

## WHAT IS BIODIVERSITY?

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Brilliant scarlet macaws, scampering gray squirrels, towering giant sequoia trees, your morning cup of coffee, industrious honey bees—mundane and spectacular, economically fundamental and simply arcane—all of these are examples of biodiversity, the dazzling variety of life on earth.

Few people are familiar with the word “biodiversity,” yet everyone is intimately connected with biodiversity in their daily life. Humanity’s fundamental reliance on and connection with natural systems creates an imperative to understand and protect biodiversity.

To conserve biodiversity, we need to understand what biodiversity is, determine where it occurs, identify strategies to conserve it, and track over time whether these strategies are working. The first of these items, knowing what biodiversity is, and therefore what to conserve, is complicated by the remarkable diversity of living things themselves.

Life on earth today is the product of about 3.5 billion years of evolution. An estimated 1.75 million species have been discovered and described, but this only represents a fraction of all the species on earth. Estimates of how many species remain to be discovered range from 3.6 million to 117.7 million, with 13 to 20 million being the most frequently agreed upon by scientists. One reason the exact number of species is still unclear is that new species are continually being described. Some of this uncertainty is also due to the increased information available to scientists since the advent of genetic analyses and because the definition of what constitutes an individual species changes.

This chapter introduces the basics of biodiversity: what biodiversity is and how to measure it. It also explores the evolution of biodiversity over time: how many species there are today, how many have disappeared,

and the “Sixth” extinction—the current rapid loss of biodiversity around the world.

## DEFINITION OF BIODIVERSITY

Scientists first coined the term biodiversity, a contraction of the phrase, “biological diversity,” in the 1980s. Most simply, biodiversity describes the entire variety of life on earth. It can also be defined more broadly incorporating not only living organisms, but also their complex interactions with one another and with the nonliving aspects of their environment. *Biodiversity* is defined as:

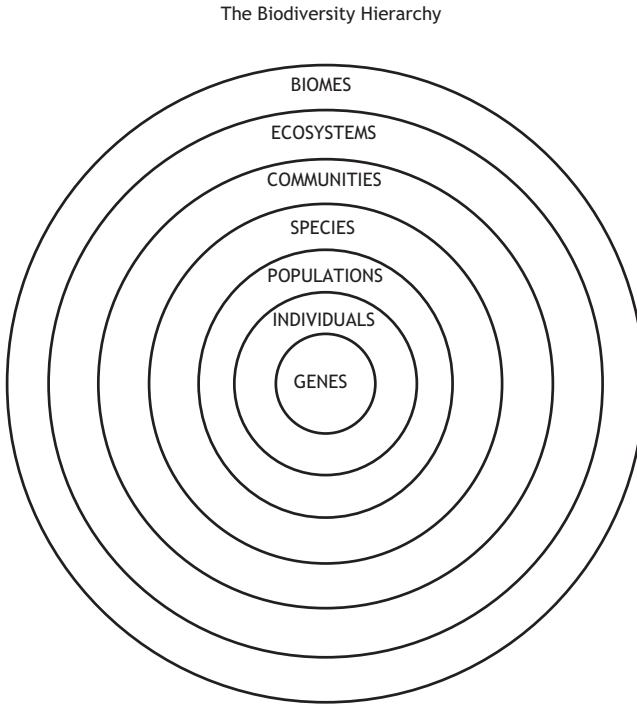
The variety of life on Earth at all its levels, from genes to ecosystems, and the ecological and evolutionary processes that sustain it.

## The Biodiversity Hierarchy

To understand and appreciate the full variety of life encapsulated by the term “biodiversity,” scientists describe it based on a nested hierarchy, beginning at the subcellular scale and ending at the continental level (see Figure 1.1). The smallest level of this hierarchy refers to the diversity of genes that can be found in individual cells. *Genetic* diversity is sometimes called the “fundamental currency of diversity,” as ultimately it is responsible for the variation among individuals, populations, and species. The next level of the hierarchy is the *species* level: this is the level of the biodiversity hierarchy that most conservation legislation targets, where most conservation organizations focus their efforts, and what most people think of when they think of biodiversity.

The interactions between the individual organisms that make up a *population* (competition, cooperation, etc.), and their specializations for their environment (including ways in which they might modify the environment itself) are important aspects of the next levels of the biodiversity hierarchy. Interactions between different species (e.g., predator-prey relationships) and their environments form the next level of the hierarchy, focusing on *community* and *ecosystem* biodiversity. The largest scales of the biodiversity hierarchy are *landscapes* and *ecoregions*.

This hierarchy is one helpful way to organize the dizzying diversity of life, but it is important to keep in mind that there are other ways of portraying the various aspects of biodiversity. One framework focuses on the distribution of biodiversity over the earth’s surface. The structure of communities and ecosystems (e.g., the number of individuals and



**Figure 1.1** Biodiversity is sometimes represented as a hierarchy beginning with the diversity found in genes and extending to diversity at the continental level. Genes at the center of this hierarchy are the fundamental diversity upon which the variation at all other levels is based (*Cullman*)

species present) varies in different parts of the world. Similarly, the interactions between organisms in ecosystems and communities vary from one place to another. Different assemblages of ecosystems make up diverse landscapes. These spatial patterns of biodiversity are affected by climate, geology, and geography. For example, the numbers and types of species found in an arctic tundra ecosystem are significantly different from those found in a tropical wetland ecosystem. These concepts are covered in more detail in Chapter 2.

Another important aspect of biodiversity not explicit in the biodiversity hierarchy is its dynamism. Life is always changing and evolving; even ecosystems that seem static at first glance may be the products of long term dynamic processes. Certain changes occur periodically; for

example, daily, seasonal, or annual changes in the species and number of organisms present in an ecosystem and how they interact. A deer may graze in one area and then bed down for the night in another. Atlantic salmon are spawned in freshwater streams, migrate out to sea to mature, and then return to freshwater to reproduce. Some ecosystems change in size or structure over time. A good example of this is the changes that forest ecosystems undergo with the presence of natural fires. Longleaf pine and scrub oak ecosystems of the southeastern United States are a good example of a fire-adapted ecosystem. With the periodic disturbance of a low-intensity fire, this forest type has an open canopy and a clear, park-like understory. Remove the fire, and the understory of the forest becomes dense with undergrowth and leaf litter. Certain ecosystems change seasonally. For example, vernal pools—depressions in the ground that flood seasonally—are important ephemeral habitat for frogs, nesting birds, invertebrates, and plants. Biodiversity also changes over longer, evolutionary time scales. Geological processes, such as the movement of the Earth's plates, mountain building and erosion, changes in sea level, and climate change cause significant, long-term changes to the structural and spatial characteristics of global biodiversity. For example, changes in sea level during different times sometimes exposed and sometimes obscured the Bering land bridge between what is now Russia and Alaska, facilitating and then impeding exchange of species between the two continents. Evidence of past sea level fluctuations—connecting and separating continents—is reflected in the evolutionary relationships between present-day species in Asia and North America. For example, the closest living relative of the towering Redwood trees of California (*Sequoia sempervirens*) are the Dawn Redwoods (*Metasequoia glyptostroboides*) found in present-day China, and the ancestors of the three extant species of Vietnamese glass lizards (a legless lizard that resembles a snake) are from North America.

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### ARE HUMANS PART OF BIODIVERSITY?

In Western culture, the dominant way of thinking considers humans to be separate and distinct from nature. Things are often described as being natural or man-made (created by the human mind), though the actual line between what is natural and what is artificial is often difficult to draw. This way of thinking can be traced to Western religious, literary, and historical traditions. For example, in the Bible, Adam was given dominion over the animals of the Garden of Eden. Writing by European colonists in North

America includes references to dominating the landscape, imposing control upon the chaos and disorder of the wilderness. Even Romanticism, the artistic and literary movement of the late eighteenth and early nineteenth centuries, which celebrated wilderness, did so from a vantage point: the emphasis was on the way that a view of nature engendered transcendental or spiritual experiences.

In our day-to-day life in the developed world, it is very easy to be ignorant of our connections to and our fundamental dependence on the natural world. Due to this cultural paradigm, many researchers confine biodiversity to natural variety and variability, excluding biotic patterns and ecosystems that result from human activity. In reality, however, it is difficult to assess the “naturalness” of an ecosystem because in most places human influence is pervasive, long-term, and varied. For example, while the Arctic may seem devoid of human activity relative to many places on Earth, many human-produced chemicals, such as mercury, lead, and PCBs, have reached Arctic environments. Recent research has also suggested that species and communities found in seemingly “untouched” ecosystems, such as the rainforests of the Amazon and Congo Basins, have been shaped by human communities in the past.

So, how to address this paradox? Some researchers consider humans to be a part of nature, and so they consider the cultural diversity of human populations and the ways that these populations use or interact with habitats and other species on Earth as a component of biodiversity too. Other researchers make a compromise between completely including or excluding humans as a part of biodiversity. They do not accept all aspects of human activity and culture as part of biodiversity, but they do recognize that the ecological and evolutionary diversity of domestic species, the species composition and ecology of agricultural ecosystems, and the landscape-level interactions between certain cultures and ecosystems are all part of biodiversity.

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### ***Genetic Diversity***

The diversity of life we see on the planet is a product of genetic diversity, that is, the variation in the DNA (deoxyribonucleic acid) that makes up the genes of organisms leads to the variation we see at all other levels.

*Genetic diversity* refers to any variation in the nucleotides, genes, chromosomes, or whole genomes of organisms (the *genome* is the entire complement of DNA within the cells or organelles of the organism). Genetic diversity, at its most elementary level, is represented by differences in the sequences of four nucleotides (adenine, cytosine, guanine, and thymine), which form the DNA within the chromosomes in the

cells of organisms. Some cells have specific organelles that contain chromosomes (for example, mitochondria and chloroplasts have their own chromosomes, which are separate from a cell’s nuclear chromosomes). Nucleotide variation is measured for discrete sections of chromosomes, called “genes.” Each gene comprises a hereditary section of DNA that occupies a specific place on the chromosome, and controls a particular characteristic of an organism. DNA provides the instructions to create proteins and in turn all other parts of a cell. Genetic diversity exists:

- within a single individual,
- between different individuals of a single population,
- between different populations of a single species (population diversity), and
- between different species (species diversity).

It is difficult, in some cases, to establish the boundaries between these levels of diversity. For example, it may be difficult to interpret whether variation between groups of individuals represents diversity between different species, or represents diversity only between different populations of the same species. Nevertheless, in general terms, these levels of genetic diversity form a convenient hierarchy for describing the overall diversity of organisms on Earth.

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development and function of adjacent organs in the head, where there is a “competition” for headspace.

The extent to which genetic variation between organisms is expressed in their phenotypes can be quite variable for different characteristics. Genetic variation between some features might be expressed as very subtle differences in their phenotype. For example, populations and subspecies of the herring gull (*Larus argentatus*) and the lesser black-backed gull (*Larus fuscus*) are distinguished by very slight differences in the coloration of individuals. In some cases these differences are difficult to detect. However, genetic variation within a species can be quite extensive, particularly in cultured plants or domesticated animals where particular features have been artificially selected in different strains or breeds. For example, broccoli, cabbage, and cauliflower look very different from one another, but are all varieties of *Brassica oleracea* (see Figure 1.2). Another everyday example is breeds of dogs: Chihuahuas and Doberman pinschers, though having very different outward appearances, are both the same species, *Canis lupus familiaris*.

### **Population Diversity**

A population is a group of the same species with a shared characteristic, usually living in the same area. Scientists also differentiate populations by their breeding rates and migration patterns, among other characteristics. The species, *Puma concolor*, for example, is known by many common names, including mountain lion, cougar, puma, catamount, because the large cat lives in wild areas from the southwestern United States to the Andes of South America. About thirty-two subspecies of *Puma concolor* have been described based on geographic location and differences in size and form; for example, their size varies from about 50 to 70 kg (100 to 155 lbs.) at the equator and reaching twice that size at the northern extent of their ranges (Canada’s Yukon and Argentina’s Patagonian pampas). Recent genetic analyses divide puma subspecies into six main groups, largely separated by geographic barriers that have restricted gene flow (or the transfer of genes between populations via migration).

Population diversity may be measured by the variation in genetic and morphological features that define different populations. This diversity may also be measured in terms of a population’s demographics, such as the number of individuals present or the proportion of different ages or sexes in the population. However, it is difficult to measure demography and genetic variation (e.g., allele frequencies). A more practical way of



**Figure 1.2** Even in one species there can be an incredible morphological diversity. Brussels sprouts (upper left), cabbage (center), kohlrabi (upper right), cauliflower (lower right), broccoli (lower left) are all the same species *Brassica oleracea*. They represent the following varieties: gemmifera, capitata, gonglyodes, botryis, and botryis (Frey © CBC-AMNH. Used by permission)

defining a population and measuring its diversity is to simply determine the area that a population occupies. Using this criterion, a population is a group of individuals of the same species occupying a particular area at the same time. The area occupied is usually defined based on ecological needs important to the species: for example, a particular pond or lake for a population of fish, or a south-facing slope for a population of light-loving trees.



The geographic range and distribution of populations (or their spatial structure) represent key factors in analyzing population diversity because they give an indication of the likelihood of movement of individuals between populations, and consequently of genetic and demographic interchange. Similarly, an estimate of the overall population size provides a measure of the potential genetic diversity within the population; large populations usually represent larger gene pools and hence greater potential diversity (see “Genetic Diversity”). Even though many species of sea turtles are wide ranging, their populations are segmented, depending in part on their tolerance for different temperatures and habitat preference. Among the world’s seven species of sea turtles, the cold-tolerant leatherback’s (*Dermochelys coriacea*) populations in the Indo-Pacific and Atlantic are genetically connected, while the tropical green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*), and olive and kemp’s ridleys (*Lepidochelys olivacea* vs. *L. kempfi*) have ancient separations between oceans.

Isolated populations, with very low levels of interchange, may show high levels of genetic divergence, and exhibit unique adaptations to the biotic and abiotic characteristics of their habitat. The genetic diversity of groups that generally do not disperse well—such as amphibians and some herbaceous plants—may be restricted to local populations. For this reason, range retractions of species leads to loss of local populations and the genetic diversity they hold. Loss of isolated populations, along with their unique genetic variation, is considered by some scientists to be one of the greatest but most overlooked tragedies of the biodiversity crisis. Isolated populations of species are basically incubators for new species; when they disappear, the potential for the evolution of a new species also disappears.

Populations can be categorized according to the level of divergence between them. Isolated and genetically distinct populations of a single species are often called subspecies. Animal populations that show less genetic divergence might be recognized as “variants” or “races.” For plants, the ranks below species include subspecies, variety, subvariety, form, and subform. However, the distinctions between subspecies and other categories can be somewhat arbitrary (see below for further discussion under “Species Diversity”).

A species with specialized habitat needs may assume the same distribution as that particular habitat type. Populations of that species are likely to be confined within patches of that habitat type. For example, alpine species may be confined to particular mountaintops, and each mountaintop would represent a population of that species. This

is the case, for example, for species that live in small wetlands, springs, caves, particular soil or forest types, and many other comparable situations. Periodically, individual organisms may disperse from one population to another, facilitating genetic exchange between the populations. This group of different but interlinked populations, with each population located in its own, discrete patch of habitat, is called a *metapopulation*.

### ***Species Diversity***

This is the level of biodiversity that most of us are aware of on a day-to-day basis, whether through information from environmental organizations, the news, or the Discovery Channel. While what exactly defines a species is a matter of debate among scientists (see description of different species concepts below), much environmental management and political attention focuses on individual species. The Endangered Species Act of the United States, which aims to protect species richness, is one example.

Species diversity has two components: the number of different species in a particular area, and the relative abundance of individuals within different species in the same area. This first component is known as *species richness*, while the second is known as *species evenness*. An ecosystem in which all the species are represented by the same number of individuals has high species evenness. In contrast, an ecosystem in which some species are represented by many individuals, and other species are represented by very few individuals, has low species evenness. *Species diversity* encompasses both species richness and evenness. It is common, though incorrect, for people to use the term “species diversity” interchangeably with species richness.

Species diversity is often described in terms of the *phylogenetic diversity*, or evolutionary relatedness, of the species present in an area. (Note that phylogenetic diversity also exists at the genus and family level.) For example, some areas may be rich in closely related taxa, having evolved from a common ancestor that was also found in that same area, whereas other areas may have an array of less closely related species descended from different ancestors.

Scientists and conservation managers use diversity indices to quantitatively describe species diversity. One of the most well known is the Shannon index, which incorporates species richness (or the number of species) and species evenness (the abundance of each species) to measure the diversity of an area. In a typical acre (4,047 sq. m.) of most northern forests, there are about a dozen tree species. For example, a

mixed-hardwood forest in the northeastern United States is dominated by beech and maple trees, with birch and ash trees at lower densities. These forests have high species evenness, but low overall species richness. In contrast, tropical rainforests have hundreds of species per acre, but each one at a low abundance. Thus, they have high species richness but low species evenness.

### What Is a Species?

To count the number of species, we must define what we mean by a *species*. There are several competing ways of defining a species. While this might seem like a strange topic to disagree on, we hope that the following explanation will reveal some of the reasons scientists have not reached a consensus on how to define a species. After all, natural selection and evolutionary theory predicts that species are not static entities. Species evolve and change, sometimes into new and different species. How does one decide when two populations are different enough to constitute two species? The different species concepts (morphological, biological, and phylogenetic) outlined below answer this question in different ways. The concepts center on ideas of genetic relatedness, or ancestry, among species. These concepts are not congruent, and considerable debate exists about their advantages and disadvantages. Different models are typically useful for different applications. Just as the behavior of light cannot be explained entirely by either the wave or the photon model, individual species concepts cannot explain all of the ways of thinking of how to distinguish between species.

The *morphological species concept* is the oldest of the approaches currently used to answer the question, what is a species, and also the most readily understandable. According to this concept, individuals that look alike and share the same identifying traits belong to the same species. While this is an outdated concept, this is still the method that biologists initially use to distinguish one species from another in a field setting: maple trees have leaves with triangular lobes; Thompson's gazelles have a white patch bisected by a black stripe on their sides; and Queen Anne's lace has small, white, composite flowers. One flaw of this concept is that it is really a matter of opinion as to how similar two individuals must be in order to count them as the same species. This method is a useful way to generally categorize species, but its application is limited at finer levels. Genetic analyses are leading to a reevaluation of the concept as discoveries reveal that individual animals that superficially look the same are actually different species.




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### CRYPTIC CASCADE FROGS

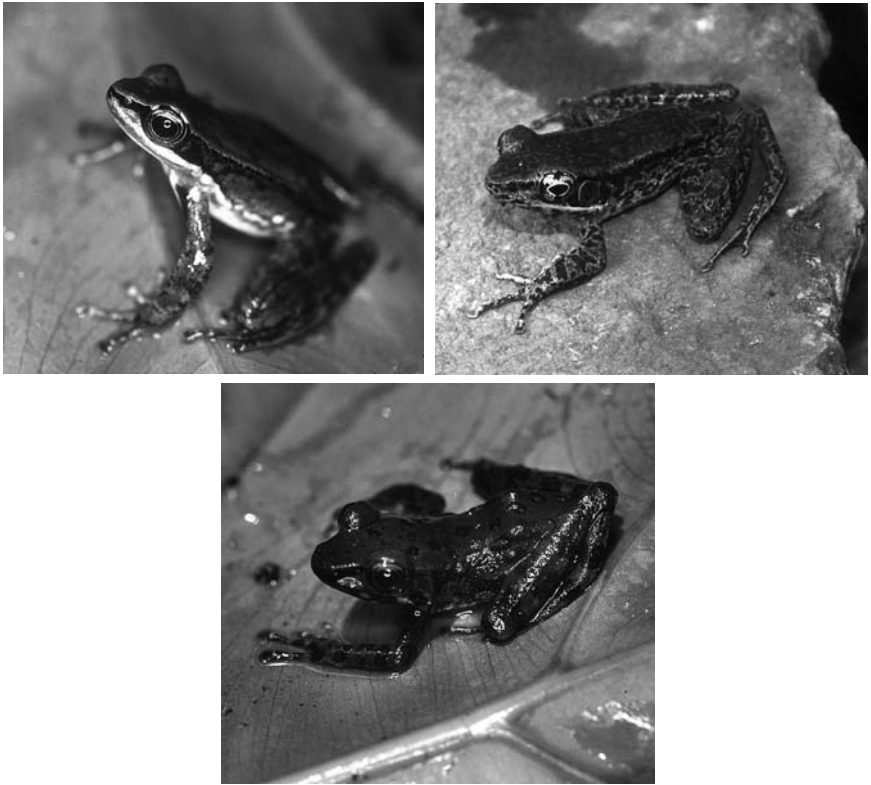
Cascade frogs of the *Rana chloronota* complex live in fast-moving montane streams and nearby forested areas in various parts of Southern Asia (see Figure 1.3). Until recently the three species of cascade frogs that make up the *Rana chloronota* complex were thought to be one species as they were very similar looking. These are often termed *cryptic species*.

*Rana chloronota* is a widespread species that is found in montane waterways of Central and Northern Vietnam, and at the same latitudes in China, Myanmar, and India. *Rana morafkai* was recently described from Vietnam's Central Highlands, but has also been documented in Lao PDR. *Rana banaorum* has only been found in the Central Highlands of Vietnam and only described in 2003. Since these species are very similar looking, their exact ranges and the relationships among the species are still unclear.

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### What Kinds of Species?

When asked what he had learned about God after studying nature, British scientist Lord Haldane famously replied that he must have had “an inordinate fondness for beetles” (Hutchinson 1959, p. 146)



**Figure 1.3** Cryptic species look so similar to other species that they are easily misidentified. These cascade frogs of the *Rana chloronota* complex are one example. Once considered to be a single species, they represent three different species: *Rana chloronota*, *Rana morafkai*, and *Rana banaorum* (Bain ©CBC-AMNH. Used by permission)

Our understanding of species reflects human biases toward species that are more like us or are important to us. So, most people's (and scientist's) attention has focused on large, charismatic, and economically important species, such as mammals, birds, and certain trees (e.g., mahogany, sequoia) and fish (e.g., salmon). However, the majority of Earth's species are found in other, generally overlooked groups, such as bacteria, mollusks, insects, and flowering plants. The largest group of described species is the Arthropods, with about 1.5 million identified to date; they make up about 75 percent of known species. Arthropods include insects, spiders, crustaceans (e.g., crabs and lobsters), and centipedes. Though often forgotten, these groups play important functional

roles in ecosystems, and future scientific effort will continue to uncover their roles.

The proportional representation of different groups of related species (e.g., bacteria, flowering plants, insects, birds, mammals) is usually referred to as taxonomic or phylogenetic diversity. Species are grouped together according to shared characteristics (genetic, anatomical, biochemical, physiological, or behavioral), which leads to a classification of species based on their apparent evolutionary or ancestral relationships. We then use this information to assess the proportion of related species with respect to the total number of species on Earth (see Tables 1.2 and 1.3).

**Table 1.2** Estimated Number of Species by Taxonomic Group

| Taxon            | Taxon Common Name   | Number of Species Described ( <i>N</i> )* | <i>N</i> as Percentage of Total Number of Described Species* |
|------------------|---|---|--|
| Bacteria         | true bacteria   | 9,021                                     | 0.5  |
| Archaea          | archaebacteria  | 259                                       | 0.01   |
| Stramenopiles    | stramenopiles   | 105,922                                   | 6.1  |
| Angiospermae     | flowering plants  | 233,885                                   | 13.4   |
| Other Plantae    | (e.g., red algae, mosses, ferns, conifers)                        | 49,530                                    | 2.8  |
| Fungi            | fungi   | 100,800                                   | 5.8  |
| Mollusca         | mollusks  | 117,495                                   | 6.7  |
| Nematoda         | nematodes   | 20,000                                    | 1.1  |
| Arachnida        | arachnids   | 74,445                                    | 4.3  |
| Crustacea        | crustaceans   | 38,839                                    | 2.2  |
| Insecta          | insects   | 827,875                                   | 47.4   |
| Other            | (e.g., cnidarians, platyhelminths, annelids, Metazoa echinoderms) | 82,047                                    | 4.7  |
| Actinopterygii   | ray-finned bony fishes  | 23,712                                    | 1.4  |
| Other Vertebrata | (e.g., amphibians, reptiles, mammals, birds)                      | 27,199                                    | 1.6  |
| Other Eucarya    | (e.g., alveolates, euglenozoans, choanoflagellates)               | 36,702                                    | 2.1  |

\* The table includes representatives from the three recognized domains of Archaea, Bacteria, and Eucarya. Examples of eucaryan groups are restricted to those that include at least 1 percent of the total number of described species on Earth. The total number of species is estimated at 1,747,851.

*Source:* This figure, and the numbers of species for representative taxa are based on Lecointre and Guyader (2001).

**Table 1.3** Of the 1.7 million species described, the vast majority of them are insects

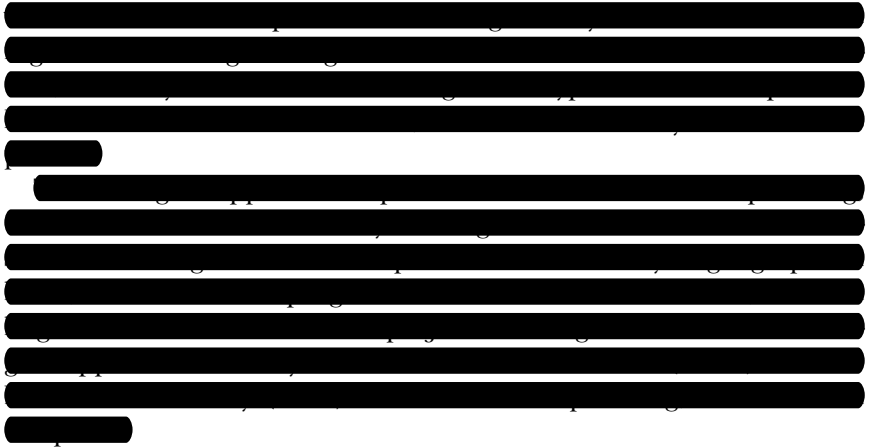
| Taxonomic Group   | Proportion of Total Described Species |
|---|---------------------------------------|
| Insects   | 47.3%                                 |
| Flowering Plants  | 13.4                                  |
| Mollusks  | 6.7                                   |
| Stramenopiles   | 6.1                                   |
| Fungi   | 5.8                                   |
| Other Invertebrates (cnidarians, annelids, echinoderms, platyhelminths)             | 4.7                                   |
| Arachnids   | 4.3                                   |
| Other Plants (red algae, moss, fern, conifers)                                      | 2.8                                   |
| Crustaceans   | 2.2                                   |
| Other Eucaryotes (choanoflagellates, euglenozoans, alveolates)                      | 2.1                                   |
| Other Vertebrates (includes all species of birds, mammals, reptiles and amphibians) | 1.6                                   |
| Ray-finned bony fishes  | 1.4                                   |
| Nematodes   | 1.1                                   |
| Bacteria  | 0.5                                   |
| Archaeobacteria   | 0.1                                   |

MEASURING BIODIVERSITY

Measuring biodiversity is not a straightforward task. Not only is it difficult to define what a species is, but it is often also a challenge to sample and identify species. Before 1982, most scientists estimated that the number of species on the planet was in the order of millions. It was a new approach to sampling beetles that led to a reevaluation of how many species exist. Forest canopies (vegetation and branches of trees above ground, including the crowns of trees and any plants growing on them) were believed to host an incredible diversity of beetles but are difficult to access. In fact, most forest species live in the canopy. An innovative sampling technique of tree canopies pioneered by scientist Dr. Terry Erwin in 1982 led to a major revision of the number of beetle species on the planet. Erwin fogged the tree canopy with a pesticide, catching all the insects below. Erwin sampled nineteen trees of one species (*Luehea seemannii*) over the course of three seasons and found over 1,200 different beetle species. He used these discoveries to calculate the total number of arthropods on the planet. Erwin calculated the number of specialized beetles per tropical tree species as 165. As beetles make up about 40 percent of arthropods, he then came up with an estimate of specialized arthropods and multiplied this by the number of

tropical tree species (~50,000) to get to an estimate of 30 million tropical insects. (Essentially Erwin used tree species richness as a proxy for insect diversity.). This led to a revision of the number of species on the planet from millions to tens of millions, though some estimates are considerably higher. However, most biologists think some of Erwin's assumptions were incorrect, for example the number of specialized insects has been reduced by a factor of four, and led to an overestimate of the number of undescribed species. Erwin's study nevertheless led to a major increase in the number of species believed to exist on the planet compared to estimates before his study. Even today no one really knows the exact number of species on the planet and some of the smallest species (bacteria) are only now being studied more intensely.





### **Biodiversity over Time**

The evolutionary history of Earth has physically and biologically shaped our contemporary environment. As noted in the section on *Biogeography*, plate tectonics and the evolution of continents and ocean basins have been instrumental in directing the evolution and distribution of the Earth's biota. The physical environment has also been extensively modified by these biota. Many existing landscapes are based on the remains of earlier life forms. For example, some existing large rock formations are the remains of ancient reefs formed 360 to 440 million years ago by communities of algae and invertebrates. Very old communities of subterranean bacteria may have been responsible for shaping many geological processes during the history of the Earth, such as the conversion of minerals from one form to another, and the erosion of rocks. The evolution of photosynthetic bacteria, sometime between 3.5 and 2.5 billion years ago, played an important role in the evolution of the Earth's atmosphere. These bacteria released oxygen into the atmosphere, changing its composition from 1 percent oxygen to the one we know today, where oxygen makes up 21 percent of the atmosphere. It probably took over 2 billion years for the oxygen concentration to reach the level it is today. The process of oxygenation of the atmosphere led to important evolutionary changes. Organisms developed mutations that enabled them to use oxygen as a source of energy. The rise of animal and plant life on land was associated with the development of an oxygen-rich atmosphere.

### **Extinction**

*Extinction*, or the complete disappearance of a species from Earth, is an important part of the evolution of life. The current diversity of species

is a product of the processes of extinction and speciation throughout the 3.5 billion year history of life. Assuming there are about 40 million species alive today, and between 5 and 50 billion species have lived at some time during the history of the Earth, then 99.9 percent of all the life that has existed on Earth is now *extinct* (Raup 1991). Most (if not all) species eventually become extinct. The average duration of a species in the fossil record [or the species turnover time] is a few million years. Most vertebrates last about 1 to 3 million years, while invertebrates last about 10 to 30 million years. Of course, there are some species that have defied the odds; these ancient species are often called “living fossils” for their ability to survive unchanged over long periods of time (see Table 1.5). The horseshoe crab is even more ancient than once thought. Recent fossils discovered in Manitoba in 2007 indicate it originated 450 million years ago. It is the oldest marine arthropod, actually more closely related to spiders than crabs. It is still widespread; besides the species in the Atlantic Ocean, three species in the same family (*Limulidae*) are found in the Indian and Pacific Oceans, it is particularly common in the Gulf of Mexico.

**Table 1.5** These “Living Fossils” Have Survived Unchanged against the Odds. Most Vertebrates Survive 1 to 3 Million Years on Earth, While Invertebrates Last About 10 to 30 Million Years

| Common Name/Scientific Name                                       | Origins           | Current Distribution   |
|---|-------------------|--|
| Horseshoe crab ( <i>Limulus polyphemus</i> )                      | 450 million years | Atlantic Ocean; three species in the same family ( <i>Limulidae</i> ) are found in the Indian and Pacific oceans |
| Ginkgo or Maidenhair Tree (tree) ( <i>Ginkgo biloba</i> )         | 170 million years | Eastern China  |
| Dawn Redwood (tree) ( <i>Metasequoia glyptostroboides</i> )       | 100 million years | remote valley in Central China   |
| Wollemi Pine ( <i>Wollemia nobilis</i> )                          | 110 million years | Australia  |
| Gladiator Insects (Mantophasmatodea—12 species in the Order)      | 45 million years  | Southern Africa  |
| Coelacanth (fish) ( <i>Latimeria spp.</i> )                       | 410 million years | Madagascar, East Africa, Indonesia   |
| Tuatara (related to lizards and snakes) ( <i>Sphenodon spp.</i> ) | 220 million years | New Zealand  |
| Chambered Nautilus ( <i>Nautilus pompilius</i> )                  | 500 million years | Andaman Sea and southern Pacific, west to the island of Fiji   |

Source: Compiled by Laverty.

**Table 1.6** Geological Timeline

| Duration (millions of years) | Era         | Period        | Events                                   |
|------------------------------|-------------|---------------|--|
| 3,800 to 570                 | Precambrian |               | Bacteria and blue-green algae            |
| 570 to 500                   | Paleozoic   | Cambrian      | First invertebrates                      |
| 500 to 440                   |             | Ordovician    |  |
| 440 to 410                   |             | Silurian      | First land plants                        |
| 410 to 365                   |             | Devonian      | First land invertebrates                 |
| 365 to 290                   |             | Carboniferous | First ferns and seed plants              |
| 290 to 245                   | Mesozoic    | Permian       | First insects                            |
| 245 to 210                   |             | Triassic      | First amphibians                         |
| 210 to 140                   |             | Jurassic      | First flying insects                     |
| 140 to 65                    |             | Cretaceous    | First reptiles                           |
| 65 to 55                     | Cenozoic    | Tertiary      | Extinction of trilobites                 |
| 55 to 38                     |             |               | First dinosaurs                          |
| 38 to 25                     |             |               | First mammals                            |
| 25 to 5                      |             |               | First birds                              |
| 5 to 2                       |             |               | First flowering plants                   |
| 0.01–2                       |             | Quaternary    | First primates                           |
| Present–0.01                 |             |               | Extinction of dinosaurs                  |
|                              |             |               | Extinction of ammonites                  |
|                              |             |               | Diversification and spreading of mammals |
|                              |             |               | Eocene                                   |
|                              |             |               | Oligocene                                |
|                              |             |               | Miocene                                  |
|                              |             |               | Pliocene                                 |
|                              |             |               | Pleistocene                              |
|                              |             |               | Holocene                                 |

Source: Compiled by Laverty.

Extinction has not occurred at a constant pace through the Earth’s history. There have been at least five *mass extinctions*, periods when the extinction has more than doubled, and the taxa affected have included representatives from many different taxonomic groups of plants and animals. They occurred at the end of the Ordovician, Devonian, Permian, Triassic, and Cretaceous periods (see Table 1.6). The most famous of these was at the end of the Cretaceous when the dinosaurs disappeared, as did two-thirds of marine life.

**Table 1.7** Major Mass Extinction Events

| Time (millions of years ago) | Extinction Event              | Description   |
|------------------------------|-------------------------------|---|
| 440                          | 1st Ordovician                | Eliminates most marine species; many groups lose more than half their species           |
| 360                          | 2nd Devonian                  | Two-thirds of all species disappear, primarily marine species                           |
| 251                          | 3rd Permian                   | More than 90 percent of all species disappear. The worst of the known extinctions       |
| 200                          | 4th Triassic                  | 20 percent of species disappear   |
| 65                           | 5th Cretaceous-Tertiary (K-T) | The most famous of past extinctions; 60 percent of species died including the dinosaurs |
| Present day                  | 6th                           |   |

Source: Compiled by Laverty.

Each of the first five mass extinctions shown in Table 1.6 and Table 1.7 represents a significant loss of biodiversity—but species diversity recovered over geologic time scales. Mass extinctions are apparently followed by a sudden burst of evolutionary diversification on the part of the remaining species; some evolutionary biologists suggest this is because the surviving species start using habitats and resources that were previously “occupied” by species that went extinct. However, these bursts of diversification do not mean that the recoveries from mass extinction have been rapid; they have usually required some tens of millions of years. The theory describing these brief bursts of evolutionary change is known as *punctuated equilibrium*.

The most striking example of diversification—rapid, on an evolutionary time scale of 10 million years—was the Cambrian explosion. During this relatively short time period, all the animal body plans existing today developed. Before this period, the vast majority of life on earth was restricted to unicellular or undifferentiated multicellular organisms. Scientists still hotly debate what caused such a spectacular spurt of evolutionary radiation and why it subsided, since evolution has proceeded at a more gradual pace subsequently.

Many scientists believe we are on the brink of a “sixth mass extinction,” but one that differs from previous events. The five other mass extinctions

predated humans, and while theories abound about their causes, they were probably due to some physical process (e.g., catastrophic climate change through meteor impacts or volcanic eruptions), rather than the direct consequence of the action of some other species. In contrast, the sixth mass extinction is the product of human activity over the last several hundred, or even thousand years. In the prehistoric past, humans caused mass extinctions when they migrated to new areas. For example, scientists hypothesize that the large-scale extinction of large mammals (including camels, bears, sloths, saber-toothed tigers, and mammoths) in North America about 12,000 years ago was due to overhunting by humans following colonization. The scale of change in the last 200 years has been similarly severe. Species that were once plentiful have now been drastically reduced in numbers or are completely gone.



**Figure 1.4** The extinction of the passenger pigeon (*Ectopistes migratorius*) in the United States is a dramatic example of human-caused extinction (See Figure 1.6) (Edouard Poppig 1841)

The extinction of the passenger pigeon (*Ectopistes migratorius*) in the United States is a dramatic example of human-caused extinction (see Figure 1.4). At the time of the European settlement of North America, passenger pigeons represented 25 to 40 percent of the total bird population of North America. Populations are estimated to have been as high as 3 to 5 billion birds; recent studies suggest that the high population may have also been due to the loss of their predators. Widespread forest clearing and then large-scale hunting of the birds for urban markets eventually led to the passenger pigeon's precipitous decline at the end of the nineteenth century. Once governments and citizens recognized the problem and attempted to address it, however, it was too late. The passenger pigeon required large flocks to breed successfully and could not adapt to survive within

smaller flocks. The last known passenger pigeon died in captivity in 1914.

It is sometimes difficult to know exactly when a species is extinct in the wild. As they near extinction they are obviously difficult to observe, since they are rare and likely living in remote areas. A species is assumed to be extinct when there is no reasonable doubt that the last individual has died. Usually the rule of thumb is that a species is extinct if after extensive field surveys the species has not been seen for 50 years (though the exact amount of time varies based on the species' lifespan). The Ivory-Billed Woodpecker (*Campephilus principalis*) was thought to be extinct in the 1980s. It may have been rediscovered in 2004, but there is still uncertainty as to whether it has been found again. It is possible the "rediscovery" is simply a misidentified Pileated Woodpecker (*Dryocopus pileatus*).