An Introduction to

Conservation Biology

THIRD EDITION

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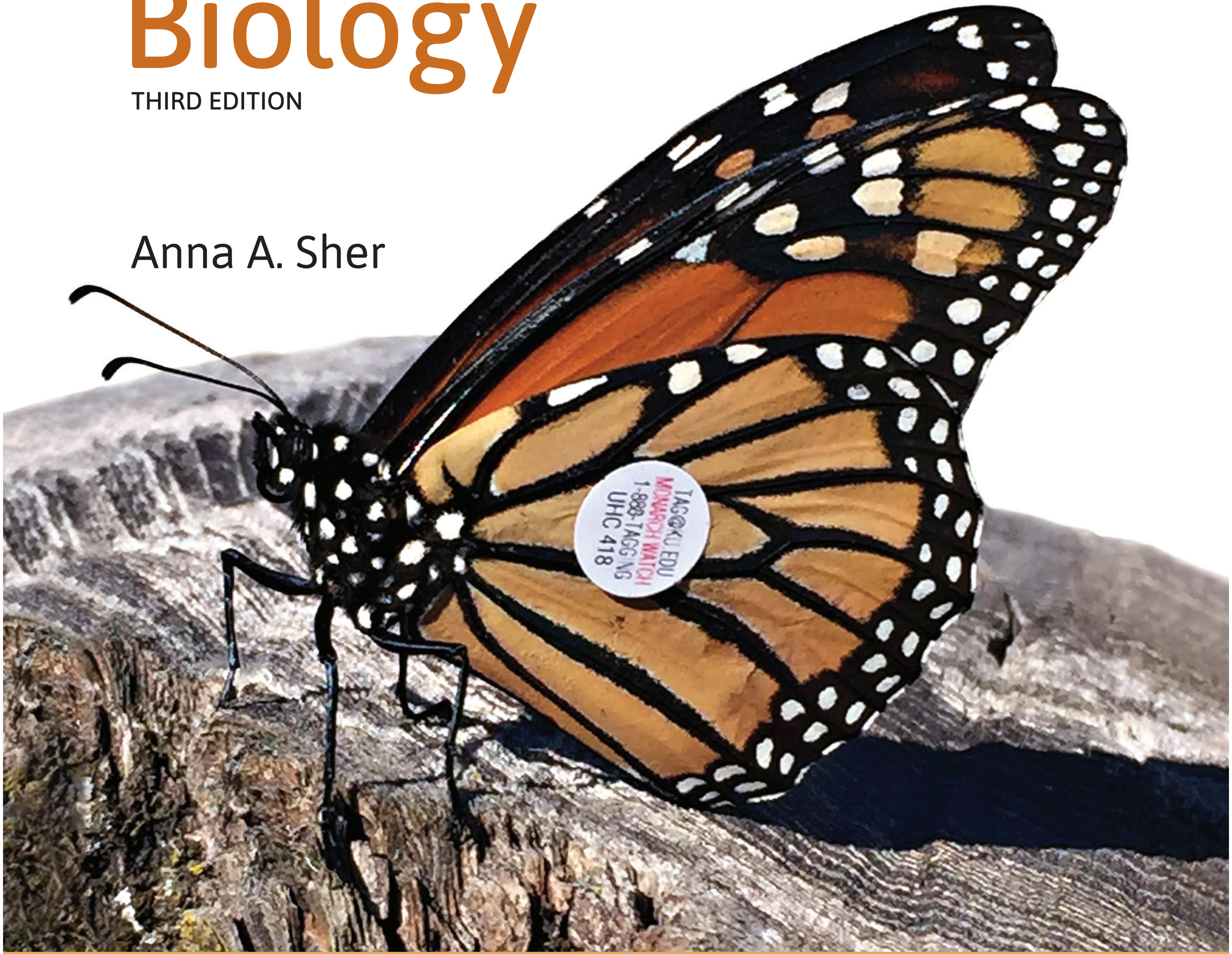
Anna A. Sher



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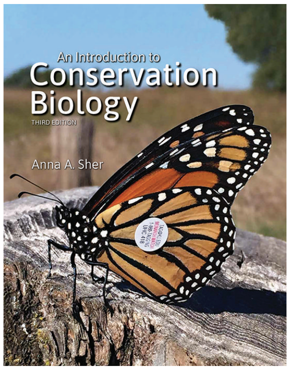

About the Cover

Monarch butterflies (*Danaus plexippus*) travel as much as 6000 km across North America in their annual migration to overwinter in Mexico. Like most species, their primary threat is habitat loss, symbolized here by the cut stump upon which the butterfly rests. The conservation effort of tracking monarchs and monitoring their populations involves gently placing labelled stickers on the wings. The scope of this work has greatly expanded with the help of citizen scientists, who both label butterflies and report recoveries of labels. Monarch Watch, whose label is shown in this picture, distributes more than a quarter million labels to thousands of volunteers each year. Tracking monarchs provides data about their origins, timing and routes of migration, mortality rates, and geographic distribution, which conservation biologists can use to help protect them in the future, in the face of climate change and other threats.

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To Dr. Richard B. Primack.
Your past and ongoing work in the discipline inspires and motivates us to do all we can for the future of biodiversity.

And for Michael Soulé (1936–2020), a father of the field.

Contents

Preface

To say that much has happened since the last edition is, of course, a gross understatement. Climate change has manifested in unprecedented wildfires, floods, and global temperatures. I spent much of the pandemic revising both this text and my other textbook in ecology, which is reflected in several chapters referencing this major historical event. I discuss how COVID-19 opened many people's eyes to the connections between wildlife, conservation, and disease (Chapter 5). A proposed vector of SARS-CoV-2, the virus that causes COVID-19, has been the pangolin, the most trafficked wild animal in the world. There are eight species of pangolin, ranging from vulnerable to critically endangered. When animals such as the pangolin are trapped and sold, the proximity to humans can lead to *zoonosis*, the spread of disease to humans from another species (a new term in this edition). The Chinese government established new protections for pangolins in 2020, and the US government may also increase protections for the pangolin in 2021.

The COVID-19 pandemic facilitated other benefits for conservation. It made people aware of the wildlife that coexists with us, even in cities, but had been rarely seen before we were sequestered in our homes (see Chapter 10 opening photo). Widespread quarantine also provided a decrease, even if short, in industrial emissions that contribute to global warming (Chapter 5). The quarantine and closures due to COVID-19 also provided taxonomists with the opportunity to work on the backlog of field-collected specimens, revealing hundreds of new species (Chapter 2).

Throughout the past two years, the increase in use of social media has helped to spread information and awareness around conservation. This has included illuminating the role African American Civil War soldiers (nicknamed Buffalo Soldiers) played in the protection of Yosemite and Sequoia National Parks under the leadership of Captain Charles Young. Several streamed movies and television series promoted a conservation message, with *David Attenborough: A Life on Our Planet, My Octopus Teacher,* and *Secrets of the Whales* recently among the most popular. Some argue that even the COVID-19 quarantine favorite *Tiger King* helped educate the public about the plight of endangered animals in private zoos. TikTok, Facebook, Instagram, and other social media platforms have become important tools to communicate conservation ideas.

Although the human population is both larger and growing faster than ever before (I had to revise the estimate for 2050 upward by 300 million people), this is the first edition to forecast a future human population decline (Chapter 1). What this may mean for global biodiversity is unclear, but given the association between human population growth and biodiversity loss, I choose to be optimistic. Other positive developments include the progress toward reaching the Aichi Biodiversity Target 11 for protected areas (Chapter 9) and the significant increases in foreign aid to developing countries to protect biodiversity (Chapter 12). We have also seen the power of effective legislation, an example being the dramatic decrease in the trade of wild-caught birds after the European Union banned it (Chapter 5).

Conservation science is necessary to continue progress where possible and to help find new solutions (Chapter 13). We must also capitalize upon the growing public awareness that the fate of biodiversity is connected to our own. It is critical that we not allow the losses we have witnessed overshadow the progress and reasons for hope. Indeed, I believe our very future depends on it.

New to the Third Edition

The following updates maintain *An Introduction to Conservation Biology* as the most current and scientifically accurate textbook of its type. For the third edition, my team's systematic review of every numerical value in the textbook resulted in over 240 changes to text and tables, 275 new citations, and new figures in every chapter. These changes include updating numbers of species, endangerment figures, trade in wildlife, nonprofit and government organization statistics, and many, many other numerical values based on the best information available.

The new citations also reflect my commitment to increase the representation of women and BIPOC in the textbook—an important and ongoing effort to make the text reflect the diversity of scientists in the field. One aspect of this work involved making significant edits and additions regarding the roles and experience of Indigenous People, also known as first people or native people, in the field of conservation biology. These included acknowledging the theft of land to create protected areas (Chapter 9 opening photo), incorporating the importance of traditional ecological knowledge (TEK) (Chapters 10 and 11), expanding coverage of the role of Indigenous People in development and implementation of environmental policy and programs (Chapters 12 and 13), and generally reviewing language used throughout the textbook.

In addition to COVID-19 and other current events, I incorporated several new discoveries and developments from the past two years, including the following:

- The latest understanding of the causes of the Permian extinction
- The UN Decade on Ecosystem Restoration (2021–2030) and its principles to guide restoration
- Connections between human disease and biodiversity conservation

GLOBAL CHANGE CONNECTION

To highlight content related to the many ways we are changing the Earth, this edition has the added feature of the "Global Change Connection" icon. *Global change* in this context refers to any impact on ecosystems caused by anthropogenic activity that can be considered a global issue, including climate change, invasive species, pollution, and habitat loss.

I have responded to the feedback of expert reviewers, instructors, and student users of the textbook with several edits. Among the dozens of changes are these:

- Additional discussion on the political aspects of climate change and of genetically modified organisms (GMOs)
- An elaboration of the concept of the types of biodiversity, including a refinement of the definition of *species diversity*, with additional examples
- A reorganization of the chapter on restoration ecology, including new graphical representation of the outcomes of restoration and new research on the importance of the human element

In addition to the aforementioned revisions to the text, the new edition includes upgraded digital resources for instructors and students. First, the text is available in a new enhanced e-book format, which includes self-assessment questions following each major section heading. The second digital resource for instructors is a curated list of freely accessible videos from various sources that can be used as teaching aids for key concepts in each chapter.

Acknowledgments

First and foremost, I acknowledge Richard B. Primack, the author of the conservation biology books that were the foundation of this series. I was honored when he asked me to be his successor author for *A Primer of Conservation Biology* and then when it was decided that my integration of that text with Primack's *Essentials of Conservation Biology* warranted a new series, *An Introduction to Conservation Biology*. There are nods to both original textbooks in this edition, the most important being my goal to uphold each book's legacy as a scientifically accurate, relevant, and accessible resource for undergraduate students. Thank you, Richard, for your past mentorship and the privilege of being the sole author of this, the newest edition.

The monumental effort necessary to keep a textbook current is not possible without the support of many people. First, I thank Eduardo González, my academic partner in all things, and Violet Butler, who together did significant research to update this edition, and the many reviewers who helped us make this the best book it can be. I am also grateful to the rest of the Sher Lab and the University of Denver DUEEB group for their general support and feedback on figures.

Thank you to our reviewers of the second edition, including Andrew J. Rassweiler, Janet Steven, Susan Margulis, Elizabeth Freeman, John B. Graham, Pamela A. Morgan, Bibit Traut, Jessica Claxton, Michael Remke, and three anonymous reviewers. Know that some of the more substantial changes among your recommendations will help shape future editions. Thank you to all those who provided data or reviewed sections, including Patrick M. Burchfield.

I am grateful for all the photos that have been donated by colleagues over the years. Wonderful new images for this edition have been provided by Wayne Armstrong, Hector R. Chenge, Scott Dressel-Martin of Denver Botanic Gardens, and Joseph Thomas. As always, a special thanks to Richard Reading for both his excellent photographs and conservation stories.

I cannot write these textbooks without the support of my wife, Fran, and our son, Jeremy. The team at Sinauer Associates and Oxford University Press who produced this book during such a challenging time also deserve special kudos: Senior Acquisitions Editor Jason Noe, Senior Production Editor Alison Hornbeck, Production Manager Joan Gemme, Production Specialist and Book Designer Rick Neilsen, Photo Researcher Mark Siddall, Permissions Supervisor Michele Beckta, Editorial Assistant Sarah D'Arienzo, the excellent copyeditor Lou Doucette, and everyone else who helped make this third edition the best possible book.

Finally, I acknowledge all the scientists and practitioners who do the work of conservation. In particular, I wish to honor the brave conservationists who lost their lives because of their dedication; there were literally dozens in only the past two years. These souls include Homero Gómez González and Raúl Hernández Romero, champions of the monarch butterfly in Mexico; Joannah Stutchbury, a Kenyan known for her work to conserve the Kiambu Forest; Irishman Rory Young, cofounder of the antipoaching organization Chengeta Wildlife; and Kavous Seyed-Emami, an environmentalist and professor studying the rare Asiatic cheetah in Iran. In most if not all cases, the violence was attributed to individuals or groups who felt that conservation work was interfering with their financial interests. May the injustice of their deaths motivate to action those of us with the privilege and capacity to act.

Anna A. Sher
Denver, Colorado
October 21, 2021

About the Author

Anna A. Sher is a Professor of Biology at the University of Denver, where she has taught conservation biology since 2003. She held a joint position as the Director of Research and Conservation at Denver Botanic Gardens from 2003–2010. Dr. Sher has published books and articles for academic, trade, and popular audiences on various topics within conservation biology, including restoration ecology, rare plant conservation, and climate change. She is one of the foremost experts on the ecology of invasive *Tamarix* trees and was the lead editor of the book *Tamarix: A Case Study of Ecological Change in the American West* (Oxford University Press, 2013). She is also first author of the textbook *Ecology: Concepts and Applications, 9th Ed.* (McGraw-Hill Education). Dr. Sher received her Ph.D. in Biology at the University of New Mexico in 1998 and was a postdoctoral fellow at the University of California, Davis and as a Fulbright Scholar in Israel. Dr. Sher also led scientific study-abroad programs in East Africa, and has been a visiting scholar at the University of Otago in New Zealand. She is an advocate for social justice and is currently leading a campus-wide coalition to support women and increase diversity in STEM academic professions. She and her wife and son live, work, and play in Denver, Colorado.

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For the Instructor

(Instructor resources are available to adopting instructors online. Registration is required. Please contact your Oxford University Press representative to request access.)

The Instructor Resources for *An Introduction to Conservation Biology*, Third Edition offer all the textbook's figures and tables, making it easy for instructors to incorporate visual resources into their lecture presentations and other course materials.

The site includes the following resources:

Figure PowerPoint Slides – All the figures and tables from each chapter, with titles on each slide, and complete captions in the Notes field.

Video Guide – A curated list of freely accessible videos from various sources that can be used as teaching aids for key concepts in each chapter.

Chapter Summaries – Useful aids summarizing each chapter's key concepts.

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Conservation Biology

THIRD EDITION

Santos Alfonso Bernal Avalos releases Kemp's ridley sea turtles (*Lepidochelys kempii*) off the coast of Tamaulipas, Mexico, in 2020. A binational conservation effort has been successful in rescuing this species from the brink of extinction.

Defining Conservation Biology

1

Popular interest in protecting the world's **biological diversity**—including its amazing range of species, its complex ecosystems, and the genetic variation within species—has intensified during the last few decades. Studies have found that the number of Google searches on conservation-related topics, including extinction, has dramatically and consistently increased each year (Burivalova et al. 2018; Williams et al. 2020). It has become increasingly evident to both scientists and the general public that we are living in a period of unprecedented losses of **biodiversity**[1] (Pimm et al. 2014). Around the globe, biological ecosystems—the interacting assemblages of living organisms and their environment that took millions of years to develop—are being devastated, including tropical rain forests, coral reefs, temperate old-growth forests, and prairies. Thousands, if not tens of thousands, of species and millions of unique populations are predicted to go extinct in the coming decades (Ceballos et al. 2015). Unlike the mass extinctions in the geologic past, which followed catastrophes such as asteroid collisions with Earth, today's extinctions have a human face.

[1] *Biological diversity* is often shortened to *biodiversity* (a term credited to biologist E. O. Wilson in 1992); it includes all species, genetic variation, and biological communities and their ecosystem-level interactions.

Photo by Hector Raul Chenge Alvarez

During the last 200 years, the human population has exploded. It took more than 160,000 years for the number of *Homo sapiens* to reach 1 billion, an event that occurred sometime around the year 1805. Estimates for 2021 put the number of humans at 7.8 billion, with a projected 9.7 billion by 2050 (https://www.worldometers.info/world-population/; United Nations 2019) (**FIGURE 1.1**). While birth rates have slowed since the 1960s due to women's increasing access to education, birth control, and other opportunities (BBC 2018), at this size, even a modest rate of population increase adds tens of millions of individuals each year. But the global population in 2050 may represent a peak; it is now projected that the world's population may actually decline in the second half of the century (Vollset et al. 2020). However, growth will continue to occur in many areas of tropical Africa, Latin America, and Asia, where the greatest biological diversity is also found.

GLOBAL CHANGE CONNECTION

The demands of the rapidly increasing human population and its rising material consumption correspond to an acceleration of threats to biodiversity. People deplete natural resources such as firewood, coal, oil, timber, fish, and game, and they convert natural habitats to land dominated by agriculture, cities, housing developments, logging, mining, industrial plants, and other human activities. These changes are not easily reversible, and even aggressive

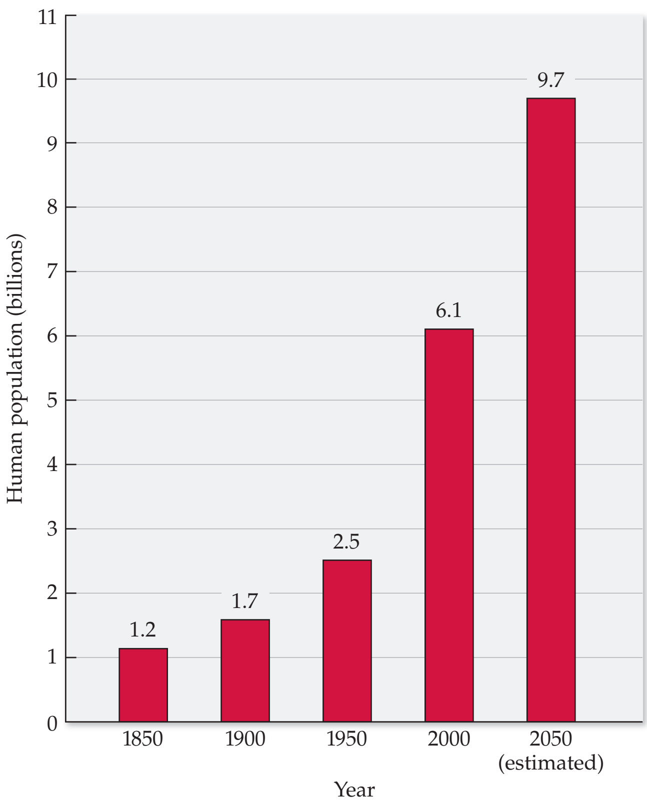


FIGURE 1.1 The human population in 2021 stood at about 7.8 billion. It is notable that the human population is growing even faster than projected; the estimate for 2050 has been revised upward by 300 million people since just 2016. (Data from K. Klein Goldewijk et al. 2016. *Earth Syst Sci Data* 9: 927-953 and World Population Prospects: The 2017 Revision. 2017. United Nations DESA/Population Division.)

programs to slow population growth do not adequately address the environmental problems we have caused (Bradshaw and Brook 2014).

Worsening the situation is the fact that as countries develop and industrialize, the consumption of resources increases. For example, the average citizen of the United States uses more than three times more total energy than the average global citizen (EIA 2018), and more than 10 times the energy of the average Indian (Richie and Roser 2019). In terms of oil, the top 10 countries account for 60% of the world's oil consumption, with the United States accounting for a full third of this (EIA 2020). However, the country with the greatest energy use is now China, reflecting recent development in that country and growing per capita use (**FIGURE 1.2**). The ever-increasing number of human beings and their intensifying use of natural resources have direct and harmful consequences for the diversity of the living world (Tilman et al. 2017).

GLOBAL CHANGE CONNECTION

Threats to biodiversity directly threaten human populations as well, because people depend on the natural environment for raw materials, food, medicines, air, and the water they drink. The poorest people are, of course, the ones who experience the greatest hardship from damaged environments because they have fewer reserves of food and less access to medical supplies, transportation, and construction materials.

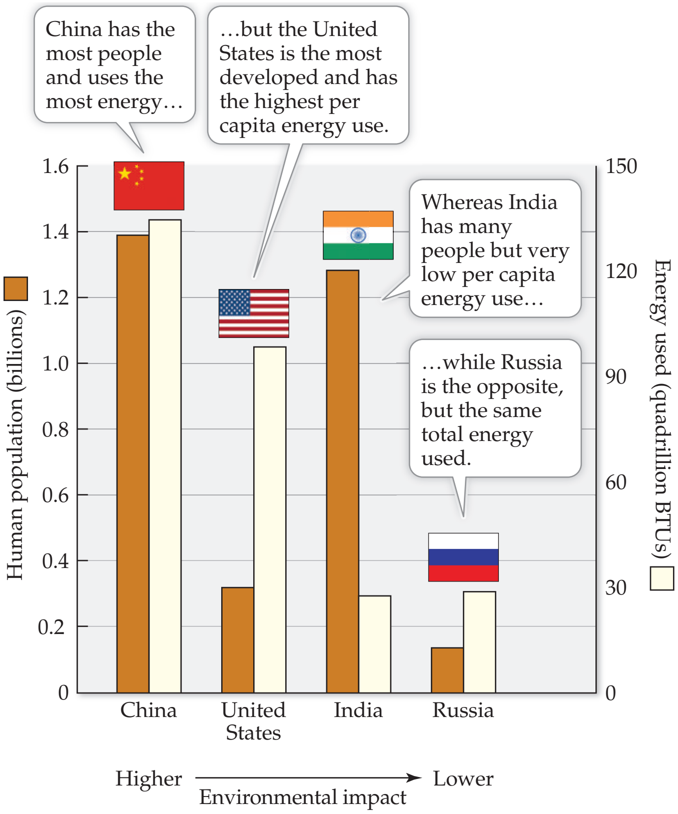


FIGURE 1.2 Population numbers and total energy use by country. Energy use, such as the burning of fossil fuels, is generally associated with negative environmental impacts. Energy use is not simply a function of population size; per capita use (energy/population) has important implications. Even though rapidly developing China's per capita use is lower than that of either the United States or Russia, its large population means that it uses the most energy and thus has the greatest environmental impact. Although India has a much larger population than either the United States or Russia, its energy use is more similar to Russia's because of India's low per capita use. (After US Energy Information Administration. 2018. *International Energy Outlook 2018*, p.2. https://www.eia.gov/outlooks/ieo/india/pdf/india_detailed.pdf.)

1.1 The New Science of Conservation Biology

LEARNING OBJECTIVES

By the end of this section you should be able to:

1.1.1 Trace the history of ideas about the conservation of nature over human history and across cultures.

1.1.2 Contrast the three guiding ethical principles of the field of conservation biology.

1.1.3 Identify the interdisciplinary elements of conservation biology for a case study of species management.

GLOBAL CHANGE CONNECTION

The avalanche of species extinctions and the wholesale habitat destruction occurring in the world today is devastating, but there is reason for hope. The last several decades have included many success stories, such as that of the American bald eagle (*Haliaeetus leucocephalus*), which was rescued from near extinction due to a combination of scientific inquiry, public awareness, and political intervention. Actions taken—or bypassed—during the next few decades will determine how many of the world's species and natural areas will survive. It is quite likely that people will someday look back on the first half of the twenty-first century as an extraordinarily exciting time, when collaborations of determined people acting locally and internationally saved many species and even entire ecosystems. In a review of nearly 13,000 conservation biology publications, more than half of the research papers measuring conservation outcomes reported positive results (Godet and Devictor 2018). Examples of such conservation efforts and positive outcomes are described throughout this book.

Conservation biology is an integrated, multidisciplinary scientific field that has developed in response to the challenge of preserving species and ecosystems. It has three goals:

1. To document the full range of biological diversity on Earth
2. To investigate human impact on species, genetic variation, and ecosystems
3. To develop practical approaches to prevent the extinction of species, maintain genetic diversity within species, and protect and restore biological communities and their associated ecosystem functions

The first two of these goals involve the dispassionate search for factual knowledge that is typical of scientific research. The third goal, however, defines conservation biology as a **normative discipline**—that is, a field that embraces certain values and attempts to apply scientific methods to achieving those values (Lindenmayer and Hunter 2010). Just as medical science values the preservation of life and health, conservation biology values the preservation of species and ecosystems as an ultimate good, and its practitioners intervene to prevent human-caused losses of biodiversity.

Conservation biology arose in the 1980s, when it became clear that the traditional applied disciplines of resource management alone were not comprehensive enough to address the critical threats to biodiversity. The applied disciplines of agriculture, forestry, wildlife management, and fisheries biology have gradually expanded to include a broader range of species and ecosystem processes. Conservation biology complements those applied disciplines and provides a more general theoretical approach to the protection of biodiversity. It differs from these disciplines in its primary goal of long-term preservation of biodiversity.

Like medicine, which applies knowledge gleaned from physiology, anatomy, biochemistry, and genetics to the goal of achieving human health and eliminating illness, conservation biology draws on other academic disciplines within biology, including taxonomy, evolution, ecology, and genetics. Many conservation biologists have come from these ranks. Others come from backgrounds in the applied disciplines, such as forestry and wildlife management. In addition, many leaders in conservation biology have come from zoos and botanical gardens, bringing with them experience in locating rare and endangered species in the wild and then maintaining and propagating them in captivity.

Conservation biology is also closely associated with, but distinct from, **environmentalism**, a widespread movement characterized by political and educational activism with the goal of protecting the natural environment. Conservation biology is a scientific discipline based on biological research whose findings often contribute to the environmental movement.

Conservation biology merges applied and theoretical biology by incorporating ideas and expertise from a broad range of scientific fields toward the goal of preserving biodiversity.

Because much of the biodiversity crisis arises from human pressures, conservation biology also incorporates ideas and expertise from a broad range of fields outside of biology (**FIGURE 1.3**). For example, environmental law and policy provide the basis for government protection of rare and endangered species and critical habitats. Environmental ethics provides a rationale for preserving species. Ecological economists provide analyses of the economic value of biological diversity to support arguments for preservation. Climatologists monitor the physical characteristics of the environment and develop models to predict environmental responses to disturbance and climate change. Both physical and cultural geography provide information about the relationships among elements of the environment, helping us understand causes and distributions of biodiversity and how humans interact with it. Social sciences, such as anthropology and sociology, provide methods to involve local people in actions to protect their immediate environment. Conservation education links academic study and fieldwork to solve environmental problems, teaching people about science and helping them realize the value of the natural environment. Because conservation biology draws on the ideas and skills of so many separate fields, it can be considered a truly multidisciplinary discipline.

GLOBAL CHANGE CONNECTION

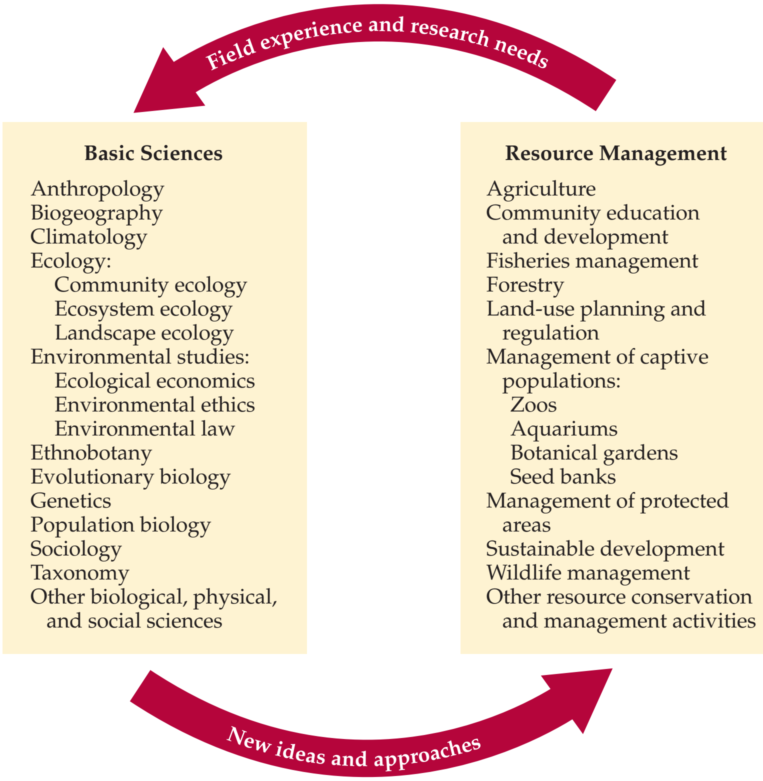


FIGURE 1.3 Conservation biology represents a synthesis of many basic sciences (left) that provide principles and new approaches for the applied fields of resource management (right). The experiences gained in the field, in turn, influence the direction of the basic sciences. (After S. A. Temple. 1991. In *Challenges in the Conservation of Biological Resources: A Practitioner's Guide*, D. J. Decker et al. [Eds.], pp. 45–54. Westview Press, Boulder, CO.)

The roots of conservation biology

Religious and philosophical beliefs about the relationship between humans and the natural world are seen by many as the foundation of conservation biology (Singh et al. 2017). Eastern philosophies such as Taoism, Hinduism, and Buddhism revere wilderness for its capacity to provide intense spiritual experiences. These traditions see a direct connection between the natural world and the spiritual world, a connection that breaks down when the natural world is altered or destroyed. Strict adherents to the Jain and Hindu religions in India believe that all killing of animal life is wrong. Islamic, Judaic, and Christian teachings are used by many people to support the idea that people are given the sacred responsibility to be guardians of nature (**FIGURE 1.4**; see Section 3.5 in Chapter 3). Many of the leaders of the early Western environmental movement that helped to establish parks and wilderness areas did so because of strong personal convictions that developed from their Christian religious beliefs. Contemporary religious leaders have pointed out that some of the most profound moments in the Bible occur on mountaintops, in the wilderness, or on the banks of rivers (Korngold 2008). In Native American tribes of the Pacific Northwest, hunters undergo purification rituals in order to be considered worthy, and the Iroquois consider how their actions would affect the lives of their descendants after seven generations. Pawnee Eagle Chief Letakots-Lesa is quoted as saying, “Tirawa, the one above, did not speak directly to man … he showed himself through the beasts, and from them and from the stars, the sun, and the moon should man learn” (from Burlin 1907).

Examples of humans safeguarding nature can be found throughout history and across the globe. For example, an ancient Greek book by Hippocrates, *De aëre, aquis et locis* (*Air, Waters, and Places*), could be considered the earliest surviving European work on the topic of protecting nature. In the early modern era, actions to protect forests include successful advocacy in the 1760s by the Frenchman Pierre Poivre, who had observed the relationship between deforestation and regional climate change (Grove 2002), and the Bishnoi Hindus of Khejarli in India, who gave their lives protecting trees from being felled for the palace of Maharaja of Jodhpur in 1720.

Photo by Anna Sher

FIGURE 1.4 Religious convictions combined with a history of traditional relationships with nature motivate the grassroots conservation organization Kakamega Environmental Education Program (KEEP), established in 1998 to protect one of the last remnants of tropical forest left in Kenya, East Africa.

Modern conservation biology in Europe and the United States arose in parallel through individuals and works concerned for landscapes and living organisms, both for their intrinsic value and their utility to humans. In Europe, Romanticism was a movement in the early 1800s that emphasized appreciation of nature, partially in response to the Industrial Revolution. Meanwhile in the United States, nineteenth-century transcendentalist philosophers Ralph Waldo Emerson and Henry David Thoreau wrote about wild nature as an important element in human moral and spiritual development. Emerson (1836) saw nature as a temple in which people could commune with the spiritual world and achieve spiritual enlightenment. Thoreau was both an advocate for nature and an opponent of materialistic society, writing about his ideas and experiences in *Walden*, a book published in 1854 that has influenced many generations of students and environmentalists. Eminent American wilderness advocate John Muir used the transcendental themes of Emerson and Thoreau in his campaigns to preserve natural areas. According to Muir’s **preservationist ethic**, natural areas such as forest groves, mountaintops, and waterfalls have spiritual value that is generally superior to the tangible material gain obtained by their exploitation (Muir 1901).

Subsequent leaders paved the way for conservation biology as an applied academic discipline. Gifford Pinchot, the first head of the US Forest Service, developed a view of nature known as the **resource conservation ethic** (Ebbin 2009). He defined natural resources as the commodities and qualities found in nature, including timber, fodder, clean water, wildlife, and even beautiful landscapes (Pinchot 1947). The proper use of natural resources, according to the resource conservation ethic, is whatever will further “the greatest good of the greatest number [of people] for the longest time.” From the perspective of conservation biology, **sustainable development** is development that best meets present and future human needs while respecting ecosystem function (Mathevet et al. 2018).

Preservation of natural resources, ecosystem management, and sustainable development are major themes in conservation biology.

A contemporary of Pinchot was biologist Aldo Leopold, who also worked for the U.S. Forest Service and is now considered by many to be a father of both conservation biology and ecology. He published *A Sand County Almanac* in 1949, a highly influential book that illustrated the interrelatedness of living things and their environment, promoting the idea that the most important goal of conservation is to maintain the health of natural ecosystems and ecological processes (Leopold 2004). As a result, Leopold and many others lobbied successfully for certain parts of national forests to be set aside as wilderness areas (Shafer 2001). This idea of considering the ecosystem as a whole, including human populations, is now termed the **land ethic**.

GLOBAL CHANGE CONNECTION

Marine biologist Rachel Carson (**FIGURE 1.5**) is credited with raising public awareness of the complexity of nature with her best-selling books, including *Silent Spring* (1962), which brought attention to the dangers of pesticides and spurred an international environmental movement. A more recent approach known as **ecosystem management**, which combines ideas of Carson, Leopold, and Pinchot, places the highest management priority on cooperation among businesses, conservation organizations, government agencies, private citizens, and other stakeholders to provide for human needs while maintaining the health of wild species and ecosystems.

Depictions of nature in the creative and performing arts have also played an important role in the growing awareness of the value of nature and its preservation in the United States. In the mid-nineteenth century, prolific painters of the Hudson River School were noted for their romantic depictions of "scenes of solitude from which the hand of nature has never been lifted" (Cole 1965). Photographer Ansel Adams (1902–1984) took breathtaking images of wild America, helping to foster public support for its protection (**FIGURE 1.6**). Popular singer-songwriter John Denver (1943–1997) inspired interest in conservation with songs such as his 1975 hit "Rocky Mountain High":

> *Now he walks in quiet solitude the forest and the streams,*
> *seeking grace in every step he takes … His life is filled*
> *with wonder but his heart still knows some fear of a simple*
> *thing he cannot comprehend: why they try to tear the*
> *mountains down … more people, more scars upon the land.*

More recently, wildlife photographer Brian Skerry has captivated audiences with his images and stories about whales; there was even an acclaimed video series made based on his

FIGURE 1.5 Rachel Carson (1907–1964) was a marine biologist who, through her popular writing, including *Silent Spring* (1962), helped to found both conservation biology and the environmental movement.

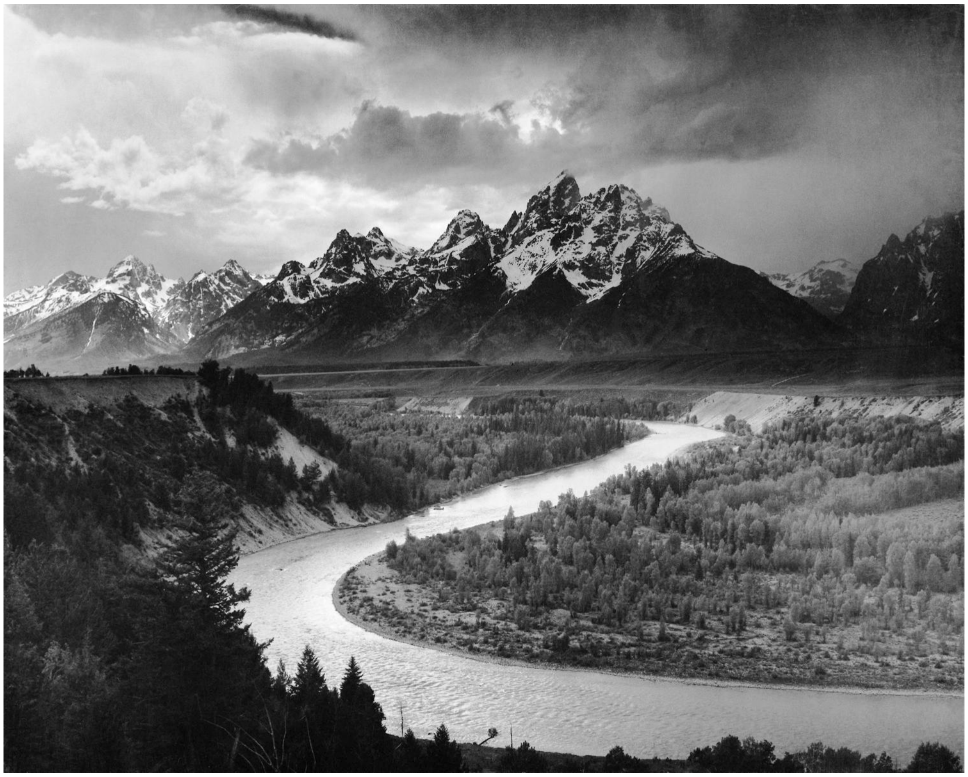


FIGURE 1.6 The photographs of Ansel Adams (1902–1984) showed the public the beauty of wild spaces, such as this image of the Snake River and the Tetons in Wyoming, USA.

experiences. Documentaries such as these are as much about beauty as they are about science, and spread messages about species preservation to a very broad audience. Clearly, the arts play a unique role in fostering interest in conservation; it has been argued that, in fact, science and art are inextricable (Bullot et al. 2017).

In Europe, dramatic losses of wildlife caused by the expansion of agriculture and use of firearms stimulated the modern British conservation movement, leading to the founding of the Commons, Open Spaces and Footpaths Preservation Society in 1865, the National Trust for Places of Historic Interest or Natural Beauty in 1895, and the Royal Society for the Protection of Birds in 1899. Altogether, these groups have preserved nearly 1 million hectares of open land (**TABLE 1.1** provides an explanation of the term *hectare* and other measurements). More recently, the formation of the European Union has facilitated conservation in a variety of ways, in part by establishing ambitious objectives for conservation and habitat management. In 2010, it established the EU Biodiversity Strategy to 2020, with a goal of halting species loss. This was supported by the establishment of "Nature Directives" and other legislation to guide resource use and species management. Perhaps the most

TABLE 1.1 Some Useful Units of Measurement

Length	
1 meter (m)	1 m = 39.4 inches = ~3.3 feet
1 kilometer (km)	1 km = 1000 m = 0.62 mile
1 centimeter (cm)	1 cm = 1/100 m = 0.39 inches
1 millimeter (mm)	1 mm = 1/1000 m = 0.039 inches
Area	
1 square meter (m^2)	Area encompassed by a square, each side of which is 1 meter
1 hectare (ha)	1 ha = 10,000 m^2 = 2.47 acres
	100 ha = 1 square kilometer (km^2)
Temperature	
degree Celsius (°C)	°C = 5/9(°F – 32)
	0°C = 32° Fahrenheit (the freezing point of water)
	100°C = 212° Fahrenheit (the boiling point of water)
	20°C = 68° Fahrenheit ("room temperature")
Energy	
British Thermal Unit (BTU)	The amount of energy it takes to increase the temperature of 1 pound of water 1 degree Fahrenheit

important action of the European Union has been the establishment of a network of protected areas, called the Natura 2000 (see Chapter 9). In contrast to its origins in the United States, biological conservation in Europe has had a more integrated view of human society and ecosystems as a whole, rather than envisioning a dichotomy of man versus nature (Linnell et al. 2015).

Many societies worldwide similarly have strong traditions of nature conservation and land protection. Tropical countries such as Brazil, Costa Rica, and Indonesia have a history of reverence for nature, and their governments have established increasing numbers and areas of national parks. The economic value of these protected areas is constantly increasing because of their importance for tourism and the valuable ecosystem services they provide, such as purifying water and absorbing carbon dioxide (see Chapter 3). Many tropical countries have established agencies to regulate the exploration and use of their biodiversity, and these efforts increasingly involve the Indigenous Peoples who depend on and have unique knowledge of these ecosystems. Hunting and gathering societies, such as the Penan of Borneo, give thousands of names to individual trees, animals, and places in their surroundings to create a cultural landscape that is vital to the well-being of the tribe. Indeed, traditional societies throughout the world have influenced and enriched modern conservation biology.

As demonstrated by the conservation tradition in Europe, habitat degradation and species loss can catalyze long-lasting conservation efforts.

A new science is born

By the early 1970s, scientists throughout the world were aware of an accelerating biodiversity crisis, but there was no central forum or organization to address the issue. Scientist Michael Soulé organized the first International Conference on Conservation Biology in 1978 so that wildlife conservationists, zoo managers, and academics could discuss their common interests. At that meeting, Soulé proposed a new interdisciplinary approach that could help save plants and animals from the threat of human-caused extinctions, which he called *conservation biology* (Soulé 1985). Subsequently, Soulé, along with colleagues including Paul Ehrlich of Stanford University and Jared Diamond of the University of California at Los Angeles, began to develop conservation biology as a discipline that would combine the practical experience of wildlife, forestry, fisheries, and national park management with the theories of population biology and biogeography. In 1985, this core of scientists founded the Society for Conservation Biology. This organization, which continues today with an international membership, sponsors conferences and publishes the scientific journal *Conservation Biology*. That journal is now joined by many peer-reviewed publications that feature research in conservation biology, such as *Biological Conservation* and *Conservation Letters*, expanding our understanding of the importance of biodiversity and how it can be protected.

Public and policymaker awareness of the value of, and threats to, biodiversity greatly increased following the international Earth Summit held in Rio de Janeiro, Brazil, in 1992 (see Chapter 12). At this meeting, representatives of 178 countries formulated and eventually signed the Convention on Biological Diversity (CBD), which obligates countries to protect their biodiversity but also allows them to obtain a share in the profits of new products developed from that diversity. In 2000, the United Nations General Assembly adopted May 22 as International Biodiversity Day to commemorate the conference, and in 2015, the United Nations Climate Change Conference (COP21) was attended by 196 parties and resulted in the Paris Agreement to reduce global greenhouse emissions. Arguably, this increase in understanding and concern would not have been possible without the foundation of a recognized scientific discipline.

Interdisciplinary approaches, the involvement of local people, and the restoration of important environments and species all attest to progress in the science of conservation biology.

GLOBAL CHANGE CONNECTION

The interdisciplinary approach: A case study with sea turtles

Throughout the world, scientists are using the approaches of conservation biology to address challenging problems, as illustrated by the efforts to save the Kemp's ridley sea turtle (*Lepidochelys kempii*). The Kemp's ridley is the rarest and smallest of the world's sea turtle species, at 70–100 cm (2–3 feet) long and about 45 kg (100 pounds). It also has the most restricted range, which has contributed to its rarity and risk of extinction (see Chapter 6). However, its numbers have dramatically increased as a result of international conservation efforts and cooperation among scientists, conservation organizations, government officials, and the interested public.

After its discovery as a distinct species in the late 1800s, it took nearly a century for scientists to determine how and where the Kemp's ridley reproduces (Wibbels and Bevan 2015). They discovered that nearly 95% of Kemp's ridley nesting takes place on beaches in the state of Tamaulipas, in the northeastern corner of Mexico, in highly synchronized gatherings of turtles called *arribadas*. The largest arribada ever documented was 40,000 nesting females in 1947 (Wibbels and Bevan 2016). This highly concentrated nesting is unusual among turtles and makes the species particularly vulnerable to intensive harvesting. Over many decades, local people collected an estimated 80% of Kemp's ridley eggs from the nesting beaches for eating, and many eggs were lost to predation by coyotes (*Canis latrans*). Thousands of turtles also drowned in fishing gear, especially when caught accidentally in shrimp nets. By 1985, turtle numbers had declined to a low point of only 702 nests (an estimate of the number of breeding females) worldwide, making the Kemp's ridley the most endangered sea turtle in the world.

Heeding the warning of wildlife biologists that the species was nearing extinction, government officials from Mexico and the United States worked together to help the species recover and establish stable populations. As a first step, nesting beaches were protected as refuges, reserves, and parks (see Chapter 9 for the importance of protected areas). Egg collection was banned. And at sea, shrimp trawlers were required to use turtle excluder devices (TEDs), consisting of a grid of bars with an opening that allows a caught turtle to escape.

In addition to reducing threats, a collaborative group of national and state agencies and conservation organizations in Mexico and the United States has undertaken an ambitious effort to increase nest and hatchling survival and to improve education and appreciation of sea turtle conservation. In the United States, national park authorities began to reestablish a population on Padre Island in Texas, where the species had formerly occurred. From 1978 to 1988, scientists, conservationists, and volunteers collected 22,507 eggs from Mexico, packed them in sand, and transported them to Padre Island National Seashore, which is managed by the US National Park Service (Caillouet et al. 1997). Because most turtles die as hatchlings, the turtles were reared in captivity for 9–11 months to allow them to grow large enough to avoid most predators before being released permanently into the Gulf of Mexico. These types of release programs will be discussed in more detail in Chapter 8.

Now, each year, the staff at Padre Island, many partner organizations, and over a hundred volunteers patrol the beach during the nesting season, searching for Kemp's ridleys and their nests. When they find nests, teams carefully excavate them and bring the eggs to an incubation facility or a large screen enclosure called a corral. When the young hatchlings are released, it is now a public event that doubles as an education tool—the hope is that the people watching each release will become advocates for the turtles' protection. Outside the national seashore, private conservation organizations also help protect the turtles on their feeding grounds (see more on conservation

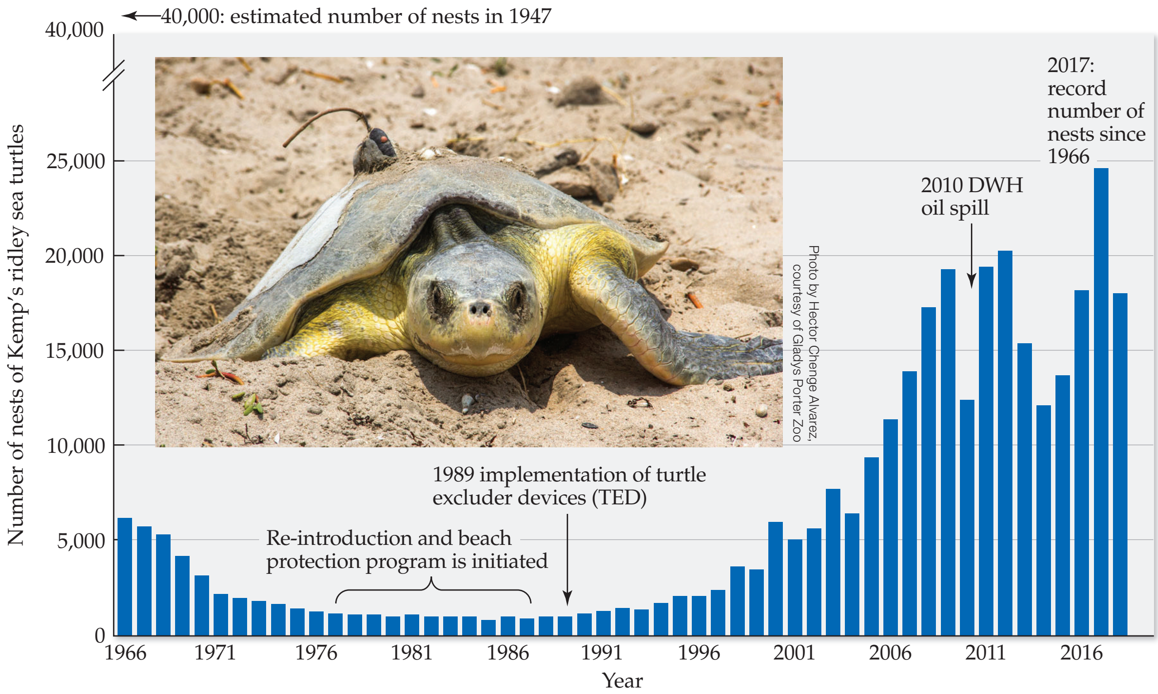


FIGURE 1.7 A Kemp's ridley sea turtle (*Lepidochelys kempii*) with a tracking device mounted on its shell climbs out of the sand. The device transmits signals to a satellite, from which they can be recorded by scientists, allowing the movements of the turtle to be determined over long distances. Populations of these turtles increased after intense conservation efforts on the part of the US and Mexican governments and the implementation of devices that reduced turtle deaths associated with fishing. Despite ongoing egg collection and reintroduction, the population decreased after the *Deepwater Horizon* (DWH) oil spill in 2010. And yet a record number of nests was recorded in 2017. However, this is far from historic numbers, and another population dip in 2018 underlines the necessity of continued research and management. (Data for 1966–2014 from La Comisión Nacional de Áreas Naturales Protegidas, as reported in Gallaway et al. 2016. *Gulf of Mexico Science* 33 [2]. Data for 2015–2021 courtesy of Gladys Porter Zoo, Mexico's Comisión Nacional de Áreas Naturales Protegidas, and the Tamaulipas Commission of Parks and Biodiversity.)

outside of protected areas in Chapter 10). The program has been tremendously successful, and there are now nearly 18,000 nests on the island each year, on average, with over 750,000 hatchlings (**FIGURE 1.7**). Unfortunately, habitat degradation is still a leading threat to this endangered species (discussed in Chapter 4), with climate change not far behind (discussed in Chapter 5). The number of nests and hatchlings dropped by 35% in 2010, the same year as the *Deepwater Horizon* oil spill, which is believed to have killed hundreds of juvenile turtles (Caillouet et al. 2018). Turtles' contact with the oil was confirmed through satellite transmitter tracking (Figure 1.7 inset) as well as chemical analysis of their shells (Reich et al. 2017). Scientists determined that turtles were ingesting oil from the spill by measuring the abundance of certain forms of carbon molecules in their shells, a process called *stable isotope analysis*.

GLOBAL CHANGE CONNECTION

However, despite the threat from the oil spill, a study of the nests in Mexico found predation rates to be low and hatchling survival high (Bevan et al. 2014), and in 2017 there were 24,586 nests recorded—the highest number in the 40-year history of the Kemp's Ridley Binational Project. Even with such success, periodic population dips since the oil spill raise concerns about food availability and habitat quality, highlighting the need for continued species management and research (Caillouet et al. 2018). Recent research also suggests that Kemp's ridley may be at risk from organic pollutants from pesticides, given the high levels found in the blood of individuals sampled in the Playa Rancho Nuevo Sanctuary in Tamaulipas, Mexico (Montes et al. 2020).

GLOBAL CHANGE CONNECTION

Climate change also poses several risks to this species. Higher than normal temperatures can affect sex ratios of eggs, since sex of the embryo is determined during the second third of incubation and can be changed by subtle changes in nest temperature. The warmer it is, the more likely the egg will produce a female (Bevan et al. 2019). Higher temperatures also threaten survivorship of nestlings; in one study of a population in Texas, nearly 23% of nestlings died from overheating or desiccation (Shaver 2020). Warmer temperatures also mean that sea turtles at higher latitudes aren't signaled to migrate south before the onset of late autumn storms, making them vulnerable to "cold-stunning" that leaves them paralyzed but alive (Griffin et al. 2019).

Even once they have begun to migrate south, they can still be in danger. In February of 2021, the largest cold-stunning event in recorded history in the United States took place: nearly 5000 sea turtles, including green, loggerhead, and Kemp's ridley, washed up on the shore of South Padre Island, Texas, following a rare cold front from the Arctic (Daly National Geographic 2021). Fortunately, residents rallied to help by transporting the cold-stunned turtles to the island's convention center, where the sea turtles could be warmed and revived (**FIGURE 1.8A**).

Sea turtles were expected to benefit from the quarantine associated with COVID-19, since there were fewer people (and their dogs) on beaches to trample nests or disturb hatchlings. However, the decimation of tourism in 2020 also meant decreased revenue that could have funded conservation efforts (CNN 2020). The loss of income and jobs also increased the threat of harvesting of eggs for food or profit. Meanwhile, fewer conservation volunteers in 2020 meant less work done surveying populations and protecting nests. Furthermore, the summer of 2020 was the hottest in recorded history for the Northern Hemisphere (NOAA 2020).

Fortunately, in the case of the Kemp's ridley sea turtle, determined staff followed COVID quarantine guidelines and continued their work. In addition to relocating eggs to nests in fenced enclosures where they could be monitored and protected from physical disturbance, staff also spread shade cloth over the area to protect the nests from overheating (**FIGURE 1.8B**). Despite all of the challenges, 2020 was a banner year for Kemp's ridley sea turtles and a credit to the efforts of many people; over 20,000 nests were recorded, and nearly a million hatchlings were released (see the chapter opening photo) (Burchfield et al. 2020).

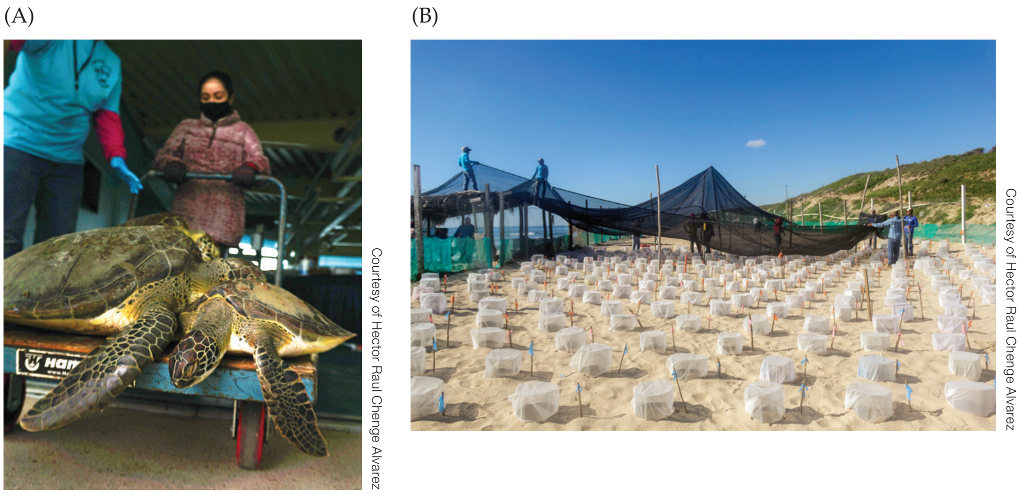


FIGURE 1.8 Sea turtles are at risk from both high and low temperature anomalies. (A) Here we see volunteers Irving A. Hernandez, David Daniel Barrera, and Robert "DJ" Lerma rescue a cold-stunned green turtle. It was one of more than 4900 sea turtles (including Kemp's ridley), a record number, that washed up on the beaches of South Padre Island, Texas. (B) Technicians cover the area of the nests with black shade cloth to protect them from record high temperatures that could alter sex ratios of eggs and/or kill hatchlings. Individual nest *corralitos* are covered with white mosquito net to exclude parasitic flies.

Scientific scrutiny, international partnerships, and the participation of volunteers and local communities have brought the Kemp's ridley sea turtle back from the brink of extinction, and all of those involved will continue to seek the answers leading to its complete recovery. A variety of scientific tools and conservation strategies have been useful in the recovery of this and many other species of sea turtles that have had significant population gains in recent years (Mazaris et al. 2017).

1.2 The Organizational Values of Conservation Biology

LEARNING OBJECTIVES

By the end of this section you should be able to:

1.2.1 Relate the five organizational values of conservation biology to its history as a normative discipline.

1.2.2 Identify novel examples of biophilia.

Earlier in the chapter, we mentioned that conservation biology is a normative discipline in which certain values are embraced. The field rests on an underlying set of principles that is generally agreed on by practitioners of the discipline (Soulé 1985; SCB 2016 [see “Organizational Values”]) and can be summarized as follows:

1. *Biological diversity has intrinsic value*. Species and the biological communities in which they live possess value of their own, regardless of their economic, scientific, or aesthetic value to human society. This value is conferred not just by their evolutionary history and unique ecological role, but also by their very existence. (See Chapter 3 for a more complete discussion of this topic.)
2. *The untimely extinction of populations and species should be prevented*. The ordinary extinction of species and populations as a result of natural processes is an ethically neutral event. In the past, the local loss of a population was usually offset by the establishment of a new population through dispersal. However, as a result of human activity, the loss of populations and the extinction of species have increased more than a hundredfold, with no simultaneous increase in the generation of new populations and species (see Chapter 6).
3. *The diversity of species and the complexity of biological communities should be preserved*. In general, most people agree with this principle simply because they appreciate biodiversity; it has even been suggested that humans may have a genetic predisposition to love biodiversity, called **biophilia** (**FIGURE 1.9**) (Wilson 2017). Many of the most valuable properties of biodiversity are expressed only in natural environments. Although the biodiversity of species may be partially preserved in zoos and botanical gardens, the ecological complexity that exists in natural communities will be lost without the preservation

There are ethical reasons why people want to conserve biodiversity, such as belief that species have intrinsic value.

FIGURE 1.9 People enjoy seeing the diversity of life, as illustrated by the popularity of planting gardens and of public botanical gardens as tourist destinations. Butchart Gardens in Victoria, British Columbia, Canada, is shown here.

of natural areas (see Chapter 9). Furthermore, biodiversity has been directly linked to ecosystem productivity and stability (Hautier et al. 2015), among other values (see Chapter 3).

4. *Science plays a critical role in our understanding of ecosystems.* It is not enough to simply value diversity and protect natural spaces; objective research is necessary to identify which species and environments are at greatest risk, as well as to understand the nature of these risks and how to mitigate them. Ideally, scientists are involved in all stages of conservation, including implementation of conservation actions and monitoring results.
5. *Collaboration among scientists, managers, policymakers, and the public is important and often necessary.* In order to achieve the goals of reduced extinction rates and preservation of biological communities, high-quality research findings must be shared with those who create the laws and provide the funding for conservation actions, with those who must implement them, and with those who live and work in the areas affected. These actions are most likely to succeed when they are based on scientifically sound information and are supported by local people.

Not every conservation biologist accepts every one of these principles, and there is no hard-and-fast requirement to do so. Individuals or organizations that agree with even two or three of these principles are often willing to support conservation efforts. Current progress in protecting species and ecosystems has been achieved in part through partnerships between traditional conservation organizations, such as The Nature Conservancy, and cattle ranchers, hunting clubs like Ducks Unlimited, and other groups with a vested interest in the health of ecosystems.

1.3 Looking to the Future

The field of conservation biology has set itself some imposing—and absolutely critical—tasks: to describe Earth's biological diversity, to protect what remains, and to restore what is degraded. The field is growing in strength, as indicated by increased governmental participation in conservation activities, increased funding of conservation organizations and projects, and an expanding professional society.

In many ways, conservation biology is a crisis discipline. Decisions about selecting national parks, species management, and other aspects of conservation are made every day under severe time pressure (Martin et al. 2017). As one of the guiding values mentioned above, biologists and scientists in related fields seek to provide the advice that governments, businesses, and the general public need in order to make crucial decisions, but because of time constraints, scientists are often compelled to make recommendations without thorough investigation. Decisions must be made, with or without scientific input, and conservation biologists must be willing to express opinions and take action based on the best available evidence and informed judgment (Garrard et al. 2016). They must also articulate a long-term conservation vision that extends beyond the immediate crisis (Wilhere 2012).

Despite the threats to biodiversity and the limitations of our knowledge, we can detect many positive signs that allow conservation biologists to be cautiously hopeful (Godet and Devictor 2018; Roman et al. 2015). Indeed, optimism may be critical for the field and our ability to motivate positive change (Beever 2020). Per capita energy use in the United States, while still high, has been decreasing; in 2014 it was the lowest it had been since the 1960s (World Bank 2014), and the percent of renewable energy had grown to 11% in 2019 (US Energy Information Administration 2021). As a consequence, the total amount of energy consumed has not grown in the past couple of decades, despite a growing population. The number of protected areas around the globe continues to increase, particularly the number of marine protected areas. The involvement of the public in collecting meaningful data and advocating for conservation continues to rise, facilitated by the ubiquity of smartphones, user-friendly apps, and social media. Technology and science are evolving, providing tools for both the study and preservation of species.

GLOBAL CHANGE CONNECTION

These gains are due in part to action spurred by the public. Increasing numbers of social and religious leaders have rallied for the protection of biodiversity, while others become leaders because of their conservation message. Figures who champion protecting life on Earth have increasingly become more famous. As an example, Greta Thunberg, a teenager from Sweden, spoke out about climate change, became *Time*'s Person of the Year, and made the *Forbes* list of the World's 100 Most Powerful Women in 2019. The optimism and determination of such individuals is powerful. As Ms. Thunberg said to the US Congress:

> *You must unite behind the science. You must take action. You must do the impossible. Because giving up can never ever be an option.*
>
> – Greta Thunberg, September 2019, Washington, DC

Our ability to protect biodiversity has been strengthened by a wide range of local, national, and international efforts. Many endangered species are now recovering as a result of such conservation measures (IUCN 2019). Effective action has resulted from our continuing expansion of knowledge in conservation science, the developing linkages with rural development and social sciences, and our increased ability to restore degraded environments. All of these advances suggest that progress is being made, despite the enormous tasks still ahead.

Summary

- Human activities are causing the extinction of thousands of species both locally and globally, with threats to species and ecosystems accelerating due to human population growth and the associated demands for resources.
- Conservation biology is a field that combines basic and applied disciplines with three goals: to describe the full range of biodiversity on Earth; to understand human impact on biodiversity; and to develop practical

approaches for preventing species extinctions, maintaining genetic diversity, and protecting and restoring ecosystems.

- Elements of conservation biology can be found in many cultures, religions, and forms of creative expression, and they began to develop in the United States and Europe in the nineteenth and twentieth centuries. The modern field of conservation biology became a recognized scientific discipline with a professional society and academic journals by the 1980s.
- Conservation biology rests on a number of underlying assumptions that are accepted by most professionals in the discipline: biodiversity has value in and of itself; extinction from human causes should be prevented; diversity at multiple levels should be preserved; science plays a critical role, and scientists must collaborate with nonscientists to achieve our goals.
- The conservation of biodiversity has become an international undertaking. Many successful projects, such as the conservation of Kemp's ridley sea turtles, indicate that progress can be made.

For Discussion

1. Explain the connection between human population growth and species loss.
2. How is conservation biology fundamentally different from other branches of biology, such as physiology, genetics, or cell biology? How is it similar to the science of medicine? How is it different from environmentalism?
3. What do you think are the major conservation and environmental problems facing the world today? What are the major problems facing your local community? What ideas for solving these problems can you suggest? (Try answering this question now, and once again when you have completed this book.)
4. Consider the public land management and private conservation organizations with which you are familiar. Do you think their guiding philosophies are closest to the resource conservation ethic, the preservation ethic, or the land ethic? What factors allow them to be successful or limit their effectiveness? Learn more about these organizations through their publications and websites.
5. How would you characterize your own viewpoint about the conservation of biodiversity and the environment? Which of the religious or philosophical viewpoints of conservation biology stated here do you agree or disagree with? How do you, or could you, put your viewpoint into practice?

Suggested Readings

Carson, R. 1962. *Silent Spring*. Houghton Mifflin, Boston. Essays written over a period from 1958 to 1962 on the devastating effects of pesticide use on ecosystems, particularly on birds.

Godet, L., and V. Devictor. 2018. What conservation does. *Trends in Ecology & Evolution* 33: 720–730. A quantitative review of the conservation literature that reveals global patterns and reasons for optimism.

Kloor, K. 2015. The battle for the soul of Conservation Science. *Issues in Science and Technology* 31: 74. The ongoing debate between those who believe that the field should be primarily guided by "nature for nature's sake" and others who believe that human needs should have greater weight.

Leopold, A. 1949. *A Sand County Almanac*. Oxford University Press, New York. Leopold's evocative essays articulate his "land ethic," defining human duty to conserve the land and the living things that thrive upon it.

Mazaris, A. D., et al. 2017. Global sea turtle conservation successes. *Science Advances* 3: e1600730. While many species are doing better, most still require intensive conservation effort to secure their future.

Rutz, C., et al. 2020. COVID-19 lockdown allows researchers to quantify the effects of human activity on wildlife. *Nature Ecology & Evolution* 4: 1156–1159. The pandemic changed our impacts on nature, including both increases and decreases, creating a unique opportunity to study anthropogenic effects.

Soulé, M. E. 1985. What is conservation biology? *BioScience* 35: 727–734. A key early paper defining the field, still relevant today for its emphasis on the intrinsic value of biodiversity.

Tilman, D., et al. 2017. Future threats to biodiversity and pathways to their prevention. *Nature* 546: 73. There are means to address conservation threats. Proactive international efforts could still preserve much of the planet's remaining biodiversity.

WWF (World Wildlife Fund). 2020. *Living Planet Report 2020: Bending the Curve of Biodiversity Loss*. R. E. A. Almond, M. Grooten, and T. Petersen (eds). WWF, Gland, Switzerland. Alarming losses still threaten species and ecosystems in many parts of the world.

KEY JOURNALS IN THE FIELD *Biodiversity and Conservation, Biological Conservation, BioScience, Conservation Biology, Conservation Letters, Ecological Applications, National Geographic, Trends in Ecology and Evolution.*

Biodiversity can be considered at a range of scales, from the genetic diversity among these Indian paintbrush flowers to the diversity of ecosystems. Ecosystems shown here include sub-alpine meadow, forest, and alpine, each with their own unique species assemblages.

What Is Biodiversity?

2

The protection of biological diversity is central to conservation biology. Conservation biologists use the term *biological diversity*, or simply *biodiversity*, to mean the complete range of species and biological communities on Earth, as well as the genetic variation within those species and all ecosystem processes. By this definition, biodiversity must be considered on at least three levels (**FIGURE 2.1**):

1. *Species diversity* All the species on Earth, including single-celled bacteria and protists as well as the species of the multicellular kingdoms (plants, fungi, and animals) may be included in this level of diversity. As we will see in this chapter, there are several ways that species diversity can be measured for a particular geographic region or ecosystem.
2. *Genetic diversity* The genetic variation within species, both among geographically separate populations and among individuals within single populations. A **population** is a group of individuals that mate with one another and produce offspring; species may contain one population or many.
3. *Ecosystem diversity* The different biological communities and their associations with the chemical and physical environment (the **ecosystem**). A **community** is an assemblage of interacting populations of different species living in a particular area.

In ecology, the term *ecosystem* is applied to biological communities at widely different scales, from the bacteria in the gut of an individual mouse to the hundreds of square kilometers of boreal forest across a mountain range. However, ecosystem diversity in a conservation

Photo by Joseph Thomas Images

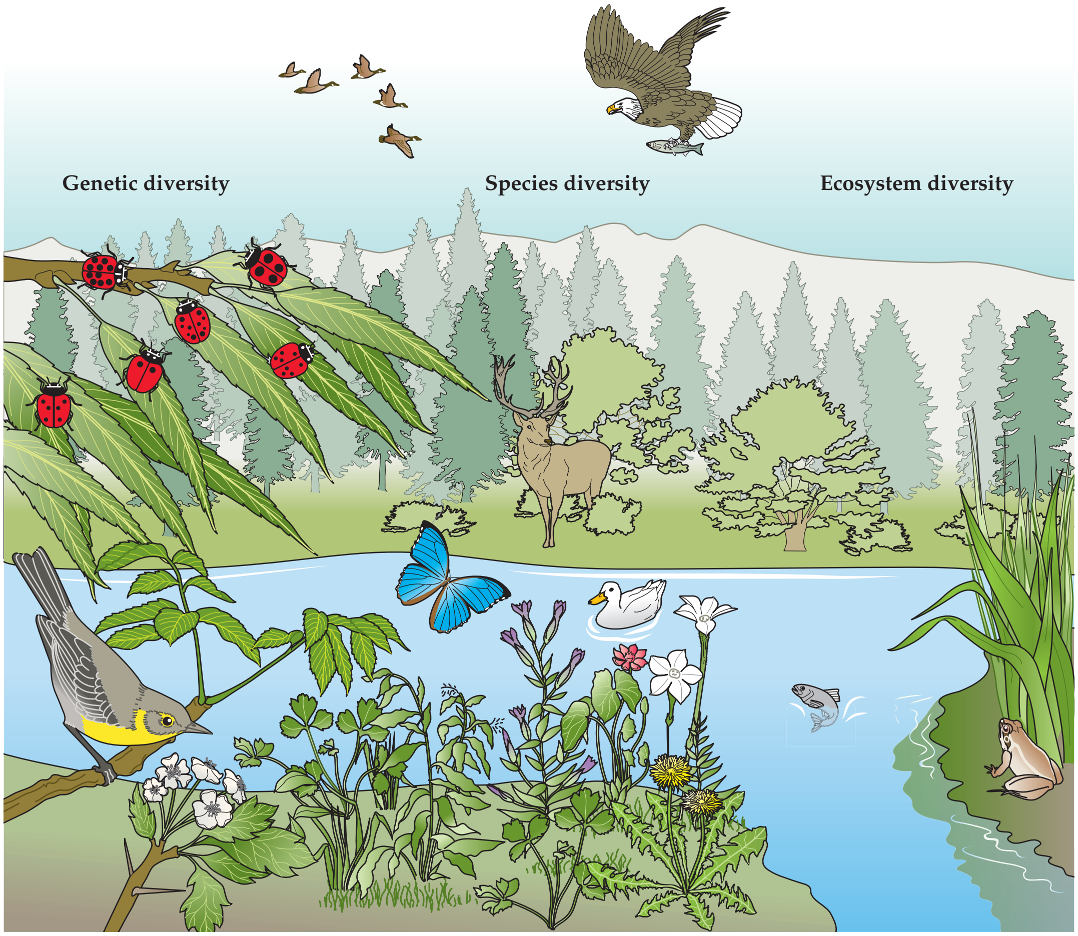


FIGURE 2.1 Biological diversity includes genetic diversity (e.g., the genetic variation found within each species, as shown with the ladybird beetles), species diversity (e.g., the range of species in a given ecosystem), and ecosystem diversity (e.g., the variety of habitat types and ecosystem processes extending over a given region).

context typically refers to the different types of communities and their associated environments within a given geographic area (see chapter opening photo). An example of ecosystem diversity is the wetland, forest, and grassland ecosystems all included within a protected wilderness area (see Chapter 9); diversity at this level would likely be lost if the area were instead converted to farmland.

Note also that this three-tiered list is a simplification that includes only the most often studied and quantified levels; conservation biologists can also be concerned with diversity at other, intermediate scales. For example, genetic diversity can be considered in terms of population diversity, that is, populations with different genetic compositions within a species. Community diversity can refer to unique assemblages of different populations of species, and so on. These different levels of biodiversity are necessary for the continued survival of life as we know it (Methorst et al. 2021; Mori et al. 2017; Xu et al. 2017). All of these levels are also currently facing significant threats, to be discussed in Chapters 4, 5, and 6, although threats to species diversity tend to receive the most attention.

Species diversity reflects the entire range of evolutionary and ecological adaptations of species to particular environments. It provides people with resources and resource alternatives; for example, a tropical rain forest or a temperate swamp with many species produces a wide variety of plant and animal products that can be used as food, shelter, and medicine. **Genetic diversity** is necessary for any species to maintain reproductive vitality, resistance to disease, and the ability to adapt to changing conditions. For example, it was discovered that genetic variability helped rare frog populations survive a deadly fungal disease (Savage et al. 2018). Genetic diversity is also of value in the breeding programs necessary to sustain and improve modern domesticated plants and animals and their disease resistance (Mastretta-Yanes et al. 2018). **Ecosystem diversity** results from the collective response of species to different environmental conditions. Biological communities found in deserts, grasslands, wetlands, and forests support the continuity of proper ecosystem functioning, which provides crucial services to people, such as water for drinking and agriculture, flood control, protection from soil erosion, and filtering of air and water (these different values are discussed further in Chapter 3). We will examine each level of biodiversity in this chapter.

2.1 Species Diversity

LEARNING OBJECTIVES

By the end of this section you should be able to:

- **2.1.1** Distinguish among different species definitions.
- **2.1.2** Explain the specific difficulties in identifying what a species is.
- **2.1.3** Calculate alpha, gamma, and beta species diversity for a sample population/region.
- **2.1.4** Calculate diversity using the Shannon index for a sample population when relative abundances are provided.

Recognizing and classifying species is one of the major goals of conservation biology. Identifying the process whereby one species evolves into one or more new species is one of the ongoing accomplishments of modern biology. The origin of new species is normally very slow, taking place over hundreds, if not thousands, of generations. The evolution of higher taxa, such as new genera and families, is an even slower process, typically lasting hundreds of thousands or even millions of years. In contrast, human activities are destroying in only a few decades the unique species built up by these slow natural processes.

GLOBAL CHANGE CONNECTION

Every four years the world's largest conservation event is held: the International Union for Conservation of Nature's World Conservation Congress (for more about the IUCN, see Chapter 7 and Chapter 9). One of the tasks of this international meeting of scientists, policymakers, and others is to come to agreements about the number of species that have currently been **described** (officially identified by science) and, for those species with enough information, how safe or endangered they are. The product of the meeting is a new formal list, representing the result of years of work by thousands of people. One of the reasons it takes so long is because what counts as a unique species is not always clear.

What is a species?

Although seemingly a straightforward concept, how to distinguish a selection of organisms as a species is subject to great scientific discussion, and at least seven different ways of doing this have been proposed (Wiens 2007). Three are most commonly used in conservation biology:

1. *Morphological species*: A group of individuals that appear different from others—that is, that are morphologically distinct. A group that is distinguished exclusively by such visible traits as form or structure may be referred to as a **morphospecies**.
2. *Biological species*: A group of individuals that can potentially breed among themselves in the wild and that do not breed with individuals of other groups.
3. *Evolutionary species*: A group of individuals that share unique similarities in their DNA and hence their evolutionary past.

Because they rely on different methods and assumptions, these three approaches to distinguishing species sometimes do not give the same results. Increasingly, DNA sequences and other molecular markers are being used to identify and distinguish species that look almost identical. For example, a commonly harvested emperor fish in the southwest Indian Ocean that was assumed from morphological characteristics to be a single species was discovered through genetic analysis to actually be two species, with important implications for their management (Healey et al. 2018).

Using morphological and genetic information to identify species is a major activity for taxonomists; accurate identification of a species is a necessary first step in its conservation.

The **morphological definition of species** is the one most commonly used by **taxonomists**, biologists who specialize in the identification of unknown specimens and the classification of species. The **biological definition of species** is widely accepted, but it is problematic for groups of organisms in which different species readily interbreed, or **hybridize**, such as plants. Furthermore, the biological definition of species is difficult to use because it requires a knowledge of which individuals have the potential to breed with one another. Similarly, the **evolutionary definition of species** requires access to expensive laboratory equipment and so cannot be used in the field. As a result, field biologists must rely on observable attributes, and they may name a group of organisms as a morphospecies until taxonomists can investigate them more carefully to determine whether they are a distinct species (e.g., Chan et al. 2015).

Ideally, specimens collected in the field are catalogued and stored in one of the world's >6500 natural history museums (for animals and other organisms) or its >300 major herbaria (for plants and fungi) (**FIGURE 2.2**). Increasingly, these physical records of global biodiversity are being digitized and shared on the World Wide Web for greater access and scientific use. Permanent collections curated by museums and herbaria form the basis of species descriptions and systems of classification. Each species is given a **binomial**—a unique two-part name—such as *Giraffa tippelskirchi* for the Maasai giraffe. The first part of the binomial, *Giraffa*, identifies the genus (the giraffes). The second part, *tippelskirchi*, identifies the smaller group within the genus, the species that is the Maasai giraffe, the iconic animal that lives in East Africa. This naming system both separates the Maasai giraffe from and connects it to similar species—such as *Giraffa camelopardalis*, the northern giraffe, and

(A) (B)

FIGURE 2.2 (A) An ornithologist at the Museum of Comparative Zoology, Harvard University, classifying collections of orioles: black-cowled orioles (*Icterus prosthemelas*), from Mexico, and Baltimore orioles (*Icterus galbula*), which occur throughout eastern North America. (B) Modern museums, including herbaria, are increasingly using digitization to safeguard data and make it available to a broader global community. At the Kathryn Kalmbach Herbarium of Vascular Plants, high-resolution photos are taken of specimens in a specially designed light box. These images and associated specimen data are put online and shared among numerous digital museum data aggregators, such as the Global Biodiversity Information Facility.

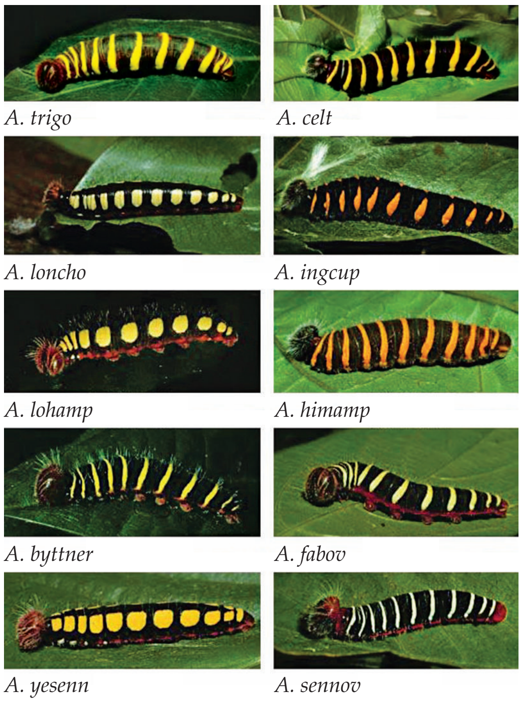
Giraffa reticulata, the reticulated giraffe. In some cases for animals, there may be the same name for both genus and species, such as *Giraffa giraffa*, the southern giraffe. *Bison bison*, the American bison, and *Gorilla gorilla*, the western gorilla, are other examples; such species were likely the first of their genus to be classified.

Problems in distinguishing and identifying species are more common than many people realize. For example, a single species may have several varieties that have observable morphological differences yet are similar enough to be a single biological or evolutionary species. Different varieties of dogs, such as German shepherds, collies, and beagles, all belong to one species; their genetic differences are actually very small, and they readily interbreed. Alternatively, closely related "sibling" species appear very similar in morphology and physiology yet are genetically quite distinct (**FIGURE 2.3**). These are also known as **cryptic species**, which include the emperor fish discussed earlier.

To further complicate matters, individuals of related but distinct species may occasionally mate and produce **hybrids**, intermediate forms that blur the distinction between species. Hybridization is particularly common among plant species in disturbed habitats. Hybridization in both plants and animals frequently occurs when a few individuals of a rare species are surrounded by large numbers of a closely related species. For example, the endangered California tiger salamander (*Ambystoma californiense*) and the introduced

(A)

(B)



From P. D. Hebert et al. 2014. *PNAS* 101(41) 14812–14817. © National Academy of Sciences, U.S.A.

FIGURE 2.3 (A) The two-barred flasher butterfly (*Astraptes* spp.) is a cryptic species complex in the skipper butterfly genus. (B) Although the individuals are nearly identical as adults, differences at the larval stage prompted further investigation into differences between populations; a molecular analysis tool called DNA barcoding revealed that they were in fact different species.

FIGURE 2.4 The hybrid tiger salamander (left) is larger than its endangered parent species, the California tiger salamander (right), and is increasing in abundance. Note the much larger head of the hybrid salamander.

barred tiger salamander (*A. mavortium*) are thought to have evolved from a common ancestor 5 million years ago, yet they readily mate in California (**FIGURE 2.4**). The hybrid salamanders have a higher fitness and are better able to tolerate environmental pollution than the native species, *A. californiense*, further complicating the conservation of this endangered species (Ryan et al. 2013).

The inability to clearly distinguish one species from another, whether due to similarities of characteristics or to confusion over the correct scientific name, often slows down efforts at species protection. It is difficult to write precise, effective laws to protect a species if scientists and lawmakers are not certain which individuals belong to which species. At the same time, species are going extinct before they are even described. More than 10,000 new species are being described each year, but even this rate is not fast enough. The key to solving this problem is to train more taxonomists and improve scientific collaboration, especially in the species-rich tropics (Baker et al. 2017).

Those conservation biologists primarily concerned with ecosystem function rather than individual species extinction have argued that a better measure than species diversity is **functional diversity**—that is, the diversity of organisms categorized by their ecological roles or traits rather than their taxonomy (Díaz and Cabido 2001; Gagic et al. 2015). Functional diversity has been found to increase ecosystem resilience against change (de la Riva et al. 2017) and is arguably more important than species diversity for understanding processes on the ecosystem scale (Dawud et al. 2017), such as in response to human interventions (Henry et al. 2021). Because of this, functional diversity is an especially important concept in the context of habitat restoration (see Chapter 11). However, if our goal is to prevent untimely extinctions, we cannot avoid the task of identifying species and measuring species diversity.

GLOBAL CHANGE CONNECTION

Measuring species diversity

Conservation biologists often want to identify locations of high species diversity. Quantitative definitions of species diversity have been developed by ecologists as a means of comparing the overall diversity of different communities at varying geographic scales (Bhatta et al. 2018).

At its simplest level, species diversity can be defined as the number of species present, called **species richness**. This number can be determined by several methods and at different geographic scales. Three diversity measurements are based on species richness:

- **Alpha diversity** is the number of species found in a given community, such as a lake or a meadow.
- **Gamma diversity** is the number of species at larger geographic scales that include a number of ecosystems, such as a mountain range or a continent.
- **Beta diversity** links alpha and gamma diversity and represents the rate of change of species composition as one moves across a large region. For example, if every lake in a region contained a similar array of fish species, then beta diversity would be low; on the other hand, if the bird species found in one forest were entirely different from the bird species in separate but nearby forests, then beta diversity would be high. There are several ways of calculating beta diversity; a simple measure of beta diversity can be obtained by dividing gamma diversity by alpha diversity.

Identifying patterns of species diversity helps conservation biologists establish which locations are most in need of protection.

We can illustrate these three types of diversity with a theoretical example of three mountain ranges (**FIGURE 2.5**). Region 1 has the highest alpha diversity, with more species per mountain on average (6 species) than the other two regions. Region 2 has the highest gamma diversity, with a total of 10 species. Dividing gamma diversity by alpha diversity shows that Region 3 has a higher beta diversity (2.7) than Region 2 (2.5) or Region 1 (1.2) because all but one of its species are found on only one mountain each. In practice, indexes of diversity are often highly correlated. The plant communities of the eastern foothills of the Andes, for instance, show high levels of diversity at alpha, beta, and gamma scales.

More-complex indexes, such as the **Shannon diversity index** (also called the Shannon-Wiener index), the Simpson index, and the Pielou evenness index, take the relative abundance of different species into account; by these measures, a community dominated by a few species is less diverse than one with a more even distribution of species, even with the same species richness. The Shannon diversity index (H) is calculated as

$$H = -\sum \left[p_i \times \ln(p_i) \right]$$

That is, the proportion (p) of each species (i) is multiplied by the natural log (ln) of that proportion, and then the sum of those results is multiplied by –1. In a simple example, let's imagine two ponds, each of which has five fish species. In

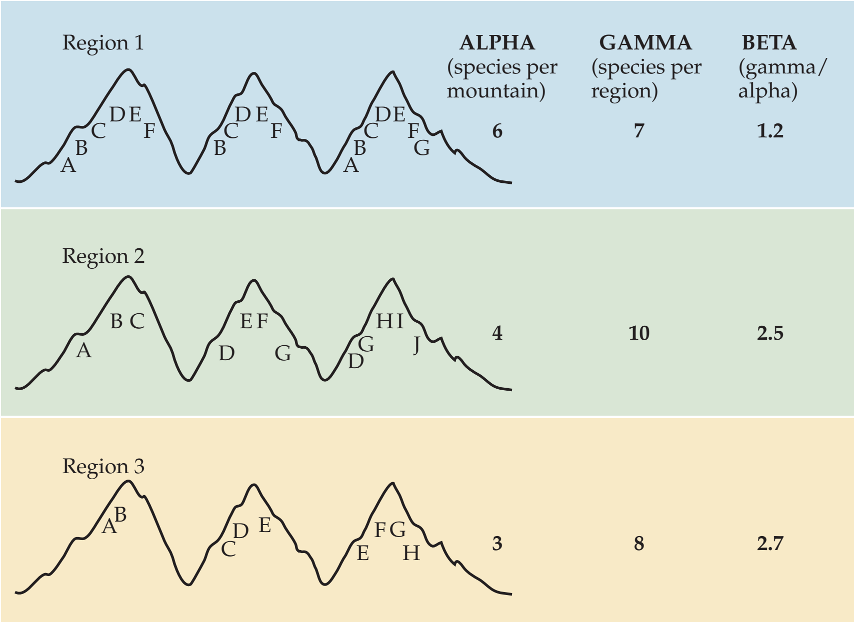
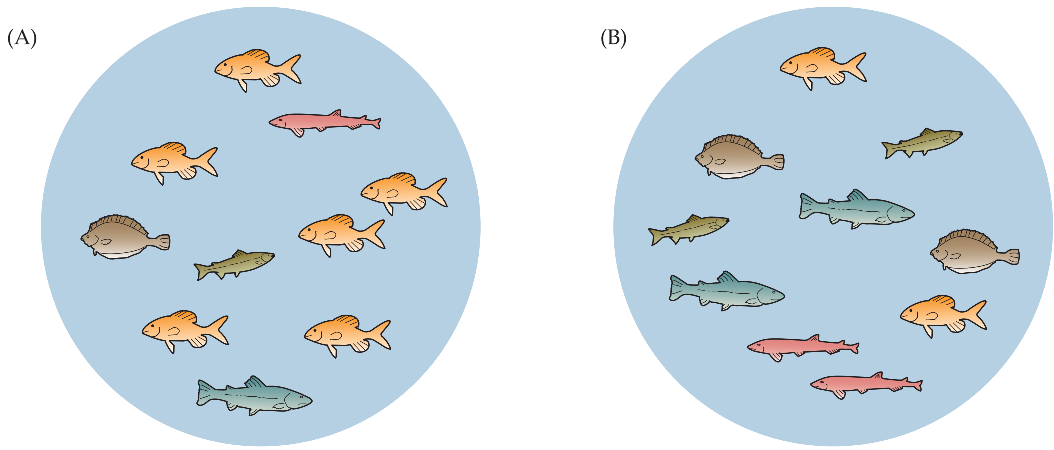


FIGURE 2.5 Biodiversity indexes for three regions, each consisting of three separate mountains. Each letter represents a population of a species; some species are found on only one mountain, while other species are found on two or three mountains. Alpha, gamma, and beta diversity values are shown for each region. If funds were available to protect only one region, Region 2 should be selected because it has the greatest gamma (total) diversity. However, if only one mountain could be protected, a mountain in Region 1 should be selected because these mountains have the highest alpha (local) diversity—that is, the greatest average number of species per mountain. Each mountain in Region 3 has a more distinct assemblage of species than the mountains in the other two regions, as shown by the higher beta diversity. If Region 3 were selected for protection, the relative priority of the individual mountains should then be judged based on how many unique species were found on each mountain.

Pond A, 60% of the individuals are orange carp and each of the remaining four species only represents 10% of the individuals. In Pond B there are also five fish species, but all the species have the same number of individuals, or 20% of the total. Using the Shannon diversity index, Pond B will have a greater diversity than Pond A (**FIGURE 2.6**). In some cases, one pond may even have a greater number of species but a lower diversity index than another pond if its community is dominated by one or just a few species. Note that, like the richness values explained previously, diversity measures of this type can be calculated at different scales and therefore are useful only as relative, rather than absolute, values. Furthermore, these quantitative definitions of diversity capture only part of the broad definition of biodiversity used by conservation biologists, and new ones continue to be developed (Iknayan et al. 2014). Although each has its limitations, they are useful for comparing regions and highlighting areas that have large numbers of native species requiring conservation protection.



(A)

	Number in sample (n)	n/total = proportion in sample (p)	ln(p)	ln(p) × (p)
	6	0.60	–0.51	–0.31
	1	0.10	–2.30	–0.23
	1	0.10	–2.30	–0.23
	1	0.10	–2.30	–0.23
	1	0.10	–2.30	–0.23
Total	10 fish	1 (100%)		–1.23
				H = 1.23

(B)

	Number in sample (n)	n/total = proportion in sample (p)	ln(p)	ln(p) × (p)
	2	0.20	–1.61	–0.32
	2	0.20	–1.61	–0.32
	2	0.20	–1.61	–0.32
	2	0.20	–1.61	–0.32
	2	0.20	–1.61	–0.32
Total	10 fish	1 (100%)		–1.61
				H = 1.61

FIGURE 2.6 If each circle represents a random sample of fish from a pond and colors represent species, both have the same species richness: 5. However, the Pond A sample is dominated by a single species (6 orange fish out of a total of 10 fish, or 60% of the total), while each of the other 4 species has only 10% of the total. In contrast, the sample from Pond B has perfect evenness; that is, each of the 5 species has the same number of individuals, or 20% of the total. Therefore, we would consider Pond B to have greater species diversity. We can further quantify this by calculating *H*, a measure of diversity, as shown in each table, with Pond A having a diversity of 1.23 and Pond B having a diversity of 1.61.

2.2 Genetic Diversity

LEARNING OBJECTIVES

By the end of this section you should be able to:

2.2.1 Predict possible outcomes of novel situations in which there is limited or no genetic diversity.

2.2.2 Identify when molecular tools are appropriate for different conservation applications.

Conservation biology also concerns itself with the preservation of genetic diversity within a species. This level of diversity is important because it provides evolutionary flexibility: when environmental conditions change, a genetically diverse species is more likely to have traits that allow it to adapt. Rare species often have less genetic variation than widespread species and, consequently, are more vulnerable to extinction (Szczecińska et al. 2016) (see Chapter 6).

How does genetic diversity arise?

Genetic diversity arises because individuals have slightly different forms of their **genes**, the units of the chromosomes that specify the synthesis of specific proteins. These different forms of a gene are known as **alleles**, and their physical position on the chromosome is the gene's **locus** (plural is *loci*). The different alleles originally arise through **mutations**—changes that occur in the deoxyribonucleic acid (DNA) that constitutes an individual's chromosomes. These changes to the DNA can be minute or quite large, as occurs when entire segments of DNA move about the genome; these DNA sequences are called **transposable elements**. For example, it was discovered that transposable elements were responsible for a mutation that turned British peppered moths (*Biston betularia*) from light to dark (van't Hof et al. 2016). Most mutations do not result in new traits, but when they do, they contribute to genetic variation that could become important for a population's survival. When pollution during the Industrial Revolution killed lichens, thus turning previously light-barked trees black, those individual moths with the mutation giving them dark wings were better able to hide from predators (Cook et al. 2012). In more recent times, however, environmental regulations have led to cleaner air, and lighter-winged moths have become more abundant. Thus, genetic diversity arising from mutations has been important for the persistence of a species in the face of environmental change over time.

Although the peppered moth example shows how a single allele can make a profound difference for a species, most traits occur because of the combined effects of many genes. Thus, genetic variation can also increase when offspring receive unique combinations of genes and chromosomes from their parents via the **recombination** of genes that occurs during sexual reproduction. Genes are exchanged between chromosomes, and new combinations are created when chromosomes from two parents combine to form a genetically unique offspring. Although mutations provide the basic material for genetic variation, the random rearrangement of alleles in different combinations that characterizes sexually reproducing species dramatically increases the potential for genetic variation (**FIGURE 2.7**).

The total array of genes and alleles in a population is the **gene pool** of the population, while the particular combination of alleles that any individual possesses is its **genotype**. The **phenotype** of an individual represents the morphological, physiological, anatomical, and biochemical characteristics of that individual that result from the expression of its genotype in a particular environment. Examples of phenotypes include eye color and blood type, physical qualities that are determined predominantly by an individual's genotype.

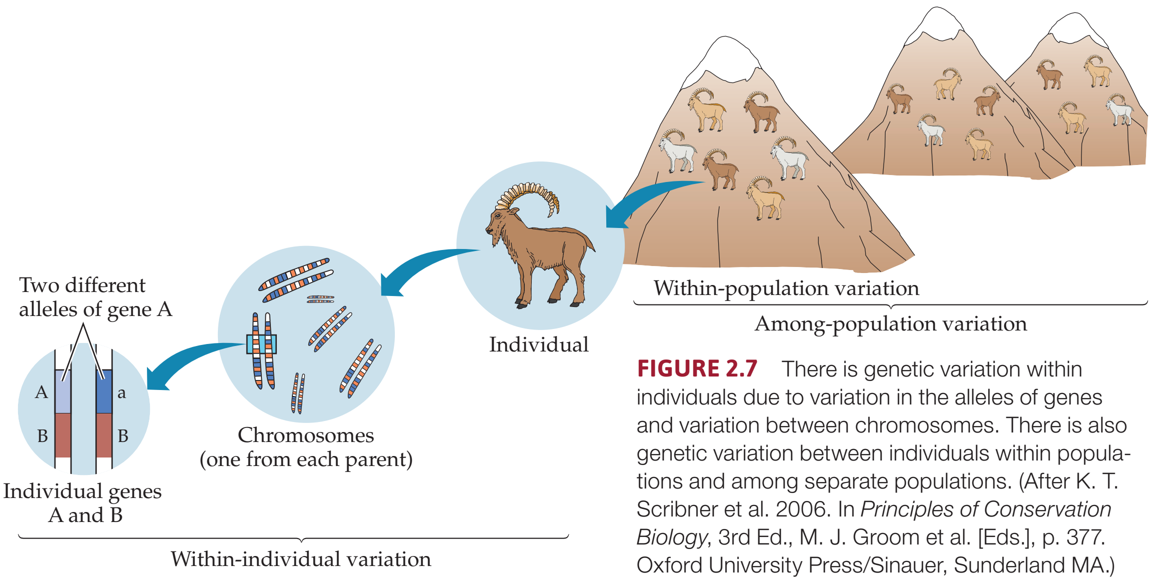


FIGURE 2.7 There is genetic variation within individuals due to variation in the alleles of genes and variation between chromosomes. There is also genetic variation between individuals within populations and among separate populations. (After K. T. Scribner et al. 2006. In *Principles of Conservation Biology*, 3rd Ed., M. J. Groom et al. [Eds.], p. 377. Oxford University Press/Sinauer, Sunderland MA.)

The amount of genetic variation in a population is determined both by the number of **polymorphic genes**—genes that have more than one allele—and by the number of alleles for each of these genes. The existence of a polymorphic gene also means that some individuals in the population will be **heterozygous** for the gene; that is, they will receive a different allele of the gene from each parent. On the other hand, some individuals will be **homozygous**; they will receive the same allele from each parent. All these levels of genetic variation contribute to a population's (and therefore a species') ability to adapt to a changing environment. We will see examples in Chapter 6 of how a species' survival can be affected by its capacity to evolve.

Measuring genetic diversity

As you can see, genetic diversity can be quantified in several ways, including measuring rates of homozygosity, figuring number and/or abundance of alleles for a gene, and identifying combinations of genes that contribute to trait diversity within a population or a species. *Conservation genetics* refers to the use of such genomic information to address issues within conservation biology. Genetic tools can also allow us to identify new species and determine when hybridization has occurred. Other uses include but are not limited to the following:

- Describing or comparing the **genetic structure** (patterns of genotypes) of managed and wild populations
- Determining the capacity of a small or endangered population to respond to environmental change
- Observing population dynamics in the context of human impacts

- Detecting the presence of a cryptic species by sampling DNA in the environment
- Identifying species and origin of biological material as a means of controlling trade in endangered species

These uses of genomics in conservation will be discussed in greater detail in the chapters that follow; as you will see, this technology touches nearly every area of conservation biology today.

In most of the uses just mentioned, genotypes of a sample of individuals are determined, such as is done with leaf samples of individual rare plants (Zhou et al. 2018). Alternatively, the diversity of an entire population can be sampled at once, such as by genotyping the microorganisms in soil or water samples, referred to as **environmental DNA** (**eDNA**) **sampling** (Deiner et al. 2021; Delgado-Baquerizo et al. 2018). Environmental DNA sampling can also be used to detect the presence of specific species that are otherwise difficult to track, such as in testing water to detect rare amphibians (Goldberg et al. 2018). The use of genomics tools ranges from identifying DNA sequences themselves to looking at the diversity of proteins created by those sequences (called allozymes), among many other approaches. The genetic material used for such analyses may be taken from the nucleus of the cell or, alternatively, from organelles such as mitochondria or chloroplasts. These latter sources of DNA are inherited only from the egg, not the sperm, and thus can provide information about the matrilineal line. Genomics is a rapidly evolving field that is increasingly being used to advance the goals of conservation biology.

Genetic variation within a species can allow the species to adapt to environmental change. New technologies allow scientists to measure multiple types of genetic diversity.

2.3 Ecosystem Diversity

LEARNING OBJECTIVES

By the end of this section you should be able to:

2.3.1 Draw, interpret, and analyze a food web, identifying trophic levels.

2.3.2 Apply the concept of "keystone" to specific species and resources.

Ecosystems are diverse, and this diversity is apparent even across a particular landscape. As we climb a mountain, for example, the structure of the vegetation and the kinds of plants and animals gradually change from those found in a tall forest to those found in a low, moss-filled forest to alpine meadow to cold, barren rock (see the chapter opening photo). As we move across the landscape, physical conditions (soil, temperature, precipitation, and so forth) change. One by one, the species present at our starting point drop out, and we encounter new species that were not found there. The landscape as a