciation	

Learning Objectives Revisited

Module 14 The Biodiversity of Earth

- **Understand how we estimate the number of species living on Earth.**

  Scientists have estimated the number of species on Earth by collecting samples of diverse groups of organisms, determining the proportion of all known species, and then extrapolating these numbers to other groups to estimate the total number of species.

- **Quantify biodiversity.**

  Biodiversity, can be quantified using a variety of measurements including species richness, species evenness, or both. Such measurements provide scientists with a baseline they can use to determine how much an ecosystem has been affected by a natural or anthropogenic disturbance.

- **Describe patterns of relatedness among species using a phylogeny.**

  Patterns of relatedness are depicted as phylogenies. Phylogenies indicate how species are related to one another and the likely steps in evolution that gave rise to current species.

Module 15 How Evolution Creates Biodiversity

- **Identify the processes that cause genetic diversity.**

  Every individual has a genotype that, in combination with the environment, determines its phenotype. In a population, genetic diversity is produced by the processes of mutation and recombination.

- **Explain how evolution can occur through artificial selection.**

  Evolution by artificial selection occurs when humans select individuals with a particular phenotypic goal in mind. Such selection has produced various breeds of domesticated animals and numerous varieties of crops. It has also produced harmful outcomes, including selection for pesticide-resistant pests and drug-resistant bacteria.

- **Explain how evolution can occur through natural selection.**

  Evolution by natural selection occurs when individuals vary in traits that can be passed on to the next generation and this variation in traits causes different abilities to survive and reproduce in the wild. Natural selection does not target particular traits, but simply favors any trait changes that result in higher survival or reproduction.

- **Explain how evolution can occur through random processes.**

  Because evolution is defined as a change in the genetic composition of a population, evolution can also occur when there are mutations within a population or gene flow into or out of a population. It can also occur due to the processes of genetic drift, the bottleneck effect, or the founder effect.

Module 16 Speciation and the Pace of Evolution

- **Explain the processes of allopatric and sympatric speciation.**

  Allopatric speciation occurs when a portion of a population experiences geographic isolation from the rest of the population. The composition of isolated populations diverges over time due to random processes or natural selection. Sympatric speciation occurs when one species separates into two species without any geographic isolation. The production of polyploidy individuals is a common mechanism of sympatric speciation.

- **Understand the factors that affect the pace of evolution.**

  Evolution can produce adapted populations more easily when environmental changes are slow rather than rapid. The populations are also more likely to adapt when they have high genetic variation, as is often found in large populations. Should there be a beneficial mutation arise, however, the mutation can spread through small populations more rapidly than large populations. Finally, evolution can occur more rapidly in populations that have shorter generation times.

Module 17 Evolution of Niches and Species Distributions

- **Explain the difference between a fundamental and a realized niche.**

  Every species has a range of tolerance to the abiotic conditions of the environment. The conditions under which a species can survive, grow, and reproduce is known as its fundamental niche. The portion of the fundamental niche that a species actually occupies due to biotic interactions, including predation, competition, and disease, is known as the realized niche. Some species are niche generalists whereas other species are niche specialists. The niche a species occupies determines its distribution.

- **Describe how environmental change can alter species distributions.**

  Because a species niche represents the environmental conditions under which a species can live, environmental change can cause a change in the distribution of a species.

- **Discuss how environmental change can cause species extinctions.**

  When environmental changes are too rapid and too extensive to permit evolutionary changes, or if a species is unable to move to more hospitable environments, a species will not be able to persist and will go extinct.

Chapter 5 AP® Environmental Science Practice Exam

Section 1: Multiple-Choice Questions

Choose the best answer for questions 1–12.

1. Which is NOT a measure of biodiversity?
   (a) Economic diversity
   (b) Ecosystem diversity
   (c) Genetic diversity
   (d) Species diversity
   (e) Species richness

2. Which statement describes an example of artificial selection?
   (a) Cichlids have diversified into nearly 200 species in Lake Tanganyika.
   (b) Thoroughbred racehorses have been bred for speed.
   (c) Whales have evolved tails that help propel them through water.
   (d) Darwin's finches have beaks adapted to eating different foods.
   (e) Ostriches have lost the ability to fly.

3. The following table represents the number of individuals of different species that were counted in three forest communities. Which statement best interprets these data?

Species	Community A	Community B	Community C
Deer	95	20	10
Rabbit	1	20	10
Squirrel	1	20	10
Mouse	1	20	10
Chipmunk	1	20	10
Skunk			10
Opossum			10
Elk			10
Raccoon			10
Porcupine			10

   (a) Community A has greater species evenness than Community B.
   (b) Community A has greater species richness than Community B.
   (c) Community B has greater species evenness than Community C.
   (d) Community C has greater species richness than Community A.
   (e) Community A has greater species evenness than Community C.

4. The yellow perch (*Perca flavescens*) is a fish that breeds in spring. A single female can produce up to 40,000 eggs at one time. This species is an example of which of the key ideas of Darwin's theory of evolution by natural selection?
   (a) Individuals produce an excess of offspring.
   (b) Humans select for predetermined traits.
   (c) Individuals vary in their phenotypes.
   (d) Phenotypic differences in individuals can be inherited.
   (e) Different phenotypes have different abilities to survive and reproduce.

5. In 2002, Peter and B. Rosemary Grant studied a population of Darwin's finches on one of the Galápagos Islands that feeds on seeds of various sizes. After a drought that caused only large seeds to be available to the birds, they found that natural selection favored those birds that had larger beaks and bodies. Once the rains returned and smaller seeds became much more abundant, however, natural selection favored those birds that had smaller beaks and bodies. Which process is the best interpretation of this scenario?
   (a) Genetic drift
   (b) Founder effect
   (c) Microevolution
   (d) Macroevolution
   (e) Bottleneck effect

6. When a population of monkeys migrates to a new habitat across a river and encounters another population of the same species, what evolutionary effect may occur as a result?
   (a) Gene flow
   (b) The founder effect
   (c) Genetic drift
   (d) The bottleneck effect
   (e) Recombination

7. The northern elephant seal (*Mirounga angustirostris*) was once hunted to near-extinction. Only 20 animals remained alive in 1890. Then, after the species was protected from hunting, its population grew to nearly 30,000 animals. However, this large population possesses very low genetic variation. Which process is the best interpretation of this scenario?
   (a) Evolution by natural selection
   (b) Evolution by artificial selection
   (c) Evolution by the founder effect
   (d) Evolution by the bottleneck effect
   (e) Evolution by genetic drift

8. Which statement is NOT correct?
   (a) Most speciation is thought to occur through allopatric speciation.
   (b) Polyploidy is an example of sympatric speciation.
   (c) Speciation can be caused by either natural selection or random processes.
   (d) Geographic isolation can eventually lead to reproductive isolation.
   (e) Speciation cannot occur without geographic isolation.

9. Which allows more-rapid evolution?
   (a) Long generation times
   (b) Rapid environmental change
   (c) Large population sizes
   (d) Low genetic variation
   (e) High genetic variation

10. Which conditions do NOT define the fundamental niche of a species?
   (a) Humidity
   (b) Predators
   (c) Temperature
   (d) Salinity
   (e) pH

11. Some scientists estimate that the current global extinction rate is about 30,000 species per year. If there are currently 10,000,000 species on Earth, how long will it take to destroy all of Earth's biodiversity?
   (a) Less than 100 years
   (b) Between 100 and 300 years
   (c) Between 300 and 500 years
   (d) Between 500 and 700 years
   (e) Between 700 and 1,000 years

12. Global climate change can cause the extinction of species due to all of the following EXCEPT
   (a) the inability of individuals to move.
   (b) the absence of a favorable environment nearby.
   (c) the presence of another species occupying a similar niche in neighboring areas.
   (d) the rapid rate of environment change.
   (e) the presence of high genetic variation.

Section 2: Free-Response Questions

Write your answer to each part clearly. Support your answers with relevant information and examples. Where calculations are required, show your work.

1. Look at the photograph below and answer the following questions.

(Radius Images/Alamy)

   (a) Explain how this human impact on a forest ecosystem might affect the ability of some species to move to more suitable habitats as Earth's climate changes. (2 points)
   (b) Propose and explain one alternative plan that could have preserved this forest ecosystem. (2 points)
   (c) Distinguish between the terms microevolution and macroevolution. Explain how the organisms in the forest on the left could evolve into species different from those in the forest on the right. (6 points)

2. Read the following article, which appears courtesy of The University of Texas Health Science Center at San Antonio, and answer the questions that follow.

Drug-Resistant E. coli and Klebsiella Bacteria Found in Hospital Samples and Elsewhere in U.S.

A research team from The University of Texas Health Science Center at San Antonio, examining bacterial isolates obtained in hospital and non-hospital clinical settings between 2000 and 2006, has identified drug-resistant strains of *E. coli* and *Klebsiella* bacteria in more than 50 blood, urine and respiratory samples. These resistant strains, which resemble bacteria reported in Latin America, Asia, and Europe, were thought to be rare in the United States.

"This antibiotic resistance problem is likely to become widespread," said paper co-author Jan Evans Patterson, M.D., professor of medicine, infectious diseases, and pathology at the UT Health Science Center. "It affects the way we will treat infections in the future. In the past, we were concerned with antibiotic resistance in the hospital primarily, but in this review many of the strains we detected were from the community. This tells us antibiotic resistance is spreading in the community as well, and will affect how we choose antibiotics for outpatient infections."

If the trend continues, it may become difficult to select appropriate antibiotic therapy for urinary tract infections, for example. "The trend over the last decade has been to treat urinary infections empirically, to pick the drug that has worked," said James Jorgensen, Ph.D., professor of pathology, medicine, microbiology, and clinical laboratory sciences at the Health Science Center. "Now it is important for physicians to culture the patient's urine to be sure they have selected the right antibiotic. The top three drugs that are often prescribed may not be effective with these resistant bacteria."

   (a) Explain how drug-resistant strains of bacteria could evolve in a hospital. (4 points)
   (b) According to the article, what are scientists now concerned about that they were not concerned about in the past? (2 points)
   (c) Explain how new drugs could be viewed as restricting the fundamental niche of a particular bacterial species. (2 points)
   (d) Propose two possible solutions to the current problem of drug-resistant bacteria. (1 point each)

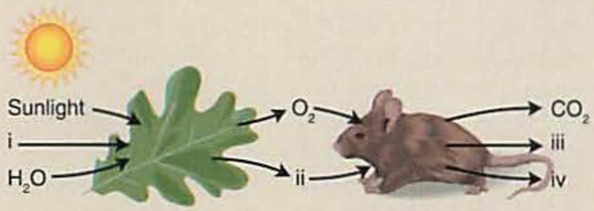
Unit 2 AP® Environmental Science Practice Exam

Section 1: Multiple-Choice Questions

Choose the best answer for questions 1–20.

1. Ecosystem boundaries are best defined as
   (a) borders that prevent migration or dispersal.
   (b) spatial divisions in abiotic and biotic conditions.
   (c) vague areas that often lack characteristic attributes.
   (d) the border of a lake or stream.
   (e) borders encompassing large areas of land or water.

Question 2 refers to the following diagram:



2. By ingesting leaf tissue, herbivores utilize the products of photosynthesis for cellular respiration. The diagram above shows the flow of inputs and outputs for these two processes. Labels i, ii, iii, and iv refer to
   (a) CO_2, $C_6H_{12}O_6$, energy, and water.
   (b) CO_2, CO_2, energy, and excreted waste.
   (c) nutrients, $C_6H_{12}O_6$, O_2, and water.
   (d) CO_2, $C_6H_6O_6$, energy, and O_2.
   (e) heat, organic tissue, energy, and O_2.

3. To estimate gross primary production, researchers can use all of the following variable combinations EXCEPT
   (a) net primary production and plant respiration.
   (b) standing crop, plant respiration, consumer biomass, and mass of consumer waste.
   (c) CO_2 taken up by plant in sunlight and CO_2 produced by plants in the dark.
   (d) CO_2 released by plants in sunlight and CO_2 produced by plants in the dark.
   (e) the amount of photosynthesis occurring over time.

4. Which explains why the distribution of biomass in ecosystems is often structured like a pyramid?
   I. The second law of thermodynamics
   II. Low ecological efficiency in natural ecosystems
   III. Photosynthesis is more efficient than cellular respiration

   (a) I only
   (b) II only
   (c) I and II
   (d) I and III
   (e) I, II, and III

5. Which process is NOT part of the carbon cycle?
   (a) Growth of algae in the open ocean
   (b) Combustion of fossil fuels
   (c) Weathering of mineral rock
   (d) Decomposition of organic material
   (e) Cellular respiration

6. Production of synthetic fertilizers is an example of ______ and one process that enables plants to use fertilizer is ________.
   (a) nitrogen fixation/nitrification
   (b) nitrification/nitrogen fixation
   (c) nitrification/assimilation
   (d) denitrification/nitrification
   (e) mineralization/leaching

7. Phosphorus is often limiting in aquatic environments because
   (a) phosphorus is in higher demand by aquatic organisms relative to all other minerals.
   (b) phosphorus is not easily leached from soils and rapidly precipitates in water.
   (c) weathering of rock is an extremely slow process.
   (d) human activity regularly absorbs phosphorus from aquatic environments.
   (e) phosphorus rarely changes form as it is cycled from land to water.

8. Intertidal communities are frequently disturbed by storms that generate large waves. Following a period of intermediate wave disturbance, a group of researchers examined the species richness of north and south Pacific intertidal communities. Four days after the disturbance, they found that northern communities had returned to their original state whereas southern communities were still recovering. This result suggests that northern intertidal communities
   (a) have greater resilience.
   (b) have greater resistance.
   (c) follow predictions of the intermediate disturbance hypothesis.
   (d) have greater species richness.
   (e) experience more frequent disturbance.

9. Which statement does NOT describe a function of ozone gas on Earth?
   (a) Ozone absorbs ultraviolet-B radiation from the Sun.
   (b) Ozone absorbs ultraviolet-C radiation from the Sun.
   (c) Ozone absorbs X-ray radiation from the Sun.
   (d) Ozone causes the upper stratosphere to become warmer than the lower stratosphere.
   (e) Ozone prevents DNA damage.

10. If Earth's axis of rotation were tilted at 45 degrees instead of 23.5 degrees, how many hours of daylight would the Northern Hemisphere receive during the March and September equinoxes?
   (a) 0 hours
   (b) 6 hours
   (c) 12 hours
   (d) 18 hours
   (e) 24 hours

11. Which order of processes results in the occurrence of hot and dry deserts at 30°S and 30°N latitudes?
   (a) Adiabatic cooling, condensation, latent heat release, adiabatic heating
   (b) Adiabatic heating, condensation, latent heat release, adiabatic cooling
   (c) Latent heat release, adiabatic cooling, air displacement, condensation
   (d) Condensation, adiabatic heating, adiabatic cooling, latent heat release
   (e) Air displacement, condensation, adiabatic heating, adiabatic cooling

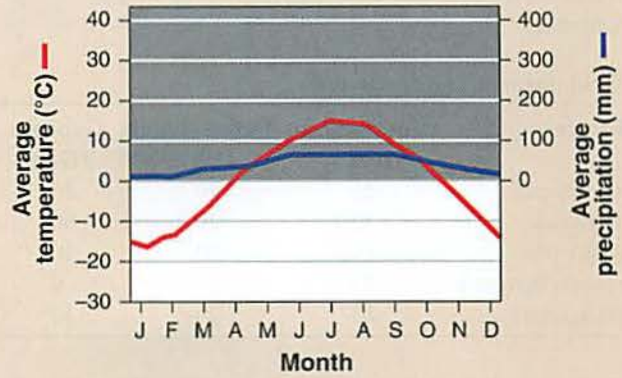
12. Lush vegetation on the western slopes of the Colorado Rockies may be attributed to
   I. trade winds generated by the Coriolis effect.
   II. a rain shadow.
   III. adiabatic cooling.

   (a) I only
   (b) III only
   (c) I and II
   (d) I and III
   (e) I, II, and III

13. The mixing of surface water and deep water in the oceans that occurs because of differences in salinity is known as
   (a) upwelling.
   (b) a gyre.
   (c) the El Niño–Southern Oscillation.
   (d) an isocline.
   (e) thermohaline circulation.

14. Which of the following is NOT a cause of the El Niño–Southern Oscillation?
   (a) The position of Australia with respect to South America
   (b) A reversal of trade wind direction
   (c) Movement of warm surface water from east to west
   (d) A buildup of warm water along the coast of South America
   (e) Upwelling of water along the coast of South America

Questions 15 and 16 refer to the following graph:



15. For the region represented by the graph, when is the growing season?
   (a) January to December
   (b) January to July
   (c) April to October
   (d) November to March
   (e) July to December

16. What biome is this graph most likely to represent?
   (a) Temperate rainforest
   (b) Boreal forest
   (c) Temperate seasonal forest
   (d) Tropical seasonal forest
   (e) Cold desert

17. Which list contains terms for lake classification, from systems with the lowest primary productivity to systems with the highest primary productivity?
   (a) Eutrophic, mesotrophic, oligotrophic
   (b) Oligotrophic, eutrophic, mesotrophic
   (c) Mesotrophic, eutrophic, oligotrophic
   (d) Mesotrophic, oligotrophic, eutrophic
   (e) Oligotrophic, mesotrophic, eutrophic

18. Iron is a limiting nutrient for algae in the open ocean. After researchers released 5,000 kg of iron into the ocean, they notice an algal bloom in the _______ zone.
   (a) photic
   (b) profundal
   (c) aphotic
   (d) intertidal
   (e) benthic

Question 19 refers to the following table comparing forest communities in different regions of North America.

Total percent statewide cover

Species	Connecticut (CT)	Pennsylvania (PA)	Georgia (GA)
Red maple	25	40	20
Black oak	30	20	50
White pine	15	10	10
Eastern hemlock	20	10	0
Black cherry	20	20	30

19. Researchers collected data on tree abundance for a group of forest communities in the three states shown in the table above. Which statement best describes the forest communities within each state?
    (a) CT has the highest species richness; PA has the highest species evenness.
    (b) PA has the highest species richness; CT has the highest species evenness.
    (c) CT and PA have equal species richness; GA has the highest species evenness.
    (d) GA and PA have equal species richness; GA has the highest species evenness.
    (e) CT and PA have equal species richness; CT has the highest species evenness.

20. Humans have developed varieties of grape vines that produce grapes that make fine wines if grown under particular environmental conditions. Therefore, the flavor of grapes on a given vine depends on
    I. genes.
    II. environments.
    III. artificial selection.

    (a) I only
    (b) II only
    (c) III only
    (d) I and II
    (e) I, II, and III

21. Which could cause a dramatic decline in genetic diversity?
    I. Mutation
    II. A bottleneck effect
    III. A founder effect

    (a) I only
    (b) II only
    (c) III only
    (d) I and II
    (e) II and III

22. Which is an example of sympatric speciation?
    (a) A stream diversion divides a single turtle population into two isolated populations that evolve into two species.
    (b) Forest fragmentation isolates two species of mice.
    (c) Two bird species from separate forests evolve reproductive isolation.
    (d) Two fish species in a single lake evolve from a single ancestor that once lived in the lake.
    (e) Artificial selection by humans for certain breeds of dog.

23. Which of the following is the best definition of a realized niche?
    (a) The range of abiotic and biotic conditions under which a species can live
    (b) The total amount of area in which a species can live
    (c) The range of abiotic and biotic conditions under which a species actually lives
    (d) The total amount of area in which a species actually lives
    (e) The range of abiotic and biotic conditions in which a species can live but its predators cannot live

Section 2: Free-Response Questions

Write your answer to each part clearly. Support your answers with relevant information and examples. Where calculations are required, show your work.

1. In temperate forests, average daily temperatures during winter often drop to 0° C or lower. During this time, many organisms burrow into the soil and remain in a dormant stage until the spring thaw. Although these organisms are able to withstand very cold temperatures, they also rely on the insulating capacity of snow, which prevents soil from experiencing temperature extremes. However, during winters when snowfall is less abundant, soil is exposed to freezing temperatures that kill many of the bacteria and fungi residing in the very top layers of soil. When bacteria and fungi die, nutrients and other organic material are easily leached out of cell membranes and these materials enter the soil.
   (a) What are two consequences of reduced winter snowfall on the nitrogen cycle in temperate forests? (4 points)
   (b) What is one consequence of reduced winter snowfall on the carbon cycle in temperate forests? (2 points)
   (c) Describe two ways in which stream and pond food webs might be affected by reduced snowfall during the winter. (2 points)
   (d) Exposure of the soil to extreme temperatures can also kill larger organisms, such as frogs and burrowing insects. For example, wood frogs (*Lithobates sylvaticus*) that burrow too close to the soil surface are likely to die whereas frogs that burrow deeper in the soil are likely to survive. Describe one way in which reduced winter snowfall could alter the local population genetics of wood frogs. (2 points)

2. During El Niño–Southern Oscillation (ENSO) years, the buildup of warm water off the coast of South America alters the circulation of the Hadley cell. One consequence of this altered circulation is a dip in the subtropical jet stream that carries storms from west to east across North America. Subsequently, southern California experiences greater precipitation during El Niño years.
   (a) Draw a diagram that shows both Hadley and Ferrell cells, noting latitudinal locations, air direction and areas of condensation, adiabatic heating, and adiabatic cooling. (4 points)
   (b) Why would the western slopes of the southern Colorado Rockies experience greater precipitation than the eastern slopes? (2 points)
   (c) A researcher wants to test the hypothesis that gross primary productivity (GPP) on the western slopes of the Rockies is greater during ENSO years.
      (i) Write an equation that defines gross primary productivity. (1 point)
      (ii) What characteristics of local plants should the researcher measure to test the hypothesis? Provide justification for your responses. (2 points)
      (iii) Provide a null hypothesis for this study. (1 point)

Jenny Pate/age fotostock

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science**applied**

How Should We Prioritize the Protection of Species Diversity?

As a result of human activities, we have seen a widespread decline in biodiversity across the globe. Many people agree that we should try to slow or even stop this loss. But how do we do this? While ideally we might want to preserve all biodiversity, in reality preserving biodiversity requires compromises. For example, in order to preserve the biodiversity of an area, we might have to set aside land that would otherwise be used for housing developments, shopping malls, or strip mines. If we cannot preserve all biodiversity, how do we decide which species receive our attention? (FIGURE SA2.1)

FIGURE SA2.1 The California tiger salamander (*Ambystoma californiense*). This salamander is endemic to the biodiversity hotspot of California and is threatened with extinction due to habitat destruction and the introduction of non-native predators. *(James Gerholdt/Getty Images)*

In 1988, Oxford University professor Norman Myers noted that much of the world's biodiversity is concentrated in areas that make up a relatively small fraction of the globe. Part of the reason for this uneven pattern of biodiversity is that so many species are *endemic species*. **Endemic species** are species that live in a very small area of the world and nowhere else, often in isolated locations such as the Hawaiian Islands. Because they are home to so many endemic species, these isolated areas end up containing a high proportion of all the species found on Earth. Myers called these areas **biodiversity hotspots.**

Endemic species A species that lives in a very small area of the world and nowhere else.

Biodiversity hotspot An area that contains a high proportion of all the species found on Earth.

Scientists originally identified 10 biodiversity hotspots, including Madagascar, western Ecuador, and the Philippines. Myers argued that these 10 areas were in need of immediate conservation attention because human activities there could have disproportionately large negative effects on the world's biodiversity. A year later, the group Conservation International adopted Myers's concept of biodiversity hotspots to guide its conservation priorities. As of 2013, Conservation International had identified the 34 biodiversity hotspots shown in FIGURE SA2.2. Although these hotspots collectively represent only 2.3 percent of the world's land area, more than 50 percent of all

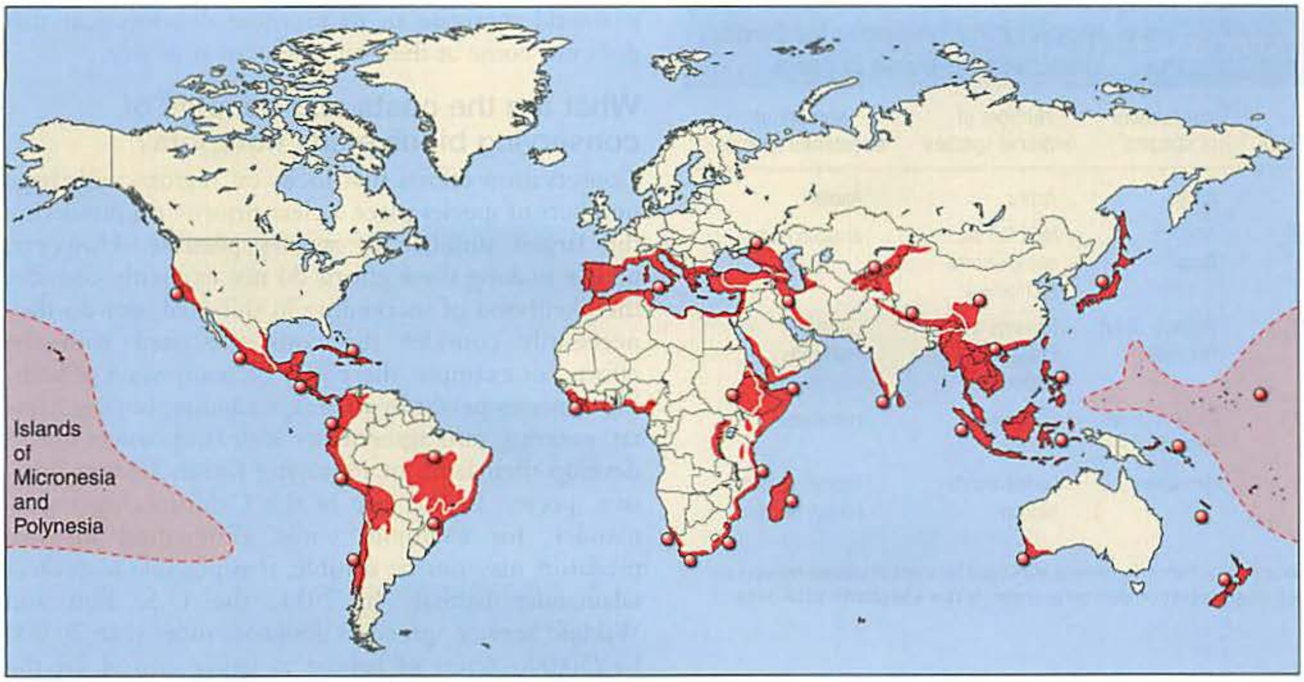

FIGURE SA2.2 Biodiversity hotspots. Conservation International has identified 34 biodiversity hotspots that have at least 1,500 endemic plant species and a loss of at least 70 percent of all vegetation. *(Data from Conservation International at http://www.conservation.org/where/priority_areas/hotspots/Documents/CI_Biodiversity-Hotspots_2013_Map.pdf)*

plant species and 42 percent of all vertebrate species are confined to these areas. As a result of this categorization, major conservation organizations have adjusted their funding priorities and are spending hundreds of millions of dollars to conserve these areas. What does environmental science tell us about the hotspot approach to conserving biodiversity?

What makes a hotspot hot?

Since Norman Myers initiated the idea of biodiversity hotspots, scientists have debated which factors should be considered most important when deciding where to focus conservation efforts. For example, most scientists agree that species richness is an important factor. There are more than 1,300 bird species in the small nation of Ecuador—more than twice the number of bird species living in the United States and Canada. For this reason, protecting a habitat in Ecuador has the potential to save many more bird species than protecting the same amount of habitat in the United States or Canada. From this point of view, the choice to protect areas with a lot of species makes sense.

Identifying biodiversity hotspots is challenging, however, because scientists have not yet discovered and identified all the species on Earth. Because the distribution of plants is typically much better known than that of animals, the most practical way to identify hotspots has been to locate areas containing high numbers of endemic plant species. It is reasonable to expect that areas with high plant diversity will contain high animal diversity as well.

Conservation International considers two criteria when determining whether an area qualifies as a hotspot. First, the area must contain at least 1,500 endemic plant species. By conserving plant diversity, the hope is that we will simultaneously conserve animal diversity, especially for those groups, such as insects, that are poorly cataloged. Second, the area must have lost more than 70 percent of the vegetation that contains those endemic plant species. In this way, high-diversity areas with a high level of habitat loss receive the highest conservation priority. High-diversity areas that are not being degraded receive lower conservation priority.

What else can make a hotspot hot?

The number of endemic species in an area is undoubtedly important in identifying biodiversity hotspots, but other scientists have argued that this criterion alone is not enough. They suggest that we also consider the total number of species in an area or the number of species currently threatened with extinction in an area. Would all three approaches identify similar regions of conservation priority? A recent analysis of birds suggests they would not. When scientists identified bird diversity hotspots using each of the three criteria—endemic species, total species richness, and threatened species—their results, shown in **TABLE SA2.1**, identified very different areas. Scientists using the three

TABLE SA2.1 **Biodiversity hotspots for birds, identified by three criteria**

Rank	Total number of species	Number of endemic species	Number of threatened species
1	Andes	Andes	Andes
2	Amazon Basin	New Guinea and Bismarck Archipelago	Amazon Basin
3	Western Great Rift Valley	Panama and Costa Rica Highlands	Guiana Highlands
4	Eastern Great Rift Valley	Caribbean	Himalayas
5	Himalayas	Lesser Sunda Islands	Atlantic Coastal Forest, Brazil

Source: Data from C.D. Orme et al., Global hotspots of species richness are not congruent with endemism or threat, *Nature* 436 (2005): 1016–1019.

criteria to identify hotspots of mammal diversity reached the same conclusion.

As we can see, some areas of the world that have high species richness do not contain high numbers of endemic species. The Amazon, for example, has a high number of bird species, but not a particularly high number of endemic bird species compared with other more-isolated regions of the world, such as the islands of the Caribbean. Similarly, areas with high numbers of threatened or endangered species do not always have high numbers of endemic species. These findings highlight the critical problem of deciding whether conservation efforts should be focused on areas containing the greatest number of species, areas containing the greatest number of threatened species, or areas containing the greatest number of endemic species. All three approaches are reasonable.

In addition to considering species diversity, some scientists have argued that we must also consider the size of the human population in diverse areas. For example, we might expect that natural areas containing more people face a greater probability of being affected by human activities. Furthermore, if we wish to project into the future, we must consider not only the size of the human population today, but also the expected size of the human population several decades from now. Scientists have found that many hotspots for endemic species have human population densities that are well above the world's average. Whereas the world has an average human population density of 42 people per square kilometer, the average hotspot has a human population of 73 people per square kilometer. Such places may be at a higher risk of degradation from human activities. This risk should be considered when determining priority areas for conservation, and it should motivate us to promote development that does not come at the cost of species diversity.

What are the costs and benefits of conserving biodiversity hotspots?

Conservation efforts that focus on regions with large numbers of species place a clear priority on preserving the largest number of species possible. However, people making these efforts do not explicitly consider the likelihood of succeeding in this goal, nor do they necessarily consider the costs associated with the effort. For example, there may be many ways of helping a species persist in an area, including buying habitat, entering into agreements with landowners not to develop their land, or removing threats such as invasive species. In the case of the California tiger salamander, for example, while eliminating invasive predators may not be feasible, it is possible to protect salamander habitat. In 2011, the U.S. Fish and Wildlife Service agreed to designate more than 20,000 ha (50,000 acres) of habitat as being critical for the salamander's persistence and in 2012 the agency agreed to develop a plan to help populations of the salamander to recover. Each option will have a different impact on the number of species that will be helped, and each option will have different costs of implementation. Given the limited funds that are available for protecting species, it is certainly worth comparing the expected costs and benefits of different options, both within and among biodiversity hotspots. In this way, we have the potential to maximize the return on our conservation investment.

What about biodiversity coldspots?

The concept of biodiversity hotspots assumes that our primary goal is to protect the maximum number of species. That goal is admirable, but it could come at the cost of many important ecosystems that do not fall within hotspots. Yellowstone National Park, for example, has a relatively low diversity of species, yet it is one of the few places in the United States that contains remnant populations of large mammals, including wolves, grizzly bears, and bison. Does this mean that places such as Yellowstone National Park should receive decreased conservation attention?

Biodiversity coldspots also provide ecosystem services that humans value at least as much as species diversity. For example, wetlands in the United States are incredibly important for flood control, water purification, wildlife habitat, and recreation. Many wetlands, however, have relatively low plant diversity and, as a result, would not be identified as biodiversity hotspots. It is true that increased species richness leads to improved ecosystem services, but only as we move from very low species richness to moderate species richness. Moving from moderate species richness to high species richness generally does not further improve the functioning of an ecosystem. Since very high species diversity is not expected to provide any substantial improvement in ecosystem function, protecting more and more species produces diminishing returns in terms of protecting ecosystem services. Hence, if our primary goal is to preserve the functioning of the ecosystems that improve our lives, we do not necessarily need to preserve every species in those ecosystems.

How can we reach a resolution?

During the past 2 decades, it has become clear that scientists and policy makers need to set priorities for the conservation of biodiversity. No single criterion may be agreed upon by everyone. However, it is important to appreciate the bias of each approach and to consider the possible unintended consequences of favoring some geographic regions over others. Our investment in conservation cannot be viewed as an all-or-nothing choice of some areas over others. Instead, our decisions must take into account the costs and benefits of alternative conservation strategies and incorporate current and future threats to both species diversity and ecosystem function. In this way, we can strike a balance between our desire to preserve Earth's species diversity and our desire to protect the functioning of Earth's ecosystems.

Questions

1. If you were in the role of a decision maker, how might you balance your desire to protect biodiversity around the world with the high cost of preserving biodiversity in any given location?
2. When identifying hotspots around the world, why is it important to simultaneously consider the biodiversity of different areas and the future human population size in each of these locations?
3. If you had to make a choice between protecting biodiversity hotspots and biodiversity coldspots, how would you make this decision?

Free-Response Question

Florida Reef is the only living coral barrier reef in the continental United States. Like other coral reefs on the planet, Florida Reef is home to many species of coral, fish, and other aquatic life forms. Also like other coral reefs, its health is at risk due to such factors as coral bleaching. However, Conservation International does not list this as a biodiversity hotspot.

(a) List two reasons why Florida Reef might not be internationally recognized as a hotspot. (2 points)

(b) List and describe two ecosystem services provided by Florida Reef. (2 points)

(c) What is coral bleaching? (2 points)

(d) Researchers recently found that the disturbance generated by hurricanes is important for maintaining the diversity of coral reef ecosystems. However, massive hurricanes often put many coral reef species at risk of local extinction. Generate a hypothesis to explain this pattern. (4 points)

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Key Terms

Endemic species
Biodiversity hotspots