ENVIRONMENTAL SCIENCE

Earth as a Living Planet

EIGHTH EDITION

BOTKIN | KELLER

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Environmental Science

Earth as a Living Planet

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DEDICATIONS

For my sister, Dorothy B. Rosenthal

who has been a source of inspiration, support, ideas,
and books to read, and is one of my harshest and best critics.

Dan Botkin

and

For Valery Rivera

who contributed so much to this book and
is a fountain of inspiration in our work and lives.

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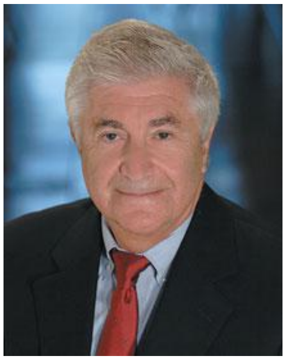

Photo by Maguire Neblet

Daniel B. Botkin is President of The Center for the Study of Environment, and Professor Emeritus of Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, where he has been on the faculty since 1978, serving as Chairman of the Environmental Studies Program from 1978 to 1985. For more than four decades, Professor Botkin has been active in the application of ecological science to environmental management. He is the winner of the Mitchell International Prize for Sustainable Development and the Fernow Prize for International Forestry, and he has been elected to the California Environmental Hall of Fame.

Trained in physics and biology, Professor Botkin is a leader in the application of advanced technology to the study of the environment. The originator of widely used forest gap-models, he has conducted research on endangered species, characteristics of natural wilderness areas, the biosphere, and global environmental problems including possible ecological effects of global warming. During his career, Professor Botkin has advised the World Bank about tropical forests, biological diversity, and sustainability; the Rockefeller Foundation about global environmental issues; the government of Taiwan about approaches to solving environmental problems; the state of California on the environmental effects of water diversion on Mono Lake. He served as the primary advisor to the National Geographic Society for its centennial edition map on "The Endangered Earth." He directed a study for the states of Oregon and California concerning salmon and their forested habitats.

He has published many articles and books about environmental issues. His latest books are *Beyond the Stoney Mountains: Nature in the American West from Lewis and Clark to Today* (Oxford University Press), *Strange Encounters: Adventures of a Renegade Naturalist* (Penguin/Tarcher), *The Blue Planet* (Wiley), *Our Natural History: The Lessons of Lewis and Clark* (Oxford University Press), *Discordant Harmonies: A New Ecology for the 21st Century* (Oxford University Press), *and Forest Dynamics: An Ecological Model* (Oxford University Press).

Professor Botkin was on the faculty of the Yale School of Forestry and Environmental Studies (1968–1974) and was a member of the staff of the Ecosystems Center at the Marine Biological Laboratory, Woods Hole, MA (1975–1977). He received a B.A. from the University of Rochester, an M.A. from the University of Wisconsin, and a Ph.D. from Rutgers University.

Edward A. Keller was chair of the Environmental Studies and Hydrologic Sciences Programs from 1993 to 1997 and is Professor of Earth Science at the University of California, Santa Barbara, where he teaches earth surface processes, environmental geology, environmental science, river processes, and engineering geology. Prior to joining the faculty at Santa Barbara, he taught geomorphology, environmental studies, and earth science at the University of North Carolina, Charlotte. He was the 1982–1983 Hartley Visiting Professor at the University of Southampton, a Visiting Fellow in 2000 at Emmanuel College of Cambridge University, England, and receipent of the Easterbrook Distinguished Scientist award from the Geological Society of America in 2004.

Professor Keller has focused his research efforts into three areas: studies of Quaternary stratigraphy and tectonics as they relate to earthquakes, active folding, and mountain building processes; hydrologic process and wildfire in the chaparral environment of Southern California; and physical habitat requirements for the endangered Southern California steelhead trout. He is the recipient of various Water Resources Research Center grants to study fluvial processes and U.S. Geological Survey and Southern California Earthquake Center grants to study earthquake hazards.

Professor Keller has published numerous papers and is the author of the textbooks *Environmental Geology, Introduction to Environmental Geology* and (with Nicholas Pinter) *Active Tectonics* (Prentice-Hall). He holds bachelor's degrees in both geology and mathematics from California State University, Fresno; an M.S. in geology from the University of California; and a Ph.D. in geology from Purdue University.

Preface

What Is Environmental Science?

Environmental science is a group of sciences that attempt to explain how life on the Earth is sustained, what leads to environmental problems, and how these problems can be solved.

Why Is This Study Important?

- We depend on our environment. People can live only in an environment with certain kinds of characteristics and within certain ranges of availability of resources. Because modern science and technology give us the power to affect the environment, we have to understand how the environment works, so that we can live within its constraints.
- People have always been fascinated with nature, which is, in its broadest view, our environment. As long as people have written, they have asked three questions about ourselves and nature:

  What is nature like when it is undisturbed by people?

  What are the effects of people on nature?

  What are the effects of nature on people?

Environmental science is our modern way of seeking answers to these questions.

- We enjoy our environment. To keep it enjoyable, we must understand it from a scientific viewpoint.
- Our environment improves the quality of our lives. A healthy environment can help us live longer and more fulfilling lives.
- It's just fascinating.

What Is the "Science" in Environmental Science?

Many sciences are important to environmental science. These include biology (especially ecology, that part of biology that deals with the relationships among living things and their environment), geology, hydrology, climatology, meteorology, oceanography, and soil science.

How Is Environmental Science Different from other Sciences?

- It involves many sciences.
- It includes sciences, but also involves related nonscientific fields that have to do with how we value the environment, from environmental philosophy to environmental economics.
- It deals with many topics that have great emotional effects on people, and therefore are subject to political debate and to strong feelings that often ignore scientific information.

What Is Your Role as a Student and as a Citizen?

Your role is to understand how to think through environmental issues so that you can arrive at your own decisions.

What Are the Professions That Grow Out of Environmental Science?

Many professions have grown out of the modern concern with environment, or have been extended and augmented by modern environmental sciences. These include park, wildlife, and wilderness management; urban planning and design; landscape planning and design; conservation and sustainable use of our natural resources.

Goals of This Book

Environmental Science: Earth as a Living Planet provides an up-to-date introduction to the study of the environment. Information is presented in an interdisciplinary perspective necessary to deal successfully with environmental problems. The goal is to teach you, the student, how to think through environmental issues.

Critical Thinking

We must do more than simply identify and discuss environmental problems and solutions. To be effective, we must know what science is and is not. Then, we need to develop critical thinking skills. Critical thinking is so important that we have made it the focus of its own chapter, Chapter 2. With this in mind, we have also developed *Environmental Science* to present the material in a factual and unbiased format. Our goal is to help you think through the issues, not tell you what to think. To this purpose, at the end of each chapter, we present "Critical Thinking Issues." Critical thinking is further emphasized throughout the text in analytical discussions of topics, evaluation of perspectives, and integration of important themes, which are described in detail later.

Interdisciplinary Approach

The approach of *Environmental Science* is interdisciplinary in nature. Environmental science integrates many disciplines, including the natural sciences, in addition to fields such as anthropology, economics, history, sociology, and philosophy of the environment. Not only do we need the best ideas and information to deal successfully with our environmental problems, but we also must be aware of the cultural and historical contexts in which we make decisions about the environment. Thus, the field of environmental science also integrates the natural sciences with environmental law, environmental impact, and environmental planning.

Themes

Our book is based on the philosophy that six threads of inquiry are of particular importance to environmental science. These key themes, called threads of inquiry, are woven throughout the book.

These six key themes are discussed in more detail in Chapter 1. They are also revisited at the end of each chapter and are emphasized in the Closer Look boxes, each of which is highlighted by an icon suggesting the major underlying theme of the discussion. In many cases, more than one theme is relevant.

Human Population

Underlying nearly all environmental problems is the rapidly increasing human population. Ultimately, we cannot expect to solve environmental problems unless the total number of people on Earth is an amount the environment can sustain. We believe that education is important to solving the population problem. As people become more educated, and as the rate of literacy increases, population growth tends to decrease.

Sustainability

Sustainability is a term that has gained popularity recently. Speaking generally, it means that a resource is used in such a way that it continues to be available. However, the term is used vaguely, and it is something experts are struggling to clarify. Some would define it as ensuring that future generations have equal opportunities to access the resources that our planet offers. Others would argue that sustainability refers to types of developments that are economically viable, do not harm the environment, and are socially just. We all agree that we must learn how to sustain our environmental resources so that they continue to provide benefits for people and other living things on our planet.

A Global Perspective

Until recently it was common to believe that human activity caused only local, or at most regional, environmental change. We now know that human activities can affect the environment globally. An emerging science known as Earth System Science seeks a basic understanding of how our planet's environment works as a global system. This understanding can then be applied to help solve global environmental problems. The emergence of Earth System Science has opened up a new area of inquiry for faculty and students.

The Urban World

An ever-growing number of people are living in urban areas. Unfortunately, our urban centers have long been neglected, and the quality of the urban environment has suffered. It is here that we experience the worst of air pollution, waste disposal problems, and other stresses on the environment. In the past we have centered our studies of the environment more on wilderness than the urban environment. In the future we must place greater focus on towns and cities as livable environments.

People and Nature

People seem to be always interested—amazed, fascinated, pleased, curious—in our environment. Why is it suitable for us? How can we keep it that way? We know that people and our civilizations are having major effects on the environment, from local ones (the street where you live) to the entire planet (we have created a hole in the Earth's ozone layer) which can affect us and many forms of life.

Science and Values

Finding solutions to environmental problems involves more than simply gathering facts and understanding the scientific issues of a particular problem. It also has much to do with our systems of values and issues of social justice. To solve our environmental problems, we must understand what our values are and which potential solutions are socially just. Then we can apply scientific knowledge about specific problems and find acceptable solutions.

Organization

Our text is divided into four parts. Part I **Introductory Chapters** provides a broad overview of the key themes in Environmental Science, introduces the scientific method and the fundamentals of a scientific approach to the environment: Earth as a system; basic biochemical cycles; population dynamics, focusing on the human population; and environmental economics. Part II **Ecology Chapters** explains the scientific basis of ecosystems, biological diversity, ecological restoration and environmental health. Part III **Resource- Management** is about management of our environmental resources: agriculture and environment; forests, parks, wilderness; wildlife and fisheries;as well as chapters on energy: basic principles of energy, fossil fuels and environment, alternative energy, and nuclear energy. Part IV: **Where People Have A Heavy Hand** discusses water pollution; climate change and air pollution; urban environments, and integrated waste management. The section ends with a capstone chapter, integrating and summarizing the main messages of the book.

Special Features

In writing *Environmental Science* we have designed a text that incorporates a number of special features that we believe will help teachers to teach and students to learn. These include the following:

- A **Case Study** introduces each chapter. The purpose is to interest students in the chapter's subject and to raise important questions on the subject matter For example, in Chapter 11, Agriculture, Aquaculture, and Environment, the opening case study tells about a farmer feeding his pigs trail mix, banana chips, yogurt-covered raisins, dried papaya, and cashews, because growing corn for biofuels is raising the costs of animal feed so much.
- **Learning Objectives** are introduced at the beginning of each chapter to help students focus on what is important in the chapter and what they should achieve after reading and studying **the chapter.**
- **A Closer Look** is the name of special learning modules that present more detailed information concerning a particular concept or issue. For example, **A Closer Look 13.2** discusses the reasons for conserving endangered species.
- Many of these special features contain figures and data to enrich the reader's understanding, and relate back to the book themes.
- Near the end of each chapter, a **Critical Thinking Issue** is presented to encourage critical thinking about the environment and to help students understand how the issue may be studied and evaluated. For example Chapter 22 presents a critical thinking issue about **How Can Urban Sprawl Be Controlled?**
- Following the Summary, a special section, **Reexamining Themes and Issues**, reinforces the six major themes of the textbook.
- **Study Questions** for each chapter provide a study aid, emphasizing critical thinking.
- **Further Readings** are provided with each chapter so that students may expand their knowledge by reading additional sources of information (both print and electronic) on the environment.
- **References** cited in the text are provided at the end of the book as notes for each chapter. These are numbered according to their citation in the text. We believe it's important that introductory textbooks carefully cite sources of information used in the writing. These are provided to help students recognize those scholars whose work we depend on, and so that students may draw upon these references as needed for additional reading and research.

Changes in the Eighth Edition

Environmental science is a rapidly developing set of fields. The scientific understanding of environment changes rapidly. Even the kinds of science, and the kinds of connections between science and our ways of life change. Also, the environment itself is changing rapidly: Populations grow; species become threatened or released from near-extinction; our actions change. To remain contemporary, a textbook in environmental science requires frequent updating and with this edition we have examined the entire text and worked to streamline and update every chapter.

Other changes and special features in the eighth edition include:

- A new capstone chapter, Chapter 24, which features a case study on the Gulf oil spill, and revisits the critical themes of the text.
- An updated Chapter on Global Warming, presenting balanced coverage of this important Environmental Science topic.

Combined Chapters

- The former chapters Air Pollution and Indoor Air Pollution have been folded into Chapter 21 to streamline the coverage of Air Pollution and Ozone Depletion.
- Former chapters on Agricultural Production and Environmental Effects of Agriculture have been combined into one.
- Biodiversity and Biogeography have been combined into one chapter.
- Biological Productivity and Energy Flow has been combined with Ecological Restoration.
- Minerals and the Environment and Waste Management have been integrated into one chapter, Materials Management.

New and updated Case Studies, Closer Look Boxes, and Critical Thinking Issues

Updated videos and resources are available to engage students in the key issues and topics of environmental science and provides resources for instructors, including PowerPoints, test bank, prelecture and post-lecture online quizzes, Lecture Launcher PowerPoints with clicker questions, and a variety of news video clips and animations.

Augmentation of Web Site References

Valid information is becoming increasingly available over the Web, and easy access to these data is of great value. Government data that used to take weeks of library search are available almost instantly over the Web. For this reason, we have greatly augmented the number of Web site references and have gathered them all on the book's companion Web site.

Updated Case Studies

Each chapter begins with a case study that helps the student learn about the chapter's topic through a specific example. A major improvement in the eighth edition is the replacement of some older case studies with new ones that discuss current issues and are more closely integrated into the chapter.

Updated Critical Thinking Issues

Each chapter ends with a discussion of an environmental issue, with critical thinking questions for the students. This is one of the ways that the text is designed to help students learn to think for themselves about the analysis of environmental issues. Answers to the end of chapter questions are available for instructor use on the Book Companion Site.

Supplementary Materials

Environmental Science, Eighth Edition, features a full line of teaching and learning resources developed to help professors create a more dynamic and innovative learning environment. For students, we offer tools to build their ability to think clearly and critically. For the convenience of both the professors and students, we provide teaching and learning tools on the Instructor and Student Companion Sites and, through the Wiley Resource Kit.

For Students

Student Web Site (www.wiley.com/college/botkin)

A content-rich Web site has been created to provide enrichment activities and resources for students. These features include review of Learning Objectives, online quizzing, Virtual Field Trips, interactive Environmental Debates, a map of regional case studies, critical thinking readings, glossary and flashcards, Web links to important data and research in the field of environmental studies, and video and animations covering a wide array of selected topics.

Also Available to Package

Environmental Science: Active Learning Laboratories and Applied Problem Sets, 2e by Travis Wagner and Robert Sanford both of University of Southern Maine, is designed to introduce environmental science students to the broad, interdisciplinary field of environmental science by presenting specific labs that use natural and social science concepts to varying degrees and by encouraging a "hands on" approach to understanding the impacts from the environmental/human interface. The laboratory and homework activities are designed to be low-cost and to reflect a sustainability approach in practice and in theory. *Environmental Science: Active Learning Laboratories and Applied Problem Sets, 2e* is available stand-alone or in a package with *Environmental Science, 8e.* Contact your Wiley representative for more information.

Earth Pulse

Utilizing full-color imagery and National Geographic photographs, ***EarthPulse*** takes you on a journey of discovery covering topics such as *The Human Condition, Our Relationship with Nature, and Our Connected World.* Illustrated by specific examples, each section focuses on trends affecting our world today. Included are extensive full-color world and regional maps for reference. *EarthPulse* is available only in a package with *Environmental Science*, *8e.* Contact your Wiley representative for more information or visit www.wiley.com/college/earthpulse.

For Instructors

Instructor's Resource Guide

The Instructor's Resource Guide (IRG), prepared by James Yount of Brevard Community College, is available on the Botkin/Keller Web site (www.wiley.com/college/botkin). The IRG provides useful tools to highlight key concepts from each chapter. Each chapter includes the following topics: Lecture Launchers that incorporate technology and opening thought questions; Discussion of Selected Sections from the text, which highlight specific definitions, equations, and examples; and Critical Thinking Activities to encourage class discussion.

Test Bank

The Test Bank, updated and revised by Anthony Gaudin of Ivy Tech Community College, is available on the Botkin/Keller Web site (www.wiley.com/college/botkin). The Test Bank includes approximately 2,000 questions, in multiple-choice, short-answer, and essay formats. The Test Bank is provided in a word.doc format for your convenience to use and edit for your individual needs. For this edition, the author has created many new questions and has labeled the boxed applications according to the six themes and issues set forth in the text. In addition, the author has created questions for the theme boxes and emphasized the themes in many of the questions throughout the test bank.

Respondus Text Bank Network

The Respondus Test Bank is available in the Wiley Resource Kit and on the Wiley Botkin/Keller Web site (www.wiley.com/college/botkin) and provides tests and quizzes for *Environmental Science* Eighth Edition for easy publication into your LMS course, as well as for printed tests. The Respondus Test Bank includes all of the files from the Test Bank, Practice Quizzes, and Pre and Post Lecture Questions in a dynamic computerized format. *For schools without a campus-wide license to Respondus, Wiley will provide one for no additional cost.

Video Lecture Launchers

A rich collection of videos have been selected to accompany key topics in the text. Accompanying each of the videos is contextualized commentary and questions that can further develop student understanding and can be assigned through the Wiley Resource Kit.

PowerPoint™ Presentations

Prepared by Elizabeth Joy Johnson these presentations are tailored to the text's topical coverage and are designed to convey key concepts, illustrated by embedded text art.

Advanced Placement® Guide for Environmental Science

Prepared by Brian Kaestner of Saint Mary's Hall these are available on the Instructor's Resource Web site (www.wiley.com/college/botkin). The Advanced Placement Guide provides a useful tool for high school instructors who are teaching the AP® Environmental Science course. This guide will help teachers to focus on the key concepts of every chapter to prepare students for the Advanced Placement® Exam. Each chapter includes a Chapter Overview that incorporates critical thinking questions, Key Topics important to the exam, and Web links to Laboratories and Activities that reinforce key topics.

Instructor's Web Site

All instructor resources are available on the instructor section of the Wiley Botkin/Keller Web site (www.wiley.com/college/botkin) and within the Wiley Resource Kit.

Completion of this book was only possible due to the cooperation and work of many people. To all those who so freely offered their advice and encouragement in this endeavor, we offer our most sincere appreciation. We are indebted to our colleagues who made contributions.

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Brief Contents

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CHAPTER 1

Key Themes in Environmental Sciences

Lions are a tourist attraction at Amboseli National Reserve in southern Kenya, and are a valuable resource. Massi people are beginning to help protect them, rather than hunt or poison them as they have traditionally done.

LEARNING OBJECTIVES

Certain themes are basic to environmental science. After reading this chapter, you should understand . . .

- That people and nature are intimately connected;
- Why rapid human population growth is the fundamental environmental issue;
- What sustainability is, and why we must learn to sustain our environmental resources;
- How human beings affect the environment of the entire planet;
- Why urban environments need attention;
- Why solutions to environmental problems involve making value judgments, based on scientific knowledge;
- What the precautionary principle is and why it is important.

CASE STUDY

Amboseli National Reserve: A Story of Change

Amboseli National Reserve in southern Kenya is home to the Maasai people, who are nomadic some of the time and raise cattle. The reserve is also a major tourist destination, where people from around the world can experience Africa and wild animals, such as lions and elephants. Today, environmental change and the future of tourism are being threatened in the area. We will consider long-term change and the more recent management of lions that may result in their local extinction.

Environmental change is often caused by a complex web of interactions among living things and between living things and their environment. In seeking to determine what caused a particular change, the most obvious answer may not be the right answer. Amboseli National Reserve is a case in point. In the short span of a few decades, this reserve, located at the foot of Mount Kilimanjaro (Figure 1.1), underwent a significant environmental change.

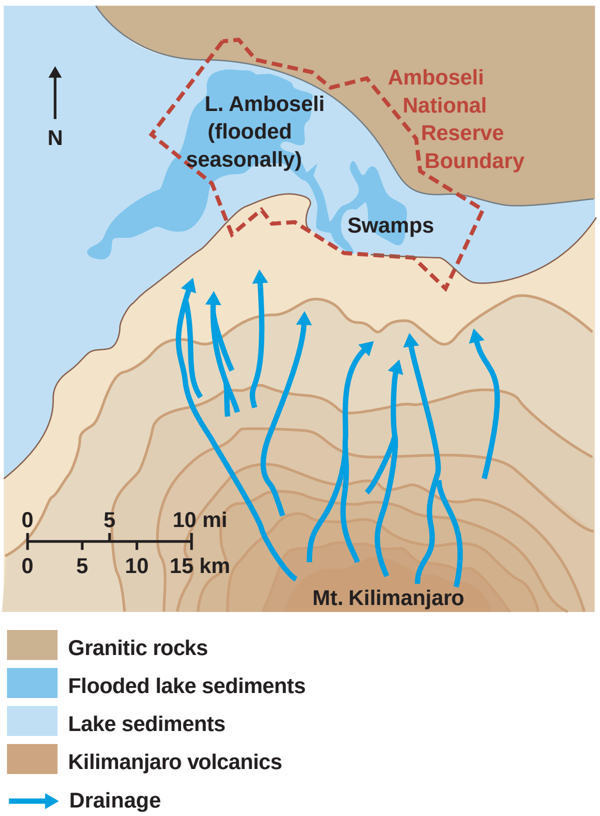


FIGURE 1.1 Generalized geology and landforms of Amboseli National Reserve, southern Kenya, Africa, and Mount Kilimanjaro. (*Source:* T. Dunn and L.B. Leopold, *Water in Environmental Planning* [San Francisco: Freeman, 1978].)

An understanding of physical, biological, and human-use factors—and how these factors are linked—is needed to explain what happened.

Before the mid-1950s, fever-tree woodlands—mostly acacia trees and associated grasses and shrubs—dominated the land and provided habitat for mammals that lived in these open woodlands, such as kudu, baboons, vervet monkeys, leopards, and impalas. Then, beginning in the 1950s and accelerating in the 1960s, these woodlands disappeared and were replaced by short grass and brush, which provided habitat for typical plains animals, such as zebras and wildebeest. Since the mid-1970s, Amboseli has remained a grassland with scattered brush and few trees.

Loss of the woodland habitat was initially blamed on overgrazing of cattle by the Maasai people (Figure 1.2) and damage to the trees from elephants (Figure 1.3). Environmental scientists eventually rejected these hypotheses as the main causes of the environmental change. Their careful work showed that changes in rainfall and soils were the primary culprits, rather than people or elephants.[1, 2] How did they arrive at this explanation?

During recent decades, the mean daily temperature rose dramatically, and annual rainfall increased but continued to vary from year to year by a factor of four, though with no regular pattern.[1, 2] Increased rainfall is generally associated with an increased abundance of trees, unlike what happened at Amboseli.

Why did scientists reject the overgrazing and elephant-damage hypothesis as the sole explanation for changes in Amboseli? Investigators were surprised to note that most dead trees were in an area that had been free of cattle since 1961, which was before the major decline in the woodland environment. Furthermore, some of the woodlands that suffered the least decline had the highest density of people and cattle. These observations suggested that overgrazing by cattle was not responsible for loss of the trees.

Elephant damage was thought to be a major factor because elephants had stripped bark from more than 83% of the trees in some areas and had pushed over some younger, smaller trees. However, researchers concluded that elephants played only a secondary role in changing the habitat. As the density of fever trees and other woodland plants decreased, the incidence of damage caused by elephants increased. In other words, elephant damage interacted with some other, primary factor in changing the habitat.[1]

FIGURE 1.2 Maasai people grazing cattle in Amboseli National Reserve, Kenya. Grazing was prematurely blamed for loss of fever-tree woodlands.

Figure 1.1 shows the boundary of the reserve and the major geologic units. The park is centered on an ancient lakebed, remnants of which include the seasonally flooded Lake Amboseli and some swampland. Mount Kilimanjaro is a well-known volcano, composed of alternating layers of volcanic rock and ash deposits. Rainfall that reaches the slopes of Mount Kilimanjaro infiltrates the volcanic material (becomes groundwater) and moves slowly down the slopes to saturate the ancient lakebed, eventually emerging at springs in the swampy, seasonally flooded land. The groundwater becomes saline (salty) as it percolates through the lakebed, since the salt stored in the lakebed sediments dissolves easily when the sediments are wet.

Because a lot of land has been transformed to agricultural uses, the slopes of Mount Kilimanjaro above Amboseli have less forest cover than they did 25 years ago. The loss of trees exposed dark soils that absorb solar energy, and this could cause local warming and drier conditions. In addition, there had been a significant decrease in snow and ice cover on the high slopes and summit of the mountain. Snow and ice reflect sunlight. As snow and ice decrease and dark rock is exposed, more solar energy is absorbed at the surface, warming it. Therefore, decreased snow and ice might cause some local warming.[3]

Research on rainfall, groundwater history, and soils suggested that the area is very sensitive to changing amounts of rainfall. During dry periods, the salty groundwater sinks lower into the earth, and the soil near the surface has a relatively low salt content. The fever trees grow well in the nonsalty soil. During wet periods, the groundwater rises closer to the surface, bringing with it salt, which invades the root zones of trees and kills them. The groundwater level rose as much as 3.5 m (11.4 ft) in response to unusually wet years in the 1960s. Analysis of the soils confirmed that the tree stands that suffered the most damage were those growing in highly saline soils. As the trees died, they were replaced by salt-tolerant grasses and low brush.[1, 2]

Evaluation of the historical record—using information from Maasai herders recorded by early European explorers—and of fluctuating lake levels in other East African lakes suggested that before 1890 there had been another period of above-normal rainfall and loss of woodland environment. Thus, the scientists concluded that cycles of greater and lesser rainfall change hydrology and soil conditions, which in turn change the plant and animal life of the area.[1] Cycles of wet and dry periods can be expected to continue, and associated with these will be changes in the soils, distribution of plants, and abundance and types of animals present.[1]

Management by the Maasai is proving difficult. Tourists want to see wild lions, but the lions sometimes kill and eat Maasai cattle, so the Maasai are killing the

FIGURE 1.3 Elephant feeding on a yellow-bark acacia tree. Elephant damage to trees is considered a factor in loss of woodland habitat in Amboseli National Reserve. However, elephants probably play a relatively minor role compared with oscillations in climate and groundwater conditions.

FIGURE 1.4 **Dead lions poisoned by a cheap agriculture pesticide.**

lions. Spearing, a Maasai passage to manhood, remains the dominant way to do it: In recent years, of 20 lions killed, 17 were speared and 3 were poisoned (Figure 1.4).[4] The poison also kills other animals that scavenge cattle, such as hyenas and vultures. Programs to pay the Maasai for cattle lost to lions have problems, so the killing continues. Over 100 lions have been killed in the past ten years, and in spite of declining lion populations, the killing is still increasing.[5] If it doesn't stop, lions may become locally extinct in the reserve, which will damage tourism which brings much needed cash to the reserve. As a result, some Massi are now protecting lions and thus the tourist income (see opening photograph). It may come down to a value judgment: lions on the one hand and cattle and people on the other. The lions may also be threatened by a loss of grasslands if the climate continues to change and becomes drier. Such a change favors woodlands, wherein the lion's natural prey, such as zebras and wildebeest, are replaced by kudu, impalas, monkeys, and baboons.

The Amboseli story illustrates that many environmental factors operate together, and that causes of change can be subtle and complex. The story also illustrates how environmental scientists attempt to work out sequences of events that follow a particular change. At Amboseli, rainfall cycles change hydrology and soil conditions, which in turn change the vegetation and animals of the area, and these in turn impact the people living there. To understand what happens in natural ecosystems, we can't just look for an answer derived from a single factor. We have to look at the entire environment and all of the factors that together influence what happens to life. In this chapter, we discuss some of the fundamental concepts of studying the environment in terms of several key themes that we will revisit at the end of each chapter.

1.1 Major Themes of Environmental Science

The study of environmental problems and their solutions has never been more important. Modern society in 2009 is hooked on oil. Production has declined, while demand has grown, and the population of the world has been increasing by more than 70 million each year. The emerging energy crisis is producing an economic crisis, as the prices of everything produced from oil (fertilizer, food, and fuel) rise beyond what some people can afford to pay. Energy and economic problems come at a time of unprecedented environmental concerns, from the local to global level.

At the beginning of the modern era—in A.D. 1—the number of people in the world was probably about 100 million, one-third of the present population of the United States. In 1960 the world contained 3 billion people. Our population has more than doubled in the last 40 years, to 6.8 billion people today. In the United States, population increase is often apparent when we travel. Urban traffic snarls, long lines to enter national parks, and difficulty getting tickets to popular attractions are all symptoms of a growing population. If recent human population growth rates continue, our numbers could reach 9.4 billion by 2050. The problem is that the Earth has not grown any larger, and the abundance of its resources has not increased—in many cases, quite the opposite. How, then, can Earth sustain all these people? And what is the maximum number of people that could live on Earth, not just for a short time but *sustained* over a long period?

Estimates of how many people the planet can support range from 2.5 billion to 40 billion (a population not possible with today's technology). Why do the estimates vary so widely? Because the answer depends on what quality of life people are willing to accept. Beyond a threshold world population of about 4–6 billion, the quality of life declines. How many people the Earth can sustain depends on *science and values* and is also a question about *people and nature*. The more people we pack onto the Earth, the less room and resources there are for wild animals and plants, wilderness, areas for recreation, and other aspects of nature—and the faster Earth's resources will be used. The answer also depends on how the people are distributed on the Earth—whether they are concentrated mostly in cities or spread evenly across the land.

Although the environment is complex and environmental issues seem sometimes to cover an unmanageable number of topics, the science of the environment comes down to the central topics just mentioned: the human population, urbanization, and sustainability within a global perspective. These issues have to be evaluated in light of the interrelations between people and nature, and the answers ultimately depend on both science and nature.

This book therefore approaches environmental science through six interrelated themes:

- *Human population growth* (the environmental problem).
- *Sustainability* (the environmental goal).
- *A global perspective* (many environmental problems require a global solution).
- *An urbanizing world* (most of us live and work in urban areas).
- *People and nature* (we share a common history with nature).
- *Science and values* (science provides solutions; which ones we choose are in part value judgments).

You may ask, "If this is all there is to it, what is in the rest of this book?" (See A Closer Look 1.1.) The answer

A CLOSER LOOK 1.1

A Little Environmental History

A brief historical explanation will help clarify what we seek to accomplish. Before 1960, few people had ever heard the word *ecology*, and the word *environment* meant little as a political or social issue. Then came the publication of Rachel Carson's landmark book, *Silent Spring* (Boston: Houghton Mifflin, 1960, 1962). At about the same time, several major environmental events occurred, such as oil spills along the coasts of Massachusetts and southern California, and highly publicized threats of extinction of many species, including whales, elephants, and songbirds. The environment became a popular issue.

As with any new social or political issue, at first relatively few people recognized its importance. Those who did found it necessary to stress the problems—to emphasize the negative—in order to bring public attention to environmental concerns. Adding to the limitations of the early approach to environmental issues was a lack of scientific knowledge and practical know-how. Environmental sciences were in their infancy. Some people even saw science as part of the problem.

The early days of modern environmentalism were dominated by confrontations between those labeled "environmentalists" and those labeled "anti-environmentalists." Stated in the simplest terms, environmentalists believed that the world was in peril. To them, economic and social development meant destruction of the environment and ultimately the end of civilization, the extinction of many species, and perhaps the extinction of human beings. Their solution was a new worldview that depended only secondarily on facts, understanding, and science. In contrast, again in simplest terms, the anti-environmentalists believed that whatever the environmental effects, social and economic health and progress were necessary for people and civilization to prosper. From their perspective, environmentalists represented a dangerous and extreme view with a focus on the environment to the detriment of people, a focus they thought would destroy the very basis of civilization and lead to the ruin of our modern way of life.

Today, the situation has changed. Public-opinion polls now show that people around the world rank the environment among the most important social and political issues. There is no longer a need to prove that environmental problems are serious.

We have made significant progress in many areas of environmental science (although our scientific understanding of the environment still lags behind our need to know). We have also begun to create legal frameworks for managing the environment, thus providing a new basis for addressing environmental issues. The time is now ripe to seek truly lasting, more rational solutions to environmental problems.

lies with the old saying "The devil is in the details." The solution to specific environmental problems requires specific knowledge. The six themes listed above help us see the big picture and provide a valuable background. The opening case study illustrates linkages among the themes, as well as the importance of details.

In this chapter we introduce the six themes with brief examples, showing the linkages among them and touching on the importance of specific knowledge that will be the concern of the rest of the book. We start with human population growth.

1.2 Human Population Growth

Our Rapid Population Growth

The most dramatic increase in the history of the human population occurred in the last part of the 20th century and continues today into the early 21st century. As mentioned, in merely the past 40 years the human population of the world more than doubled, from 2.5 billion to about 6.8 billion. Figure 1.5 illustrates this population explosion, sometimes referred to as the "population bomb." The figure shows that the expected decrease in population in the developed regions (for example, the U.S. and Western Europe) is more than offset by rapid population growth in the developing regions (for example, Africa, India, and South America).

Human population growth is, in some important ways, *the* underlying issue of the environment. Much current environmental damage is directly or indirectly the result of the very large number of people on Earth and our rate of increase. As you will see in Chapter 4, where we consider the human population in more detail, for most of human history the total population was small and the average long-term rate of increase was low relative to today's growth rate.[6, 7]

Although it is customary to think of the population as increasing continuously without declines or fluctuations, the growth of the human population has not been a steady march. For example, great declines occurred during the time of the Black Death in the 14th century. At that time, entire towns were abandoned, food production declined, and in England one-third of the population died within a single decade.[8]

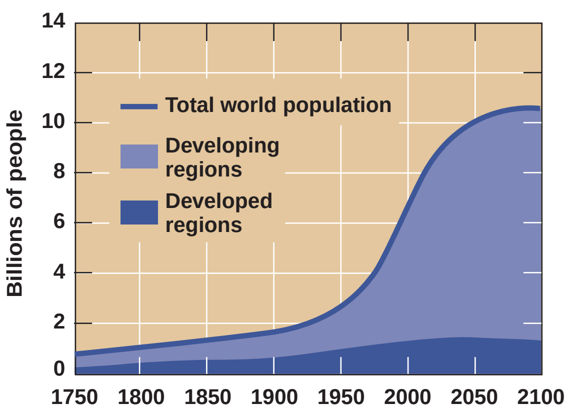


FIGURE 1.5 Population growth in developed and developing nations, 1750 projected to 2100.

Famine and Food Crisis

Famine is one of the things that happen when a human population exceeds its environmental resources. Famines have occurred in recent decades in Africa. In the mid-1970s, following a drought in the Sahel region, 500,000 Africans starved to death and several million more were permanently affected by malnutrition.[9] Starvation in African nations gained worldwide attention some ten years later, in the 1980s.[10, 11]

Famine in Africa has had multiple interrelated causes. One, as suggested, is drought. Although drought is not new to Africa, the size of the population affected by drought is new. In addition, deserts in Africa appear to be spreading, in part because of changing climate but also because of human activities. Poor farming practices have increased erosion, and deforestation may be helping to make the environment drier. In addition, the control and destruction of food have sometimes been used as a weapon in political disruptions (Figure 1.6). Today, malnutrition contributes to the death of about 6 million children per year. Low- and middle-income countries suffer the most from malnutrition, as measured by low weight for age (underweight, as shown in Figure 1.7).[12]

Famines in Africa illustrate another key theme: people and nature. People affect the environment, and the environment affects people. The environment affects agriculture, and agriculture affects the environment. Human population growth in Africa has severely stretched the capacity of the land to provide sufficient food and has threatened its future productivity.

The emerging global food crisis in the first decade of the 21st century has not been caused by war or drought but by rising food costs. The cost of basic items, such as rice, corn, and wheat, has risen to the point where low- and moderate-income countries are experiencing a serious crisis. In 2007 and 2008, food riots occurred in many locations, including Mexico, Haiti, Egypt, Yemen, Bangladesh, India, and Sudan (Figure 1.8). The rising cost of oil used to produce food (in fertilizer, transportation, working fields, etc.) and the conversion of some corn production to biofuels have been blamed. This situation involves yet another key theme: science and values. Scien-

FIGURE 1.6 Science and values. Social conditions affect the environment, and the environment affects social conditions. Political disruption in Somalia (illustrated by a Somalian boy with a gun, left photo) interrupted farming and food distribution, leading to starvation. Overpopulation, climate change, and poor farming methods also lead to starvation, which in turn promotes social disruption. Famine has been common in parts of Africa since the 1980s, as illustrated by gifts of food from aid agencies.

tific knowledge has led to increased agricultural production and to a better understanding of population growth and what is required to conserve natural resources. With this knowledge, we are forced to confront a choice: Which is more important, the survival of people alive today or conservation of the environment on which future food production and human life depend?[13]

Answering this question demands *value judgments* and the information and knowledge with which to make such judgments. For example, we must determine whether we can continue to increase agricultural production without destroying the very environment on which agriculture and, indeed, the persistence of life on Earth depend. Put another way, a technical, scientific investigation provides a basis for a value judgment.

The human population continues to grow, but humans' effects on the environment are growing even faster.[14] People cannot escape the laws of population growth (this is discussed in several chapters). The broad science-and-values question is: What will we do about the increase in our own species and its impact on our planet and on our future?

FIGURE 1.7 Underweight children under the age of 5 by region. Most are in low- and middle-income countries. (Source*:* World Population Data Sheet [Washington, DC: Population Reference Bureau, 2007. Accessed 5/19/08 @www.prb.org].)

(a) (b)

FIGURE 1.8 Food riots over the rising cost of food in 2007. (a) Haiti and **(b)** Bangladesh.

1.3 Sustainability and Carrying Capacity

The story of recent famines and food crises brings up one of the central environmental questions: What is the maximum number of people the Earth can sustain? That is, what is the sustainable human carrying capacity of the Earth? Much of this book will deal with information that helps answer this question. However, there is little doubt that we are using many renewable environmental resources faster than they can be replenished—in other words, we are using them *unsustainably*. In general, we are using forests and fish faster than they can regrow, and we are eliminating habitats of endangered species and other wildlife faster than they can be replenished. We are also extracting minerals, petroleum, and groundwater without sufficient concern for their limits or the need to recycle them. As a result, there is a shortage of some resources and a probability of more shortages in the future. Clearly, we must learn how to sustain our environmental resources so that they continue to provide benefits for people and other living things on our planet.

Sustainability: The Environmental Objective

The environmental catchphrase of the 1990s was "saving our planet." Are all life and the environments on which life depends really in danger? Will we leave behind a dead planet?

In the long view of planetary evolution, it is certain that planet Earth will survive us. Our sun is likely to last another several billion years, and if all humans became extinct in the next few years, life would still flourish here on Earth. The changes we have made—in the landscape, the atmosphere, the waters—would last for a few hundred or thousands of years but in a modest length of time would be erased by natural processes. What we are concerned with, as environmentalists, is the quality of the *human* environment on Earth, for us today and for our children.

Environmentalists agree that sustainability must be achieved, but we are unclear about how to achieve it, in part because the word is used to mean different things, often leading to confusion that causes people to work at cross-purposes. **Sustainability** has two formal scientific meanings with respect to environment: (1) *sustainability of resources*, such as a species of fish from the ocean, a kind of tree from a forest, coal from mines; and (2) *sustainability of an ecosystem*. Strictly speaking, harvesting a resource at a certain rate is sustainable if we can continue to harvest that resource at that same rate for some specified time well into the future. An ecosystem is sustainable if it can continue its primary functions for a specified time in the future. (Economists refer to the specified time in the future as a "planning time horizon.") Commonly, in discussions about environmental problems, the time period is not specified and is assumed to be very long—mathematically an infinite planning time, but in reality as long as it could possibly matter to us. For conservation of the environment and its resources to be based on quantitative science, both a rate of removal and a planning time horizon must be specified. However, ecosystems and species are always undergoing change, and a completely operational definition of *sustainability* will have to include such variation over time.

Economists, political scientists, and others also use the term *sustainability* in reference to types of development that are economically viable, do not harm the environment, and are socially just (fair to all people). We should also point out that the term *sustainable growth* is an oxymoron (i.e., a contradictory term) because any steady growth (fixed-percentage growth per year) produces large numbers in modest periods of time (see Exponential Growth in Chapter 3).

One of the environmental paradigms of the 21st century will be sustainability, but how will it be attained? Economists have begun to consider what is known as the *sustainable global economy:* the careful management and wise use of the planet and its resources, analogous to the management of money and goods. Those focusing on a sustainable global economy generally agree that under present conditions the global economy is *not* sustainable. Increasing numbers of people have resulted in so much pollution of the land, air, and water that the ecosystems that people depend on are in danger of collapse. What, then, are the attributes of a sustainable economy in the information age?[15]

- Populations of humans and other organisms living in harmony with the natural support systems, such as air, water, and land (including ecosystems).
- An energy policy that does not pollute the atmosphere, cause climate change (such as global warming), or pose unacceptable risk (a political or social decision).
- A plan for renewable resources—such as water, forests, grasslands, agricultural lands, and fisheries—that will not deplete the resources or damage ecosystems.
- A plan for nonrenewable resources that does not damage the environment, either locally or globally, and ensures that a share of our nonrenewable resources will be left to future generations.
- A social, legal, and political system that is dedicated to sustainability, with a democratic mandate to produce such an economy.

Recognizing that population is the environmental problem, we should keep in mind that a sustainable global economy will not be constructed around a completely stable global population. Rather, such an economy will take into account that the size of the human population will fluctuate within some stable range necessary to maintain healthy relationships with other components of the environment. To achieve a sustainable global economy, we need to do the following:[15]

- Develop an effective population-control strategy. This will, at least, require more education of people, since literacy and population growth are inversely related.
- Completely restructure our energy programs. A sustainable global economy is probably impossible if it is based on the use of fossil fuels. New energy plans will be based on an integrated energy policy, with more emphasis on renewable energy sources (such as solar and wind) and on energy conservation.
- Institute economic planning, including a tax structure that will encourage population control and wise use of resources. Financial aid for developing countries is absolutely necessary to narrow the gap between rich and poor nations.
- Implement social, legal, political, and educational changes that help to maintain a quality local, regional, and global environment. This must be a serious commitment that all the people of the world will cooperate with.

Moving toward Sustainability: Some Criteria

Stating that we wish to develop a sustainable future acknowledges that our present practices are not sustainable. Indeed, continuing on our present paths of overpopulation, resource consumption, and pollution will not lead to sustainability. We will need to develop new concepts that will mold industrial, social, and environmental interests into an integrated, harmonious system. In other words, we need to develop a new paradigm, an alternative to our present model for running society and creating wealth.[16] The new paradigm might be described as follows.[17]

- *Evolutionary rather than revolutionary.* Developing a sustainable future will require an evolution in our values that involves our lifestyles as well as social, economic, and environmental justice.
- *Inclusive, not exclusive.* All peoples of Earth must be included. This means bringing all people to a higher standard of living in a sustainable way that will not compromise our environment.
- *Proactive, not reactive.* We must plan for change and for events such as human population problems, resource shortages, and natural hazards, rather than waiting for them to surprise us and then reacting. This may sometimes require us to apply the Precautionary Principle, which we discuss with science and values (Section 1.7).
- *Attracting, not attacking.* People must be attracted to the new paradigm because it is right and just. Those who speak for our environment should not take a hostile stand but should attract people to the path of sustainability through sound scientific argument and appropriate values.
- *Assisting the disadvantaged, not taking advantage.* This involves issues of environmental justice. All people have the right to live and work in a safe, clean environment. Working people around the globe need to receive a living wage—wages sufficient to support their families. Exploitation of workers to reduce the costs of manufacturing goods or growing food diminishes us all.

(a)

(b)

FIGURE 1.9 How many people do we want on Earth? (a) Streets of Calcutta; **(b)** Davis, California.

The Carrying Capacity of the Earth

Carrying capacity is a concept related to sustainability. It is usually defined as the maximum number of individuals of a species that can be sustained by an environment without decreasing the capacity of the environment to sustain that same number in the future.

There are limits to the Earth's potential to support humans. If we used Earth's total photosynthetic potential with present technology and efficiency to support 6.8 billion people, Earth could support a human population of about 15 billion. However, in doing this, we would share our land with very little else.[18, 19] When we ask "What is the maximum number of people that Earth can sustain?" we are asking not just about Earth's carrying capacity but also about sustainability.

As we pointed out, what we consider a "desirable human carrying capacity" depends in part on our values (Figure 1.9). Do we want those who follow us to live short lives in crowded conditions, without a chance to enjoy Earth's scenery and diversity of life? Or do we hope that our descendants will have a life of high quality and good health? Once we choose a goal regarding the quality of life, we can use scientific information to understand what the sustainable carrying capacity might be and how we might achieve it.

1.4 A Global Perspective

Our actions today are experienced worldwide. Because human actions have begun to change the environment all over the world, the next generation, more than the present generation, will have to take a global perspective on environmental issues (Figure 1.10).

Recognition that civilization can change the environment at a global level is relatively recent. As we discuss in detail in later chapters, scientists now believe that emissions of modern chemicals are changing the ozone layer high in the atmosphere. Scientists also believe that burning fossil fuels increases the concentration of greenhouse gases in the atmosphere, which may change Earth's climate. These atmospheric changes suggest that the actions of many groups of people, at many locations, affect the environment of the entire world.[20] Another new idea explored in later chapters is that not only human life but also nonhuman life affects the environment of our whole planet and has changed it over the course of several billion years. These two new ideas have profoundly affected our approach to environmental issues.

Awareness of the global interactions between life and the environment has led to the development of the **Gaia hypothesis**. Originated by British chemist James Lovelock and American biologist Lynn Margulis, the Gaia hypothesis (discussed in Chapter 3) proposes that over the

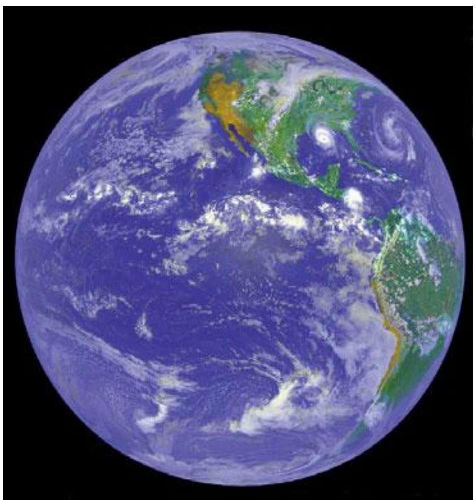


FIGURE 1.10 Earth from space. Isolated from other planets, Earth is "home," the only habitat we have.

history of life on Earth, life has profoundly changed the global environment, and that these changes have tended to improve the chances for the continuation of life. Because life affects the environment at a global level, the environment of our planet is different from that of a lifeless one.

1.5 An Urban World

In part because of the rapid growth of the human population and in part because of changes in technology, we are becoming an urban species, and our effects on the environment are more and more the effects of urban life (Figure 1.11a). Economic development leads to urbanization; people move from farms to cities and then perhaps to suburbs. Cities and towns get larger, and because they are commonly located near rivers and along coastlines, urban sprawl often overtakes the agricultural land of river floodplains, as well as the coastal wetlands, which are important habitats for many rare and endangered species. As urban areas expand, wetlands are filled in, forests cut down, and soils covered over with pavement and buildings.

In developed countries, about 75% of the population live in urban areas and 25% in rural areas, but in developing countries only 40% of the people are city dwellers. By 2008, for the first time, more than half of the people on Earth lived in urban areas, and it is estimated that by 2025 almost two-thirds of the population—5 billion people—will live in cities. Only a few urban areas had populations

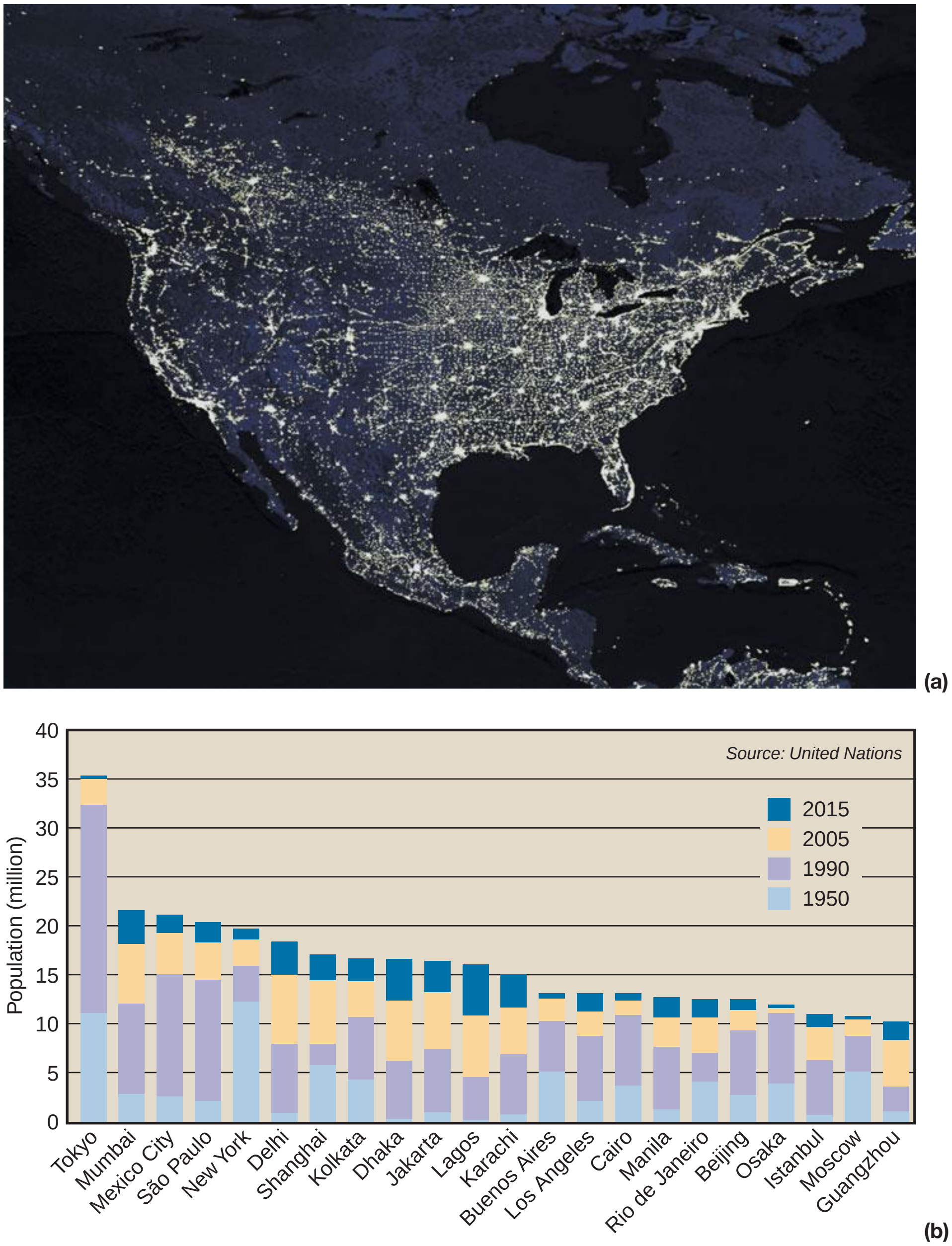


FIGURE 1.11 **(a) An urban world and a global perspective.** When the United States is viewed at night from space, the urban areas show up as bright lights. The number of urban areas reflects the urbanization of our nation. **(b) Megacities by 2015.** (*Source:* Data from United Nations Population Division, World Urbanization 2005, and *State of the World 2007*. World Watch Institute.)

FIGURE 1.12 An aerial photo of Los Angeles shows the large extent of a megacity.

over 4 million in 1950. In 1999 Tokyo, Japan, was the world's largest city, with a population of about 12 million, and by 2015 Tokyo will likely still be the world's largest city, with a projected population of 28.9 million. The number of **megacities**—urban areas with at least 10 million inhabitants—increased from 2 (New York City and London) in 1950 to 22 (including Los Angeles and New York City) in 2005 (Figures 1.11b and 1.12). Most megacities are in the developing world, and it is estimated that by 2015 most megacities will be in Asia.[21, 22]

In the past, environmental organizations often focused on nonurban issues—wilderness, endangered species, and natural resources, including forests, fisheries, and wildlife. Although these will remain important issues, in the future we must place more emphasis on urban environments and their effects on the rest of the planet.

1.6 People and Nature

Today we stand at the threshold of a major change in our approach to environmental issues. Two paths lie before us. One path is to assume that environmental problems are the result of human actions and that the solution is simply to stop these actions. Based on the notion, popularized some 40 years ago, that people are separate from nature, this path has led to many advances but also many failures. It has emphasized confrontation and emotionalism and has been characterized by a lack of understanding of basic facts about the environment and how natural ecological systems function, often basing solutions instead on political ideologies and ancient myths about nature.

The second path begins with a scientific analysis of an environmental controversy and leads from there to cooperative problem solving. It accepts the connection between people and nature and offers the potential for long-lasting, successful solutions to environmental problems. One purpose of this book is to take the student down the second pathway.

People and nature are intimately integrated. Each affects the other. We depend on nature in countless ways. We depend on nature directly for many material resources, such as wood, water, and oxygen. We depend on nature indirectly through what are called public-service functions. For example, soil is necessary for plants and

(a)

FIGURE 1.13 **(a)** Cross section of a soil; **(b)** earthworms are among the many soil animals important to maintaining soil fertility and structure.

(b)

FIGURE 1.14 Land cleared by African elephants, Tsavo National Park, Kenya.

FIGURE 1.15 People and nature. We feel safe around a campfire—a legacy from our Pleistocene ancestors?

therefore for us (Figure 1.13); the atmosphere provides a climate in which we can live; the ozone layer high in the atmosphere protects us from ultraviolet radiation; trees absorb some air pollutants; wetlands can cleanse water. We also depend on nature for beauty and recreation—the needs of our inner selves—as people always have.

We in turn affect nature. For as long as we have had tools, including fire, we have changed nature, often in ways that we like and have considered "natural." One can argue that it is natural for organisms to change their environment. Elephants topple trees, changing forests to grasslands, and people cut down trees and plant crops (Figure 1.14). Who is to say which is more natural? In fact, few organisms do *not* change their environment.

People have known this for a long time, but the idea that people might change nature to their advantage was unpopular in the last decades of the 20th century. At that time, the word *environment* suggested something separate—"out there"—implying that people were not part of nature. Today, environmental sciences are showing us how people and nature connect, and in what ways this is beneficial to both.

With growing recognition of the environment's importance, we are becoming more Earth-centered. We seek to spend more time in nature for recreation and spiritual activities. We accept that we have evolved on and with the Earth and are not separate from it. Although we are evolving fast, we remain genetically similar to people who lived more than 100,000 years ago. Do you ever wonder why we like to go camping, to sit around a fire at night roasting marshmallows and singing, or exchanging scary stories about bears and mountain lions (Figure 1.15)? More than ever, we understand and celebrate our union with nature as we work toward sustainability.

Most people recognize that we must seek sustainability not only of the environment but also of our economic activities, so that humanity and the environment can persist together. The dichotomy of the 20th century is giving way to a new unity: the idea that a sustainable environment and a sustainable economy may be compatible, that people and nature are intertwined, and that success for one involves success for the other.

1.7 Science and Values

Deciding what to do about an environmental problem involves both values and science, as we have already seen. We must choose what we want the environment to be. But to make this choice, we must first know what is possible. That requires knowing the scientific data and understanding its implications. Scientists rely on critical thinking. Critical scientific thinking is disciplined, using intellectual standards, effective communication, clarity, and commitment to developing scientific knowledge and skills. It leads to conclusions, generalizations, and, sometimes, scientific theories and even scientific laws. Taken together, these comprise a body of beliefs that, at the present time, account for all known observations about a particular phenomenon. Some of the intellectual standards are as follows:

Selected Intellectual Standards

- ***Clarity:*** If a statement is unclear, you can't tell whether it is relevant or accurate.
- ***Accuracy:*** Is a statement true? Can it be checked? To what extent does a measurement agree with the accepted value?
- ***Precision:*** The degree of exactness to which something is measured. Can a statement be more specific, detailed, and exact?

- ***Relevance:*** How well is a statement connected to the problem at hand?
- ***Depth:*** Did you deal with the complexities of a question?
- ***Breadth:*** Did you consider other points of view or look at it from a different perspective?
- ***Logic:*** Does a conclusion make sense and follow from the evidence?
- ***Significance:*** Is the problem an important one? Why?
- ***Fairness:*** Are there any vested interests, and have other points of view received attention?

Modified after R. Paul, and L. Elder, *Critical Thinking* (Dillon Beach, CA: The Foundation for Critical Thinking, 2003).

Once we know our options, we can select from among them. What we choose is determined by our values. An example of a value judgment regarding the world's human environmental problem is the choice between the desire of an individual to have many children and the need to find a way to limit the human population worldwide.

After we have chosen a goal based on knowledge and values, we have to find a way to attain that goal. This step also requires knowledge. And the more technologically advanced and powerful our civilization, the more knowledge is required. For example, current fishing methods enable us to harvest very large numbers of chinook salmon from the Columbia River, and public demand for salmon encourages us to harvest as many as possible. To determine whether chinook salmon are sustainable, we must know how many there are now and how many there have been in the past. We must also understand the processes of birth and growth for this fish, as well as its food requirements, habitat, life cycle, and so forth—all the factors that ultimately determine the abundance of salmon in the Columbia River.

Consider, in contrast, the situation almost two centuries ago. When Lewis and Clark first made an expedition to the Columbia, they found many small villages of Native Americans who depended in large part on the fish in the river for food (Figure 1.16). The human population was small, and the methods of fishing were simple. The maximum number of fish the people could catch probably posed no threat to the salmon, so these people could fish without scientific understanding of numbers and processes. (This example does not suggest that prescientific societies lacked an appreciation for the idea of sustainability. On the contrary, many so-called primitive societies held strong beliefs about the limits of harvests.)

The Precautionary Principle

Science and values come to the forefront when we think about what action to take about a perceived environmental problem for which the science is only partially known. This is often the case because all science is preliminary and subject to analysis of new data, ideas, and tests of hypotheses. Even with careful scientific research, it can be difficult, even impossible, to prove with absolute certainty how relationships between human activities and other physical and biological processes lead to local and global environmental problems, such as global warming, depletion of ozone in the upper atmosphere, loss of biodiversity, and declining resources. For this reason, in 1992 the Rio Earth Summit on Sustainable Development listed as one of its principles what we now call the **Precautionary Principle**. Basically, it says that when there is a threat of serious, perhaps even irreversible, environmental damage, we should not wait for scientific proof before taking precautionary steps to prevent potential harm to the environment.

The Precautionary Principle requires critical thinking about a variety of environmental concerns, such as the manufacture and use of chemicals, including pesticides, herbicides, and drugs; the use of fossil fuels and nuclear energy; the conversion of land from one use to another (for example, from rural to urban); and the management of wildlife, fisheries, and forests.[23]

FIGURE 1.16 Native Americans fishing for salmon on the Columbia River.

FIGURE 1.17 The city of San Francisco, with its scenic bayside environment, has adopted the Precautionary Principle.

One important question in applying the Precautionary Principle is how much scientific evidence we should have before taking action on a particular environmental problem. The principle recognizes the need to evaluate all the scientific evidence we have and to draw provisional conclusions while continuing our scientific investigation, which may provide additional or more reliable data. For example, when considering environmental health issues related to the use of a pesticide, we may have a lot of scientific data, but with gaps, inconsistencies, and other scientific uncertainties. Those in favor of continuing to use that pesticide may argue that there isn't enough proof of its danger to ban it. Others may argue that absolute proof of safety is necessary before a new pesticide is used. Those advocating the Precautionary Principle would argue that we should continue to investigate but, to be on the safe side, should not wait to take cost-effective precautionary measures to prevent environmental damage or health problems. What constitutes a cost-effective measure? Certainly we would need to examine the benefits and costs of taking a particular action versus taking no action. Other economic analyses may also be appropriate.[23, 24]

The Precautionary Principle is emerging as a new tool for environmental management and has been adopted by the city of San Francisco (Figure 1.17) and the European Union. There will always be arguments over what constitutes sufficient scientific knowledge for decision making. Nevertheless, the Precautionary Principle, even though it may be difficult to apply, is becoming a common part of environmental analysis with respect to environmental protection and environmental health issues. It requires us to think ahead and predict potential consequences before they occur. As a result, the Precautionary Principle is a *proactive*, rather than *reactive*, tool—that is, we can use it when we see real trouble coming, rather than reacting after the trouble arises.

Placing a Value on the Environment

How do we place a value on any aspect of our environment? How do we choose between two different concerns? The value of the environment is based on eight justifications: utilitarian (materialistic), ecological, aesthetic, recreational, inspirational, creative, moral, and cultural.

The **utilitarian justification** is that some aspect of the environment is valuable because it benefits individuals economically or is directly necessary to human survival. For example, conserving lions in Africa as part of tourism provides a livelihood for local people.

The **ecological justification** is that an ecosystem is necessary for the survival of some species of interest to us, or that the system itself provides some benefit. For example, a mangrove swamp (a type of coastal wetland) provides habitat for marine fish, and although we do not eat mangrove trees, we may eat the fish that depend on them. Also, the mangroves are habitat for many noncommercial species, some endangered. Therefore, conservation of the mangrove is important ecologically. Another example: Burning coal and oil adds greenhouse gases to the atmosphere, which may lead to a climate change that could affect the entire Earth. Such ecological reasons form a basis for the conservation of nature that is essentially enlightened self-interest.

Aesthetic and **recreational justifications** have to do with our appreciation of the beauty of nature and our desire to get out and enjoy it. For example, many people find wilderness scenery beautiful and would rather live in a world with wilderness than without it. One way we enjoy nature's beauty is to seek recreation in the outdoors.

The aesthetic and recreational justifications are gaining a legal basis. The state of Alaska acknowledges that sea otters have an important recreational role in that people enjoy watching and photographing them in a wilderness setting. And there are many other examples of the aesthetic importance of the environment. When people mourn the death of a loved one, they typically seek out places with grass, trees, and flowers; thus we use these to beautify our graveyards. Conservation of nature can be based on its benefits to the human spirit, our "inner selves" (*inspirational justification*). Nature is also often an aid to human creativity (the *creative justification*). The creativity of artists and poets, among others, is often inspired by their contact with nature. But while nature's aesthetic, recreational, and inspirational value is a widespread reason that people enjoy nature, it is rarely used in formal environmental arguments, perhaps in the belief that they might seem superficial justifications for conserving nature. In fact, however, beauty in their surroundings is of profound importance to people. Frederick Law Olmsted, the great American landscape planner, argued that plantings of vegetation provide medical, psychological, and social benefits and are essential to city life.[18]

Moral justification has to do with the belief that various aspects of the environment have a right to exist and that it is our moral obligation to help them, or at least allow them, to persist. Moral arguments have been extended to many nonhuman organisms, to entire ecosystems, and even to inanimate objects. The historian Roderick Nash, for example, wrote an article entitled "Do Rocks Have Rights?" that discusses such moral justification,[29] and the United Nations General Assembly World Charter for Nature, signed in 1982, states that species have a moral right to exist.

Cultural justification refers to the fact that different cultures have many of the same values but also some different values with respect to the environment. This may also be in terms of specifics of a particular value. All cultures may value nature, but, depending on their religious beliefs, may value it in different degrees of intensity. For example, Buddhist monks when preparing ground for a building may pick up and move disturbed eathhworms, something few others would do. Different cultures integrate nature into their towns, cities, and homes in different ways depending on their view of nature.

Analysis of environmental values is the focus of a new discipline, known as environmental ethics. Another concern of environmental ethics is our obligation to future generations: Do we have a moral obligation to leave the environment in good condition for our descendants, or are we at liberty to use environmental resources to the point of depletion within our own lifetimes?

CRITICAL THINKING ISSUE

Easter Island

The story of Easter Island has been used as an example of how people may degrade the environment as they grow in number, until eventually their overuse of the environment results in the collapse of the society. This story has been challenged by recent work. We will present what is known, and you should examine the case history critically. To help with this issue, look back to the list of intellectual standards useful in critical thinking.

Easter Island's history spans approximately 800 to 1,500 years and illustrates the importance of science and the sometimes irreversible consequences of human population growth and the introduction of a damaging exotic species, accompanied by depletion of resources necessary for survival. Evidence of the island's history is based on detailed studies by earth scientists and social scientists who investigated the anthropological record left in the soil where people lived and the sediment in ponds where pollen from plants that lived at different times was deposited. The goals of the studies were to estimate the number of people, their diet, and their use of resources. This was linked to studies of changes in vegetation, soils, and land productivity.

Easter Island lies about 3,700 km west of South America and 4,000 km from Tahiti (Figure 1.18a), where the people may have come from. The island is small, about 170 km^2, with a rough triangular shape and an inactive volcano at each corner. The elevation is less than about 500 m (1,500 ft) (Figure 1.18b), too low to hold clouds like those in Hawaii that bring rain. As a result, water resources are limited. When Polynesian people first reached it about 800–1,500 years ago, they colonized a green island covered with rich soils and forest. The small group of settlers grew rapidly, to perhaps over 10,000 people, who eventually established a complex society that was spread among a number of small villages. They raised crops and chickens, supplementing their diet with fish from the sea. They used the island's trees to build their homes and to build boats. They also carved massive 8-meter-high statues from volcanic rock and moved them into place at various parts of the island using tree trunks as rollers (Figure 1.18b, c).

When Europeans first reached Easter Island in 1722, the only symbols of the once-robust society were the statues. A study suggested that the island's population had collapsed in just a few decades to about 2,000 people because they had used up (degraded) the isolated island's limited resource base.[25, 26]

At first there were abundant resources, and the human population grew fast. To support their growing population, they cleared more and more land for agriculture and cut more trees for fuel, homes, and boats—and for moving the statues into place. Some of the food plants they brought to the island didn't survive, possibly because the voyage was too long or the climate unsuitable for them. In particular, they did not have the breadfruit tree, a nutritious starchy food source, so they relied more heavily on other crops, which required clearing more land for planting. The island was also relatively dry, so it is likely that fires for clearing land got out of control sometimes and destroyed even more forest than intended.[25, 26]

The cards were stacked against the settlers to some extent—but they didn't know this until too late. Other islands of similar size that the Polynesians had settled did not suffer forest depletion and fall into ruin.[25, 26] This isolated island, however, was more sensitive to change. As the forests were cut down, the soils, no longer protected by forest cover, were lost to erosion. Loss of the soils reduced agricultural productivity, but the biggest loss was the trees. Without wood to build homes and boats, the people were forced to live in caves and could no longer venture out into the ocean for fish.[25]

These changes did not happen overnight—it took more than 1,000 years for the expanding population to deplete its resources. Loss of the forest was irreversible: Because it led to loss of soil, new trees could not grow to replace the forests. As resources grew scarcer, wars between the villages became common, as did slavery, and perhaps even cannibalism.

Easter Island is small, but its story is a dark one that suggests what can happen when people use up the resources of an isolated area. We note, however, that some aspects of the above history of Easter Island have recently been challenged. New data suggest that people first arrived about 800 years ago, not 1,500; thus, much less time was available for people to degrade the land.[27, 28] Deforestation certainly played a role in the loss of trees, and the rats that arrived with the Polynesians were evidently responsible for eating seeds of the palm trees, preventing regeneration. According to the alternative explanation of the island's demise, the Polynesian people on the island at the time of European contact in 1722 numbered about 3,000; this may have been close to the maximum reached around the year 1350. Contact with Europeans introduced new diseases and enslavement, which reduced the population to about 100 by the late 1870s.[27]

Easter Island, also called Rapa Nui, was annexed by Chile in 1888. Today, about 3,000 people live on the island. Tourism is the main source of income; about 90% of the island is grassland, and thin, rocky soil is common. There have been reforestation projects, and about 5% of the island is now forested, mostly by eucalyptus plantations in the central part of the island. There are also fruit trees in some areas.

As more of the story of Easter Island emerges from scientific and social studies, the effects of resource exploitation, invasive rats, and European contact will become clearer, and the environmental lessons of the collapse will lead to a better understanding of how we can sustain our global human culture. However, the primary lesson is that *limited resources can support only a limited human population.*

Like Easter Island, our planet Earth is isolated in our solar system and universe and has limited resources. As a result, the world's growing population is facing the problem of how to conserve those resources. We know it takes a while before environmental damage begins to show, and we know that some environmental damage may be irreversible. We are striving to develop plans to ensure that our natural resources, as well as the other living things we share our planet with, will not be damaged beyond recovery.[29]

Critical Thinking Questions

1. What are the main lessons to take from Easter Island's history?
2. People may have arrived at Easter Island 1,500 years ago or later, perhaps 800 years ago. Does the timing make a significant difference in the story? How?
3. Assuming that an increasing human population, introduction of invasive rats, loss of trees, the resulting soil erosion, and, later, introduced European diseases led to collapse of the society, can Easter Island be used as a model for what could happen to Earth? Why? Why not?

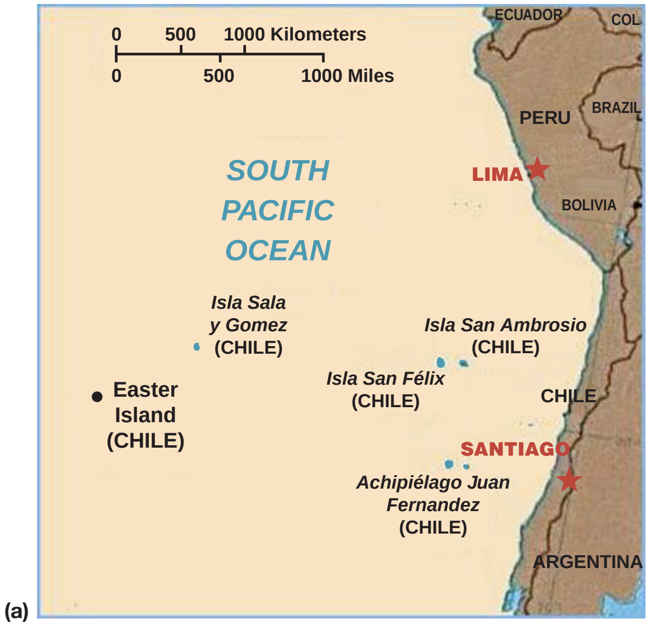
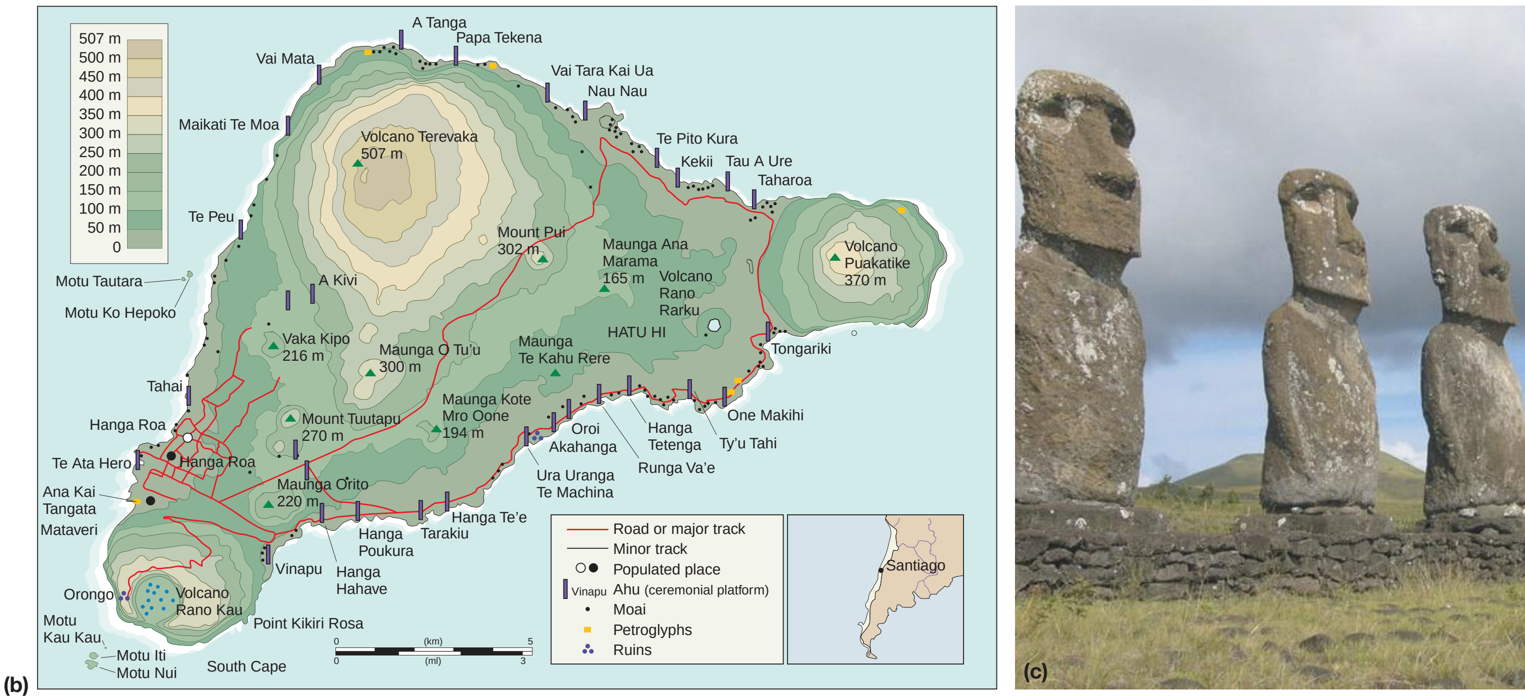


FIGURE 1.18 **Easter Island, collapse of a society. (a)** Location of Easter Island in the Pacific Ocean, several thousand kilometers west of South America; **(b)** map of Easter Island showing the three major volcanoes that anchor the three corners of the small island; and **(c)** large statues carved from volcanic rock before the collapse of a society with several thousand people.



SUMMARY

- Six themes run through this text: the urgency of the population issue; the importance of urban environments; the need for sustainability of resources; the importance of a global perspective; people and nature; and the role of science and values in the decisions we face.
- People and nature are intertwined. Each affects the other.
- The human population grew at a rate unprecedented in history in the 20th century. Population growth is the underlying environmental problem.
- Achieving sustainability, the environmental goal, is a long-term process to maintain a quality environment for future generations. Sustainability is becoming an important environmental paradigm for the 21st century.
- The combined impact of technology and population multiplies the impact on the environment.
- In an increasingly urban world, we must focus much of our attention on the environments of cities and the effects of cities on the rest of the environment.
- Determining Earth's carrying capacity for people and levels of sustainable harvests of resources is difficult but crucial if we are to plan effectively to meet our needs in the future. Estimates of Earth's carrying capacity for people range from 2.5 to 40 billion, but about 15 billion is the upper limit with today's technology. The differences in capacity have to do with the quality of life projected for people—the poorer the quality of life, the more people can be packed onto the Earth.
- Awareness of how people at a local level affect the environment globally gives credence to the Gaia hypothesis. Future generations will need a global perspective on environmental issues.
- Placing a value on various aspects of the environment requires knowledge and understanding of the science, but also depends on our judgments about the uses and aesthetics of the environment and on our moral commitments to other living things and to future generations.
- The Precautionary Principle is emerging as a powerful new tool for environmental management.

REEXAMINING THEMES AND ISSUES

Human Population

What is more important: the quality of life of people alive today or the quality of life of future generations?

Sustainability

What is more important: abundant resources today—as much as we want and can obtain—or the availability of these resources for future generations?

Global Perspective

What is more important: the quality of your local environment or the quality of the global environment—the environment of the entire planet?

Urban World

What is more important: human creativity and innovation, including arts, humanities, and science, or the persistence of certain endangered species? Must this always be a trade-off, or are there ways to have both?

People and Nature

If people have altered the environment for much of the time our species has been on Earth, what then is "natural"?

Science and Values

Does nature know best, so that we never have to ask what environmental goal we should seek, or do we need knowledge about our environment, so that we can make the best judgments given available information?

KEY TERMS

aesthetic justification **15**
carrying capacity **10**
cultural justification **16**
ecological justification **15**
Gaia hypothesis **10**
megacities **12**
moral justification **16**
Precautionary Principle **14**
recreational justification **15**
sustainability **8**
utilitarian justification **15**

STUDY QUESTIONS

1. Why is there a convergence of energy, economics, and environment?

2. In what ways do the effects on the environment of a resident of a large city differ from the effects of someone living on a farm? In what ways are the effects similar?

3. Programs have been established to supply food from Western nations to starving people in Africa. Some people argue that such programs, which may have short-term benefits, actually increase the threat of starvation in the future. What are the pros and cons of international food relief programs?

4. Why is there an emerging food crisis that is different from any in the past?

5. Which of the following are global environmental problems? Why?
(a) Growth of the human population.
(b) Furbish's lousewort, a small flowering plant found in the state of Maine and in New Brunswick, Canada. It is so rare that it has been seen by few people and is considered endangered.
(c) The blue whale, listed as an endangered species under the U.S. Marine Mammal Protection Act.
(d) A car that has air-conditioning.
(e) Seriously polluted harbors and coastlines in major ocean ports.

6. How could you determine the carrying capacity of Earth?

7. Is it possible that sometime in the future all the land on Earth will become one big city? If not, why not? To what extent does the answer depend on the following:
(a) global environmental considerations
(b) scientific information
(c) values

FURTHER READING

Botkin, D.B., ***No Man's Garden: Thoreau and a New Vision for Civilization and Nature*** (Washington, DC: Island Press, 2000). Discusses many of the central themes of this textbook, with special emphasis on values and science and on an urban world. Henry David Thoreau's life and works illustrate approaches that can help us deal with modern environmental issues.

Botkin, D.B., ***Discordant Harmonies: A New Ecology for the 21st Century*** (New York: Oxford University Press, 1990). An analysis of the myths that underlie attempts to solve environmental issues.

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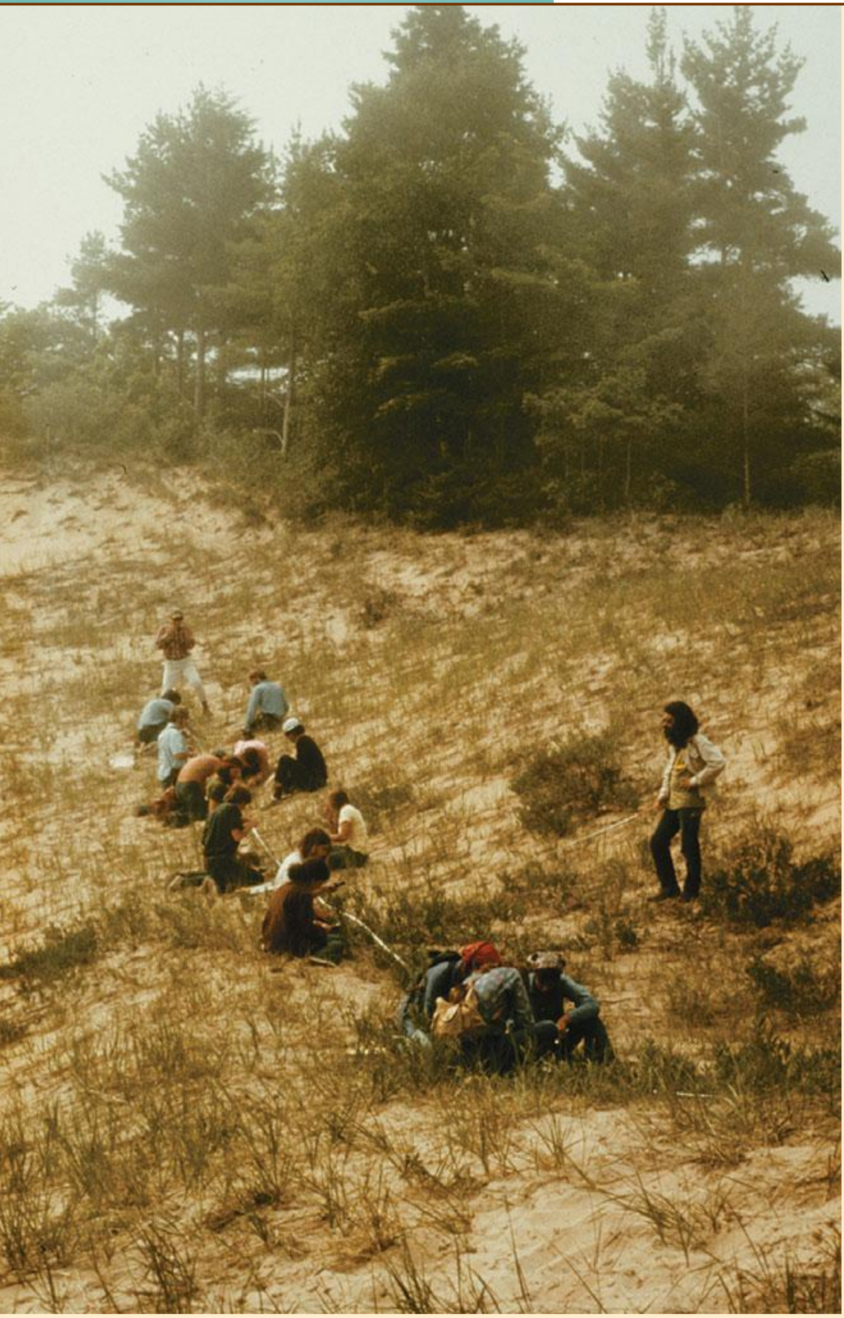
CHAPTER 2

Science as a Way of Knowing: Critical Thinking about the Environment



Environmental science poses challenges to traditional science, as these students taking a field course in ecology are finding out. No data were available to tell them about the age of the forests or the grasses growing on the dunes. It's also more difficult to apply the scientific method when you are working in the field rather than in the controlled environment of a laboratory.

LEARNING OBJECTIVES

Science is a process of refining our understanding of nature through continual questioning and active investigation. It is more than a collection of facts to be memorized. After reading this chapter, you should understand that . . .

- Thinking about environmental issues requires thinking scientifically;
- We acquire scientific knowledge of the natural world through observations. The conclusions that we draw from these observations can be stated as hypotheses, theories, and scientific "laws." If they can be disproved, they are scientific. If they can't, they are not;
- Scientific understanding is not fixed; it changes over time as new data, observations, theories, and tests become available;
- Deductive and inductive reasoning are different, and we need to use both in scientific thinking;
- Every measurement involves some degree of approximation—that is, uncertainty—and a measurement without a statement about its degree of uncertainty is meaningless;
- Technology, the application of scientific knowledge, is not science, but science and technology interact, stimulating growth in each other;
- Decision-making about environmental issues involves society, politics, culture, economics, and values, as well as scientific information;
- Environmental scientific findings often get politicized when the use of scientific information is guided by a political goal and only data supporting that goal are selected;
- Forms of life seem so incredible and so well fitted to their environment that we wonder how they have come about. This question leads us to seek to understand different ways of knowing.

CASE STUDY

Birds at Mono Lake: Applying Science to Solve an Environmental Problem

Mono Lake is a large salt lake in California, just east of the Sierra Nevada and across these mountains from Yosemite National Park (Figure 2.1). More than a million birds use the lake; some feed and nest there, some stop on their migrations to feed. Within the lake, brine shrimp and brine fly larvae grow in great abundance, providing food for the birds. The shrimp and fly larvae, in turn, feed on algae and bacteria that grow in the lake (Figure 2.2).

The lake persisted for thousands of years in a desert climate because streams from the Sierra Nevada—fed by mountain snow and rain—flowed into it. But in the 1940s the city of Los Angeles diverted all stream water—beautifully clear water—to provide 17% of the water supply for the city. The lake began to dry out. It covered 60,000 acres in the 1940s, but only 40,000 by the 1980s.

Environmental groups expressed concern that the lake would soon become so salty and alkaline that all the brine shrimp and flies—food for the birds—would die, the birds would no longer be able to nest or feed there, and the beautiful lake would become a hideous eyesore—much like what happened to the Aral Sea in Asia. The Los Angeles Department of Water and Power argued that everything would be all right because rain falling directly on the lake and water flowing underground would provide ample water for the lake. People were unconvinced. "Save Mono Lake" became a popular bumper sticker in California, and the argument about the future of the lake raged for more than a decade.

Scientific information was needed to answer key questions: Without stream input, how small would the lake become? Would it really become too salty and alkaline for the shrimp, fly larvae, algae, and bacteria? If so, when?

The state of California set up a scientific panel to study the future of Mono Lake. The panel discovered that two crucial pieces of knowledge necessary to answer these questions had not been studied: the size and shape of the basin of the lake (so one could determine the lake's volume and, from this, how its salinity and alkalinity would change) and the rate at which water evaporated from the lake (to determine whether and how fast the lake would become too dry to sustain life within it). New research was commissioned that answered these questions. The answers: By about the turn of the 21st century the lake would become so small that it would be too salty for the shrimp, fly larvae, algae, and bacteria.[1]

With this scientific information in hand, the courts decided that Los Angeles would have to stop the removal of water that flowed into Mono Lake. By 2008 the lake still had not recovered to the level required by the courts, indicating that diversion of water had been undesirable for the lake and its ecosystem.

Scientific information had told Californians what would happen, when it would likely happen, and what management approaches were possible. Science was essential to finding a solution that would work. But ultimately

FIGURE 2.1 Mono Lake's watershed below the beautiful east slope of the Sierra Nevada. Streams flowing into the lake are visible as winding blue lines on the lower slopes. The lake and its sandy beaches form the flatlands in the mid-distance.

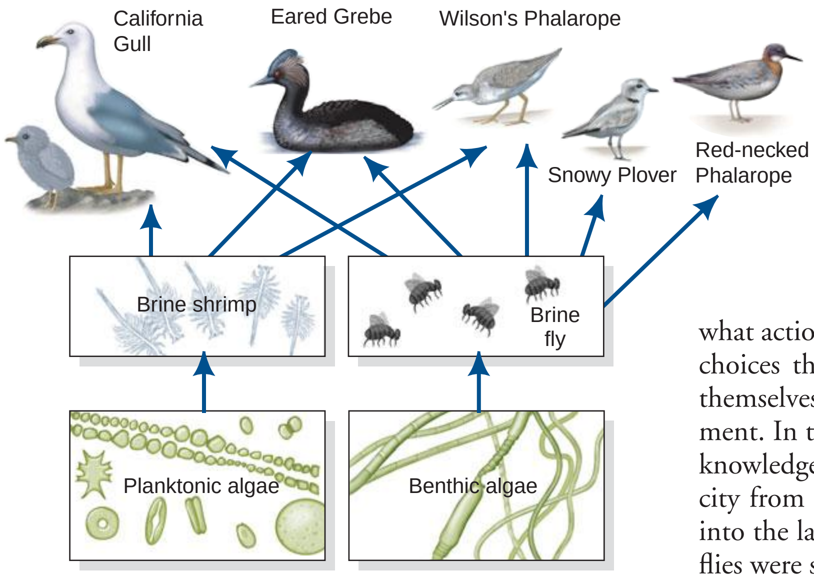


FIGURE 2.2 The Mono Lake food chain. The arrows show who feeds on whom. Just five species of birds are the top predators. This lake is one of the world's simpler ecosystems.

what actions to take, given this scientific knowledge, were choices that depended on values people held regarding themselves, their wants and desires, and the environment. In the end, decisions based on values and scientific knowledge were made by the courts, which stopped the city from diverting any of the stream waters that flowed into the lake. The birds, scenery, brine shrimp, and brine flies were saved.[2]

2.1 Understanding What Science Is—and What It Isn't

As the Mono Lake case study illustrates, modern civilization depends on science. The complexity of environmental sciences raises two fundamental questions: How does science differ from other ways of knowing? And how can we use science to answer practical questions about our effects on nature and what actions we should take to solve environmental problems?

Thinking about the environment is as old as our first human ancestors. Before humans developed the technology to deal with their environment, their very survival depended on knowledge of it. The environment also plays a crucial role in the development of each of us; normal human development does not occur in the absence of environmental stimuli.

However, thinking *scientifically* about the environment is only as old as science itself. Science had its roots in the ancient civilizations of Babylonia and Egypt, where observations of the environment were carried out primarily for practical reasons, such as planting crops, or for religious reasons, such as using the positions of the planets and stars to predict human events. Ancient precursors of science differed from modern science in that they did not distinguish between science and technology, nor between science and religion.

These distinctions first appeared in classical Greek science. Because of their general interest in ideas, the Greeks developed a more theoretical approach to science, in which knowledge for its own sake became the primary goal. At the same time, their philosophical approach began to move science away from religion and toward philosophy.

Modern science is usually considered to have begun toward the end of the 16th and the beginning of the 17th centuries with the development of the **scientific method** by Gilbert (magnets), Galileo (physics of motion), and Harvey (circulation of blood). Earlier classical scientists had asked "Why?" in the sense of "For what purpose?" But these three made important discoveries by asking "How?" in the sense of "How does it work?" Galileo also pioneered in the use of numerical observations and mathematical models. The scientific method, which quickly proved very successful in advancing knowledge, was first described explicitly by Francis Bacon in 1620. Although not a practicing scientist himself, Bacon recognized the importance of the scientific method, and his writings did much to promote scientific research.[3]

Our cultural heritage, therefore, gives us two ways of thinking about the environment: the kind of thinking we do in everyday life and the kind of thinking scientists try to do (Table 2.1). There are crucial differences between these two ways of thinking, and ignoring these differences can lead to invalid conclusions and serious errors in making critical decisions about the environment.

We can look at the world from many points of view, including religious, aesthetic, and moral. They are not science, however, because they are based ultimately on faith, beliefs, and cultural and personal choices, and are not open to disproof in the scientific sense. The distinction between a scientific statement and a nonscientific statement is not a value judgment—there is no implication that science is the only "good" kind of knowledge. The distinction is simply a philosophical one about kinds of knowledge and logic. Each way of viewing the world gives us a different way of perceiving and of making sense of our world, and each is valuable to us.

Table 2.1 KNOWLEDGE IN EVERYDAY LIFE COMPARED WITH KNOWLEDGE IN SCIENCE

FACTOR IN	EVERYDAY LIFE	AND IN SCIENCE
Goal	To lead a satisfying life (implicit)	To know, predict, and explain (explicit)
Requirements	Context-specific knowledge; no complex series of inferences; can tolerate ambiguities and lack of precision	General knowledge; complex, logical sequences of inferences, must be precise and unambiguous
Resolution of questions	Through discussion, compromise, consensus	Through observation, experimentation, logic
Understanding	Acquired spontaneously through interacting with world and people; criteria not well defined	Pursued deliberately; criteria clearly specified
Validity	Assumed, no strong need to check; based on observations, common sense, tradition, authorities, experts, social mores, faith	Must be checked; based on replications, converging evidence, formal proofs, statistics, logic
Organization of knowledge	Network of concepts acquired through experience; local, not integrated	Organized, coherent, hierarchical, logical; global, integrated
Acquisition of knowledge	Perception, patterns, qualitative; subjective	Plus formal rules, procedures, symbols, statistics, mental models; objective
Quality control	Informal correction of errors	Strict requirements for eliminating errors and making sources of error explicit

Source: Based on F. Reif and J.H. Larkin, "Cognition in Scientific and Everyday Domains: Comparison and Learning Implications," *Journal of Research in Science Teaching* 28(9), pp. 733–760.

Science as a Way of Knowing

Science is a process, a way of knowing. It results in conclusions, generalizations, and sometimes scientific theories and even scientific laws. *Science begins with questions arising from curiosity about the natural world*, such as: How many birds nest at Mono Lake? What species of algae live in the lake? Under what conditions do they live?

Modern science does not deal with things that cannot be tested by observation, such as the ultimate purpose of life or the existence of a supernatural being. Science also does not deal with questions that involve values, such as standards of beauty or issues of good and evil—for example, whether the scenery at Mono Lake is beautiful. On the other hand, the statement that "more than 50% of the people who visit Mono Lake find the scenery beautiful" is a hypothesis (discussed later) that can be tested by public-opinion surveys and can be treated as a scientific statement if the surveys confirm it.

Disprovability

Here's the key to science: It is generally agreed today that the essence of the scientific method is **disprovability** (see Figure 2.3, a diagram that will be helpful throughout this chapter). A statement can be termed "scientific" if someone can state a method of disproving it. If no one can think of such a test, then the statement is said to be nonscientific. Consider, for example, the crop circles discussed in A Closer Look 2.1. One Web site says that some people believe the crop circles are a "spiritual nudge . . . designed to awaken us to our larger context and milieu, which is none other than our collective earth soul." Whether or not this is true, it does not seem open to disproof.

Science is a process of discovery—a continuing process whose essence is change in ideas. The fact that scientific ideas change is frustrating. Why can't scientists agree on what is the best diet for people? Why is a chemical considered dangerous in the environment for a while and then determined not to be? Why do scientists in one decade consider forest fires undesirable disturbances and in a later decade decide forest fires are natural and in fact important? Are we causing global warming or not? And on and on. Can't scientists just find out the truth and give us the final word on all these questions once and for all, and agree on it?

The answer is no—because science is a continuing adventure during which scientists make better and better approximations of how the world works. Sometimes changes in ideas are small, and the major context remains the same. Sometimes a science undergoes a fundamental revolution in ideas.

Science makes certain assumptions about the natural world: that events in the natural world follow patterns that can be understood through careful observation and scientific analysis, which we will describe later; and that these basic patterns and the rules that describe them are the same throughout the universe.

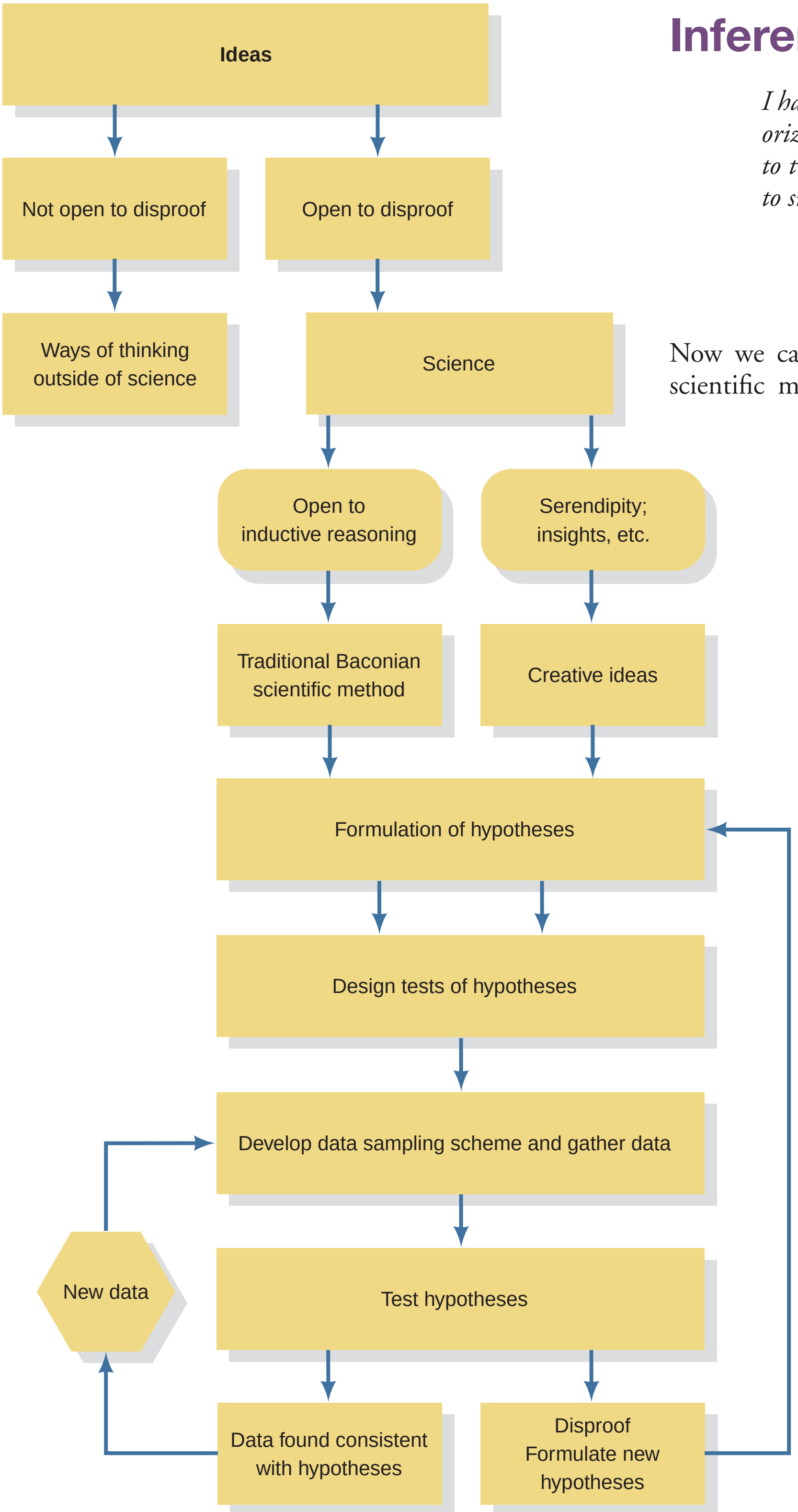


FIGURE 2.3 Schematic diagram of the scientific method. This diagram shows the steps in the scientific method, both traditional and nontraditional, as explained in the text.

2.2 Observations, Facts, Inferences, and Hypotheses

I have no data yet. It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.

—Sherlock Holmes,
in Sir Arthur Conan Doyle's
A Scandal in Bohemia

Now we can turn to the specific characteristics of the scientific method. (The steps in the scientific method are shown in Table 2.2.) It is important to distinguish between observations and inferences. **Observations**, the basis of science, may be made through any of the five senses or by instruments that measure beyond what we can sense. **Inferences** are generalizations that arise from a set of observations. When everyone or almost everyone agrees with what is observed about a particular thing, the inference is often called a **fact**.

We might *observe* that a substance is a white, crystalline material with a sweet taste. We might *infer* from these observations alone that the substance is sugar. Before this inference can be accepted as fact, however, it must be subjected to further tests. Confusing observations with inferences and accepting untested inferences as facts are kinds of sloppy thinking described as "Thinking makes it so." When scientists wish to test an inference, they convert it into a **hypothesis**, which is a statement that can be disproved. The hypothesis continues to be accepted until it is disproved.

For example, a scientist is trying to understand how a plant's growth will change with the amount of light it receives. She proposed a hypothesis that a plant can use only so much light and no more—it can be "saturated" by an abundance of light. She measures the rate of photosynthesis at a variety of light intensities. The rate of photosynthesis is called the **dependent variable** because it is affected by, and in this sense depends on, the amount of light, which is called the **independent variable**. The independent variable is also sometimes called a **manipulated variable**

Table 2.2 STEPS IN THE SCIENTIFIC METHOD (TERMS USED HERE ARE DEFINED IN THE TEXT.)

1. Make observations and develop a question about the observations.
2. Develop a tentative answer to the question—a hypothesis.
3. Design a controlled experiment to test the hypothesis (implies identifying and defining independent and dependent variables).
4. Collect data in an organized form, such as a table.
5. Interpret the data visually (through graphs), quantitatively (using statistical analysis) and/or by other means.
6. Draw a conclusion from the data.
7. Compare the conclusion with the hypothesis and determine whether the results support or disprove the hypothesis.
8. If the hypothesis is consistent with observations in some limited experiments, conduct additional experiments to test it further. If the hypothesis is rejected, make additional observations and construct a new hypothesis.

because it is deliberately changed, or manipulated, by the scientist. The dependent variable is then referred to as a **responding variable**—one that responds to changes in the manipulated variable. These values are referred to as *data* (singular: *datum*). They may be numerical, **quantitative data**, or nonnumerical, **qualitative data**. In our example, qualitative data would be the species of a plant; quantitative data would be the tree's mass in grams or the diameter in centimeters. The result of the scientist's observations: The hypothesis is confirmed: The rate of photosynthesis increases to a certain level and does not go higher at higher light intensities (Figure 2.4).

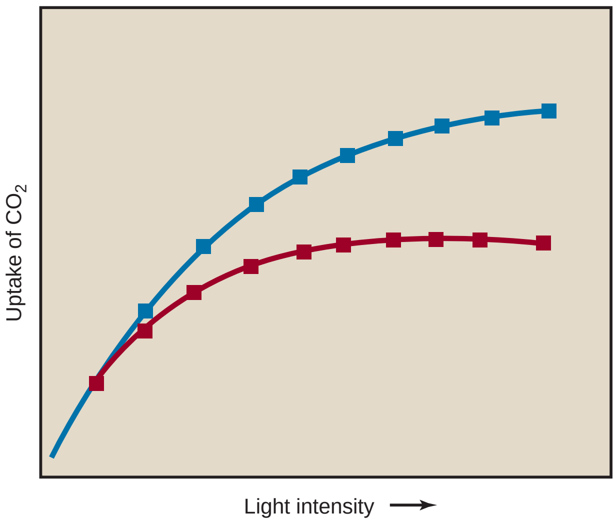


FIGURE 2.4 Dependent and independent variables: Photosynthesis as affected by light. In this diagram, photosynthesis is represented by carbon dioxide (CO_2) uptake. Light is the independent variable, uptake is the dependent variable. The blue and red lines represent two plants with different responses to light.

Controlling Variables

In testing a hypothesis, a scientist tries to keep all relevant **variables** constant except for the independent and dependent variables. This practice is known as *controlling variables*. In a **controlled experiment**, the experiment is compared to a standard, or control—an exact duplicate of the experiment except for the one variable being tested (the **independent variable**). Any difference in outcome (dependent variable) between the experiment and the control can be attributed to the effect of the independent variable.

An important aspect of science, but one frequently overlooked in descriptions of the scientific method, is the need to define or describe variables in exact terms that all scientists can understand. The least ambiguous way to define or describe a variable is in terms of what one would have to do to duplicate the measurement of that variable. Such definitions are called **operational definitions**. Before carrying out an experiment, both the independent and dependent variables must be defined operationally. Operational definitions allow other scientists to repeat experiments exactly and to check on the results reported.

Science is based on **inductive reasoning**, also called *induction*: It begins with specific observations and then extends to generalizations, which may be disproved by testing them. If such a test cannot be devised, then we cannot treat the generalization as a scientific statement. Although new evidence can disprove existing scientific theories, science can never provide absolute proof of the truth of its theories.

The Nature of Scientific Proof

One source of serious misunderstanding about science is the use of the word *proof*, which most students encounter in mathematics, particularly in geometry. Proof in mathematics and logic involves reasoning from initial definitions and assumptions. If a conclusion follows logically from these assumptions, or premises, we say it is proven. This process is known as **deductive reasoning**. An example of deductive reasoning is the following syllogism, or series of logically connected statements:

Premise: A straight line is the shortest distance between two points.

Premise: The line from A to B is the shortest distance between points A and B.

Conclusion: Therefore, the line from A to B is a straight line.

Note that the conclusion in this syllogism follows directly from the premises.

Deductive proof does not require that the premises be true, only that the reasoning be foolproof. Statements that are logically valid but untrue can result from false premises, as in the following example (Figure 2.5):

Premise: Humans are the only toolmaking organisms.

Premise: The woodpecker finch uses tools.

Conclusion: Therefore, the woodpecker finch is a human being.

In this case, the concluding statement must be true if both of the preceding statements are true. However, we know that the conclusion is not only false but ridiculous. If the second statement is true (which it is), then the first cannot be true.

The rules of deductive reasoning govern only the process of moving from premises to conclusion. *Science, in contrast, requires not only logical reasoning but also correct premises*. Returning to the example of the woodpecker finch, to be scientific the three statements should be expressed conditionally (that is, with reservation):

If humans are the only toolmaking organisms

and

the woodpecker finch is a toolmaker,

then

the woodpecker finch is a human being.

When we formulate generalizations based on a number of observations, we are engaging in inductive reasoning. To illustrate: One of the birds that feeds at Mono Lake is the eared grebe. The "ears" are a fan of golden feathers that occur behind the eyes of males during the breeding season. Let us define birds with these golden feather fans as eared grebes (Figure 2.6). If we always observe that the breeding male grebes have this feather fan, we may make the inductive statement "All male eared grebes have golden feathers during the breeding season." What we really mean is "All of the male eared grebes *we*

FIGURE 2.5 A woodpecker finch in the Galápagos Islands uses a twig to remove insects from a hole in a tree, demonstrating tool use by nonhuman animals. Because science is based on observations, its conclusions are only as true as the premises from which they are deduced.

FIGURE 2.6 Male eared grebe in breeding season.

have seen in the breeding season have golden feathers." We never know when our very next observation will turn up a bird that is like a male eared grebe in all ways except that it lacks these feathers in the breeding season. This is not impossible; it could occur somewhere due to a mutation.

Proof in inductive reasoning is therefore very different from proof in deductive reasoning. When we say something is proven in induction, what we really mean is that it has a very high degree of probability. Probability is a way of expressing our certainty (or uncertainty)—our estimation of how good our observations are, how confident we are of our predictions.

Theory in Science and Language

A common misunderstanding about science arises from confusion between the use of the word *theory* in science and its use in everyday language. A **scientific theory** is a grand scheme that relates and explains many observations and is supported by a great deal of evidence. In contrast, in everyday usage a theory can be a guess, a hypothesis, a prediction, a notion, a belief. We often hear the phrase "It's just a theory." That may make sense in everyday conversation but not in the language of science. In fact, theories have tremendous prestige and are considered the greatest achievements of science.[3]

Further misunderstanding arises when scientists use the word *theory* in several different senses. For example, we may encounter references to a currently accepted, widely supported theory, such as the theory of evolution by natural selection; a discarded theory, such as the theory of inheritance of acquired characteristics; a new theory, such as the theory of evolution of multicellular organisms by symbiosis; and a model dealing with a specific or narrow area of science, such as the theory of enzyme action.[4]

One of the most important misunderstandings about the scientific method pertains to the relationship between research and theory. Theory is usually presented as growing out of research, but in fact theories also guide research. When a scientist makes observations, he or she does so in the context of existing theories. At times, discrepancies between observations and accepted theories become so great that a scientific revolution occurs: The old theories are discarded and are replaced with new or significantly revised theories.[5]

Knowledge in an area of science grows as more hypotheses are supported. Ideally, scientific hypotheses are continually tested and evaluated by other scientists, and this provides science with a built-in self-correcting feedback system. This is an important, fundamental feature of the scientific method. If you are told that scientists have reached a consensus about something, you want to check carefully to see if this feedback process has been used correctly and is still possible. If not, what began as science can be converted to ideology—a way that certain individuals, groups, or cultures may think despite evidence to the contrary.

Models and Theory

Scientists use accumulated knowledge to develop explanations that are consistent with currently accepted hypotheses. Sometimes an explanation is presented as a model. A **model** is "a deliberately simplified construct of nature."[6] It may be a physical working model, a pictorial model, a set of mathematical equations, or a computer simulation. For example, the U.S. Army Corps of Engineers has a physical model of San Francisco Bay. Open to the public to view, it is a miniature in a large aquarium with the topography of the bay reproduced to scale and with water flowing into it in accordance with tidal patterns. Elsewhere, the Army Corps develops mathematical equations and computer simulations, which are models and attempt to explain some aspects of such water flow.

As new knowledge accumulates, models may no longer be consistent with observations and may have to be revised or replaced, with the goal of finding models more consistent with nature.[5] Computer simulation of the atmosphere has become important in scientific analysis of the possibility of global warming. Computer simulation is becoming important for biological systems as well, such as simulations of forest growth (Figure 2.7).

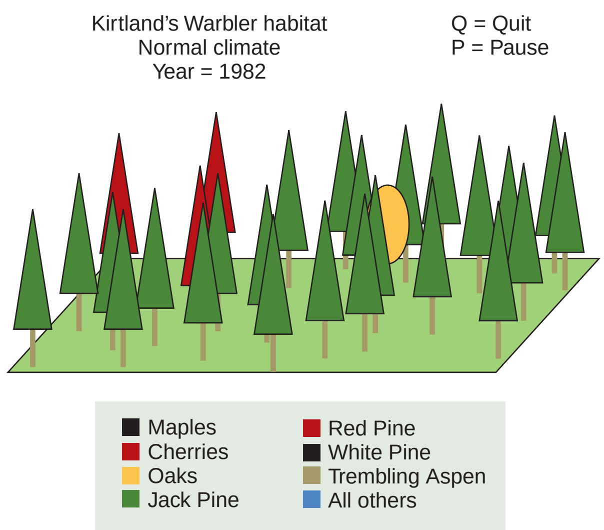


FIGURE 2.7 A computer simulation of forest growth. Shown here is a screen display of individual trees whose growth is forecast year by year, depending on environmental conditions. In this computer run, only three types of trees are present. This kind of model is becoming increasingly important in environmental sciences. (*Source: JABOWA-II* by D.B. Botkin. Copyright © 1993, 2009 by D.B. Botkin.)

A CLOSER LOOK 2.1

The Case of the Mysterious Crop Circles

For 13 years, circular patterns appeared "mysteriously" in grainfields in southern England (Figure 2.8). Proposed explanations included aliens, electromagnetic forces, whirlwinds, and pranksters. The mystery generated a journal and a research organization headed by a scientist, as well as a number of books, magazines, and clubs devoted solely to crop circles. Scientists from Great Britain and Japan brought in scientific equipment to study the strange patterns. Then, in September 1991, two men confessed to having created the circles by entering the fields along paths made by tractors (to disguise their footprints) and dragging planks through the fields. When they made their confession, they demonstrated their technique to reporters and some crop-circle experts.[4, 5]

Despite their confession, some people still believe that the crop circles were caused by something else, and crop-circle organizations not only still exist but also now have Web sites. One report published on the World Wide Web in 2003 stated that "strange orange lightning" was seen one evening and that crop circles appeared the next day.[7, 8]

How is it that so many people, including some scientists, still take those English crop circles seriously? Probably some of these people misunderstand the scientific method and used it incorrectly—and some simply want to believe in a mysterious cause and therefore chose to reject scientific information. We run into this way of thinking frequently with environmental issues. People often believe that some conclusions or some action is good, based on their values. They wish it were so, and decide therefore that it must be so. The false logic here can be phrased: *If it sounds good, it must be good, and if it must be good, we must make it happen.*

(a)

(b)

FIGURE 2.8 **(a)** A crop circle close up at the Vale of Pewsey in southern England in July 1990. **(b)** Crop circles seen from the air make distinctive patterns.

Some Alternatives to Direct Experimentation

Environmental scientists have tried to answer difficult questions using several approaches, including historical records and observations of modern catastrophes and disturbances.

Historical Evidence

Ecologists have made use of both human and ecological historical records. A classic example is a study of the history of fire in the Boundary Waters Canoe Area (BWCA) of Minnesota, 1 million acres of boreal forests, streams, and lakes well known for recreational canoeing.

Murray ("Bud") Heinselman had lived near the BWCA for much of his life and was instrumental in having it declared a wilderness area. A forest ecological scientist, Heinselman set out to determine the past patterns of fires in this wilderness. Those patterns are important in maintaining the wilderness. If the wilderness has been characterized by fires of a specific frequency, then one can argue that this frequency is necessary to maintain the area in its most "natural" state.

Heinselman used three kinds of historical data: written records, tree-ring records, and buried records (fossil and prefossil organic deposits). Trees of the boreal forests, like most trees that are conifers or angiosperms (flowering plants),

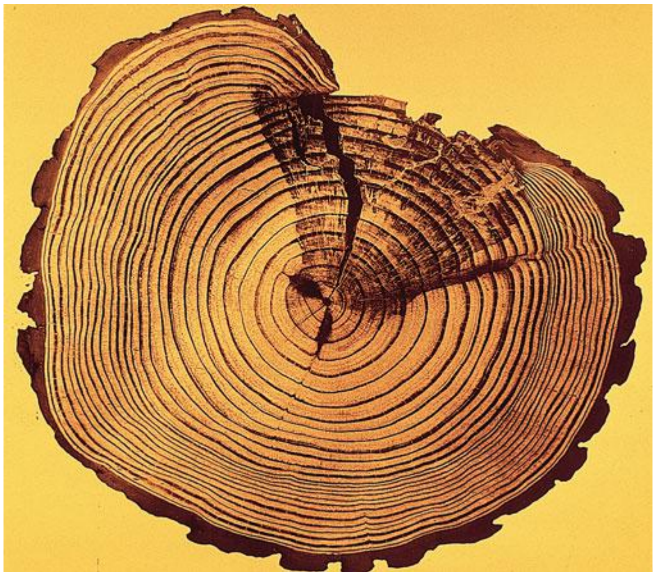


FIGURE 2.9 Cross section of a tree showing fire scars and tree rings. Together these allow scientists to date fires and to average the time between fires.

produce annual growth rings. If a fire burns through the bark of a tree, it leaves a scar, just as a serious burn leaves a scar on human skin. The tree grows over the scar, depositing a new growth ring for each year. (Figure 2.9 shows fire scars and tree rings on a cross section of a tree.) By examining cross sections of trees, it is possible to determine the date of each fire and the number of years between fires. From written and tree-ring records, Heinselman found that the frequency of fires had varied over time but that since the 17th century the BWCA forests had burned, on average, once per century. Furthermore, buried charcoal dated using carbon-14 revealed that fires could be traced back more than 30,000 years.[9]

The three kinds of historical records provided important evidence about fire in the history of the BWCA. At the time Heinselman did his study, the standard hypothesis was that fires were bad for forests and should be suppressed. The historical evidence provided a disproof of this hypothesis. It showed that fires were a natural and an integral part of the forest and that the forest had persisted with fire for a very long time. Thus, the use of historical information meets the primary requirement of the scientific method—the ability to disprove a statement. Historical evidence is a major source of data that can be used to test scientific hypotheses in ecology.

Modern Catastrophes and Disturbances as Experiments

Sometimes a large-scale catastrophe provides a kind of modern ecological experiment. The volcanic eruption of Mount St. Helens in 1980 supplied such an experiment, destroying vegetation and wildlife over a wide area. The recovery of plants, animals, and ecosystems following this explosion gave scientists insights into the dynamics of ecological systems and provided some surprises. The main surprise was how quickly vegetation recovered and wildlife returned to parts of the mountain. In other ways, the recovery followed expected patterns in ecological succession (see Chapters 5 and 12).

It is important to point out that the greater the quantity and the better the quality of ecological data prior to such a catastrophe, the more we can learn from the response of ecological systems to the event. This calls for careful monitoring of the environment.

Uncertainty in Science

In science, when we have a fairly high degree of confidence in our conclusions, we often forget to state the degree of certainty or uncertainty. Instead of saying, "There is a 99.9% probability that . . . ," we say, "It has been proved that . . ." Unfortunately, many people interpret this as a deductive statement, meaning the conclusion is absolutely true, which has led to much misunderstanding about science. Although science begins with observations and therefore inductive reasoning, deductive reasoning is useful in helping scientists analyze whether conclusions based on inductions are logically valid. *Scientific reasoning combines induction and deduction*—different but complementary ways of thinking.

Leaps of Imagination and Other Nontraditional Aspects of the Scientific Method

What we have described so far is the classic scientific method. Scientific advances, however, often happen somewhat differently. They begin with instances of insight—leaps of imagination that are then subjected to the stepwise inductive process. And some scientists have made major advances by being in the right place at the right time, noticing interesting oddities, and knowing how to put these clues together. For example, penicillin was discovered "by accident" in 1928 when Sir Alexander Fleming was studying the pus-producing bacterium *Staphylococcus aureus*. When a culture of these bacteria was accidentally contaminated by the green fungus *Penicillium notatum*, Fleming noticed that the bacteria did not grow in areas of the culture where the fungus grew. He isolated the mold, grew it in a fluid medium, and found that it produced a substance that killed many of the bacteria that caused diseases. Eventually this discovery led other scientists to develop an injectable agent to treat diseases. *Penicillium notatum* is a common mold found on stale bread. No doubt many others had seen it, perhaps even noticing that other strange growths on bread did not overlap with *Penicillium notatum*. But it took Fleming's knowledge and observational ability for this piece of "luck" to occur.

2.3 Measurements and Uncertainty

A Word about Numbers in Science

We communicate scientific information in several ways. The written word is used for conveying synthesis, analysis, and conclusions. When we add numbers to our analysis, we obtain another dimension of understanding that goes beyond qualitative understanding and synthesis of a problem. Using numbers and statistical analysis allows us to visualize relationships in graphs and make predictions. It also allows us to analyze the strength of a relationship and in some cases discover a new relationship.

People in general put more faith in the accuracy of measurements than do scientists. Scientists realize that all measurements are only approximations, limited by the accuracy of the instruments used and the people who use them. Measurement uncertainties are inevitable; they can be reduced but never completely eliminated. For this reason, *a measurement is meaningless unless it is accompanied by an estimate of its uncertainty.*

Consider the loss of the *Challenger* space shuttle in 1986, the first major space shuttle accident, which appeared to be the result of the failure of rubber O-rings that were supposed to hold sections of rockets together. Imagine a simplified scenario in which an engineer is given a rubber O-ring used to seal fuel gases in a space shuttle. The engineer is asked to determine the flexibility of the O-rings under different temperature conditions to help answer two questions: At what temperature do the O-rings become brittle and subject to failure? And at what temperature(s) is it unsafe to launch the shuttle? After doing some tests, the engineer says that the rubber becomes brittle at –1°C (30°F). So, can you assume it is safe to launch the shuttle at 0°C (32°F)?

At this point, you do not have enough information to answer the question. You assume that the temperature data may have some degree of uncertainty, but you have no idea how great a degree. Is the uncertainty ±5°C, ±2°C, or ±0.5°C? To make a reasonably safe and economically sound decision about whether to launch the shuttle, you must know the amount of uncertainty of the measurement.

Dealing with Uncertainties

There are two sources of uncertainty. One is the real variability of nature. The other is the fact that every measurement has some error. Measurement uncertainties and other errors that occur in experiments are called **experimental errors**. Errors that occur consistently, such as those resulting from incorrectly calibrated instruments, are **systematic errors**.

Scientists traditionally include a discussion of experimental errors when they report results. Error analysis often leads to greater understanding and sometimes even to important discoveries. For example, scientists discovered the eighth planet in our solar system, Neptune, when they investigated apparent inconsistencies—observed "errors"—in the orbit of the seventh planet, Uranus.

We can reduce measurement uncertainties by improving our measurement instruments, standardizing measurement procedures, and using carefully designed experiments and appropriate statistical procedures. Even then, however, uncertainties can never be completely eliminated. Difficult as it is for us to live with uncertainty, that is the nature of nature, as well as the nature of measurement and of science. Our awareness of these uncertainties should lead us to read reports of scientific studies critically, whether they appear in science journals or in popular magazines and newspapers. (See A Closer Look 2.2.)

Accuracy and Precision

A friend inherited some land on an island off the coast of Maine. However, the historical records were unclear about the land's boundaries, and to sell any portion of the land, he first had to determine where his neighbor's land ended and his began. There were differences of opinion about this. In fact, some people said one boundary went right through the house, which would have caused a lot of problems! Clearly what was needed was a good map that everybody could agree on, so our friend hired a surveyor to determine exactly where the boundaries were.

The original surveyor's notes from the early 19th century had vague guidelines, such as "beginning at the mouth of Marsh brook on the Eastern side of the bars at a stake and stones. . . thence running South twenty six rods to a stake & stones. . . ." Over time, of course, the shore, the brook, its mouth, and the stones had moved and the stakes had disappeared. The surveyor was clear about the total distance (a rod, by the way, is an old English measure equal to 16.5 feet or 5.02 meters), but "South" wasn't very specific. So where and in exactly which direction was the true boundary? (This surveyor's method was common in early-19th-century New England. One New Hampshire survey during that time began with "Where you and I were standing yesterday . . ." Another began, "Starting at the hole in the ice [on the pond] . . .").

The 21st-century surveyor who was asked to find the real boundary used the most modern equipment—laser and microwave surveying transits, GPS devices—so he knew where the line he measured went to in millimeters. He could remeasure his line and come within

A CLOSER LOOK 2.2

Measurement of Carbon Stored in Vegetation

A number of people have suggested that a partial solution to global warming might be a massive worldwide program of tree planting. Trees take carbon dioxide (an important greenhouse gas) out of the air in the process of photosynthesis. And because trees live a long time, they can store carbon for decades, even centuries. But how much carbon can be stored in trees and in all perennial vegetation? Many books and reports published during the past 20 years contained numbers representing the total stored carbon in Earth's vegetation, but all were presented without any estimate of error (Table 2.3). Without an estimate of that uncertainty, the figures are meaningless, yet important environmental decisions have been based on them.

Recent studies have reduced error by replacing guesses and extrapolations with scientific sampling techniques similar to those used to predict the outcomes of elections. Even these improved data would be meaningless, however, without an estimate of error. The new figures show that the earlier estimates were three to four times too large, grossly overestimating the storage of carbon in vegetation and therefore the contribution that tree planting could make in offsetting global warming.

Table 2.3 ESTIMATES OF ABOVEGROUND BIOMASS IN NORTH AMERICAN BOREAL FOREST

SOURCE	BIOMASS[a] (kg/m^2)	CARBON[b] (kg/m^2)	TOTAL BIOMASS[c] (10^9 metric tons)	TOTAL CARBON[c] (10^9 metric tons)
This study[d]	4.2 ± 1.0	1.9 ± 0.4	22 ± 5	9.7 ± 2
Previous estimates[e]				
1	17.5	7.9	90	40
2	15.4	6.9	79	35
3	14.8	6.7	76	34
4	12.4	5.6	64	29
5	5.9	2.7	30	13.8

Source: D.B. Botkin and L. Simpson, "The First Statistically Valid Estimate of Biomass for a Large Region," *Biogeochemistry* 9 (1990): 161–274. Reprinted by permission of Klumer Academic, Dordrecht, The Netherlands.

[a]Values in this column are for total aboveground biomass. Data from previous studies giving total biomass have been adjusted using the assumption that 23% of the total biomass is in below-ground roots. Most references use this percentage; Leith and Whittaker use 17%. We have chosen to use the larger value to give a more conservative comparison.

[b]Carbon is assumed to be 45% of total biomass following R.H. Whittaker, *Communities and Ecosystems* (New York: Macmillan, 1974).

[c]Assuming our estimate of the geographic extent of the North American boreal forest: 5,126,427 km^2 (324,166 mi^2).

[d]Based on a statistically valid survey; aboveground woodplants only.

[e]Lacking estimates of error: Sources of previous estimates by number (1) G.J. Ajtay, P. Ketner, and P. Duvigneaud, "Terrestial Primary Production and Phytomass," in B. Bolin, E.T. Degens, S. Kempe, and P. Ketner, eds., *The Global Carbon Cycle* (New York: Wiley, 1979), pp. 129–182. (2) R.H. Whittaker and G.E. Likens, "Carbon in the Biota," in G.M. Woodwell and E.V. Pecam, eds., *Carbon and the Biosphere* (Springfield, VA: National Technical Information Center, 1973), pp. 281–300. (3) J.S. Olson, H.A. Pfuderer, and Y.H. Chan, *Changes in the Global Carbon Cycle and the Biosphere*, ORNL/EIS-109 (Oak Ridge, TN: Oak Ridge National Laboratory, 1978). (4) J.S. Olson, I.A. Watts, and L.I. Allison, *Carbon in Live Vegetation of Major World Ecosystems*, ORNL-5862 (Oak Ridge, TN: Oak Ridge National Laboratory, 1983). (5) G.M. Bonnor, *Inventory of Forest Biomass in Canada* (Petawawa, Ontario: Canadian Forest Service, Petawawa National Forest Institute, 1985).

millimeters of his previous location. But because the original starting point couldn't be determined within many meters, the surveyor didn't know where the true boundary line went; it was just somewhere within 10 meters or so of the line he had surveyed. So the end result was that even after this careful, modern, high-technology survey, nobody really knew where the original boundary lines went. Scientists would say that the modern surveyor's work was precise but not accurate. *Accuracy* refers to what we know; *precision* to how well we measure. With such things as this land survey, this is an important difference.

Accuracy also has another, slightly different scientific meaning. In some cases, certain measurements have been made very carefully by many people over a long period, and accepted values have been determined. In that kind of situation, *accuracy* means the extent to which a measurement agrees with the accepted value. But as before, *precision* retains its original meaning, the degree of exactness with which a quantity is measured. In the case of the land in Maine, we can say that the new measurement had no accuracy in regard to the previous ("accepted") value.

Although a scientist should make measurements as precisely as possible, this friend's experience with surveying his land shows us that it is equally important not to report measurements with more precision than they warrant. Doing so conveys a misleading sense of both precision and accuracy.

2.4 Misunderstandings about Science and Society

Science and Decision Making

Like the scientific method, the process of making decisions is sometimes presented as a series of steps:

1. Formulate a clear statement of the issue to be decided.
2. Gather the scientific information related to the issue.
3. List all alternative courses of action.
4. Predict the positive and negative consequences of each course of action and the probability that each consequence will occur.
5. Weigh the alternatives and choose the best solution.

Such a procedure is a good guide to rational decision making, but it assumes a simplicity not often found in real-world issues. It is difficult to anticipate all the potential consequences of a course of action, and unintended consequences are at the root of many environmental problems. Often the scientific information is incomplete and even controversial. For example, the insecticide DDT causes eggshells of birds that feed on insects to be so thin that unhatched birds die. When DDT first came into use, this consequence was not predicted. Only when populations of species such as the brown pelican became seriously endangered did people become aware of it.

In the face of incomplete information, scientific controversies, conflicting interests, and emotionalism, how can we make sound environmental decisions? We need to begin with the scientific evidence from all relevant sources and with estimates of the uncertainties in each. Avoiding emotionalism and resisting slogans and propaganda are essential to developing sound approaches to environmental issues. Ultimately, however, environmental decisions are policy decisions negotiated through the political process. Policymakers are rarely professional scientists; generally, they are political leaders and ordinary citizens. Therefore, the scientific education of those in government and business, as well as of all citizens, is crucial.

Science and Technology

Science is often confused with technology. As noted earlier, science is a search for understanding of the natural world, whereas technology is the application of scientific knowledge in an attempt to benefit people. Science often leads to technological developments, just as new technologies lead to scientific discoveries. The telescope began as a technological device, such as an aid to sailors, but when Galileo used it to study the heavens, it became a source of new scientific knowledge. That knowledge stimulated the technology of telescope-making, leading to the production of better telescopes, which in turn led to further advances in the science of astronomy.

Science is limited by the technology available. Before the invention of the electron microscope, scientists were limited to magnifications of 1,000 times and to studying objects about the size of one-tenth of a micrometer. (A micrometer is 1/1,000,000 of a meter, or 1/1,000 of a millimeter.) The electron microscope enabled scientists to view objects far smaller by magnifying more than 100,000 times. The electron microscope, a basis for new science, was also the product of science. Without prior scientific knowledge about electron beams and how to focus them, the electron microscope could not have been developed.

Most of us do not come into direct contact with science in our daily lives; instead, we come into contact with the products of science—technological devices such as computers, iPods, and microwave ovens. Thus, people tend to confuse the products of science with science itself. As you study science, it will help if you keep in mind the distinction between science and technology.

Science and Objectivity

One myth about science is the myth of objectivity, or value-free science—the notion that scientists are capable of complete objectivity independent of their personal values and the culture in which they live, and that science deals only with objective facts. Objectivity is certainly a goal of scientists, but it is unrealistic to think they can be totally free of influence by their social environments and personal values. It would be more realistic to admit that scientists do have biases and to try to identify these biases rather than deny or ignore them. In some ways, this situation is similar to that of measurement error: It is inescapable, and we can best deal with it by recognizing it and estimating its effects.

To find examples of how personal and social values affect science, we have only to look at recent controversies about environmental issues, such as whether or not to adopt more stringent automobile emission standards. Genetic engineering, nuclear power, global warming, and the preservation of threatened or endangered species involve conflicts among science, technology, and society. When we function as *scientists* in society, we want to explain the results of science objectively. As citizens who are not scientists, we want scientists to always be objective and tell us the truth about their scientific research.

That science is not entirely value-free should not be taken to mean that fuzzy thinking is acceptable in science. It is still important to think critically and logically about science and related social issues. Without the high standards of evidence held up as the norm for science, we run the risk of accepting unfounded ideas about the world. When we confuse what we would like to believe with what we have the evidence to believe, we have a weak basis for making critical environmental decisions that could have far-reaching and serious consequences.

The great successes of science, especially as the foundation for so many things that benefit us in modern technological societies—from cell phones to CAT scans to space exploration—give science and scientists a societal authority that makes it all the more difficult to know when a scientist might be exceeding the bounds of his or her scientific knowledge. It may be helpful to realize that scientists play three roles in our society: first, as researchers simply explaining the results of their work; second, as almost priestlike authorities who often seem to speak in tongues the rest of us can't understand; and third, as what we could call expert witnesses. In this third role, they will discuss broad areas of research that they are familiar with and that are within their field of study, but about which they may not have done research themselves. Like an expert testifying in court, they are basically saying to us, "Although I haven't done this particular research myself, my experience and knowledge suggest to me that . . ."

The roles of researcher and expert witness are legitimate as long as it is clear to everybody which role a scientist is playing. Whether you want a scientist to be your authority about everything, within science and outside of science, is a personal and value choice.

In the modern world, there is another problem about the role of scientists and science in our society. Science has been so potent that it has become fundamental to political policies. As a result, science can become politicized, which means that rather than beginning with objective inquiry, people begin with a belief about something and pick and choose only the scientific evidence that supports that belief. This can even be carried to the next step, where research is funded only if it fits within a political or an ethical point of view.

Scientists themselves, even acting as best they can *as* scientists, can be caught up in one way of thinking when the evidence points to another. These scientists are said to be working under a certain paradigm, a particular theoretical framework. Sometimes their science undergoes a paradigm shift: New scientific information reveals a great departure from previous ways of thinking and from previous scientific theories, and it is difficult, after working within one way of thinking, to recognize that some or all of their fundamentals must change. Paradigm shifts happen over and over again in science and lead to exciting and often life-changing results for us. The discovery and understanding of electricity are examples, as is the development of quantum mechanics in physics in the early decades of the 20th century.

We can never completely escape biases, intentional and unintentional, in fundamental science, its interpretation, and its application to practical problems, but understanding the nature of the problems that can arise can help us limit this misuse of science. The situation is complicated by legitimate scientific uncertainties and differences in scientific theories. It is hard for us, as citizens, to know when scientists are having a legitimate debate about findings and theories, and when they are disagreeing over personal beliefs and convictions that are outside of science. Because environmental sciences touch our lives in so many ways, because they affect things that are involved with choices and values, and because these sciences deal with phenomena of great complexity, the need to understand where science can go astray is especially important.

Science, Pseudoscience, and Frontier Science

Some ideas presented as scientific are in fact not scientific, because they are inherently untestable, lack empirical support, or are based on faulty reasoning or poor scientific methodology, as illustrated by the case of the mysterious crop circles (A Closer Look 2.1). Such ideas are referred to as pseudoscientific (the prefix *pseudo-* means false).

CRITICAL THINKING ISSUE

How Do We Decide What to Believe about Environmental Issues?

When you read about an environmental issue in a newspaper or magazine, how do you decide whether to accept the claims made in the article? Are they based on scientific evidence, and are they logical? Scientific evidence is based on observations, but media accounts often rely mainly on inferences (interpretations) rather than evidence. Distinguishing inferences from evidence is an important first step in evaluating articles critically. Second, it is important to consider the source of a statement. Is the source a reputable scientific organization or publication? Does the source have a vested interest that might bias the claims? When sources are not named, it is impossible to judge the reliability of claims. If a claim is based on scientific evidence presented logically from a reliable, unbiased source, it is appropriate to accept the claim tentatively, pending further information. Practice your critical evaluation skills by reading the article below and answering the critical thinking questions.

Critical Thinking Questions

1. What is the major claim made in the article?
2. What evidence does the author present to support the claim?
3. Is the evidence based on observations, and is the source of the evidence reputable and unbiased?
4. Is the argument for the claim, whether or not based on evidence, logical?
5. Would you accept or reject the claim?
6. Even if the claim were well supported by evidence based on good authority, why would your acceptance be only tentative?

CLUE FOUND IN DEFORMED FROG MYSTERY

BY MICHAEL CONLON

Reuters News Agency (as printed in the *Toronto Star*)
November 6, 1996

A chemical used for mosquito control could be linked to deformities showing up in frogs across parts of North America, though the source of the phenomenon remains a mystery. "We're still at the point where we've got a lot of leads that we're trying to follow but no smoking gun," says Michael Lannoo of Ball State University in Muncie, Ind. "There are an enormous number of chemicals that are being applied to the environment and we don't understand what the breakdown products of these chemicals are," says Lannoo, who heads the U.S. section of the worldwide Declining Amphibian Population Task Force.

He says one suspect chemical was methoprene, which produces a breakdown product resembling retinoic acid, a substance important in development. "Retinoic acid can produce in the laboratory all or a majority of the limb deformities that we're seeing in nature," he says. "That's not to say that's what's going on. But it is the best guess as to what's happening." Methoprene is used for mosquito control, among other things, Lannoo says.

Both the decline in amphibian populations and the deformities are of concern because frogs and related creatures are considered "sentinel" species that can provide early warnings of human risk. The skin of amphibians is permeable and puts them at particular risk to agents in the water.

Lannoo says limb deformities in frogs had been reported as far back as 1750, but the rate of deformities showing up today was unprecedented in some species. Some were showing abnormalities that affected more than half of the population of a species living in certain areas, he adds. He says he doubted that a parasite believed to have been the cause of some deformities in frogs in California was to blame for similar problems in Minnesota and nearby states. Deformed frogs have been reported in Minnesota, Wisconsin, Iowa, South Dakota, Missouri, California, Texas, Vermont, and Quebec. The deformities reported have included misshapen legs, extra limbs, and missing or misplaced eyes.

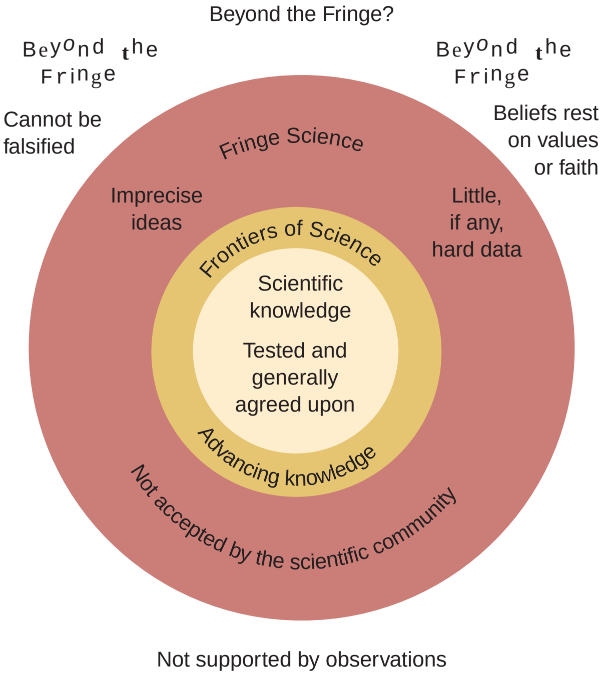


FIGURE 2.10 **Beyond the fringe? A diagrammatic view of different kinds of knowledge and ideas.**

Pseudoscientific ideas arise from various sources. With more research, however, some of the frontier ideas may move into the realm of accepted science, and new ideas will take their place at the advancing frontier (Figure 2.10).[10] Research may not support other hypotheses at the frontier, and these will be discarded. Accepted science may merge into frontier science, which in turn may merge into farther-out ideas, or fringe science. Really wild ideas may be considered beyond the fringe.

2.5 Environmental Questions and the Scientific Method

Environmental sciences deal with especially complex systems and include a relatively new set of sciences. Therefore, the process of scientific study has not always neatly followed the formal scientific method discussed earlier in this chapter. Often, observations are not used to develop formal hypotheses. Controlled laboratory experiments have been the exception rather than the rule. Much environmental research has been limited to field observations of processes and events that have been difficult to subject to controlled experiments.

Environmental research presents several obstacles to following the classic scientific method. The long time frame of many ecological processes relative to human lifetimes, professional lifetimes, and lengths of research grants poses problems for establishing statements that can in practice be subject to disproof. What do we do if a theoretical disproof through direct observation would take a century or more? Other obstacles include difficulties in setting up adequate experimental controls for field studies, in developing laboratory experiments of sufficient complexity, and in developing theory and models for complex systems. Throughout this text, we present differences between the "standard" scientific method and the actual approach that has been used in environmental sciences.

SUMMARY

- Science is one path to critical thinking about the natural world. Its goal is to gain an understanding of how nature works. Decisions on environmental issues must begin with an examination of the relevant scientific evidence. However, environmental decisions also require careful analysis of economic, social, and political consequences. Solutions will reflect religious, aesthetic, and ethical values as well.
- Science is an open-ended process of finding out about the natural world. In contrast, science lectures and texts are usually summaries of the answers arrived at through this process, and science homework and tests are exercises in finding the right answer. Therefore, students often perceive science as a body of facts to be memorized, and they view lectures and texts as authoritative sources of absolute truths about the world.
- Science begins with careful observations of the natural world, from which scientists formulate hypotheses. Whenever possible, scientists test hypotheses with controlled experiments.
- Although the scientific method is often taught as a prescribed series of steps, it is better to think of it as a general guide to scientific thinking, with many variations.
- We acquire scientific knowledge through inductive reasoning, basing general conclusions on specific observations. Conclusions arrived at through induction can never be proved with certainty. Thus, because of the inductive nature of science, it is possible to disprove hypotheses but not possible to prove them with 100% certainty.

- Measurements are approximations that may be more or less exact, depending on the measuring instruments and the people who use them. A measurement is meaningful when accompanied by an estimate of the degree of uncertainty, or error.
- Accuracy in measurement is the extent to which the measurement agrees with an accepted value. Precision is the degree of exactness with which a measurement is made. A precise measurement may not be accurate. The estimate of uncertainty provides information on the precision of a measurement.
- A general statement that relates and explains a great many hypotheses is called a theory. Theories are the greatest achievements of science.
- Critical thinking can help us distinguish science from pseudoscience. It can also help us recognize possible bias on the part of scientists and the media. Critical thinking involves questioning and synthesizing information rather than merely acquiring information.

REEXAMINING THEMES AND ISSUES

Global Perspective

The global perspective on environment arises out of new findings in environmental science.

Urban World

Our increasingly urbanized world is best understood with the assistance of scientific investigation.

People and Nature

Solutions to environmental problems require both values and knowledge. Understanding the scientific method is especially important if we are going to understand the connection between values and knowledge, and the relationship between people and nature. Ultimately, environmental decisions are policy decisions, negotiated through the political process. Policymakers often lack sufficient understanding of the scientific method, leading to false conclusions. Uncertainty is part of the nature of measurement and science. We must learn to accept uncertainty as part of our attempt to conserve and use our natural resources.

Science and Values

This chapter summarizes the scientific method, which is essential to analyzing and solving environmental problems and to developing sound approaches to sustainability.

KEY TERMS

controlled experiment **27**
deductive reasoning **28**
dependent variable **26**
disprovability **25**
experimental errors **32**
fact **26**
hypothesis **26**
independent variable **26**
inductive reasoning **27**
inferences **26**
manipulated variable **26**
model **29**
observations **26**
operational definitions **27**
qualitative data **27**
quantitative data **27**
responding variable **27**
scientific method **24**
scientific theory **29**
systematic errors **32**
variables **27**

STUDY QUESTIONS

1. Which of the following are scientific statements and which are not? What is the basis for your decision in each case?
(a) The amount of carbon dioxide in the atmosphere is increasing.
(b) Condors are ugly.
(c) Condors are endangered.
(d) Today there are 280 condors.
(e) Crop circles are a sign from Earth to us that we should act better.
(f) Crop circles can be made by people.
(g) The fate of Mono Lake is the same as the fate of the Aral Sea.

2. What is the logical conclusion of each of the following syllogisms? Which conclusions correspond to observed reality?
(a) All men are mortal. Socrates is a man.
Therefore______________________________
(b) All sheep are black. Mary's lamb is white.
Therefore______________________________
(c) All elephants are animals. All animals are living beings.
Therefore______________________________

3. Which of the following statements are supported by deductive reasoning and which by inductive reasoning?
(a) The sun will rise tomorrow.
(b) The square of the hypotenuse of a right triangle is equal to the sum of the squares of the other two sides.
(c) Only male deer have antlers.
(d) If $A = B$ and $B = C$, then $A = C$.
(e) The net force acting on a body equals its mass times its acceleration.

4. The accepted value for the number of inches in a centimeter is 0.3937. Two students mark off a centimeter on a piece of paper and then measure the distance using a ruler (in inches). Student A finds the distance equal to 0.3827 in., and student B finds it equal to 0.39 in. Which measurement is more accurate? Which is more precise? If student B measured the distance as 0.3900 in., what would be your answer?

5. (a) A teacher gives five students each a metal bar and asks them to measure the length. The measurements obtained are 5.03, 4.99, 5.02, 4.96, and 5.00 cm. How can you explain the variability in the measurements? Are these systematic or random errors?
(b) The next day, the teacher gives the students the same bars but tells them that the bars have contracted because they have been in the refrigerator. In fact, the temperature difference would be too small to have any measurable effect on the length of the bars. The students' measurements, in the same order as in part (a), are 5.01, 4.95, 5.00, 4.90, and 4.95 cm. Why are the students' measurements different from those of the day before? What does this illustrate about science?

6. Identify the independent and dependent variables in each of the following:
(a) Change in the rate of breathing in response to exercise.
(b) The effect of study time on grades.
(c) The likelihood that people exposed to smoke from other people's cigarettes will contract lung cancer.

7. (a) Identify a technological advance that resulted from a scientific discovery.
(b) Identify a scientific discovery that resulted from a technological advance.
(c) Identify a technological device you used today. What scientific discoveries were necessary before the device could be developed?

8. What is fallacious about each of the following conclusions?
(a) A fortune cookie contains the statement "A happy event will occur in your life." Four months later, you find a $100 bill. You conclude that the prediction was correct.
(b) A person claims that aliens visited Earth in prehistoric times and influenced the cultural development of humans. As evidence, the person points to ideas among many groups of people about beings who came from the sky and performed amazing feats.
(c) A person observes that light-colored animals almost always live on light-colored surfaces, whereas dark forms of the same species live on dark surfaces. The person concludes that the light surface causes the light color of the animals.
(d) A person knows three people who have had fewer colds since they began taking vitamin C on a regular basis. The person concludes that vitamin C prevents colds.

9. Find a newspaper article on a controversial topic. Identify some loaded words in the article—that is, words that convey an emotional reaction or a value judgment.

10. Identify some social, economic, aesthetic, and ethical issues involved in a current environmental controversy.

FURTHER READING

American Association for the Advancement of Science (AAAS), *Science for All Americans* (Washington, DC: AAAS, 1989). This report focuses on the knowledge, skills, and attitudes a student needs in order to be scientifically literate.

Botkin, D.B., *No Man's Garden: Thoreau and a New Vision for Civilization and Nature* (Washington, DC: Island Press, 2001). The author discusses how science can be applied to the study of nature and to problems associated with people and nature. He also discusses science and values.

Grinnell, F., *The Scientific Attitude* (New York: Guilford, 1992). The author uses examples from biomedical research to illustrate the processes of science (observing, hypothesizing, experimenting) and how scientists interact with each other and with society.

Kuhn, Thomas S., *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1996). This is a modern classic in the discussion of the scientific method, especially regarding major transitions in new sciences, such as environmental sciences.

McCain, G., and E.M. Segal, *The Game of Science* (Monterey, CA: Brooks/Cole, 1982). The authors present a lively look into the subculture of science.

Sagan, C., *The Demon-Haunted World* (New York: Random House, 1995). The author argues that irrational thinking and superstition threaten democratic institutions and discusses the importance of scientific thinking to our global civilization.

CHAPTER 3

The Big Picture: Systems of Change

The Missouri River at Sioux City is a complex system of water, sediment, animals, and fish, all affected by the city and its processes of runoff and river flood control, as well as upstream human intervention in the flow of the river.

LEARNING OBJECTIVES

In this book we discuss a wide range of phenomena. One thing that links them is that they are all part of complex systems. Systems have well-defined properties. Understanding these properties, common to so much of the environment, smooths our way to achieving an understanding of all aspects of environmental science. Changes in systems may occur naturally or may be induced by people, but a key to understanding these systems is that change in them is natural. After reading this chapter you should understand . . .

- Why solutions to many environmental problems involve the study of systems and rates of change;
- What feedback is, the difference between positive and negative feedback, and how these are important to systems;
- The difference between open and closed systems and between static and dynamic systems, and know which kind is characteristic of the environment and of life;
- What residence time is and how it is calculated;
- The principle of uniformitarianism and how it can be used to anticipate future changes;
- The principle of environmental unity and why it is important in studying environmental problems;
- Some helpful ways to think about systems when trying to solve environmental problems that arise from complex natural systems;
- What a stable system is and how this idea relates to the prescientific idea of a balance of nature.

CASE STUDY

Trying to Control Flooding of the Wild Missouri River

The Missouri River drains one-sixth of the United States (excluding Alaska and Hawaii) and flows for more than 3,200 km (2,000 miles). After the land along the Missouri was settled by Europeans, and after large towns and cities were built on the land near the river, flooding of the Missouri became a major problem. The "wild Missouri" became famous in history and folklore for its great fluctuations, its flows and droughts, and as the epitome of unpredictability in nature. One settler said that the Missouri "makes farming as fascinating as gambling. You never know whether you are going to harvest corn or catfish."[1,2]

Two of the river's great floods were in 1927 and 1993 (Figure 3.1). After the 1927 flood, the federal government commissioned the Army Corps of Engineers to build six major dams on the river (Figure 3.2). (The attempt to control the river's flow also included many other alterations of the river, such as straightening the channel and building levees.) Of the six dams, the three largest were built upstream, and each of their reservoirs was supposed to hold the equivalent of an entire year's average flow. The three smaller, downstream dams were meant to serve as safety valves to control the flow more precisely.

The underlying idea was to view the Missouri as a large plumbing system that needed management. When rainfall was sparse in the huge watershed of the river, the three upstream dams were supposed to be able to augment

FIGURE 3.1 St. Louis, Missouri, during the 1993 flood of the Missouri River. No matter how hard we try to keep this huge river flowing at a fixed rate, neither flooding nor in drought, we always seem to fail. So it is when we try to tame most natural ecological and environmental systems that are naturally dynamic and always changing.

FIGURE 3.2 The six major dams on the Missouri River. (Based on drawing by Gary Pound from Daniel B. Botkin, *Passage of Discovery: The American Rivers Guide to the Missouri River of Lewis and Clark* [New York: Perigee Books, a division of Penguin-Putnam, 1999].)

the flow for up to three years, ensuring a constant and adequate supply of water for irrigation and personal use. In flood years, the six dams were supposed to be able to store the dangerous flow, so that the water could be released slowly, the floods controlled, and the flow once again constant. In addition, levees—narrow ridges of higher ground—were built along the river and into it to protect the settled land along the river from floodwaters not otherwise contained. But these idealistic plans did not stop the Missouri from flooding in 1993 (Figures 3.1 and 3.3).

Taking the large view, standing way back from the river, this perception of the Missouri River was akin to thinking about it as one huge lake (Figure 3.4) into which water flowed, then drained downstream and out at its mouth at St. Louis, Missouri, into the Mississippi, which carried the waters to New Orleans, Louisiana, and out into the Gulf of Mexico. The hope was that the Missouri River could be managed the way we manage our bathwater—keeping it at a constant level by always matching the outflow down the drain with inflow from the spigot. This is a perception of the river as a system held in *steady state,* a term we will define shortly.

Before there were permanent settlements along the river—both by American Indians and by Europeans—the Missouri's flooding didn't matter. Nomadic peoples could move away from the river when it flooded during the rainy seasons, and wildlife and vegetation generally benefited from the variations in water flow, as will be explained in later chapters. Only with modern civilization

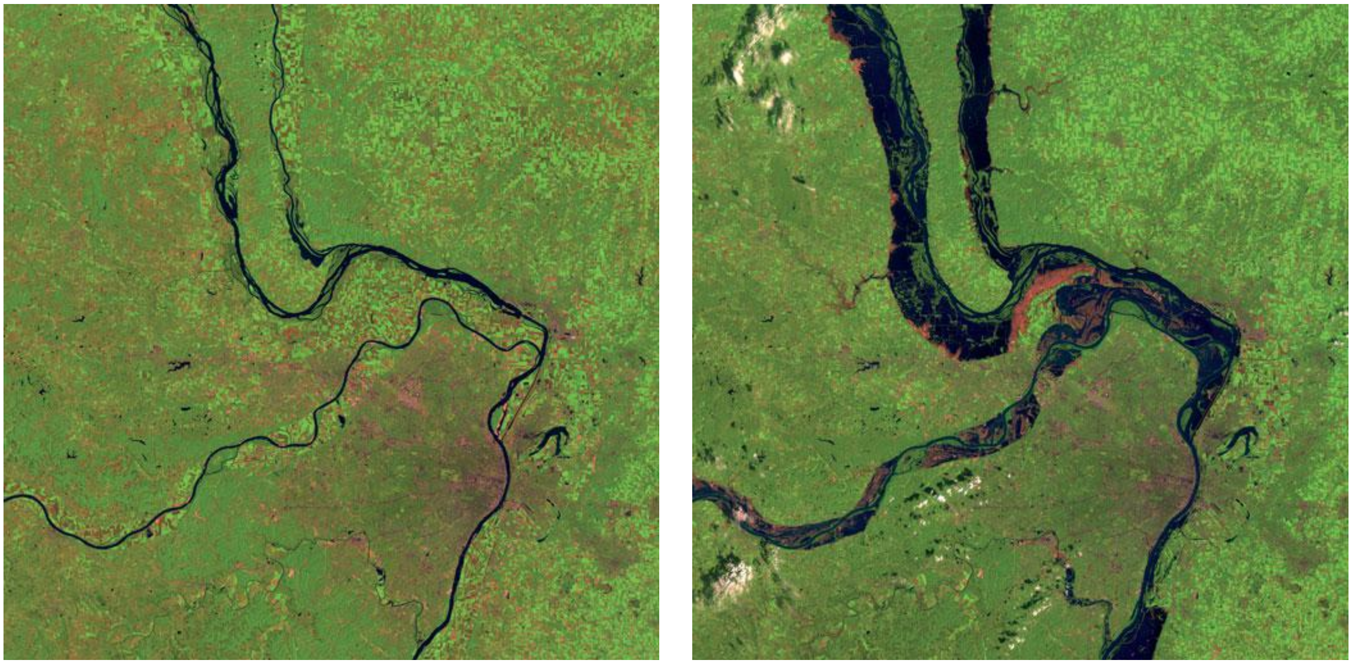
(a)  (b)

FIGURE 3.3 Satellite image of the Missouri River at St. Louis before the flood in 1991 (left) and during the 1993 flood. The dark area is water.

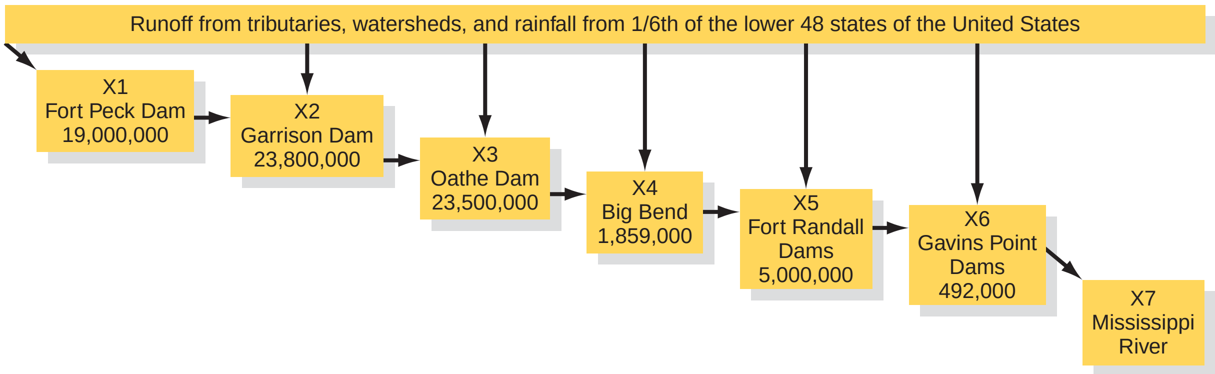


FIGURE 3.4 Imagine the Missouri River as one large lake (composed of the series of dams showed in Figure 3.2) whose water level is controlled. The water level remains constant as water flows into the lake (Fort Peck Dam) at the same rate as water flows out. If more water comes in, more leaves (Gavins Point Dam); if less water comes in, less flows out, and the water level remains at the spillway level. The number inside each box is the dam's maximum storage in acre-feet. The average annual water flow for the Missouri River is 25 million acre-feet (the amount reaching its mouth where it meets the Mississippi at St. Louis, MO)

did it become important to force a huge natural system like the Missouri to flow in steady state.

Unfortunately, people who lived along the Missouri River in 1993 learned that sometimes plans that looked good on paper did not succeed. The Missouri was just too wild and unpredictable—too non-steady-state, to use a systems-analysis term that we will define shortly—for people to control, no matter how great their efforts. The big flood of 1993 breached many levees and affected many lives (Figures 3.1 and 3.3).

The attempt to control the flow of the Missouri is just one of many examples of natural ecological and environmental systems that people thought could be engineered, controlled, tamed, and made to do what they wanted. To understand the environment and people's relation to it, it is necessary to take a systems view, and that is the purpose of this chapter. Once you have read this chapter, you will have one of the foundations for the study of all environmental systems. To understand what happens in natural ecosystems, we can't just look for an answer derived from a single factor. We have to look at the entire system and all of the factors that, together, influence what happens to life.

3.1 Basic Systems Concepts

A **system** is a set of components, or parts, that function together as a whole. A single organism, such as your body, is a system, as are a sewage-treatment plant, a city, and a river. On a much different scale, the entire Earth is a system. In a broader sense, a system is any part of the universe you can isolate in thought (in your brain or on your computer) or, indeed, physically, for the purpose of study. Key systems concepts that we will explain are (1) how a system is connected to the rest of the environment; (2) how matter and energy flow between parts of a system; (3) whether a system is static or dynamic—whether it changes over time; (4) average residence time—how long something stays within a system or part of a system; (5) feedback—how the output from a system can affect its inputs; and (6) linear and nonlinear flows.

In its relation to the rest of the environment, a system can be open or closed. In an **open system**, some energy or material (solid, liquid, or gas) moves into or out of the system. The ocean is an open system with regard to water because water moves into the ocean from the atmosphere and out of the ocean into the atmosphere. In a **closed system**, no such transfers take place. For our purposes, a **materially closed system** is one in which no matter moves in and out of the system, although energy and information can move across the system's boundaries. Earth is a materially closed system (for all practical purposes).

Systems respond to **inputs** and have **outputs**. For example, think of your body as a complex system and imagine you are hiking in Yellowstone National Park and see a grizzly bear. The sight of the bear is an input. Your body reacts to that input: The adrenaline level in your blood goes up, your heart rate increases, and the hair on your head and arms may rise. Your response—perhaps to move slowly away from the bear—is an output.

Static and Dynamic Systems

A **static system** has a fixed condition and tends to remain in that exact condition. A **dynamic system** changes, often continually, over time. A birthday balloon attached to a pole is a static system in terms of space—it stays in one place. A hot-air balloon is a simple dynamic system in terms of space—it moves in response to the winds, air density, and controls exerted by a pilot (Figure 3.5a and b). An important kind of static system is one with **classical stability**. Such a system has a constant condition, and if it is disturbed from that condition, it returns to it once the disturbing factor is removed. The pendulum of an old-fashioned grandfather clock is an example of classical stability. If you push it, the pendulum moves back and forth for a while, but then friction gradually dissipates the energy you just gave it and the pendulum comes to rest exactly where it began. This rest point is known as the **equilibrium** (Figure 3.5c).

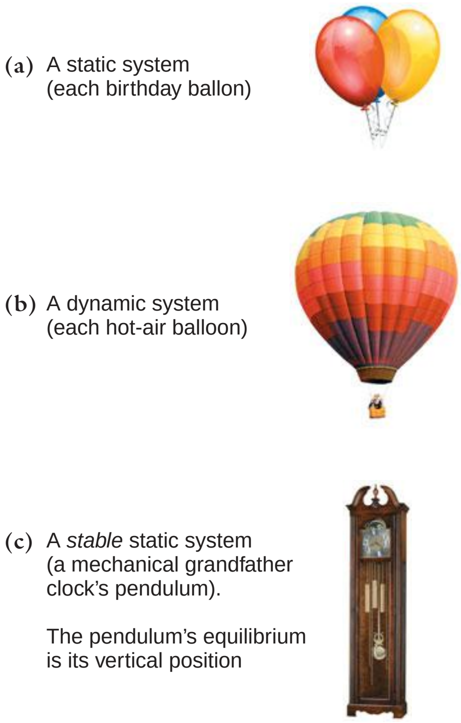


FIGURE 3.5 Static and dynamic systems. (a) *A static system* (each birthday balloon). Balloons are tied down and can't move vertically. **(b)** *A dynamic system* (each hot-air balloon). Hot air generated by a heater fills the balloon with warm air, which is lighter than outside air, so it rises; as air in the balloon cools, the balloon sinks, and winds may move it in any direction. **(c)** *A classical stable static system* (the pendulum on a mechanical grandfather clock). The pendulum's equilibrium is its vertical position. The pendulum will move if you push it or if the clock's mechanism is working. When the source of energy is no longer active (you forgot to wind the clock), the pendulum will come to rest exactly where it started.

We will see that the classic interpretation of populations, species, ecosystems, and Earth's entire biosphere has been to assume that each is a stable, static system. But the more these ecological systems are studied scientifically, the clearer it becomes that these are dynamic systems, always changing *and always requiring change.* An important practical question that keeps arising in many environmental controversies is whether we want to, and should, force ecological systems to be static if and when they are naturally dynamic. You will find this question arising in many of the chapters in this book.

Open Systems

With few exceptions, all real systems that we deal with in the environment are open to the flow of matter, energy, and information. (For all practical purposes, as we noted earlier, Earth as a planet is a materially closed system.) An important distinction for open systems is whether they are steady-state or non-steady-state. In a

steady-state system, the inputs (of anything of interest) are equal to the outputs, so the amount stored within the system is constant. An idealized example of a steady-state system is a dam and lake into which water enters from a river and out of which water flows (Figure 3.4). If the water input equals the water output and evaporation is not considered, the water level in the lake does not change, and so, in regard to water, the lake is in a steady state. (Additional characteristics of systems are discussed in A Closer Look 3.1.)

A CLOSER LOOK 3.1

Simple Systems

A simple way to think about a system is to view it as a series of compartments (also called "reservoirs," and we will use these terms interchangeably), each of which can store a certain amount of something you are interested in, and each of which receives input from other compartments and transfers some of its stored material to other compartments (Figure 3.6a).

The general equation is

$$I = O \pm \Delta S$$

where I is input into a compartment; O is output, and ΔS is change in storage. This equation defines a budget for what is being considered. For example, if your checking account has $1,000 in it (no interest rate) and you earn $500 per month at the bookstore, input is $500 per month. If you spend $500 per month, the amount in your account will be $1,000 at the end of the month (no change in storage). If you spend less than $500 per month, your account will grow ($+\Delta S$). If you spend more than $500 per month, the amount of money in your account will decrease ($-\Delta S$).

An environmental water engineer could use this kind of systems diagram (Figure 3.6a) to plan the size of the various dams to be built on the Missouri River, taking into account the desired total storage among the dams (Figure 3.4) and the role of each dam in managing the river's flow (refer back to the opening case study and also see Figure 3.7). In Figure 3.7, the amount stored in a dam's reservoir is listed as Xn, where X is the amount of water stored and n is the number of the compartment. (In this case the dams are numbered in order from upstream to downstream.) Water flows from the environment—tributaries, watersheds, and direct rainfall—into each of the reservoirs, and each is connected to the adjacent reservoirs by the river. Finally, all of the Missouri's water flows into the Mississippi, which carries it to the Gulf of Mexico.

For this water-flow system, we can make a complete flow diagram. This kind of diagramming helps us to think about and do a scientific analysis of many environmental problems, so you will find such diagrams throughout this book.

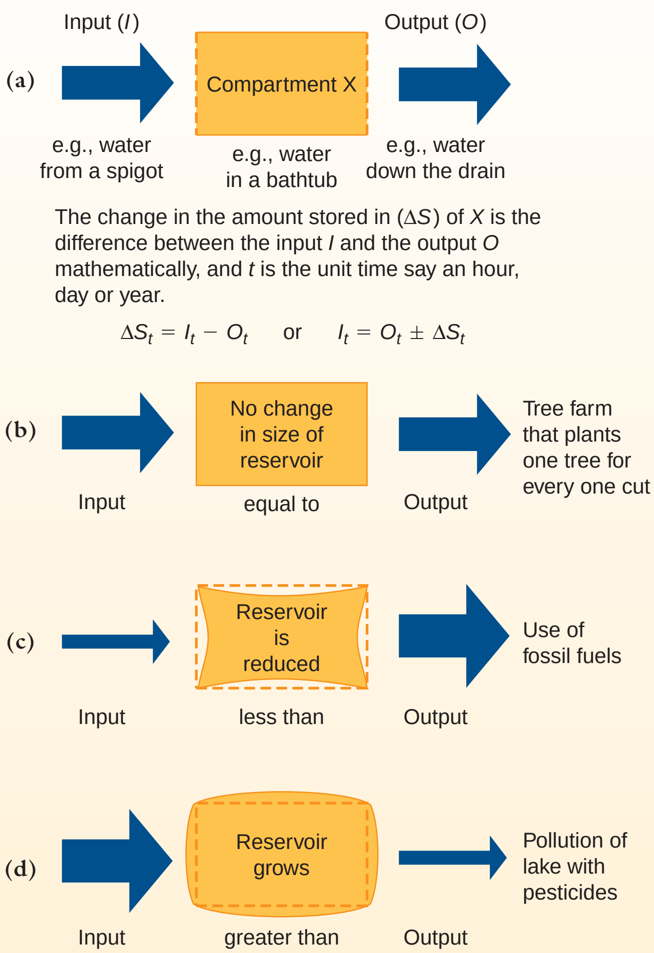


FIGURE 3.6 **(a)** General equation for ways in which a compartment of some material can change. (*Source*: Modified from P.R. Ehrlich, A.H. Ehrlich, and J.P. Holvren, *Ecoscience: Population, Resources, Environment*, 3rd ed. [San Francisco: W.H. Freeman, 1977].) Row **(b)** represents steady-state conditions; rows **(c)** and **(d)** are examples of negative and positive changes in storage.

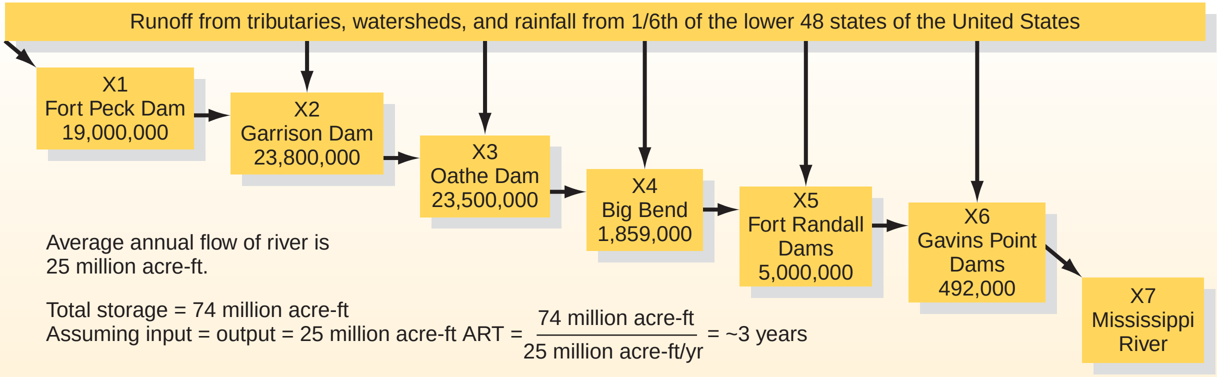


FIGURE 3.7 The Missouri River and its dams viewed as a systems flow chart. The number inside each box is the dam's maximum storage in acre-feet, where one acre-foot is the volume of water that would cover one acre to a depth of 1 foot (1,233 m^3). The average annual water flow for the Missouri River is 25 million acre-feet (the amount reaching its mouth where it meets the Mississippi at St. Louis, Missouri).

Often we want real systems in the environment to be in steady state, and we try to manage many of them so they will be. This has been the case with the Missouri River, the subject of this chapter's opening case study. As with that river, attempts to force natural ecological and environmental systems into a steady state often fail. In fact, such attempts commonly make things worse instead of better, as we will see in many chapters in this book.

The Balance of Nature: Is a Steady State Natural?

An idea frequently used and defended in the study of our natural environment is that natural systems, left undisturbed by people, tend toward some sort of steady state. The technical term for this is **dynamic equilibrium**, but it is more familiarly referred to as the **balance of nature** (see Figure 3.8). Certainly, negative feedback operates in many natural systems and may tend to hold a system at equilibrium. Nevertheless, we need to ask how often the equilibrium model really applies.[3]

If we examine natural ecological systems or **ecosystems** (simply defined here as communities of organisms and their nonliving environment in which nutrients and other chemicals cycle and energy flows) in detail and over a variety of time frames, it is evident that a steady state is seldom attained or maintained for very long. Rather, systems are characterized not only by human-induced disturbances but also by natural disturbances (sometimes large-scale ones called natural disasters, such as floods and wildfires). Thus, changes over time can be expected. In fact, studies of such diverse systems as forests, rivers, and coral reefs suggest that disturbances due to natural events, such as storms, floods, and fires, are necessary for the maintenance of those systems, as we will see in later chapters. The environmental lesson is that systems change naturally. If we are going to manage systems for the betterment of the environment, we need to gain a better understanding of how they change.[3,4]

FIGURE 3.8 The balance of nature. This painting, *Morning in the Tropics* by Frederic Edwin Church, illustrates the idea of the balance of nature and a dynamic steady state, with everything stationary and still, unchanging.

Residence Time

By using rates of change or input-output analysis of systems, we can derive an **average residence time**—how long, on average, a unit of something of interest to us will remain in a reservoir. This is obviously important, as in the case of how much water can be stored for how long in one of the reservoirs on the Missouri River. To compute the average residence time (assuming input is equal to output), we divide the total volume of stored water in the series of dams (Figures 3.4 and 3.7) by the average rate of transfer through the system (Figure 3.7) For example, suppose a university has 10,000 students, and each year 2,500 freshmen start and 2,500 seniors graduate. The average residence time for students is 10,000 divided by 2,500, or four years.

Average residence time has important implications for environmental systems. A system such as a small lake with an inlet and an outlet and a high transfer rate of water has a short residence time for water. On the one hand, from our point of view, that makes the lake especially vulnerable to change because change can happen quickly. On the other hand, any pollutants soon leave the lake.

In large systems with a slow rate of transfer of water, such as oceans, water has a long residence time, and such systems are thus much less vulnerable to quick change. However, once polluted, large systems with slow transfer rates are difficult to clean up. (See Working It Out 3.1.)

WORKING IT OUT 3.1 Average Residence Time (ART)

The average residence time (ART) is the ratio of the size of a reservoir of some material—say, the amount of water in a reservoir—to the rate of its transfer through the reservoir. The equation is

$$ART = S/F$$

where S is the size of the reservoir and F is the rate of transfer.

For example, we can calculate the average residence time for water in the Gavins Point Dam (see Figure 3.7), the farthest downstream of all the dams on the Missouri River, by realizing that the average flow into and out of the dam is about 25 million acre-feet (31 km^3) a year, and that the dam stores about 492,000 acre-feet (0.6 km^3). This suggests that the average residence time in the dam is only about seven days:

$$ART = S/F = 0.6\ km^3\ per\ year\ (31\ km^3\ per\ year)$$

$$S/F = 0.019/year\ (about\ 7\ days)$$

If the total flow were to go through Garrison Dam, the largest of the dams, the residence time would be 347 days, almost a year.

The ART for a chemical element or compound is important in evaluating many environmental problems. For example, knowing the ART of a pollutant in the air, water, or soil gives us a more quantitative understanding of that pollutant, allows us to evaluate the extent to which the pollutant acts in time and space, and helps us to develop strategies to reduce or eliminate the pollutant.

Figure 3.9 shows a map of Big Lake, a hypothetical reservoir impounded by a dam. Three rivers feed a combined 10 m^3/sec (2,640 gal/sec) of water into the lake, and the outlet structure releases an equal 10 m^3/sec. In this simplified example, we will assume that evaporation of water from the lake is negligible. A water pollutant, MTBE (methyl tertiary—butyl ether), is also present in the lake. MTBE is added to gasoline to help reduce emissions of carbon monoxide. MTBE readily dissolves in water and so travels with it. It is toxic; in small concentrations of 20–40 μg/l (thousandths of grams per liter) in water, it smells like turpentine and is nauseating to some people. Concern over MTBE in California led to a decision to stop adding it to gasoline. The sources of MTBE in "Big Lake" are urban runoff from Bear City gasoline stations, gasoline spills on land or in the lake, and gasoline engines used by boats on the lake.

We can ask several questions concerning the water and MTBE in Big Lake.

1. What is the ART of water in the lake?
2. What is the amount of MTBE in the lake, the rate (amount per time) at which MTBE is being put into the lake, and the ART of MTBE in the lake? Because the water and MTBE move together, their

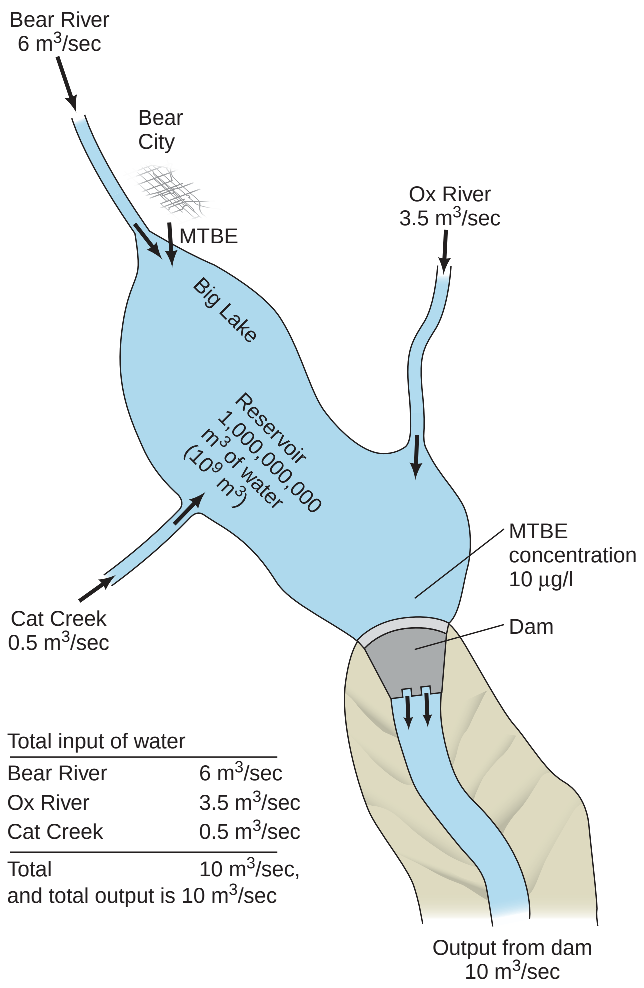


FIGURE 3.9 Idealized diagram of a lake system with MTBE contamination.

ARTs should be the same. We can test this.

ART of Water in Big Lake

For these calculations, use multiplication factors and conversions in Appendixes B and C at the end of this book.

$$ART_{water} = \frac{S}{F} = ART_{water} = \frac{1{,}000{,}000{,}000\, m^3}{10\, m^3/sec}$$

$$or\ \frac{10^9\ m^3}{10\, m^3/sec}$$

The units m^3 cancel out and

$$ART = 100{,}000{,}000\ sec\ or\ 10^8\ sec$$

Convert 10^8 sec to years:

$$\frac{seconds}{year} = \frac{60\ sec}{1\ minute} \times \frac{60\ minutes}{1\ hour} \times \frac{24\ hours}{1\ day} \times \frac{365\ days}{1\ year}$$

Canceling units and multiplying, there are 31,536,000 sec/year, which is

$$3.1536 \times 10^7\ sec/year$$

Then the ART for Big Lake is

$$\frac{100{,}000{,}000\, sec}{31{,}536{,}000\, sec/yr}\ or\ \frac{10^8\ sec}{3.1536 \times 10^7\ sec/yr}$$

Therefore the ART for water in Big Lake is 3.17/years.

ART of MTBE in Big Lake

The concentration of MTBE in water near the dam is measured as 10 μg/l. Then the total amount of MTBE in the lake (size of reservoir or pool of MTBE) is the product of volume of water in the lake and concentration of MTBE:

$$10^9\ m^3 \times \frac{10^3\, 1}{m^3} \times \frac{10\, \mu g}{1} = 10^{13}\, \mu g\ or\ 10^7\ g$$

which is 10^4 kg, or 10 metric tons, of MTBE.

The output of water from Big Lake is 10 m^3/sec, and this contains 10 μg/l of MTBE; the transfer rate of MTBE (g/sec) is

$$MTBE/sec = \frac{10\, m^3}{sec} \times \frac{10^3\, 1}{m^3} \times \frac{10\, \mu g}{1} \times \frac{10^6}{\mu g}$$
$$= 0.1\, g/sec$$

Because we assume that input and output of MTBE are equal, the input is also 0.1 *g/sec*.

$$ART_{MTBE} = \frac{S}{F} = \frac{10^7\, g}{0.1\, g/sec} = 10^8\ sec\text{, or } 3.17\ years$$

Thus, as we suspected, the ARTs of the water and MTBE are the same. This is because MTBE is dissolved in the water. If it attached to the sediment in the lake, the ART of the MTBE would be much longer. Chemicals with large reservoirs or small rates of transfer tend to have long ARTs. In this exercise we have calculated the ART of water in Big Lake as well as the input, total amount, and ART of MTBE.

Feedback

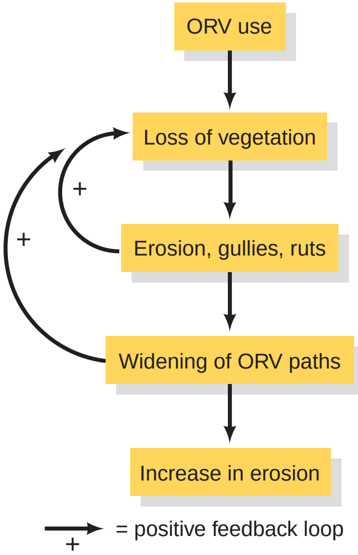
Feedback occurs when the output of a system (or a compartment in a system) affects its input. Changes in the output "feed back" on the input. There are two kinds of feedback: negative and positive. A good example of feedback is human temperature regulation. If you go out in the sun and get hot, the increase in temperature affects your sensory perceptions (input). If you stay in the sun, your body responds physiologically: Your pores open, and you are cooled by evaporating water (you sweat). The cooling is output, and it is also input to your sensory perceptions. You may respond behaviorally as well: Because you feel hot (input), you walk into the shade (output) and your temperature returns to normal. In this example, an increase in temperature is followed by a response that leads to a decrease in temperature. This is an example of negative feedback, in which an increase in output now leads to a later *decrease* in output. **Negative feedback** is self-regulating, or stabilizing. It is the way that steady-state systems can remain in a constant condition.

Positive feedback occurs when an increase in output leads to a further *increase* in output. A fire starting in a forest provides an example of positive feedback. The wood may be slightly damp at the beginning and so may not burn readily. Once a fire starts, wood near the flame dries out and begins to burn, which in turn dries out a greater quantity of wood and leads to a larger fire. The larger the fire, the faster more wood becomes dry and the more rapidly the fire grows. Positive feedback, sometimes called a "vicious cycle," is destabilizing.

Environmental damage can be especially serious when people's use of the environment leads to positive feedback. For example, off-road vehicles—including bicycles—may cause positive feedback to soil erosion (Figure 3.10).

(a)

(c)



(b)

FIGURE 3.10 How off-road vehicles **(a)** create positive feedback on soil erosion **(b)** and **(c)**.

The vehicles' churning tires are designed to grip the earth, but they also erode the soil and uproot plants. Without vegetation, the soil erodes faster, exposing even more soil (positive feedback). As more soil is exposed, rainwater more easily carves out ruts and gullies (more positive feedback). Drivers of off-road vehicles then avoid the ruts and gullies by driving on adjacent sections that are not as eroded, thus widening paths and further increasing erosion (more positive feedback). The gullies themselves increase erosion because they concentrate runoff and have steep side slopes. Once formed, gullies tend to get longer, wider, and deeper, causing additional erosion (even more positive feedback). Eventually, an area of intensive off-road vehicle use may become a wasteland of eroded paths and gullies. Positive feedback has made the situation increasingly worse.

Some systems have both positive and negative feedbacks, as can occur, for example, for the human population in large cities (Figure 3.11). Positive feedback on the population size may occur when people perceive greater opportunities in cities and move there hoping for a higher standard of living. As more people move to cities, opportunities may increase, leading to even more migration to cities. Negative feedback can then occur when crowding increases air and water pollution, disease, crime, and discomfort. These negatives encourage some people to migrate from the cities to rural areas, reducing the city's population.

Practicing your critical-thinking skills, you may ask, "Is negative feedback generally desirable, and is positive feedback generally undesirable?" Reflecting on this question, we can see that although negative feedback is self-regulating, it may in some instances not be

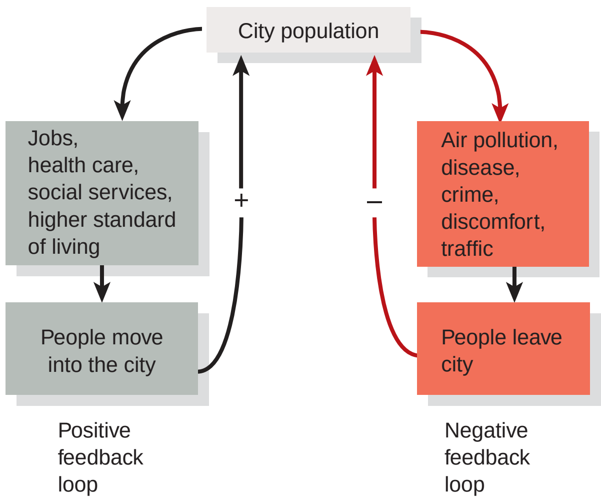


FIGURE 3.11 Potential positive and negative feedback loops for changes of human population in large cities. The left side of the figure shows that as jobs increase and health care and the standard of living improve, migration and the city population increase. Conversely, the right side of the figure shows that increased air pollution, disease, crime, discomfort, and traffic tend to reduce the city population. (*Source:* Modified from M. Maruyama, the second cybernetics: Deviation-amplifying mutual causal processes, *American Scientist* 51 [1963]:164–670. Reprinted by permission of *American Scientist* magazine of Sigma Xi, The Scientific Research Society.)

desirable. The period over which the positive or negative feedback occurs is the important factor. For example, suppose we are interested in restoring wolves to Yellowstone National Park. We will expect positive feedback in the wolf population for a time as the number of wolves grows. (The more wolves, the greater their population growth, through exponential growth.) Positive feedback, for a time, is desirable because it produces a change we want.

We can see that whether we view positive or negative feedback as desirable depends on the system and potential changes. Nevertheless, some of the major environmental problems we face today result from positive feedback mechanisms. These include resource use and growth of the human population.

3.2 System Responses: Some Important Kinds of Flows[4]

Within systems, there are certain kinds of flows that we come across over and over in environmental science. (Note that **flow** is an amount transferred; we also refer to the **flux**, which is the rate of transfer per unit time.) Because these are so common, we will explain a few of them here.

Linear and Nonlinear Flows

An important distinction among environmental and ecological systems is whether they are characterized by linear or nonlinear processes. Put most simply, in a **linear process**, if you add the same amount of anything to a compartment in a system, the change will always be the same, no matter how much you have added before and no matter what else has changed about the system and its environment. If you harvest one apple and weigh it, then you can estimate how much 10 or 100 or 1,000 or more of the apples will weigh—adding another apple to a scale does not change the amount by which the scale shows an increase. One apple's effect on a scale is the same, no matter how many apples were on the scale before. This is a linear effect.

Many important processes are **nonlinear**, which means that the effect of adding a specific amount of something changes depending on how much has been added before. If you are very thirsty, one glass of water makes you feel good and is good for your health. Two glasses may also be helpful. But what about 100 glasses? Drinking more and more glasses of water leads quickly to diminishing returns and eventually to water's becoming a poison.

Lag Time

Many responses to environmental inputs (including human population change; pollution of land, water, and air; and use of resources) are nonlinear and may involve delays, which we need to recognize if we are to understand and solve environmental problems. For example, when you add fertilizer to help a tree grow, it takes time for it to enter the soil and be used by the tree.

Lag time is the delay between a cause and the appearance of its effect. (This is also referred to as the time between a stimulus and the appearance of a response.) If the lag time is long, especially compared to human lifetimes (or attention spans or our ability to continue measuring and monitoring), we can fail to recognize the change and know what is the cause and what is the effect. We can also come to believe that a possible cause is not having a detrimental effect, when in reality the effect is only delayed. For example, logging on steep slopes can increase the likelihood and rate of erosion, but in comparatively dry environments this may not become apparent until there is heavy rain, which might not occur until a number of years afterward. If the lag time is short, cause and effect are easier to identify. For example, highly toxic gas released from a chemical plant will likely have rapid effects on the health of people living nearby.

With an understanding of input and output, positive and negative feedback, stable and unstable systems, and systems at steady state, we have a framework for interpreting some of the changes that may affect systems.

Selected Examples of System Responses

Although environmental science deals with very complex phenomena, there are recurring relationships that we can represent with a small number of graphs that show how one part of a system responds to inputs from another part. These graphs include responses of individual organisms, responses of populations and species, responses of entire ecosystems and then large units of the **biosphere**, the planetary system that includes and sustains life, such as how the atmosphere responds to the burning of fossil fuels. Each of these graphs has a mathematical equation that can explain the curve, but it is the shape of the graph and what that shape represents that are key to understanding environmental systems. These curves represent, in one manifestation or another, the fundamental dynamics found in these systems. The graphs show (1) a straight line (linear); (2) the positive exponential; (3) the negative exponential; (4) the logistic curve; and (5) the saturation (Michaelis-Menton) curve. An example of each is shown in Figures 3.12 to 3.15.

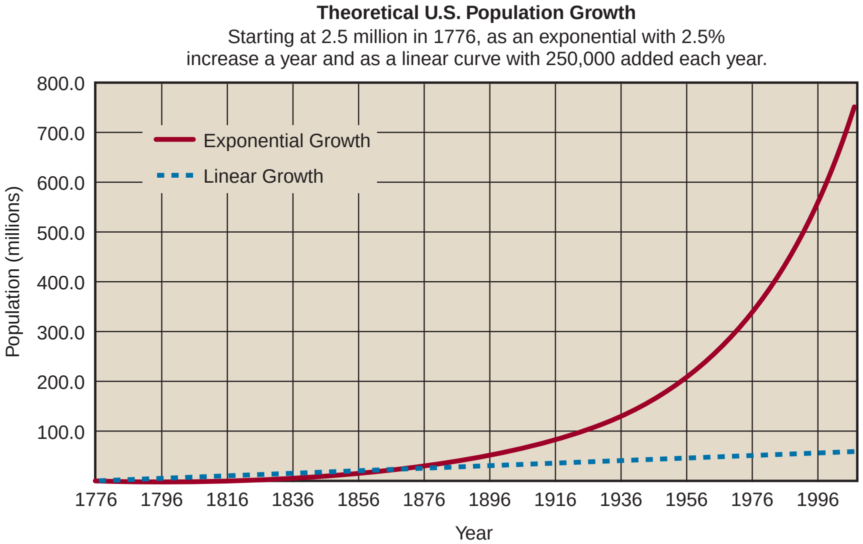


FIGURE 3.12 Curves 1 and 2: linear and positive exponential. This graph shows theoretical growth of the population of the United States, starting with the 2.5 million people estimated to have been here in 1776 and growing as an exponential and a linear curve. Even though the linear curve adds 250,000 people a year—10% of the 1776 population—it greatly lags the exponential by the beginning of the 20th century, reaching fewer than 100 million people today, while the exponential would have exceeded our current population.

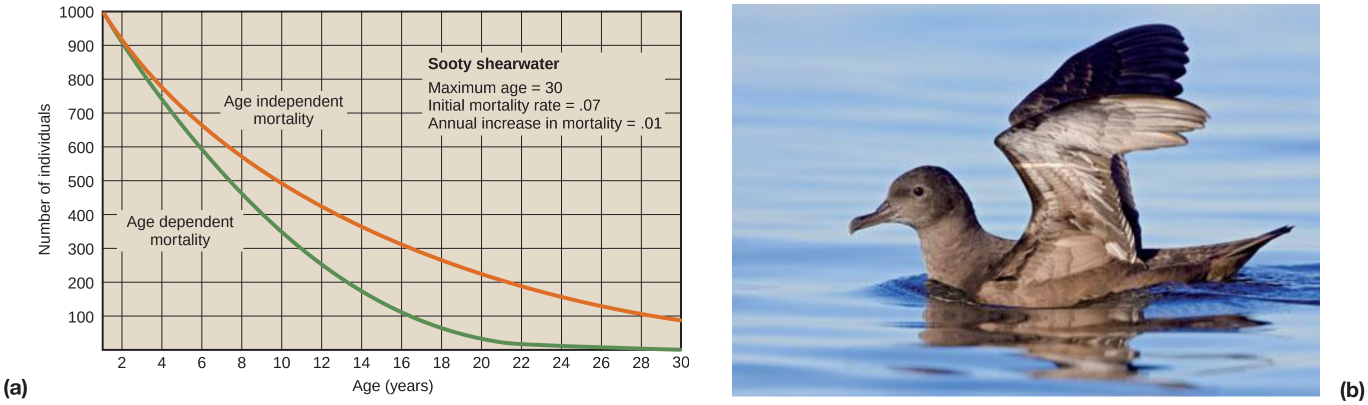


FIGURE 3.13 Negative exponential. Example: the decline in a population of a species of birds when there are no births and the mortality rate is 7% per year. The upper curve is a pure negative exponential. (*Source*: D.B. Botkin and R.S. Miller, 1974, Mortality rates and survival of birds, *American Nat.* 108: 181–192.)

Figure 3.12 shows both a linear relation and a positive exponential relation. A linear relation is of the form $y = a + bx$, where a is the y intercept (in this case, *o*) and b is the slope of the line (change in y to change in x, where y is the vertical axis and x the horizontal). The form of the positive exponential curve is $y = ax^b$, where a is the y intercept (in this case *o*) and b is the slope. However, b is a positive exponent (power). (See A Closer Look 3.2, Exponential Growth.)

Figure 3.13 shows two examples of negative exponential relations. Figure 3.14 is the logistic curve, which often has the shape of a lazy *S*; the logistic carrying *k* is the population eventually reached or approached, based on environmental factors. The saturation (Michaelis-Menton) curve (Figure 3.15) shows initial fast change, followed by a leveling off at saturation. At the point of saturation, the net CO_2 fixed (for soybean)is at a light-intensity value of about 3,000. As light intensity increases above about 3,000, net fixed CO_2 is nearly constant (that is, fixed CO_2 saturates at light intensity of 3,000 and does not change if intensity increases).

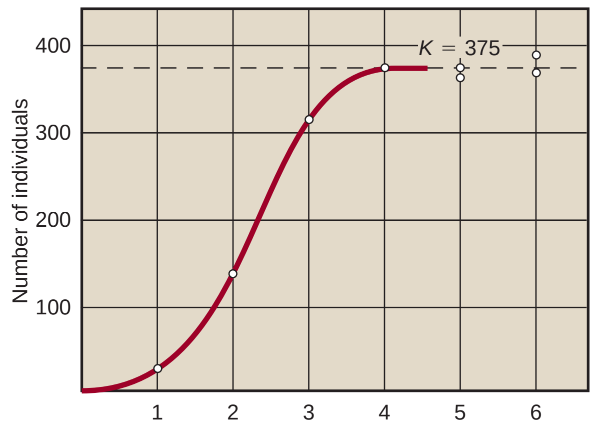
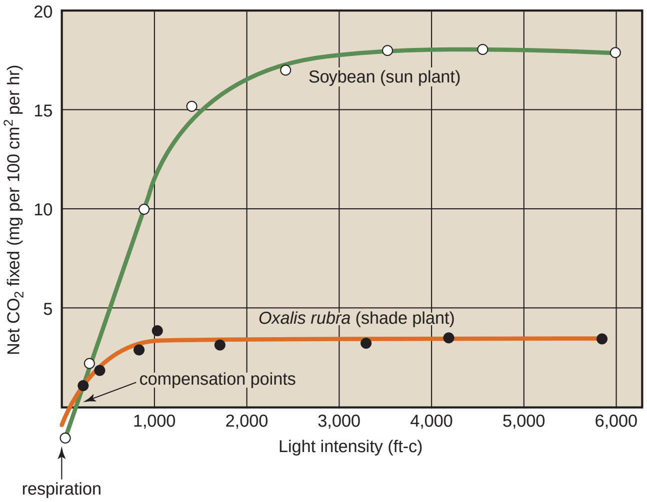


FIGURE 3.14 (a) The logistic curve. Growth of a population of a microorganism in a laboratory test tube under constant conditions with a constant supply of food. (From G.F. Gause, *The Struggle for Existence.*) The logistic carrying capacity is *k*. If you take a population of such bacteria into a laboratory and grow them under constant conditions, you might get the population to change according to the curve above, as Gause did in the 1930s with other microorganisms. (*Source:* D.B. Botkin, *Discordant Harmonies: A New Ecology for the 21st Century* [New York: Oxford University Press, 1990].)



(a)


(b)


(c)

FIGURE 3.15 **(a) The saturation (Michaelis-Menton) curve.** (*Source:* F.B. Salisbury and C. Ross, *Plant Physiology* [Belmont, CA: Wadsworth, 1969, p. 292, Figure 14-9.] Data from R. Bohning and C. Burnside, 1956, *American Journal of Botany* 43:557].); **(b)** *Glycine max* (soybeans); **(c)** *Oxalis rubra* (shade plant).

A CLOSER LOOK 3.2

Exponential Growth Defined, and Putting Some Numbers on It

Exponential growth is a particularly important kind of feedback. Change is exponential when it increases or decreases at a constant rate per time period, rather than by a constant amount. For instance, suppose you have $1,000 in the bank and it grows at 10% per year. The first year, $100 in interest is added to your account. The second year, you earn more, $110, because you earn 10% on a higher total amount of $1,100. The greater the amount, the greater the interest earned, so the money increases by larger and larger amounts. When we plot data in which exponential growth is occurring, the curve we obtain is said to be **J**-shaped. It looks like a skateboard ramp, starting out nearly flat and then rising steeply.

Two important qualities of exponential growth are (1) the rate of growth measured as a percentage and (2) the doubling time in years. The **doubling time** is the time necessary for the quantity being measured to double. A useful rule is that the doubling time is approximately equal to 70 divided by the annual percentage growth rate. Working It Out 3.2 describes exponential growth calculations and explains why 70 divided by the annual growth rate is the doubling time.

WORKING IT OUT 3.2 Exponential Growth

If the quantity of something (say, the number of people on Earth) increases or decreases at a fixed fraction per unit of time, whose symbol is k (for example, $k = +0.02$ per year), then the quantity is changing exponentially. With positive k, we have exponential growth. With negative k, we have exponential decay.

The growth rate R is defined as the percent change per unit of time—that is, $k = R/100$. Thus, if $R = 2\%$ per year, then $k = +0.02$ per year. The equation to describe exponential growth is

$$N = N_o e^{kt}$$

where N is the future value of whatever is being evaluated; N_o is present value; e, the base of natural logarithms, is a constant 2.71828; k is as defined above; and t is the number of years over which the growth is to be calculated.

This equation can be solved using a simple hand calculator, and a number of interesting environmental questions can then be answered. For example, assume that we want to know what the world population is going to be in the year 2020, given that the population in 2003 is 6.3 billion and the population is growing at a constant rate of 1.36% per year ($k = 0.0136$). We can estimate N, the world population for the year 2020, by applying the preceding equation:

$$\begin{aligned} N &= (6.3 \times 10^9) \times e^{(0.0136 \times 17)} \\ &= 6.3 \times 10^9 \times e^{0.2312} \\ &= 6.3 \times 10^9 \times 2.718^{0.231} \\ &= 7.94 \times 10^9, \text{ or } 7.94 \text{ billion people} \end{aligned}$$

The doubling time for a quantity undergoing exponential growth (i.e., increasing by 100%) can be calculated by the following equation:

$$2N_T = N_0\, e^{kTd}$$

where T_d is the doubling time.

Take the natural logarithm of both sides.

$$\ln 2 = kT_d \quad \text{and} \quad T_d = \ln 2/k$$

Then, remembering that $k = R/100$,

$$\begin{aligned} T_d &= 0.693/(R/100) \\ &= 100(0.693)/R \\ &= 69.3/R, \textit{ or about } 70/R \end{aligned}$$

This result is our general rule—that the doubling time is approximately 70 divided by the growth rate. For example, if $R = 10\%$ per year, then $T = 7$ years.

3.3 Overshoot and Collapse

Figure 3.16 shows the relationship between carrying capacity (maximum population possible without degrading the environment necessary to support the population) and the human population. The carrying capacity starts out being much higher than the human population, but if a population grows exponentially (see Working It Out 3.2), it eventually exceeds—**overshoots**—the carrying capacity. This ultimately results in the **collapse** of a population to some lower level, and the carrying capacity may be reduced as well. In this case, the lag time is the period of exponential growth of a population before it exceeds the carrying capacity. A similar scenario may be posited for harvesting species of fish or trees.

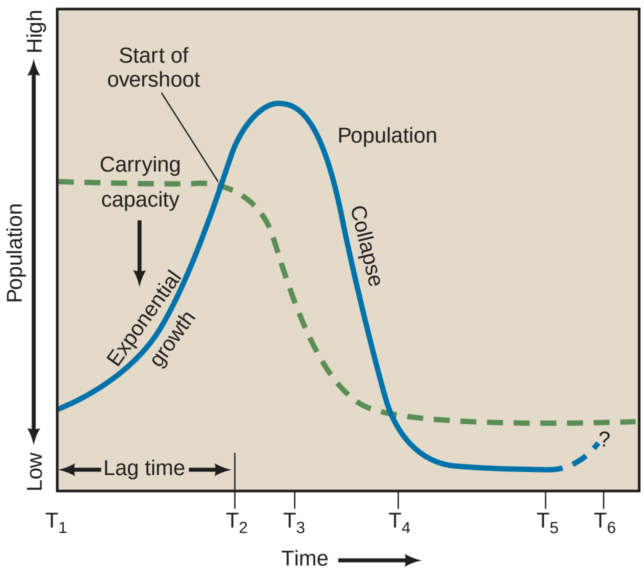


FIGURE 3.16 The concept of overshoot. A population starts out growing exponentially, but as this growth cannot continue indefinitely, it reaches a peak, then declines sharply. Sometimes the population is assumed to have a carrying capacity, which is the maximum number possible, and if the population's habitat is damaged by too great an abundance, the carrying capacity also decreases. (*Source*: Modified after D.H. Meadows and others, 1992.)

3.4 Irreversible Consequences

Adverse consequences of environmental change do not necessarily lead to irreversible consequences. Some do, however, and these lead to particular problems. When we talk about irreversible consequences, we mean

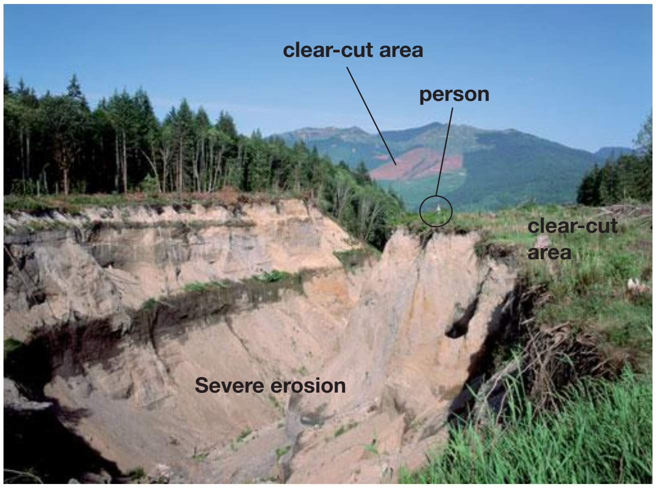


FIGURE 3.17 Timber harvest (clear-cut) can result in soil erosion. Once soil is removed, it can take such a long time for it to rebuild that the damage may be viewed as irreversible on a human time scale.

consequences that may not be easily rectified on a human scale of decades or a few hundred years.

Good examples of this are soil erosion and the harvesting of old-growth forest (Figure 3.17). With soil erosion, there may be a long lag time until the soil erodes to the point where crops no longer have their roots in active soil that has the nutrients necessary to produce a successful crop. But once the soil is eroded, it may take hundreds or thousands of years for new soil to form, and so the consequences are irreversible in terms of human planning. Similarly, when old-growth forests are harvested, it may take hundreds of years for them to be restored. Lag times may be even longer if the soils have been damaged or eroded by timber harvesting.

3.5 Environmental Unity

Our discussion of positive and negative feedback sets the stage for another fundamental concept in environmental science: **environmental unity**—the idea that it is impossible to change only one thing; everything affects everything else. Of course, this is something of an overstatement; the extinction of a species of snails in North America, for instance, is hardly likely to change the flow characteristics of the Amazon River. However, many aspects of the natural environment are in fact closely linked, and thus changes in one part of a system often have secondary and tertiary effects within the system, and on adjacent systems as well. Earth and its ecosystems are complex entities in which any action may have many effects.

We will find many examples of environmental unity throughout this book. Urbanization illustrates it. When cities, such as Chicago and Indianapolis, were developed in the eastern and midwestern United States, the clearing of forests and prairies and the construction of buildings and paved streets increased surface-water runoff and soil erosion, which in turn affected the shape of river channels—some eroded soil was deposited on the bottom of the channel, reducing channel depth and increasing flood hazard. Increased fine sediment made the water muddy, and chemicals from street and yard runoff polluted the stream.[5,6] These changes affected fish and other life in the river, as well as terrestrial wildlife that depended on the river. The point here is that land-use conversion can set off a series of changes in the environment, and each change is likely to trigger additional changes.

3.6 Uniformitarianism

Uniformitarianism is the idea that geological and biological processes that occur today are the same kinds of processes that occurred in the past, and vice versa. Thus, the present is the key to the past, and the past the key to the future. For example, we use measurements of the current rate of erosion of soils and bedrock by rivers and streams to calculate the rate at which this happened in the past and to estimate how long it took for certain kinds of deposits to develop. If a deposit of gravel and sand found at the top of a mountain is similar to stream gravels found today in an adjacent valley, we may infer by uniformitarianism that a stream once flowed in a valley where the mountaintop is now. The concept of uniformitarianism helps explain the geologic and evolutionary history of Earth.

Uniformitarianism was first suggested in 1785 by the Scottish scientist James Hutton, known as the father of geology. Charles Darwin was impressed by the concept, and it pervades his ideas on biological evolution. Today, uniformitarianism is considered one of the fundamental principles of the biological and Earth sciences.

Uniformitarianism does not demand or even suggest that the magnitude and frequency of natural processes remain constant, only that the processes themselves continue. For the past several billion years, the continents, oceans, and atmosphere have been similar to those of today. We assume that the physical and biological processes that form and modify the Earth's surface have not changed significantly over this period. To be useful from an environmental standpoint, the principle of uniformitarianism has to be more than a key to the past; we must turn it around and say that a study of past and present processes is the key to the future. That is, we can assume that in the future the same physical and biological processes will operate, although the rates will vary as the environment is influenced by natural change and human activity. Geologically short-lived landforms, such as beaches (Figure 3.18) and lakes, will continue to appear and disappear in response to storms, fires, volcanic eruptions, and earthquakes. Extinctions of animals and plants will continue, in spite of, as well as because of, human activity.

Obviously, some processes do not extend back through all of geologic time. For example, the early Earth atmosphere did not contain free oxygen. Early photo-

FIGURE 3.18 This beach on the island of Bora Bora, French Polynesia, is an example of a geologically short-lived landform, vulnerable to rapid change from storms and other natural processes.

synthetic bacteria converted carbon dioxide in the atmosphere to hydrocarbons and released free oxygen; before life, this process did not occur. But the process began a long time ago—3.5 billion years ago—and as long as there are photosynthetic organisms, this process of carbon dioxide uptake and oxygen release will continue.

Knowledge of uniformitarianism is one way that we can decide what is "natural" and ascertain the characteristics of nature undisturbed by people. One of the environmental questions we ask repeatedly, in many contexts, is whether human actions are consistent with the processes of the past. If not, we are often concerned that these actions will be harmful. We want to improve our ability to predict what the future may bring, and uniformitarianism can assist in this task.

3.7 Earth as a System

The discussion in this chapter sets the stage for a relatively new way of looking at life and the environment—a global perspective, thinking about our entire planet's life-supporting and life-containing system. This is known as Earth systems science, and it has become especially important in recent years, with concerns about climate change (see Chapter 20).

Our discussion of Earth as a system—life in its environment, the biosphere, and ecosystems—leads us to the question of how much life on Earth has affected our planet. In recent years, the **Gaia hypothesis**—named for Gaia, the Greek goddess Mother Earth—has become a hotly debated subject.[7] The hypothesis states that life manipulates the environment for the maintenance of life. For example, some scientists believe that algae floating near the surface of the ocean influence rainfall at sea and the carbon dioxide content of the atmosphere, thereby significantly affecting the global climate. It follows, then, that the planet Earth is capable of physiological self-regulation.

The idea of a living Earth can be traced back at least to Roman times in the writing of Lucretius.[3] James Hutton, whose theory of uniformitarianism was discussed earlier, stated in 1785 that he believed Earth to be a superorganism, and he compared the cycling of nutrients from soils and rocks in streams and rivers to the circulation of blood in an animal.[7] In this metaphor, the rivers are the arteries and veins, the forests are the lungs, and the oceans are the heart of Earth.

The Gaia hypothesis is really a series of hypotheses. The first is that life, since its inception, has greatly affected the planetary environment. Few scientists would disagree. The second hypothesis asserts that life has altered Earth's environment in ways that have allowed life to persist. Certainly, there is some evidence that life has had such an effect on Earth's climate. A popularized extension of the Gaia hypothesis is that life *deliberately* (consciously) controls the global environment. Few scientists accept this idea.

The extended Gaia hypothesis may have merit in the future, however. We have become conscious of our effects on the planet, some of which influence future changes in the global environment. Thus, the concept that we can consciously make a difference in the future of our planet is not as extreme a view as many once thought. The future status of the human environment may depend in part on actions we take now and in coming years. This aspect of the Gaia hypothesis exemplifies the key theme of thinking globally, which was introduced in Chapter 1.

3.8 Types of Change

Change comes in several forms. Some changes brought on by human activities involve rather slow processes—at least from our point of view—with cumulative effects. For example, in the middle of the 19th century, people began to clear-cut patches of the Michigan forests. It was commonly believed that the forests were so large that it would be impossible to cut them all down before they grew back just as they were. But with many people logging in different, often isolated areas, it took less than 100 years for all but about 100 hectares to be clear-cut.

Another example: With the beginning of the Industrial Revolution, people in many regions began to burn fossil fuels, but only since the second half of the 20th century have the possible global effects become widely evident. Many fisheries appear capable of high harvests for many years. But then suddenly, at least from our perspective—sometimes within a year or a few years—an entire species of fish suffers a drastic decline. In such cases, long-term damage can be done. It has been difficult to recognize when harvesting fisheries is overharvesting and, once it has started, figuring out what can be done to enable a fishery to recover in time for fishermen to continue making a living. A famous example of this was the harvesting of anchovies off the coast of Peru. Once the largest fish catch in the world, within a few years the fish numbers declined so greatly that commercial harvest was threatened. The same thing has happened with the fisheries of Georges Banks and the Grand Banks in the Atlantic Ocean.

You can see from these few examples that environmental problems are often complex, involving a variety of linkages among the major components and within each component, as well as linear and exponential change, lag times, and the possibility of irreversible consequences.

As stated, one of our goals in understanding the role of human processes in environmental change is to help manage our global environment. To accomplish this goal, we need to be able to predict changes, but as the examples above demonstrate, prediction poses great challenges. Although some changes are anticipated, others come as a surprise. As we learn to apply the principles of environmental unity and uniformitarianism more skillfully, we will be better able to anticipate changes that would otherwise have been surprises.

CRITICAL THINKING ISSUE

Is the Gaia Hypothesis Science?

According to the Gaia hypothesis, Earth and all living things form a single system with interdependent parts, communication among these parts, and the ability to self-regulate. Are the Gaia hypothesis and its component hypotheses science, fringe science, or pseudoscience? Is the Gaia hypothesis anything more than an attractive metaphor? Does it have religious overtones? Answering these questions is more difficult than answering similar questions about, say, crop circles, described in Chapter 2. Analyzing the Gaia hypothesis forces us to deal with some of our most fundamental ideas about science and life.

Critical Thinking Questions

1. What are the main hypotheses included in the Gaia hypothesis?
2. What kind of evidence would support each hypothesis?
3. Which of the hypotheses can be tested?
4. Is each hypothesis science, fringe science, or pseudoscience?
5. Some scientists have criticized James E. Lovelock, who formulated the Gaia hypothesis, for using the term *Gaia*. Lovelock responds that it is better than referring to a "biological cybernetic system with homeostatic tendencies." What does this phrase mean?
6. What are the strengths and weaknesses of the Gaia hypothesis?

SUMMARY

- A system is a set of components or parts that function together as a whole. Environmental studies deal with complex systems, and solutions to environmental problems often involve understanding systems and their rates of change.
- Systems respond to inputs and have outputs. Feedback is a special kind of system response, where the output affects the input. Positive feedback, in which increases in output lead to increases in input, is destabilizing, whereas negative feedback, in which increases in output lead to decreases in input, tends to stabilize or encourage more constant conditions in a system.
- Relationships between the input (cause) and output (effect) of systems may be linear, exponential, or represented by a logistic curve or a saturation curve .
- The principle of environmental unity, simply stated, holds that everything affects everything else. It emphasizes linkages among parts of systems.
- The principle of uniformitarianism can help predict future environmental conditions on the basis of the past and the present.
- Although environmental and ecological systems are complex, much of what happens with them can be characterized by just a few response curves or equations: the straight line, the exponential, the logistic, and the saturation curves.
- Exponential growth, long lag times, and the possibility of irreversible change can combine to make solving environmental problems difficult.
- Change may be slow, fast, expected, unexpected, or chaotic. One of our goals is to learn to better recognize change and its consequences in order to better manage the environment.

REEXAMINING THEMES AND ISSUES

Human Population

Due partly to a variety of positive-feedback mechanisms, Earth's human population is increasing. Of particular concern are local or regional increases in population density (the number of people per unit area), which strain resources and lead to human suffering.

Sustainability

Negative feedback is stabilizing. If we are to have a sustainable human population and use our resources sustainably, then we need to put in place a series of negative feedbacks within our agricultural, urban, and industrial systems.

Global Perspective

This chapter introduced Earth as a system. One of the most fruitful areas for environmental research remains the investigation of relationships between physical and biological processes on a global scale. More of these relationships must be discovered if we are to solve environmental problems related to such issues as potential global warming, ozone depletion, and disposal of toxic waste.

Urban World

The concepts of environmental unity and uniformitarianism are particularly applicable to urban environments, where land-use changes result in a variety of changes that affect physical and biochemical processes.

People and Nature

People and nature are linked in complex ways in systems that are constantly changing. Some changes are not related to human activity, but many are—and human-caused changes from local to global in scale are accelerating.

Science and Values

Our discussion of the Gaia hypothesis reminds us that we still know very little about how our planet works and how physical, biological, and chemical systems are linked. What we do know is that we need more scientific understanding. This understanding will be driven, in part, by the value we place on our environment and on the well-being of other living things.

KEY TERMS

average residence time **46**
balance of nature **46**
biosphere **50**
classical stability **44**
closed system **44**
doubling time **52**
dynamic equilibrium **46**
dynamic system **44**
ecosystem **46**
environmental unity **54**
equilibrium **44**
exponential growth **52**
feedback **48**
flow **50**
flux **50**
Gaia hypothesis **55**
input **44**
lag time **50**
linear process **50**
materially closed system **44**
negative feedback **48**
nonlinear process **50**
open system **44**
output **44**
overshoot and collapse **53**
positive feedback **48**
static system **44**
steady-state system **45**
system **44**
uniformitarianism **54**

STUDY QUESTIONS

1. What is the difference between positive and negative feedback in systems? Provide an example of each.
2. What is the main point concerning exponential growth? Is exponential growth good or bad?
3. Why is the idea of equilibrium in systems somewhat misleading in regard to environmental questions? Is it ever possible to establish a balance of nature?
4. Why is the average residence time important in the study of the environment?
5. Is the Gaia hypothesis a true statement of how nature works, or is it simply a metaphor? Explain.
6. How might you use the principle of uniformitarianism to help evaluate environmental problems? Is it possible to use this principle to help evaluate the potential consequences of too many people on Earth?
7. Why does overshoot occur, and what could be done to anticipate and avoid it?

FURTHER READING

Botkin, D.B., M. Caswell, J.E. Estes, and A. Orio, eds., *Changing the Global Environment: Perspectives on Human Involvement* (NewYork: Academic Press, 1989). One of the first books to summarize the effects of people on nature; it includes global aspects and uses satellite remote sensing and advanced computer technologies.

Bunyard, P., ed., *Gaia in Action: Science of the Living Earth* (Edinburgh: Floris Books, 1996). This book presents investigations into implications of the Gaia hypothesis.

Lovelock, J., *The Ages of Gaia: A Biography of Our Living Earth* (New York: Norton, 1995). This small book explains the Gaia hypothesis, presenting the case that life very much affects our planet and in fact may regulate it for the benefit of life.

CHAPTER 4

The Human Population and the Environment

In 2009, people around the world wore masks to protect themselves against swine flu.

LEARNING OBJECTIVES

The human population has been growing rapidly for centuries. What is happening and, most important, what *will* happen to all of us and our planet if this continues? After reading this chapter, you should understand that . . .

- Ultimately, there can be no long-term solutions to environmental problems unless the human population stops increasing;
- Two major questions about the human population are (1) what controls its rate of growth and (2) how many people Earth can sustain;
- Modern medical practices and improvements in sanitation, control of disease-spreading organisms, and supplies of human necessities have lowered death rates and accelerated the net rate of human population growth;
- Although the death rate has declined, so more people live longer, the rapid increase in the human population has occurred with little or no change in the maximum lifetime of an individual, which is still less than 120 years;
- In general, countries with a high standard of living have moved more quickly to a lower birth rate than have countries with a low standard of living;
- Although we cannot predict with absolute certainty what the future human carrying capacity of Earth will be, an understanding of human population dynamics can help us make useful forecasts;
- The principles of population dynamics discussed in this chapter apply to populations of all species and will be useful throughout this book.

CASE STUDY

Pandemics and World Population Growth

On April 14, 2009, the Mexican government reported the first case of a new strain of flu. A genetic combination of flu found in pigs, birds, and people, it was immediately called "swine flu" but formally referred to as flu strain A (H1N1). Because this was a new strain, little natural resistance to it could be expected, and it thus might cause a worldwide disease outbreak—the kind known as a **pandemic**. Indeed, this flu traveled rapidly. By May 1, it had spread to 11 nations.[1]

Nations responded quickly. The government of Hong Kong quarantined a major hotel where one guest from Mexico was diagnosed with the flu. The Mexican government provided open access to information and declared a special "holiday" in Mexico City to prevent the spread of the disease there.

Even so, by mid-May 2009 the disease had spread to 33 nations, causing almost 6,500 cases but few deaths (Figure 4.1). Although it had become widespread rapidly, concerns about swine flu had greatly diminished because it appeared to be a rather mild form of the disease and quick responses seemed to have mostly contained it. Concerns remained, however, that it might spread to the Southern Hemisphere and, during its winter, mutate to a more virulent form, then return to the Northern Hemisphere in the winter of 2009 as a greater threat.

Because this strain of flu did not become a full-blown pandemic and seemed relatively mild, it is easy to believe that nations overreacted. But the failure of this flu to spread more widely appears due in large part to the rapid and widespread response. And the history of recent new diseases—particularly West Nile virus and SARS—supported such a response.

Before 1999, West Nile virus occurred in Africa, West Asia, and the Middle East, but not in the New World. Related to encephalitis, West Nile virus is spread by mosquitoes, which bite infected birds, ingest the virus, and then bite people. It reached the Western Hemisphere through infected birds and has now been found in more than 25 species of birds native to the United States, including crows, the bald eagle, and the black-capped chickadee—a common visitor to bird feeders in the U.S. Northeast. Fortunately, in human beings this disease has lasted only a few days and has rarely caused severe symptoms.[2] By 2007, more than 3,600 people in the United States had contracted this disease, most in California and Colorado, with 124 fatalities.[3] But the speed with which it spread led to concerns about other possible new pandemics.

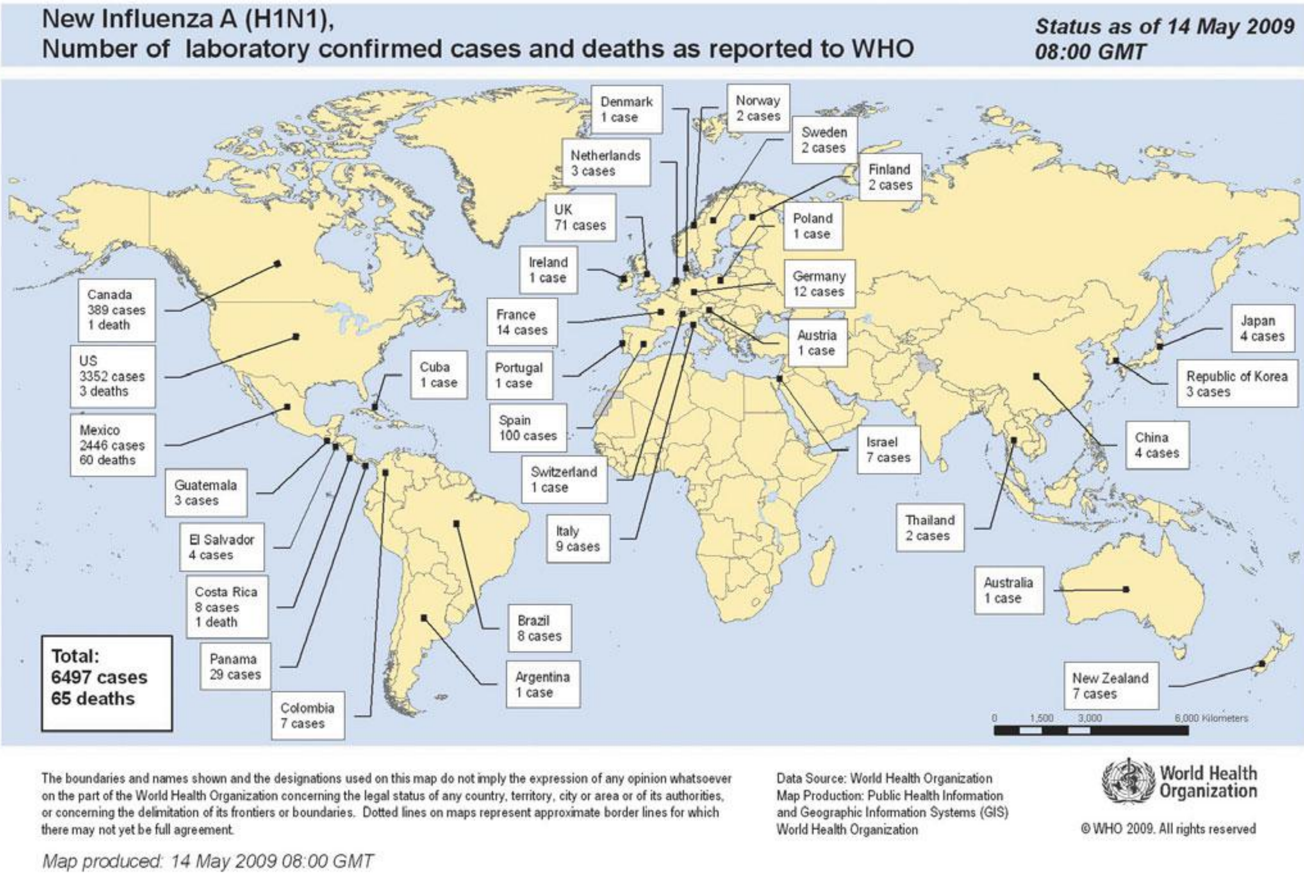
Four years earlier, in February 2003, the sudden occurrence of a new disease, severe acute respiratory syndrome (SARS), had demonstrated that modern transportation and the world's huge human population could lead to the rapid spread of epidemic diseases. Jet airliners daily carry vast numbers of people and goods around the world. The disease began in China, perhaps spread from some wild animal to human beings. China had become much more open to foreign travelers, with more than 90 million visitors in a recent year.[4] By late spring 2003, SARS had spread to two dozen countries; more than 8,000 people were affected and 774 died. Quick action, led by the World Health Organization (WHO), contained the disease.[5]

And behind all of this is the knowledge of the 1918 world flu virus, which is estimated to have killed as many as 50 million people in one year, probably more than any other single epidemic in human history. It spread around the world in the autumn, striking otherwise healthy young adults in particular. Many died within hours! By the spring of 1919, the virus had virtually disappeared.[6]

Although outbreaks of the well-known traditional epidemic diseases have declined greatly during the past century in industrialized nations, there is now concern that the incidence of pandemics may increase due to several factors. One is that as the human population grows, people live in new habitats, where previously unknown diseases occur. Another is that strains of disease organisms have developed resistance to antibiotics and other modern methods of control.

A broader view of why diseases are likely to increase comes from an ecological and evolutionary perspective (which will be explained in later chapters). Stated simply, the more than 6.6 billion people on Earth constitute a great resource and opportunity for other species; it is naive to think that other species will not take advantage of this huge and easily accessible host. From this perspective, the future promises more diseases rather than fewer. This is a new perspective. In the mid-20th century it was easy to believe that modern medicine would eventually cure all diseases and that most people would live the maximum human life span. It is generally believed, and often forecast, that the human population will simply continue increasing, without any decline. But with increased crowding and its many effects on the environment, there is also concern that the opposite might happen, that our species might suffer a large, if temporary, dieback. This leads us to consider how populations change over time and space, especially our own populations, and this is the subject of the present chapter.

FIGURE 4.1 **(a)** A couple try to take appropriate measures to protect against swine flu. **(b)** Map of the flu's distribution by mid-May 2009.
(*Source*: **(b)** World Health Organization).



4.1 Basic Concepts of Population Dynamics

One of the most important properties of living things is that their abundances change over time and space. This is as true for our own species as it is for all others, including those that directly or indirectly affect our lives—for example, by providing our food, or materials for our shelter, or causing diseases and other problems—and those that we just like having around us or knowing that they exist.

In this chapter we focus on the human population because it is so important to all environmental problems, but the concepts we discuss here are useful for the populations of all species, and we will use these concepts throughout this book. You should also familiarize yourself with the following definitions and ideas:

- **Population dynamics** is the general study of population changes.
- A **population** is a group of individuals of the same species living in the same area or interbreeding and sharing genetic information.

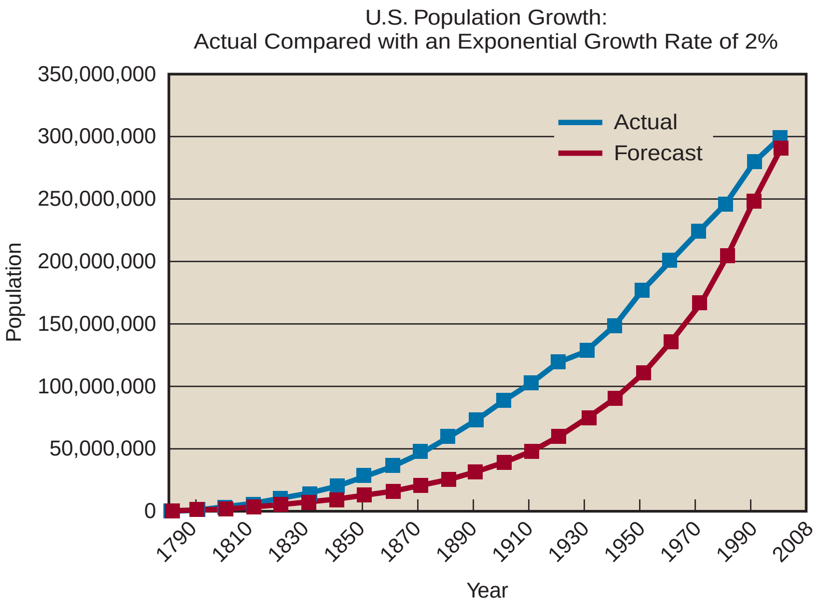


FIGURE 4.2 U.S. population, 1790 to 2008. The actual population growth is shown compared to an exponential curve with an annual growth rate of 2%. (*Source*: Data from U.S. Census Bureau, *US Historical Population Information*.)

- A **species** is all individuals that are capable of interbreeding, and so a species is composed of one or more populations.
- **Demography** is the statistical study of human populations, and people who study the human population include demographers.
- Five key properties of any population are **abundance**, which is the size of a population; **birth rates**; **death rates**; **growth rates**; and **age structure.** How rapidly a population's abundance changes over time depends on its growth rate, which is the difference between the birth rate and the death rate.
- The three rates—birth, death, and growth—are usually expressed as a percentage of a population per unit of time. For people, the unit of time is typically a year or greater. Sometimes these rates are expressed as actual numbers within a population during a specified time. (See Useful Human-Population Terms in Section 4.1.)

Let us begin with the population of the United States, which has grown rapidly since European settlement (Figure 4.2).

The Human Population as an Exponential Growth Curve

It is common to say that human populations, like that of the United States, grow at an **exponential rate**, which means that the annual growth rate is a constant percentage of the population (see Chapter 3). But Figure 4.2 shows that for much of the nation's history the population has grown at a rate that exceeds an exponential. The annual growth rate has changed over time, increasing in the early years, in part because of large immigrations to North America, and decreasing later. An exponential curve growing at 2% per year lags the actual increase in the U.S. population for most of the nation's history but catches up with it today. That is because the growth rate has slowed considerably. It is now 0.6%; in contrast, between 1790 and 1860, the year the Civil War began, the population increased more than 30% per year! (This is a rate that for a human population can be sustained only by immigration.)

Like that of the U.S. population, the world's human population growth is typically also shown as an exponential (Figure 4.3), although we know very little about the variation in the number of people during the early history of our species.

We can divide the history of our species' population into four phases (see A Closer Look 4.1 for more about this history). In Stage 1, the early period of hunters and gatherers, the world's total human population was probably less than a few million. Stage 2 began with the rise of agriculture, which allowed a much greater density of people and the first major increase in the human population. Stage 3, the Industrial Revolution in the late 18th and early 19th centuries, saw improvements in health care and the food supply, which led to a rapid increase in the human population. The growth rate of the world's human population, like that of the early population of the United States, increased but varied during the first part of the 20th century, peaking in 1965–1970 at 2.1% because of improved health care and food production. Stage 4 began around the late 20th century. In this stage, population growth slowed in wealthy, industrialized nations, and although it has continued to increase rapidly in many poorer, less developed nations, globally the growth rate is declining and is now approximately 1.2%.[8]

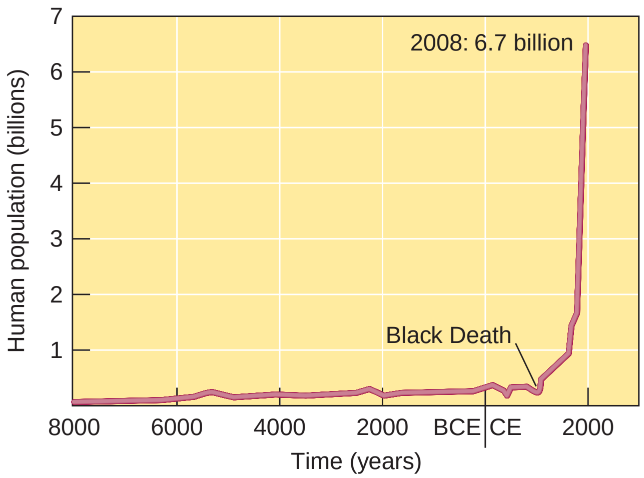


FIGURE 4.3 Human Population Growth. It took thousands of years for the human population to reach 1 billion (in 1800) but only 130 years to reach 2 billion (1930). It only took 130 years to reach 3 billion (1960), 15 years to reach 4 billion (1975), 12 years to reach 5 billion (1987), and 12 years to year 6 billion (1999). (*Source*: Reprinted with permission of John Wiley & Sons, Inc.)

Usually in discussions of population dynamics, birth, death, and growth rates are expressed as percentages (the number per 100 individuals). But because the human population is so huge, percentages are too crude a measure, so it is common to state these rates in terms of the number per 1,000, which is referred to as the crude rate. Thus we have the *crude birth rate*, *crude death rate*, and *crude growth rate*. More specifically, here is a list of terms that are used frequently in discussions of human population change and will be useful to us in this book from time to time.

Table 4.1 USEFUL HUMAN-POPULATION TERMS

Crude birth rate: number of births per 1,000 individuals per year; called "crude" because population age structure is not taken into account.

Crude death rate: number of deaths per 1,000 individuals per year.

Crude growth rate: net number added per 1,000 individuals per year; also equal to the crude birth rate minus crude death rate.

Fertility: pregnancy or the capacity to become pregnant or to have children.

General fertility rate: number of live births expected in a year per 1,000 women aged 15–49, considered the childbearing years.

Total fertility rate (TFR): the average number of children expected to be born to a woman throughout her childbearing years.

Age-specific birth rate: number of births expected per year among a fertility-specific age group of women in a population.The fertility-specific age group is, in theory, all ages of women that could have children. In practice, it is typically assumed to be all women between 15 and 49 years old.

Cause-specific death rate: the number of deaths from one cause per 100,000 total deaths.

Morbidity: a general term meaning the occurrence of disease and illness in a population.

Incidence: with respect to disease, the number of people contracting a disease during a specific time period, usually measured per 100 people.

Prevalence: with respect to a disease, the number of people afflicted at a particular time.

Case fatality rate: the percentage of people who die once they contract a disease.

Rate of natural increase (RNI): the birth rate minus the death rate, implying an annual rate of population growth not including migration.

Doubling time: the number of years it takes for a population to double, assuming a constant rate of natural increase.

Infant mortality rate: the annual number of deaths of infants under age 1 per 1,000 live births.

Life expectancy at birth: the average number of years a newborn infant can expect to live given current mortality rates.

GNP per capita: gross national product (GNP), which includes the value of all domestic and foreign output.

(Source: C. Haub and D. Cornelius, *World Population Data Sheet* [Washington, DC: Population Reference Bureau, 1998].)

A CLOSER LOOK 4.1

A Brief History of Human Population Growth

STAGE 1. Hunters and Gatherers: From the first evolution of humans to the beginning of agriculture.[7]

Population density: About 1 person per 130–260 km^2 in the most habitable areas.

Total human population: As low as one-quarter million, less than the population of modern small cities like Hartford, Connecticut, and certainly fewer than the number of people—commonly a few million—who now live in many of our largest cities.

Average rate of growth: The average annual rate of increase over the entire history of human population is less than 0.00011% per year.

STAGE 2. Early, Preindustrial Agriculture: Beginning sometime between 9000 B.C. and 6000 B.C. and lasting until approximately the 16th century.

Population density: With the domestication of plants and animals and the rise of settled villages, human population density increased greatly, to about 1 or 2 people/km^2 or more, beginning a second period in human population history.

Total human population: About 100 million by A.D. 1 and 500 million by A.D. 1600.

Average rate of growth: Perhaps about 0.03%, which was high enough to increase the human population from 5 million in 10,000 B.C. to about 100 million in A.D. 1. The Roman Empire accounted for about 54 million. From A.D. 1 to A.D. 1000, the population increased to 200–300 million.

STAGE 3. The Machine Age: Beginning in the 16th century.

Some experts say that this period marked the transition from agricultural to literate societies, when better medical care and sanitation were factors in lowering the death rate.

Total human population: About 900 million in 1800, almost doubling in the next century and doubling again (to 3 billion) by 1960.

Average rate of growth: By 1600, about 0.1% per year, with rate increases of about 0.1% every 50 years until 1950. This rapid increase occurred because of the discovery of causes of diseases, invention of vaccines, improvements in sanitation, other advances in medicine and health, and advances in agriculture that led to a great increase in the production of food, shelter, and clothing.

STAGE 4. The Modern Era: Beginning in the mid-20th century.

Total human population: Reaching and exceeding 6.6 billion.

Average rate of growth: The growth rate of the human population reached 2% in the middle of the 20th century and has declined to 1.2%.[8]

How Many People Have Lived on Earth?

Before written history, there were no censuses. The first estimates of population in Western civilization were attempted in the Roman era. During the Middle Ages and the Renaissance, scholars occasionally estimated the number of people. The first modern census was taken in 1655 in the Canadian colonies by the French and the British.[9] The first series of regular censuses by a country began in Sweden in 1750, and the United States has taken a census every decade since 1790. Most countries began counting their populations much later. The first Russian census, for example, was taken in 1870. Even today, many countries do not take censuses or do not do so regularly. The population of China has only recently begun to be known with any accuracy. However, studying modern primitive peoples and applying principles of ecology can give us a rough idea of the total number of people who may have lived on Earth.

Summing all the values, including those since the beginning of written history, about 50 billion people are estimated to have lived on Earth.[10] If so, then, surprisingly, the more than 6.6 billion people alive today represent more than 10% of all of the people who have ever lived.

4.2 Projecting Future Population Growth

With human population growth a central issue, it is important that we develop ways to forecast what will happen to our population in the future. One of the simplest approaches is to calculate the doubling time.

Exponential Growth and Doubling Time

Recall from Chapter 3 and from the preceding list of Useful Human Population Terms that **doubling time**, a concept used frequently in discussing human population growth, is the time required for a population to double in size (see Working It Out 4.1). The standard way to estimate doubling time is to assume that the population is growing exponentially and then divide 70 by the annual growth rate stated as a percentage. (Dividing into 70 is a consequence of the mathematics of exponential growth.)

The doubling time based on exponential growth is very sensitive to the growth rate—it changes quickly as the growth rate changes (Figure 4.4). A few examples demonstrate this sensitivity. With a current population growth of 1.0%, the United States has a doubling time of 70 years. In contrast, the current growth rate of Nicaragua is 2.0%, giving that nation a doubling time of 35 years. Sweden, with an annual rate of about 0.2%, has a doubling time of 350 years. The world's most populous country, China, has a growth rate of 0.6% and a 117-year doubling time.[11]

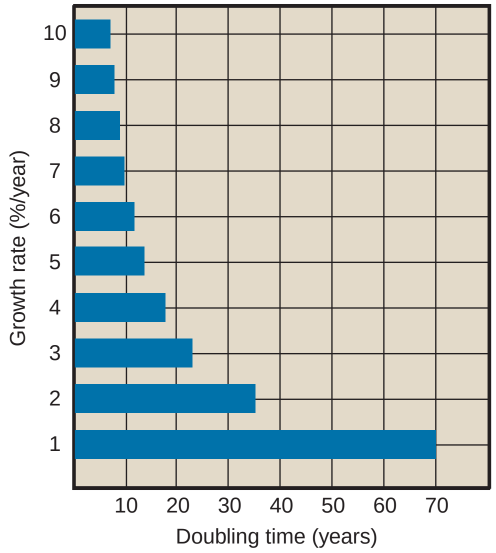


FIGURE 4.4 Doubling time changes rapidly with the population growth rate. Because the world's population is increasing at a rate between 1 and 2%, we expect it to double within the next 35 to 70 years.

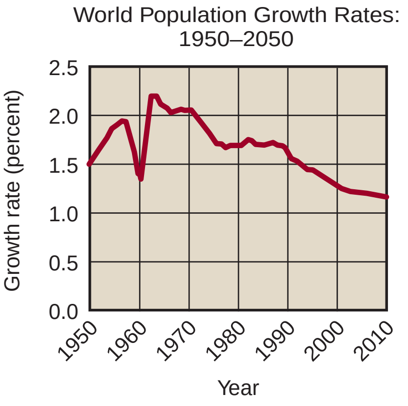


FIGURE 4.5 The annual growth rate of the world's population has been declining since the 1960s.

The world's population growth rate peaked in the 1960s at about 2.2% and is now about 1.1% (Figure 4.5). If the growth rate had continued indefinitely at the 1960s peak, the world population would have doubled in 32 years. At today's rate, it would double in 64 years.

Human Population as a Logistic Growth Curve

An exponentially growing population theoretically increases forever. However, on Earth, which is limited in size, this is not possible, as Thomas Henry Malthus pointed out in the 18th century (see A Closer Look 4.2). Eventually the population would run out of food and space and become increasingly vulnerable to catastrophes, as we are already beginning to observe. Consider, a population of 100 increasing at 5% per year would grow to 1 billion in less than 325 years. If the human population had increased at this rate since the beginning of recorded history, it would now exceed all the known matter in the universe.

If a population cannot increase forever, what changes in the population can we expect over time? One of the first suggestions made about population growth is that it would follow a smooth S-shaped curve known as the **logistic growth curve** (see Chapter 3). This was first suggested in 1838 by a European scientist, P. F. Verhulst, as a theory for the growth of animal populations. It has been applied widely to the growth of many animal populations, including those important in wildlife management, endangered species and those in fisheries (see Chapter 13), as well as the human population.

WORKING IT OUT 4.1 Forecasting Population Change

Populations change in size through births, deaths, immigration (arrivals), and emigration (departures). We can write a formula to represent population change in *terms of actual numbers in a population*:

$$P_2 = P_1 + (B - D) + (I - E)$$

where P_1 is the number of individuals in a population at time 1, P_2 is the number of individuals in that population at some later time 2, B is the number of births in the period from time 1 to time 2, D is the number of deaths from time 1 to time 2, I is the number entering as immigrants, and E is the number leaving as emigrants.

So far we have expressed population change in terms of total numbers in the population. We can also express these as rates, including the birth rate (number born divided by the total number in the population), death rate (number dying divided by the total number in the population), and growth rate (change in the population divided by the total number in the population). (In this section, we will use lowercase letters to represent a rate, uppercase letters to represent total amounts.)

Ignoring for the moment immigration and emigration, how rapidly a population changes depends on the growth rate, g, which is the difference between the birth rate and the death rate (see earlier list of useful terms). For example, in 1999 the crude death rate, d, in the United States was 9, meaning that 9 of every 1,000 people died each year. (The same information expressed as a percentage is a rate of 0.9%.) In 1999 the crude birth rate, b, in the United States was 15.[12] The crude growth rate is the net change—the birth rate minus the death rate. Thus the crude growth rate, g, in the United States in 1999 was 6. For every 1,000 people at the beginning of 1999, there were 1,006 at the end of the year.

Continuing for the moment to ignore immigration and emigration, we can state that how rapidly a population grows depends on the difference between the birth rate and the death rate. The growth rate of a population is then

$$g = (B - D)/N \text{ or } g = G/N$$

Note that in all these cases, the units are numbers per unit of time.

It is important to be consistent in using the population at the beginning, middle, or end of the period. Usually, the number at the beginning or the middle is used. Consider an example: There were 19,700,000 people in Australia in mid-2002, and 394,000 births from 2002 to 2003. The birth rate, b, calculated against the mid-2002 population was 394,000/19,700,000, or 2%. During the same period, there were 137,900 deaths; the death rate, d, was 137,900/19,700,000, or 0.7%. The growth rate, g, was (394,000 – 137,900)/19,700,000, or 1.3%.[13]

Recall from Chapter 3 that doubling time—the time it takes a population to reach twice its present size—can be estimated by the formula

$$T = 70/\text{annual growth rate}$$

where T is the doubling time and the annual growth rate is expressed as a percentage. For example, a population growing 2% per year would double in approximately 35 years.

A logistic population would increase exponentially only temporarily. After that, the rate of growth would gradually decline (i.e., the population would increase more slowly) until an upper population limit, called the **logistic carrying capacity**, was reached. Once that had been reached, the population would remain at that number.

Although the logistic growth curve is an improvement over the exponential, it too involves assumptions that are unrealistic for humans and other mammals. Both the exponential and logistic assume a constant environment and a homogeneous population—one in which all individuals are identical in their effects on each other. In addition to these two assumptions, the logistic assumes a constant carrying capacity, which is also unrealistic in most cases, as we will discuss later. There is, in short, little evidence that human populations—or any animal populations, for that matter—actually follow this growth curve, for reasons that are pretty obvious if you think about all the things that can affect a population.[14]

Nevertheless, the logistic curve has been used for most long-term forecasts of the size of human populations in specific nations. As we said, this S-shaped curve first rises steeply upward and then changes slope, curving toward the horizontal carrying capacity. The point at which the curve changes is the **inflection point**, and until a population has reached this point, we cannot project its final logistic size. The human population had not yet made the bend around the inflection point, but forecasters typically dealt with this problem by assuming that the population was just reaching the inflection point at the time the forecast was made. This standard practice inevitably led to a great underestimate of the maximum population. For example, one of the first projections of the upper limit of the U.S. population, made in the 1930s, assumed that the inflection point had been reached then. That assumption resulted in an estimate that the final population of the United States would be approximately 200 million.[15]

Fortunately for us, Figure 4.5 suggests that our species' growth rate has declined consistently since the 1960s, as we noted before, and therefore we can make projections using the logistic, assuming that we have passed the inflection point. The United Nations has made a series of projections based on current birth rates and death rates and assumptions about how these rates will change. These projections form the basis for the curves presented in Figure 4.6. The logistic projections assume that (1) mortality will fall everywhere and level off when female life expectancy reaches 82 years; (2) fertility will reach replacement levels everywhere between 2005 and 2060; and (3) there will be no worldwide catastrophe. This approach projects an equilibrium world population of 10.1–12.5 billion.[16] Developed nations would experience population growth from 1.2 billion today to 1.9 billion, but populations in developing nations would increase from 4.5 billion to 9.6 billion. Bangladesh (an area the size of Wisconsin) would reach 257 million; Nigeria, 453 million; and India, 1.86 billion. In these projections, the developing countries contribute 95% of the increase.[14]

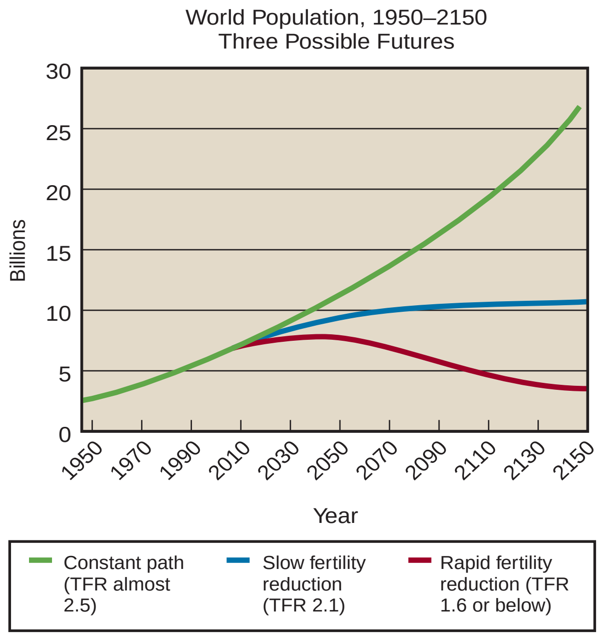


FIGURE 4.6 **U.N. projections of world population growth based on the logistic curve and using different total fertility rates (the expected number of children a woman will have during her life—see Chapter 3.** The constant path assumes the 1998 growth rate will continue unchanged, resulting in an exponential increase. The slow-fertility-reduction path assumes the world's fertility will decline, reaching replacement level by 2050, so the world's population will stabilize at about 11 billion by the 22nd century. The rapid-fertility-reduction path assumes the total fertility rate will go into decline in the 21st century, with the population peaking at 7.7 billion in 2050 and dropping to 3.6 billion by 2150. These are theoretical curves. The total fertility rate has remained high and is now 2.7. (*Source:* U.S. Census Bureau, *Global Population Profile: 2002*, Table A-10,. p.1. http://www.census.gov/ipc/prod/wp02/tabA-10.pdf).

4.3 Age Structure

As we noted earlier, the two standard methods for forecasting human population growth—the exponential and the logistic—ignore all characteristics of the environment and in that way are seriously incomplete. A more comprehensive approach would take into account the effects of the supply of food, water, and shelter; the prevalence of diseases; and other factors that can affect birth and death rates. But with long-lived organisms like ourselves, these environmental factors have different effects on different age groups, and so the next step is to find a way to express how a population is divided among ages. This is known as the population age structure, which is the proportion of the population of each age group. The age structure of a population affects current and future birth rates, death rates, and growth rates; has an impact on the environment; and has implications for current and future social and economic conditions.

We can picture a population's age structure as a pile of blocks, one for each age group, with the size of each block representing the number of people in that group (Figure 4.7). Although age structures can take many shapes, four general types are most important to our discussion: a pyramid, a column, an inverted pyramid (top-heavy), and a column with a bulge. The pyramid age structure occurs in a population that has many young people and a high death rate at each age—and therefore a high birth rate, characteristic of a rapidly growing population and also of a population with a relatively short average lifetime. A column shape occurs where the birth rate and death rate are low and a high percentage of the population is elderly. A bulge occurs if some event in the past caused a high birth rate or death rate for some age group but not others. An inverted pyramid occurs when a population has more older than younger people.

Age structure varies considerably by nation (Figure 4.7) and provides insight into a population's history, its current status, and its likely future. Kenya's pyramid-shaped age structure reveals a rapidly growing population heavily weighted toward youth. In developing

A CLOSER LOOK 4.2

The Prophecy of Malthus

Almost 200 years ago, the English economist Thomas Malthus eloquently stated the human population problem. His writings have gone in and out of fashion, and some people think his views may be out-of-date, but in 2008 Malthus was suddenly back on the front page, the focus of major articles in the *New York Times*[17] and the *Wall Street Journal*, among other places. Perhaps this is because recent events—from natural catastrophes in Asia to rising prices for oil, food, and goods in general—suggest that the human population problem really is a problem.

Malthus based his argument on three simple premises: [18]

- **Food is necessary for people to survive.**
- **"Passion between the sexes is necessary and will remain nearly in its present state"—so children will continue to be born.**
- **The power of population growth is infinitely greater than the power of Earth to produce subsistence.**

Malthus reasoned that it would be impossible to maintain a rapidly multiplying human population on a finite resource base. His projections of the ultimate fate of humankind were dire, as dismal a picture as that painted by today's most extreme pessimists. The power of population growth is so great, he wrote, that "premature death must in some shape or other visit the human race. The vices of mankind are active and able ministers of depopulation, but should they fail, sickly seasons, epidemics, pestilence and plague, advance in terrific array, and sweep off their thousands and ten thousands." Should even these fail, he said, "gigantic famine stalks in the rear, and with one mighty blow, levels the population with the food of the world."

Malthus's statements are quite straightforward. From the perspective of modern science, they simply point out that in a finite world nothing can grow or expand forever, not even the population of the smartest species ever to live on Earth. Critics of Malthus continue to point out that his predictions have yet to come true, that whenever things have looked bleak, technology has provided a way out, allowing us to live at greater densities. Our technologies, they insist, will continue to save us from a Malthusian fate, so we needn't worry about human population growth. Supporters of Malthus respond by reminding them of the limits of a finite world.

Who is correct? Ultimately, in a finite world, Malthus must be correct about the final outcome of unchecked growth. He may have been wrong about the timing; he did not anticipate the capability of technological changes to delay the inevitable. But although some people believe that Earth can support many more people than it does now, in the long run there must be an upper limit. The basic issue that confronts us is this: How can we achieve a constant world population, or at least halt the increase in population, in a way most beneficial to most people? This is undoubtedly one of the most important questions that has ever faced humanity, and it is coming home to roost now.

Recent medical advances in our understanding of aging, along with the potential of new biotechnology to increase both the average longevity and maximum lifetime of human beings, have major implications for the growth of the human population. As medical advances continue to take place, the death rate will drop and the growth rate will rise even more. Thus, a prospect that is positive from the individual's point of view—a longer, healthier, and more active life—could have negative effects on the environment. We will therefore ultimately face the following choices: Stop medical research into chronic diseases of old age and other attempts to increase people's maximum lifetime; reduce the birth rate; or do neither and wait for Malthus's projections to come true—for famine, environmental catastrophes, and epidemic diseases to cause large and sporadic episodes of human death. The first choice seems inhumane, but the second is highly controversial, so doing nothing and waiting for Malthus's projections may be what actually happens, a future that nobody wants. For the people of the world, this is one of the most important issues concerning science and values and people and nature.

countries today, about 34% of the populations are under 15 years of age. Such an age structure indicates that the population will grow very rapidly in the future, when the young reach marriage and reproductive ages, and it suggests that the future for such a nation requires more jobs for the young. This type of age structure has many other social implications that go beyond the scope of this book.

In contrast, the age structure of the United States is more like a column, showing a population with slow growth, while Japan's top-heavy pyramid shows a nation with declining growth.[8] The U.S. age struc-

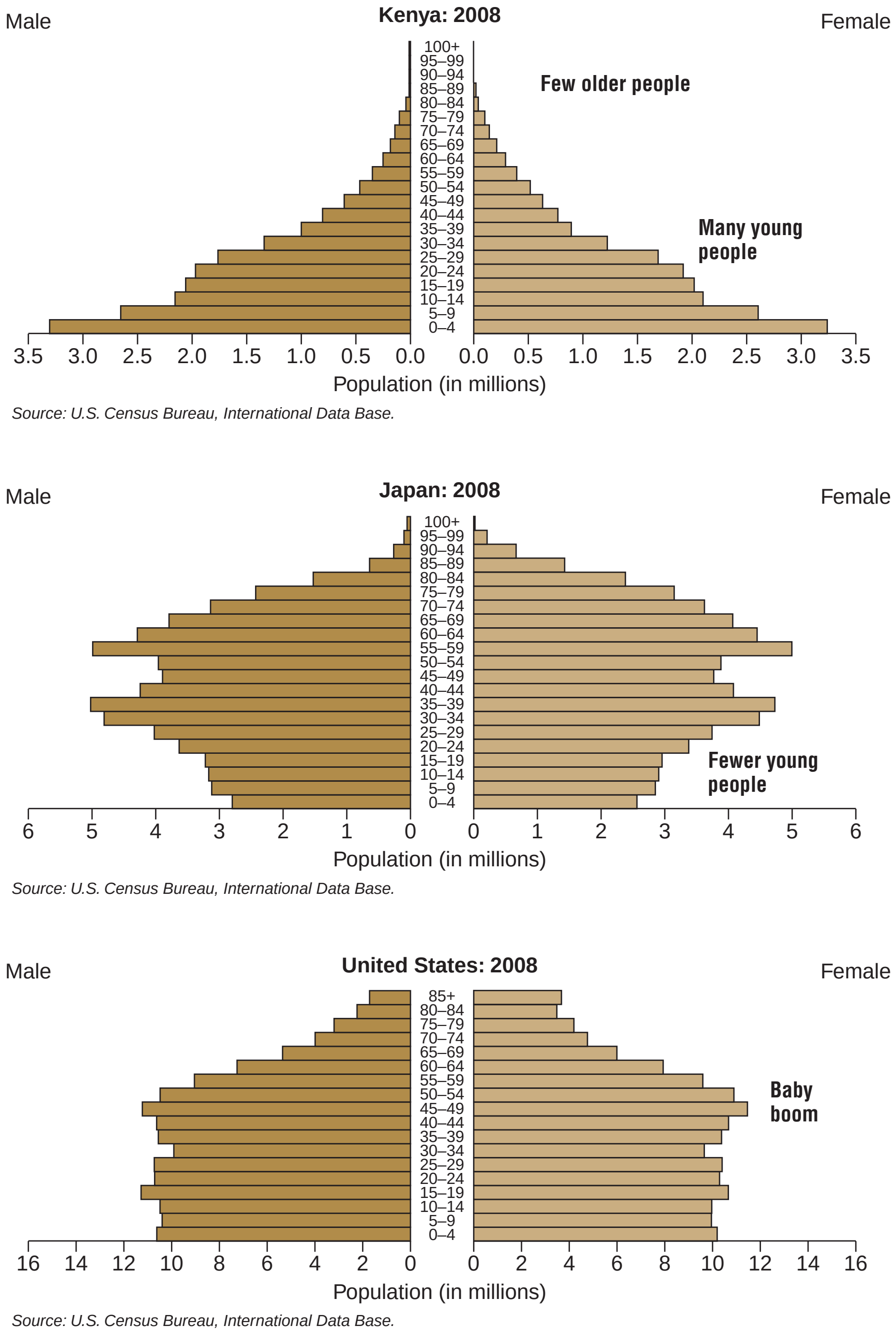


FIGURE 4.7 Age structure of Kenya, the United States, and Japan, 2008. The bars to the left are males; those to the right are females. (*Source*: U.S. Bureau of the Census.)

ture also shows the baby boom that occurred in the United States after World War II; a great increase in births from 1946 through 1964 forms a pulse in the population that can be seen as a bulge in the age structure, especially of those aged 45–55 in 2008. At each age, the baby boomers increased demand for social and economic resources; for example, schools were crowded when the baby boomers were of primary- and secondary-school age.

4.4 The Demographic Transition

The **demographic transition** is a three-stage pattern of change in birth rates and death rates that has occurred during the process of industrial and economic development of Western nations. It leads to a decline in population growth.

A decline in the death rate is the first stage of the demographic transition (Figure 4.8).[7] In a nonindustrial country, birth rates and death rates are high, and the growth rate is low. With industrialization, health and sanitation improve and the death rate drops rapidly. The birth rate remains high, however, and the population enters Stage II, a period with a high growth rate. Most European nations passed through this period in the 18th and 19th centuries. As education and the standard of living increase and as family-planning methods become more widely used, the population reaches Stage III. The birth rate drops toward the death rate, and the growth rate therefore declines, eventually to a low or zero growth rate. However, the birth rate declines only if families believe there is a direct connection between future economic well-being and funds spent on the education and care of their young. Such families have few children and put all their resources toward the education and well-being of those few.

Historically, parents have preferred to have large families. Without other means of support, aging parents can depend on grown children for a kind of "social security," and even young children help with many kinds of hunting, gathering, and low-technology farming. Unless there is a change in attitude among parents—unless they see more benefits from a few well-educated children than from many poorer children—nations face a problem in making the transition from Stage II to Stage III (see Figure 4.8c).

Some developed countries are approaching Stage III, but it is an open question whether developing nations will make the transition before a serious population crash occurs. *The key point here is that the demographic transition will take place only if parents come to believe that having a small family is to their*

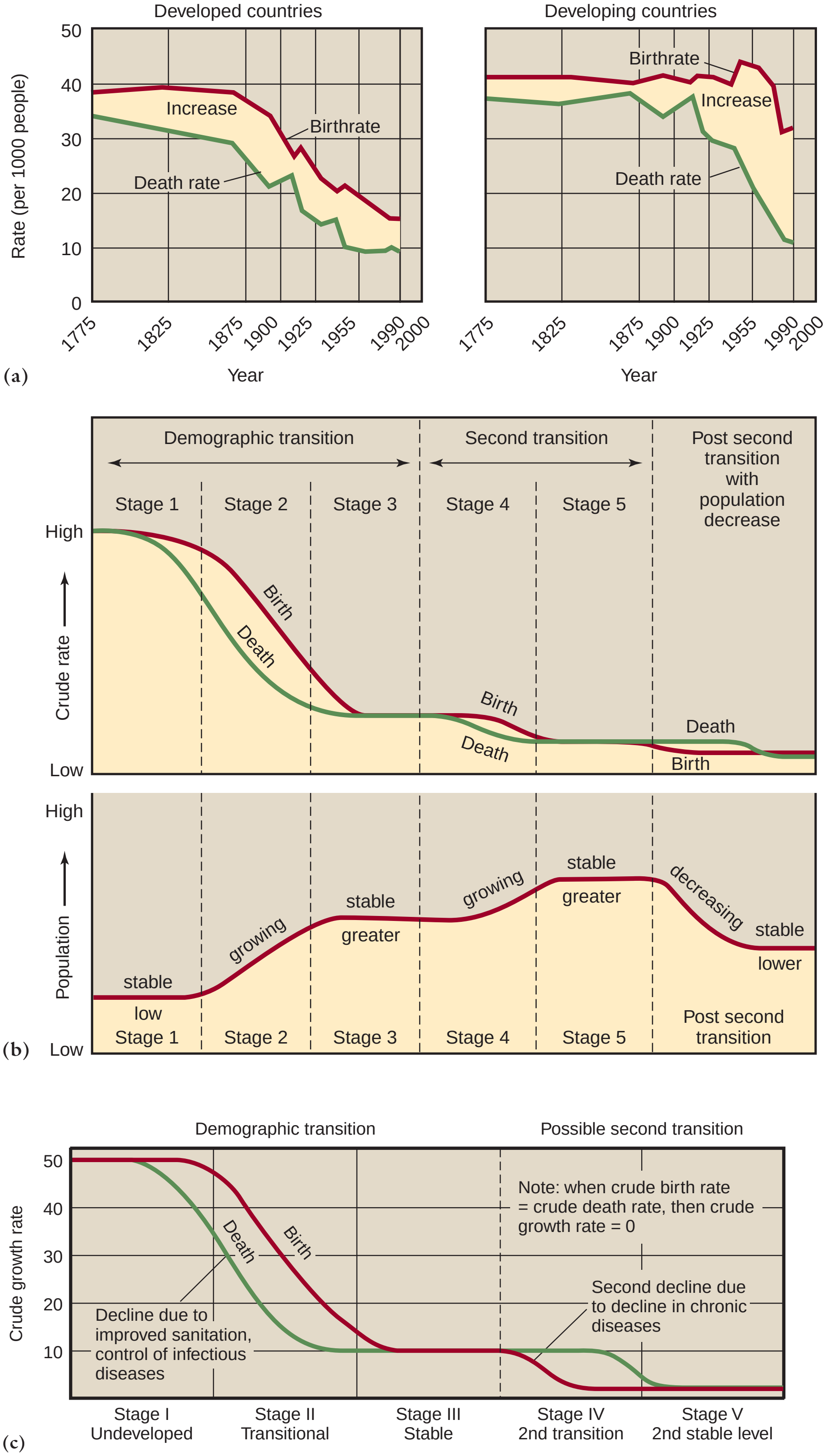


FIGURE 4.8 The demographic transition: (a) Theoretical, including possible fourth and fifth stages that might take place in the future; **(b)** the resulting relative change in population; **(c)** the change in birth rates and death rates from 1775 to 2000 in developed and developing countries. (*Source:* M.M. Kent and K.A. Crews, *World Population: Fundamentals of Growth* [Washington, DC: Population Reference Bureau, 1990]. Copyright 1990 by the Population Reference Bureau, Inc. Reprinted by permission.)

benefit. Here we again see the connection between science and values. Scientific analysis can show the value of small families, but this knowledge must become part of cultural values to have an effect.

Potential Effects of Medical Advances on the Demographic Transition

Although the demographic transition is traditionally defined as consisting of three stages, advances in treating chronic health problems such as heart disease can lead a Stage III country to a second decline in the death rate. This could bring about a second transitional phase of population growth (Stage IV), in which the birth rate would remain the same while the death rate fell. A second stable phase of low or zero growth (Stage V) would be achieved only when the birth rate declined even further to match the decline in the death rate. Thus, there is danger of a new spurt of growth even in industrialized nations that have passed through the standard demographic transition.

4.5 Longevity and Its Effect on Population Growth

The **maximum lifetime** is the genetically determined maximum possible age to which an individual of a species *can* live. **Life expectancy** is the average number of years an individual *can expect* to live given the individual's present age. Technically, life expectancy is an age-specific number: Each age class within a population has its own life expectancy. For general comparison, however, we use the life expectancy at birth.

Life expectancy is much higher in developed, more prosperous nations. Nationally, the highest life expectancy is 84 years, in the tiny nation of Macau. Of the major nations, Japan has the highest life expectancy, 82.1 years. Sixteen other nations have a life expectancy of 80 years or more: Singapore, Hong Kong, Australia, Canada, France, Guernsey, Sweden, Switzerland, Israel, Anguilla, Iceland, Bermuda, Cayman Islands, New Zealand, Gibraltar, and Italy. The United States, one of the richest countries in the world, ranks 50th among nations in life expectancy, at 78 years. China has a life expectancy of just over 73 years; India just over 69 years. Swaziland has the lowest of all nations at 32 years. The ten nations with the shortest life expectancies are all in Africa.[19] Not surprisingly, there is a relationship between per capita income and life expectancy.

A surprising aspect of the second and third periods in the history of human population is that population growth occurred with little or no change in the maximum lifetime. What changed were birth rates, death rates, population growth rates, age structure, and average life expectancy.

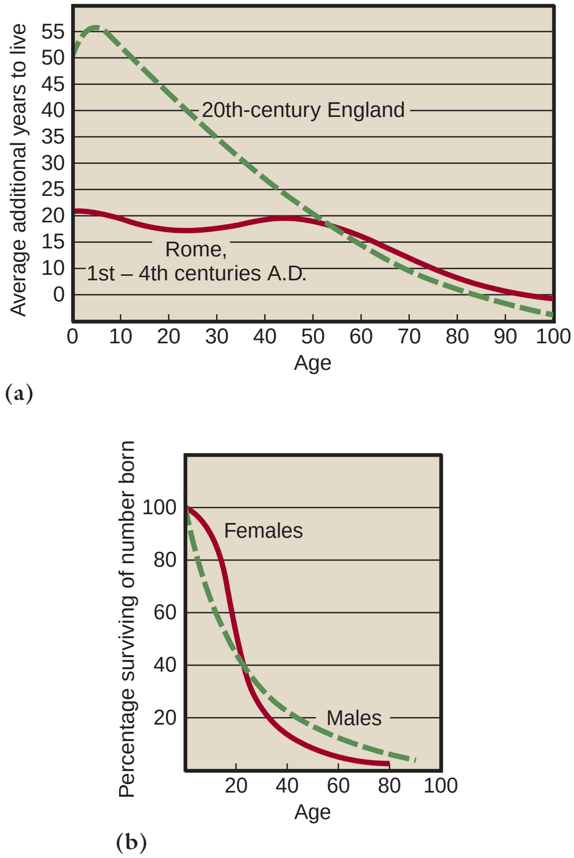


FIGURE 4.9 (a). Life expectancy in ancient Rome and 20th-century England. This graph shows the average number of years one could expect to live after reaching a given age: for example, a 10-year-old in England could expect to live about 55 more years; a 10-year-old in Rome, about 20 more years. Life expectancy was greater in 20th-century England than in ancient Rome until about age 55. An 80-year-old Roman could expect to live longer than an 80-year-old Briton. Data for Romans is reconstructed from ages on tombstones. **(b)**. Approximate survivorship curve for Rome for the first four centuries C.E. The percentage surviving drops rapidly in the early years, reflecting high mortality rates for children in ancient Rome. Females had a slightly higher survivorship rate until age 20, after which males had a slightly higher rate. (*Source*: Modified from G.E. Hutchinson, *An Introduction to Population Ecology* [New Haven, CT: Yale University Press, 1978]. Copyright 1978 by Yale University Press. Used by permission.)

Ages at death, from information carved on tombstones, tell us that the chances of a 75-year-old living to age 90 were greater in ancient Rome than they are today in England (Figure 4.9). These also suggest that death rates were much higher in Rome than in 20th-century England. In ancient Rome, the life expectancy of a 1-year-old was about 22 years, while in 20th-century England it was about 50 years. Life expectancy in 20th-century England was greater than in ancient Rome for all ages until age 55, after which it appears to have been higher for ancient Romans than for 20th-century Britons. This suggests that many hazards of modern life may be concentrated more on the aged. Pollution-induced diseases are one factor in this change.

Human Death Rates and the Rise of Industrial Societies

We return now to further consideration of the first stage in the demographic transition. We can get an idea of the first stage by comparing a modern industrialized country, such as Switzerland, which has a crude death rate of 8.59 per 1,000, with a developing nation, such as Sierra Leone, which has a crude death rate of 21.9.[20] Modern medicine has greatly reduced death rates from disease in countries such as Switzerland, particularly with respect to death from acute or epidemic diseases, such as flu, SARS, and West Nile virus, which we discussed in the chapter's opening case study.

An **acute disease** or **epidemic disease** appears rapidly in the population, affects a comparatively large percentage of it, and then declines or almost disappears for a while, only to reappear later. Epidemic diseases typically are rare but have occasional outbreaks during which a large proportion of the population is infected. A **chronic disease**, in contrast, is always present in a population, typically occurring in a relatively small but relatively constant percentage of the population. Heart disease, cancer, and stroke are examples.

The great decrease in the percentage of deaths due to acute or epidemic diseases can be seen in a comparison of causes of deaths in Ecuador in 1987 and in the United States in 1900, 1987, and 1998 (Figure 4.10).[21] In Ecuador, a developing nation, acute diseases and those listed as "all others" accounted for about 60% of mortality in 1987. In the United States in 1987, these accounted for only 20% of mortality. Chronic diseases account for about 70% of mortality in the modern United States. In

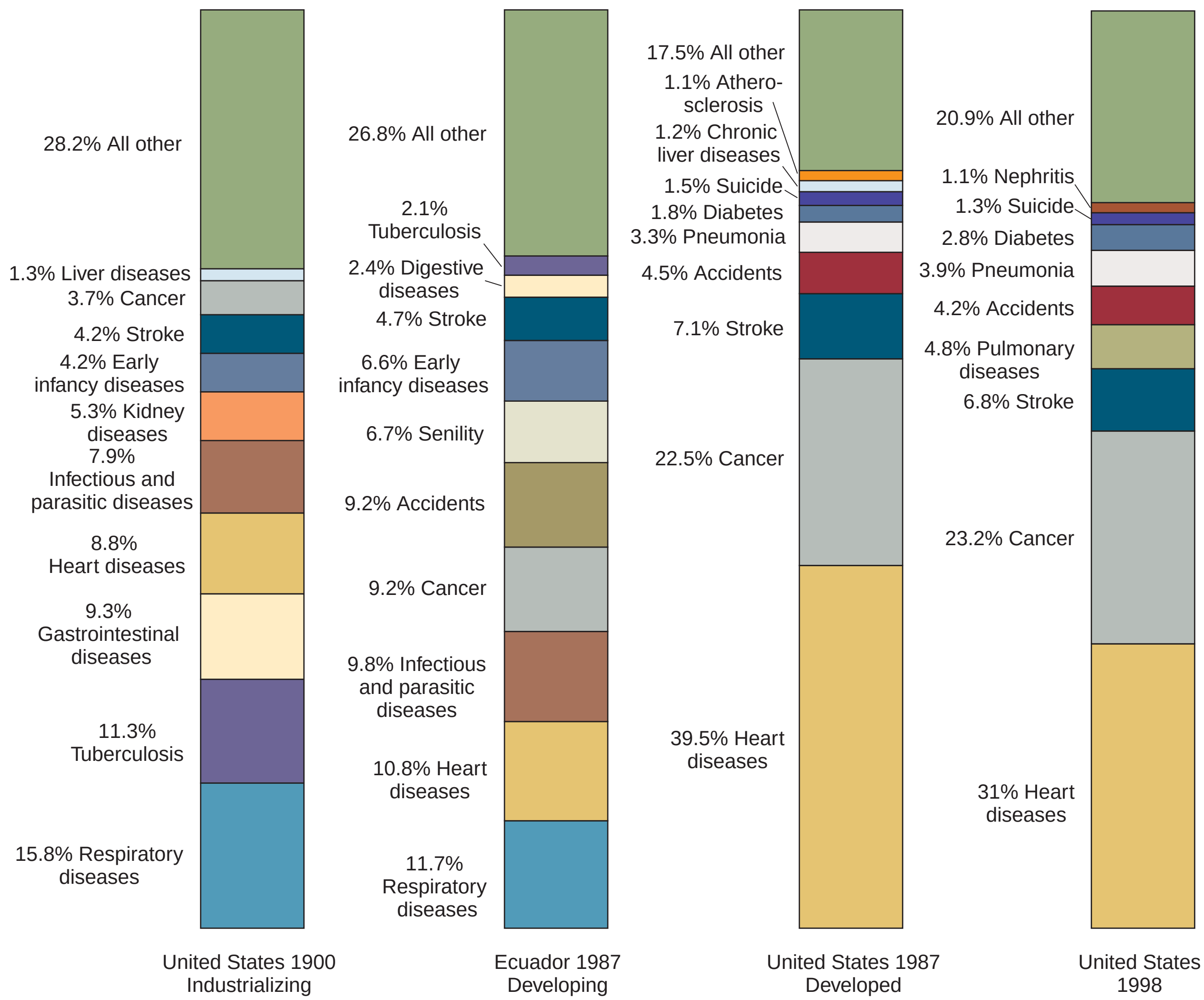


FIGURE 4.10 Causes of mortality in industrializing, developing, and industrialized nations. (*Sources:* U.S. 1900, Ecuador 1987, and U.S. 1987 data from M.M. Kent and K. A. Crews, *World Population: Fundamentals of Growth* [Washington, DC: Population Reference Bureau, 1990]. Copyright 1990 by the Population Reference Bureau, Inc. Reprinted by permission. *National Vital Statistics Report* 48 [11], July 24, 2000.)

contrast, chronic diseases accounted for less than 20% of the deaths in the United States in 1900 and about 33% in Ecuador in 1987. Ecuador in 1987, then, resembled the United States of 1900 more than it resembled the United States of either 1987 or 1998.

4.6 The Human Population's Effects on the Earth

The danger that the human population poses to the environment is the result of two factors: the number of people and the environmental impact of each person. When there were few people on Earth and limited technology, the human impact was primarily local. Even so, people have affected the environment for a surprisingly long time. It started with the use of fire to clear land, and it continued, new research shows, with large effects on the environment by early civilizations. For example, the Mayan temples in South America, standing now in the midst of what were recently believed to be ancient rain forests, actually stood in large areas of farmed land cleared by the Maya. Large areas of North America were modified by American Indians, who used fire for a variety of reasons and modified the forests of the eastern United States.[22] The problem now is that there are so many people and our technologies are so powerful that our effects on the environment are even more global and significant. This could cause a negative feedback—the more people, the worse the environment; the worse the environment, the fewer people.

The simplest way to characterize the total impact of the human population on the environment is to multiply the average impact of an individual by the total number of individuals,[23] or

$$T = P \times I$$

where P is the population size—the number of people—and I is the average environmental impact per person. Of course, the impact per person varies widely, within the same nation and also among nations. The average impact of a person who lives in the United States is much greater than the impact of a person who lives in a low-technology society. But even in a poor, low-technology nation like Bangladesh, the sheer number of people leads to large-scale environmental effects.

Modern technology increases the use of resources and enables us to affect the environment in many new ways, compared with hunters and gatherers or people who farmed with simple wooden and stone tools. For example, before the invention of chlorofluorocarbons (CFCs), which are used as propellants in spray cans and as coolants in refrigerators and air conditioners, we were not causing depletion of the ozone layer in the upper atmosphere. Similarly, before we started driving automobiles, there was much less demand for steel, little demand for oil, and much less air pollution. These linkages between people and the global environment illustrate the global theme and the people-and-nature theme of this book.

The population-times-technology equation reveals a great irony involving two standard goals of international aid: improving the standard of living and slowing overall human population growth. Improving the standard of living increases the total environmental impact, countering the environmental benefits of a decline in population growth.

4.7 The Human Carrying Capacity of Earth

What is the **human carrying capacity** of Earth—that is, how many people can live on Earth at the same time? The answer depends on what quality of life people desire and are willing to accept.

As we have made clear in this chapter, on our finite planet the human population will eventually be limited by some factor or combination of factors. We can group limiting factors into those that affect a population during the year in which they become limiting (short-term factors), those whose effects are apparent after one year but before ten years (intermediate-term factors), and those whose effects are not apparent for ten years (long-term factors). Some factors fit into more than one category, having, say, both short-term and intermediate-term effects.

An important *short-term* factor is the disruption of food distribution in a country, commonly caused by drought or by a shortage of energy for transporting food.

Intermediate-term factors include desertification; dispersal of certain pollutants, such as toxic metals, into waters and fisheries; disruption in the supply of nonrenewable resources, such as rare metals used in making steel alloys for transportation machinery; and a decrease in the supply of firewood or other fuels for heating and cooking.

Long-term factors include soil erosion, a decline in groundwater supplies, and climate change. A decline in resources available per person suggests that we may already have exceeded Earth's long-term human carrying capacity. For example, wood production peaked at 0.67 m^3/person (0.88 yd^3/person) in 1967, fish production at 5.5 kg/person (12.1 lb/person) in 1970, beef at 11.81 kg/person (26.0 lb/person) in 1977, mutton at 1.92 kg/person (4.21 lb/person) in 1972, wool at

0.86 kg/person (1.9 lb/person) in 1960, and cereal crops at 342 kg/person (754.1 lb/person) in 1977.[24] Before these peaks were reached, per capita production of each resource had grown rapidly.

Since the rise of the modern environmental movement in the second half of the 20th century, much attention has focused on estimating the human carrying capacity of Earth—the total number of people that our planet could support indefinitely. This estimation has typically involved three methods. One method, which we have already discussed, is to simply extrapolate from past growth, assuming that the population will follow an S-shaped logistic growth curve and gradually level off (Figure 4.6).

The second method can be referred to as the packing-problem approach. This method simply considers how many people might be packed onto Earth, not taking into sufficient account the need for land and oceans to provide food, water, energy, construction materials, the need to maintain biological diversity, and the human need for scenic beauty. This approach, which could also be called the standing-room-only approach, has led to very high estimates of the total number of people that might occupy Earth—as many as 50 billion.

More recently, a philosophical movement has developed at the other extreme. Known as deep ecology, this third method makes sustaining the biosphere the primary moral imperative. Its proponents argue that the whole Earth is necessary to sustain life, and therefore everything else must be sacrificed to the goal of sustaining the biosphere. People are considered active agents of destruction of the biosphere, and therefore the total number of people should be greatly reduced.[25] Estimates based on this rationale for the desirable number of people vary greatly, from a few million up.

Between the packing-problem approach and the deep-ecology approach are a number of options. It is possible to set goals in between these extremes, but each of these goals is a value judgment, again reminding us of one of this book's themes: *science and values*. What constitutes a desirable quality of life is a value judgment. The perception of what is desirable will depend in part on what we are used to, and this varies greatly. For example, in the United States, New Jersey has only a half acre (0.22 ha) per person, while Wyoming, the most sparsely populated of the lower 48 states, has 116 acres (47.2 ha) per person. For comparison, New York City's Manhattan Island has 71,000 people per square mile, which works out to an area of about 20 × 20 feet per person. Manhattanites manage to live comfortably by using not just the land area but also the airspace to a considerable height. Still, it's clear that people used to living in Wyoming and people living in New Jersey or in Manhattan skyscrapers are likely to have very different views on what is a desirable population density.

Moreover, what quality of life is possible depends not just on the amount of space available but also on technology, which in turn is affected by science. Scientific understanding also tells us what is required to meet each quality-of-life level. The options vary. If all the people of the world were to live at the same level as those of the United States, with our high resource use, then the carrying capacity would be comparatively low. If all the people of the world were to live at the level of those in Bangladesh, with all of its risks as well as its poverty and its heavy drain on biological diversity and scenic beauty, the carrying capacity would be much higher.

In summary, the acceptable carrying capacity is not simply a scientific issue; it is an issue combining science and values, within which science plays two roles. First, by leading to new knowledge, which in turn leads to new technology, it makes possible both a greater impact per individual on Earth's resources and a higher density of human beings. Second, scientific methods can be used to forecast a probable carrying capacity once a goal for the average quality of life, in terms of human values, is chosen. In this second use, science can tell us the implications of our value judgments, but it cannot provide those value judgments.

4.8 Can We Achieve Zero Population Growth?

We have surveyed several aspects of population dynamics. The underlying question is: Can we achieve **zero population growth**—a condition in which the human population, on average, neither increases nor decreases? Much of environmental concern has focused on how to lower the human birth rate and decrease our population growth. As with any long-lived animal population, our species could take several possible approaches to achieving zero population growth. Here are a few.

Age of First Childbearing

The simplest and one of the most effective means of slowing population growth is to delay the age of first childbearing.[26] As more women enter the workforce and as education levels and standards of living rise, this delay occurs naturally. Social pressures that lead to deferred marriage and childbearing can also be effective (Figure 4.11).

FIGURE 4.11 As more and more women enter the workforce and establish professional careers, the average age of first childbearing tends to rise. The combination of an active lifestyle that includes children is illustrated here by the young mother jogging with her child in Perth, Australia.

Typically, countries where early marriage is common have high population growth rates. In South Asia and in Sub-Saharan Africa, about 50% of women marry between the ages of 15 and 19, and in Bangladesh women marry on average at age 16. In Sri Lanka, however, the average age for marriage is 25. The World Bank estimates that if Bangladesh adopted Sri Lanka's marriage pattern, families could average 2.2 fewer children.[26] For many countries, raising the marriage age could account for 40–50% of the drop in fertility required to achieve zero population growth.

Birth Control: Biological and Societal

Another simple way to lower the birth rate is breast feeding, which can delay resumption of ovulation after childbirth.[27] Women in a number of countries use this deliberately as a birth-control method—in fact, according to the World Bank, in the mid-1970s breast feeding provided more protection against conception in developing countries than did family-planning programs.[26]

Family planning is still emphasized, however.[28] Traditional methods range from abstinence to the use of natural agents to induced sterility. Modern methods include the birth-control pill, which prevents ovulation through control of hormone levels; surgical techniques for permanent sterility; and mechanical devices. Contraceptive devices are used widely in many parts of the world, especially in East Asia, where data show that 78% of women use them. In Africa, only 18% of women use them; in Central and South America, the numbers are 53% and 62%, respectively.[26] Abortion is also widespread and is one of the most important birth-control methods in terms of its effects on birth rates—approximately 46 million abortions are performed each year.[29] However, although now medically safe in most cases, abortion is one of the most controversial methods from a moral perspective.

National Programs to Reduce Birth Rates

Reducing birth rates requires a change in attitude, knowledge of the means of birth control, and the ability to afford these means. As we have seen, a change in attitude can occur simply with a rise in the standard of living. In many countries, however, it has been necessary to provide formal family-planning programs to explain the problems arising from rapid population growth and to describe the ways that individuals will benefit from reduced population growth. These programs also provide information about birth-control methods and provide access to these methods.[30] Which methods to promote and use involves social, moral, and religious beliefs, which vary from country to country.

The first country to adopt an official population policy was India in 1952. Few developing countries had official family-planning programs before 1965. Since 1965, many such programs have been introduced, and the World Bank has lent \$4.2 billion to more than 80 countries to support "reproductive" health projects.[26,31] Although most countries now have some kind of family-planning program, effectiveness varies greatly.

A wide range of approaches have been used, from simply providing more information to promoting and providing means for birth control, offering rewards, and imposing penalties. Penalties usually take the form of taxes. Ghana, Malaysia, Pakistan, Singapore, and the Philippines have used a combination of methods, including limits on tax allowances for children and on maternity benefits. Tanzania has restricted paid maternity leave for women to a frequency of once in three years. Singapore does not take family size into account in allocating government-built housing, so larger families are more crowded. Singapore also gives higher priority in school admission to children from smaller families. Some countries, including Bangladesh, India, and Sri Lanka, have paid people to be voluntarily sterilized. In Sri Lanka, this practice has applied only to families with two children, and only when a voluntary statement of consent is signed.

CRITICAL THINKING ISSUE

Will the Demographic Transition Hold in the United States?

Earlier in this chapter, we presented the idea of the demographic transition and suggested that it has occurred in developed nations and may continue in the future. But we also noted that improvements in health care can further decrease death rates, which is something everybody wants to see happen but which will increase the human population growth rate, even in technologically developed nations. Recently, Robert Engelman, a vice president of the Worldwatch Institute of Washington, DC, proposed another problem for the demographic transition—an increase in birth rates in nations such as the United States.[32] The accompanying text box has selections from Engelman's article. Using the material in the chapter, the quotes from Engelman here, and any other information you would like to introduce, present an argument either for or against the following: Growth rates will continue to decline in technologically developed nations, leading toward zero population growth.

Robert Engelman, Vice President of the Worldwatch Institute, "World Population Growth: Fertile Ground for Uncertainty," 2008.

Although the average woman worldwide is giving birth to fewer children than ever before, an estimated 136 million babies were born in 2007. Global data do not allow demographers to be certain that any specific year sets a record for births, but this one certainly came close. The year's cohort of babies propelled global population to an estimated 6.7 billion by the end of 2007.

The seeming contradiction between smaller-than-ever families and near-record births is easily explained. The number of women of childbearing age keeps growing and global life expectancy at birth continues to rise. These two trends explain why population continues growing despite declines in family size. There were 1.7 billion women aged 15 to 49 in late 2007, compared with 856 million in 1970. The average human being born today can expect to live 67 years, a full decade longer than the average newborn could expect in 1970.

Only the future growth of the reproductive-age population is readily predictable, however: all but the youngest of the women who will be in this age group in two decades are already alive today. But sustaining further declines in childbearing and increases in life expectancy will require continued efforts by governments to improve access to good health care, and both trends could be threatened by environmental or social deterioration. The uncertain future of these factors makes population growth harder to predict than most people realize.

SUMMARY

- The human population is often referred to as the underlying environmental issue because much current environmental damage results from the very high number of people on Earth and their great power to change the environment.
- Throughout most of our history, the human population and its average growth rate were small. The growth of the human population can be divided into four major phases. Although the population has increased in each phase, the current situation is unprecedented.
- Countries whose birth rates have declined have experienced a demographic transition marked by a decline in death rates followed by a decline in birth rates. In contrast, many developing nations have undergone a great decline in their death rates but still have very high birth rates. It remains an open question whether some of these nations will be able to achieve a lower birth rate before reaching disastrously high population levels.
- The maximum population Earth can sustain and how large a population will ultimately be attained by human beings are controversial questions. Standard estimates

suggest that the human population will reach 10–16 billion before stabilizing.

- How the human population might stabilize, or be stabilized, raises questions concerning science, values, people, and nature.
- One of the most effective ways to lower a population's growth rate is to lower the age of first childbearing. This approach also involves relatively few societal and value issues.

REEXAMINING THEMES AND ISSUES

Human Population

Our discussion in this chapter reemphasizes the point that there can be no long-term solution to our environmental problems unless the human population stops growing at its present rate. This makes the problem of human population a top priority.

Sustainability

As long as the human population continues to grow, it is doubtful that our other environmental resources can be made sustainable.

Global Perspective

Although the growth rate of the human population varies from nation to nation, the overall environmental effects of the rapidly growing human population are global. For example, the increased use of fossil fuels in Western nations since the beginning of the Industrial Revolution has affected the entire world. The growing demand for fossil fuels and their increasing use in developing nations are also having a global effect.

Urban World

One of the major patterns in the growth of the human population is the increasing urbanization of the world. Cities are not self-contained but are linked to the surrounding environment, depending on it for resources and affecting environments elsewhere.

People and Nature

As with any species, the growth rate of the human population is governed by fundamental laws of population dynamics. We cannot escape these basic rules of nature. People greatly affect the environment, and the idea that human population growth is *the* underlying environmental issue illustrates the deep connection between people and nature.

Science and Values

The problem of human population exemplifies the connection between values and knowledge. Scientific and technological knowledge has helped us cure diseases, reduce death rates, and thereby increase growth of the human population. Our ability today to forecast human population growth provides a great deal of useful knowledge, but what we do with this knowledge is hotly debated around the world because values are so important in relation to birth control and family size.

KEY TERMS

abundance **62**
acute disease **72**
age structure **62**
birth rate **62**
chronic disease **72**
death rate **62**
demographic transition **69**
demography **62**
doubling time **65**
epidemic disease **72**
exponential rate **62**
growth rate **62**
human carrying capacity **73**
inflection point **66**
life expectancy **71**
logistic carrying capacity **66**
logistic growth curve **65**
maximum lifetime **71**
pandemic **60**
population **61**
population dynamics **61**
species **62**
zero population growth **74**

STUDY QUESTIONS

1. Refer to three forecasts for the future of the world's human population in Figure 4.6. Each forecast makes a different assumption about the future total fertility rate: that the rate remains constant; that it decreases slowly and smoothly; and that it decreases rapidly and smoothly. Which of these do you think is realistic? Explain why.
2. Why is it important to consider the age structure of a human population?
3. Three characteristics of a population are the birth rate, growth rate, and death rate. How has each been affected by (a) modern medicine, (b) modern agriculture, and (c) modern industry?
4. What is meant by the statement "What is good for an individual is not always good for a population"?
5. Strictly from a biological point of view, why is it difficult for a human population to achieve a constant size?
6. What environmental factors are likely to increase the chances of an outbreak of an epidemic disease?
7. To which of the following can we attribute the great increase in human population since the beginning of the Industrial Revolution: changes in human (a) birth rates, (b) death rates, (c) longevity, or (d) death rates among the very old? Explain.
8. What is the demographic transition? When would one expect replacement-level fertility to be achieved—before, during, or after the demographic transition?
9. Based on the history of human populations in various countries, how would you expect the following to change as per capita income increased: (a) birth rates, (b) death rates, (c) average family size, and (d) age structure of the population? Explain.

FURTHER READING

Barry, J.M., ***The Great Influenza: The Story of the Deadliest Pandemic in History*** (New York: Penguin Books, paperback, 2005). Written for the general reader but praised by such authorities as the *New England Journal of Medicine,* this book discusses the connection between politics, public health, and pandemics.

Cohen, J.E., ***How Many People Can the Earth Support?*** (New York: Norton, 1995). A detailed discussion of world population growth, Earth's human carrying capacity, and factors affecting both.

Ehrlich, P.R., and A.H. Ehrlich, ***One with Nineveh: Politics, Consumption, and the Human Future*** (Washington, DC: Island Press, 2004). An extended discussion of the effects of the human population on the world's resources, and of Earth's carrying capacity for our species. Ehrlich's 1968 book, *The Population Bomb* (New York: Ballantine Books), played an important role in the beginning of the modern environmental movement, and for this reason can be considered a classic.

Livi-Bacci, Massimo, A *Concise History of World Population* (Hoboken, NJ: Wiley-Blackwell, paperback, 2001). A well-written introduction to the field of human demography.

McKee, J.K., *Sparing Nature: The Conflict between Human Population Growth and Earth's Biodiversity* (New Brunswick, NJ: Rutgers University Press, 2003). One of the few recent books about human populations.

CHAPTER 5

Ecosystems: Concepts and Fundamentals

Ecotourists see the first stages in ecological succession at Doñana National Park, Spain—plants that can germinate and grow in sandy soil recently deposited by the winds. Doñana National Park is one of the major stopovers for birds migrating from Europe to Africa, and is one of Europe's most important wildlife parks.

LEARNING OBJECTIVES

Life on Earth is sustained by ecosystems, which vary greatly but have certain attributes in common. After reading this chapter, you should understand . . .

- Why the ecosystem is the basic system that supports life and allows it to persist;
- What food chains, food webs, and trophic levels are;
- What ecosystem chemical cycling is;
- What the ecological community is;
- How to determine the boundaries of an ecosystem;
- How species affect one another indirectly through their ecological community;
- How ecosystems recover from disturbances through ecological succession;
- Whether ecosystems are generally in a steady state.

CASE STUDY

Sea Otters, Sea Urchins, and Kelp: Indirect Effects of Species on One Another

Sea otters, the lovable animals often shown lying faceup among kelp as they eat shellfish, play an important role in their ecosystems. Although they feed on a variety of shellfish, sea otters especially like sea urchins. Sea urchins, in turn, feed on kelp, large brown algae that form undersea "forests" and provide important habitat for many species that require kelp beds for reproduction, places to feed, or havens from predators. Sea urchins graze along the bottoms of the beds, feeding on the base of kelp, called *holdfasts*, which attach the kelp to the bottom. When holdfasts are eaten through, the kelp floats free and dies. Sea urchins thus can clear kelp beds—clear-cutting, so to speak.

While sea otters affect the abundance of kelp, their influence is indirect (Figure 5.1)—they neither feed on kelp nor protect individual kelp plants from attack by sea urchins. But sea otters reduce the number of sea urchins. With fewer sea urchins, less kelp is destroyed. With more kelp, there is more habitat for many other species; so sea otters indirectly increase the diversity of species.[1,2] This is called a **community effect**, and the otters are referred to as **keystone species** in their ecological community and ecosystem.

Sea otters originally occurred throughout a large area of the Pacific coasts, from northern Japan northeastward along the Russian and Alaskan coasts, and southward along the coast of North America to Morro Hermoso in Baja California and to Mexico.[4] But sea otters also like to eat abalone, and this brings them into direct conflict with people, since abalone is a prized seafood for us, too. They also have one of the finest furs in the world and were brought almost to extinction by commercial hunting for their fur during the 18th and 19th centuries. By the end of the 19th century, there were too few otters left to sustain commercial fur hunters.

Several small populations survived and have increased since then, so that today sea otters number in the hundreds of thousands—3,000 in California, 14,000 in southeastern Alaska, and the rest elsewhere in Alaska. According to the Marine Mammal Center, approximately 2,800 sea otters live along the coast of California,[5] a few hundred in Washington State and British Columbia, and about 100,000 worldwide, including Alaska and the coast of Siberia.[6]

Legal protection of the sea otter by the U.S. government began in 1911 and continues under the U.S. Marine Mammal Protection Act of 1972 and the Endangered Species Act of 1973. Today, however, the sea otter continues

(a)

(b)

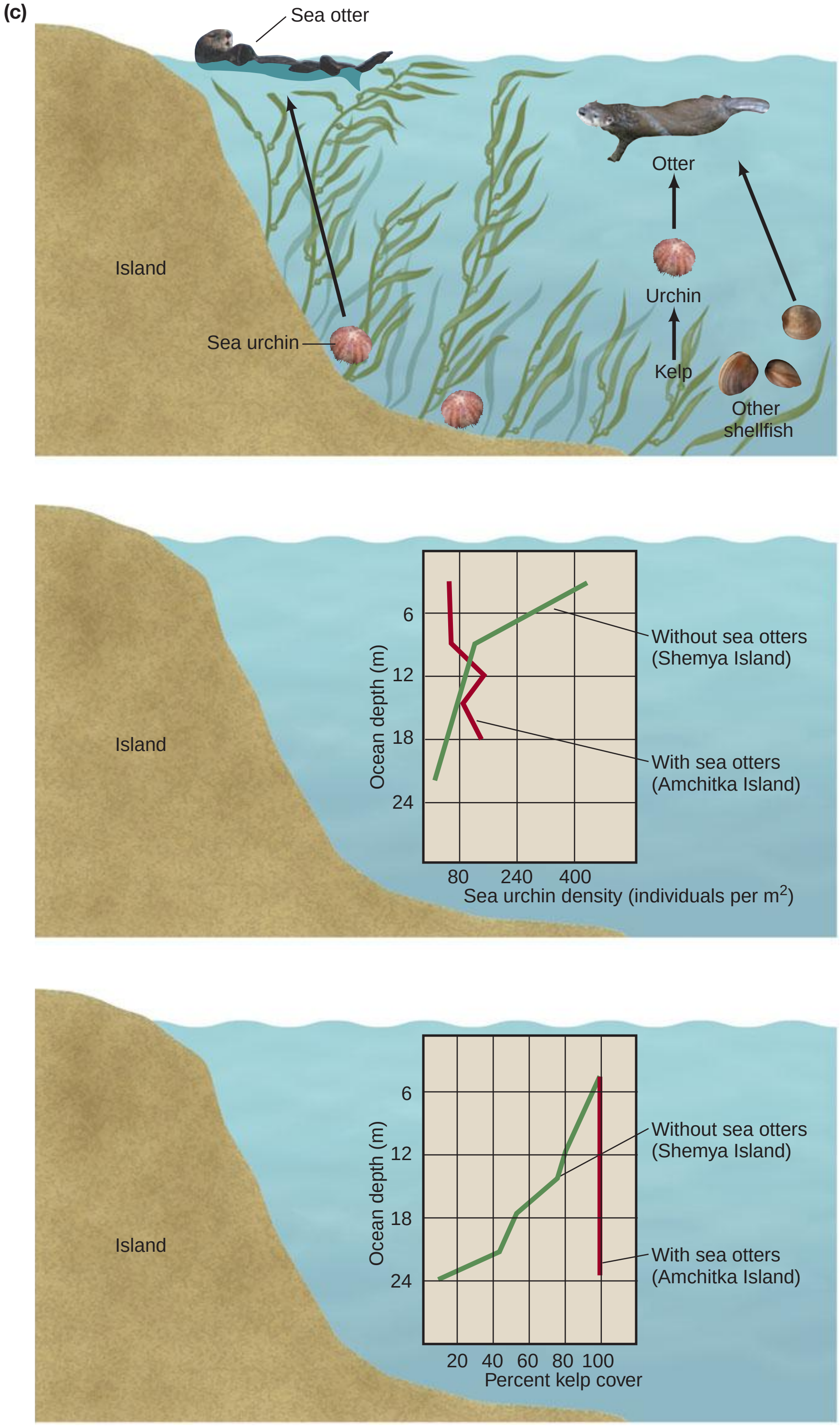


FIGURE 5.1 The effect of sea otters on kelp. (a) Sea otter eating a crab. Sea otters feed on shellfish, including sea urchins. Sea urchins feed on kelp. Where sea otters are abundant, as on Amchitka Island in the Aleutian Islands, there are few sea urchins and kelp beds are abundant (**b** and **c**). At nearby Shemya Island, which lacks sea otters, sea urchins are abundant and there is little kelp.[3] Experimental removal of sea urchins has led to an increase in kelp.[2]

to be a focus of controversy. On the one hand, fishermen argue that the sea otter population has recovered—so much so that they now interfere with commercial fishing because they take large numbers of abalone.[7] On the other hand, conservationists argue that community and ecosystem effects of sea otters make them necessary for the persistence of many oceanic species, and that there are still not enough sea otters to maintain this role at a satisfactory level. Thus, sea otters' indirect effects on many other species have practical consequences. They also demonstrate certain properties of ecosystems and ecological communities that are important to us in understanding how life persists, and how we may be able to help solve certain environmental problems.

5.1 The Ecosystem: Sustaining Life on Earth

We tend to associate life with individual organisms, for the obvious reason that it is individuals that are alive. But sustaining life on Earth requires more than individuals or even single populations or species. Life is sustained by the interactions of many organisms functioning together, interacting through their physical and chemical environments. We call this an **ecosystem**. Sustained life on Earth, then, is a characteristic of ecosystems, not of individual organisms or populations.[8] As the opening case study about sea otters illustrates, to understand important environmental issues—such as conserving endangered species, sustaining renewable resources, and minimizing the effects of toxic substances—we must understand the basic characteristics of ecosystems.

Basic Characteristics of Ecosystems

Ecosystems have several fundamental characteristics, which we can group as *structure* and *processes.*

Ecosystem Structure

An ecosystem has two major parts: nonliving and living. The nonliving part is the physical-chemical environment, including the local atmosphere, water, and mineral soil (on land) or other substrate (in water). The living part, called the **ecological community**, is the set of species interacting within the ecosystem.

Ecosystem Processes

Two basic kinds of processes must occur in an ecosystem: a cycling of chemical elements and a flow of energy. These processes are necessary for all life, but no single species can carry out all necessary chemical cycling and energy flow alone. That is why we said that sustained life on Earth is a characteristic of ecosystems, not of individuals or populations. At its most basic, an ecosystem consists of several species and a fluid medium—air, water, or both (Figure 5.2). Ecosystem energy flow places a fundamental limit on the abundance of life. Energy flow is a difficult subject, which we will discuss in Section 5.4.

Ecosystem chemical cycling is complex as well, and for that reason we have devoted a separate chapter (Chapter 6) to chemical cycling within ecosystems and throughout the entire Earth's biosphere. Briefly, 21 chemical elements are required by at least some form of life, and each chemical element required for growth and reproduction must be available to each organism at the right time, in the right amount, and in the right ratio relative to other elements. These chemical elements must also be recycled—converted to a reusable form: Wastes are converted into food, which is converted into wastes, which must be converted once again into food, with the cycling going on indefinitely if the ecosystem is to remain viable.

For complete recycling of chemical elements to take place, several species must interact. In the presence of light, green plants, algae, and photosynthetic bacteria produce sugar from carbon dioxide and water. From sugar and inorganic compounds, they make many organic compounds, including proteins and woody tissue. But no green plant, algae, or photosynthetic bacteria can decompose woody tissue back to its original inorganic compounds. Other forms of life—primarily bacteria and fungi—can decompose organic matter. But they cannot produce their own food; instead, they obtain energy and chemical nutrition from the dead tissues on which they feed. In an ecosystem, chemical elements recycle, but energy flows one way, into and out of the system, with a small fraction of it stored, as we will discuss later in this chapter.

To repeat, theoretically, at its simplest, an ecosystem consists of at least one species that produces its own food from inorganic compounds in its environment and another species that decomposes the wastes of the first species, plus a fluid medium—air, water, or both (Figure 5.2). But the reality is never as simple as that.

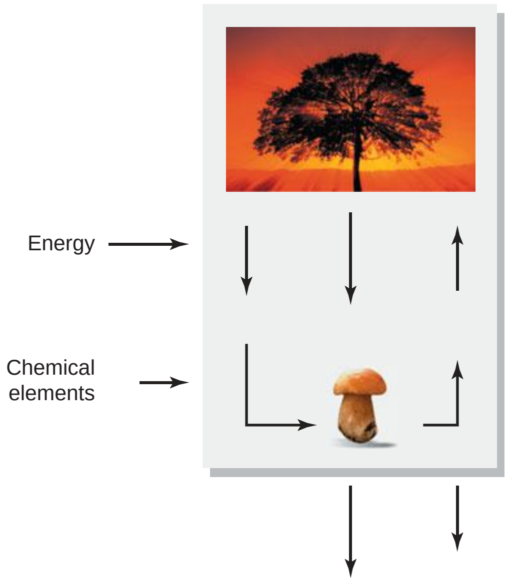


FIGURE 5.2 An idealized minimum ecosystem. Energy flows through an ecosystem one way. A small amount is stored within the system. As chemical elements cycle, there is some small loss, depending on the characteristics of the ecosystem. The size of the arrows in the figure approximates the amount of flow.

5.2 Ecological Communities and Food Chains

In practice, ecologists define the term *ecological community* in two ways. One method defines the community as a set of *interacting* species found in the same place and functioning together, thus enabling life to persist. That is essentially the definition we used earlier. A problem with this definition is that it is often difficult in practice to know the entire set of interacting species. Ecologists therefore may use a practical or an operational definition, in which the community consists of all the species found in an area, whether or not they are known to interact. Animals in different cages in a zoo could be called a community according to this definition.

One way that individuals in a community interact is by feeding on one another. Energy, chemical elements, and some compounds are transferred from creature to creature along **food chains**, the linkage of who feeds on whom. The more complex linkages are called **food webs**. Ecologists group the organisms in a food web into trophic levels. A **trophic level** (from the Greek word *trephein*, meaning to nourish, thus the "nourishing level") consists of all organisms in a food web that are the same number of feeding levels away from the original energy source. The original source of energy in most ecosystems is the sun. In other cases, it is the energy in certain inorganic compounds.

Green plants, algae, and certain bacteria produce sugars through the process of **photosynthesis**, using only energy from the sun and carbon dioxide (CO_2) from the air. They are called **autotrophs**, from the words *auto* (self) and *trephein* (to nourish), thus "self-nourishing," and are grouped into the first trophic level. All other organisms are called **heterotrophs**. Of these, **herbivores**—organisms that feed on plants, algae, or photosynthetic bacteria—are members of the second trophic level. **Carnivores**, or meat-eaters, that feed directly on herbivores make up the third trophic level. Carnivores that feed on third-level carnivores are in the fourth trophic level, and so on. **Decomposers**, those that feed on dead organic material, are classified in the highest trophic level in an ecosystem.

Food chains and food webs are often quite complicated and thus not easy to analyze. For starters, the number of trophic levels differs among ecosystems.

A Simple Ecosystem

One of the simplest natural ecosystems is a hot spring, such as those found in geyser basins in Yellowstone National Park, Wyoming.[9] They are simple because few organisms can live in these severe environments. In and near the center of a spring, water is close to the boiling point, while at the edges, next to soil and winter snow, water is much cooler. In addition, some springs are very acidic and others are very alkaline; either extreme makes a harsh environment.

Photosynthetic bacteria and algae make up the spring's first trophic level. In a typical alkaline hot spring, the hottest waters, between 70° and 80°C (158–176°F), are colored bright yellow-green by photosynthetic blue-green bacteria. One of the few kinds of photosynthetic organisms that can survive at those temperatures, these give the springs the striking appearance for which they are famous (Figure 5.3). In slightly cooler waters, 50° to 60°C (122–140°F), thick mats of other kinds of bacteria and algae accumulate, some becoming 5 cm thick (Figures 5.3 and 5.4).

Ephydrid flies make up the second (herbivore) trophic level. Note that they are the only genus on that entire trophic level, so stressful is the environment, and they live only in the cooler areas of the springs. One of these species, *Ephydra bruesi*, lays bright orange-pink egg masses on stones and twigs that project above the mat. These larvae feed on the bacteria and algae.

The third (carnivore) trophic level is made up of a dolichopodid fly, which feeds on the eggs and larvae of the herbivorous flies, and dragonflies, wasps, spiders,

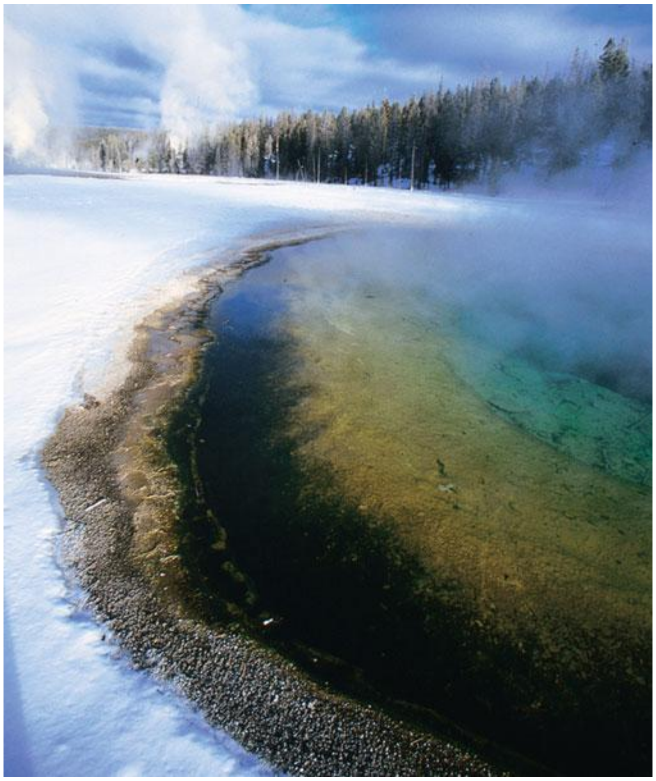


FIGURE 5.3 One of the many hot springs in Yellowstone National Park. The bright yellowish-green color comes from photosynthetic bacteria, one of the few kinds of organisms that can survive in the hot temperatures and chemical conditions of the springs.

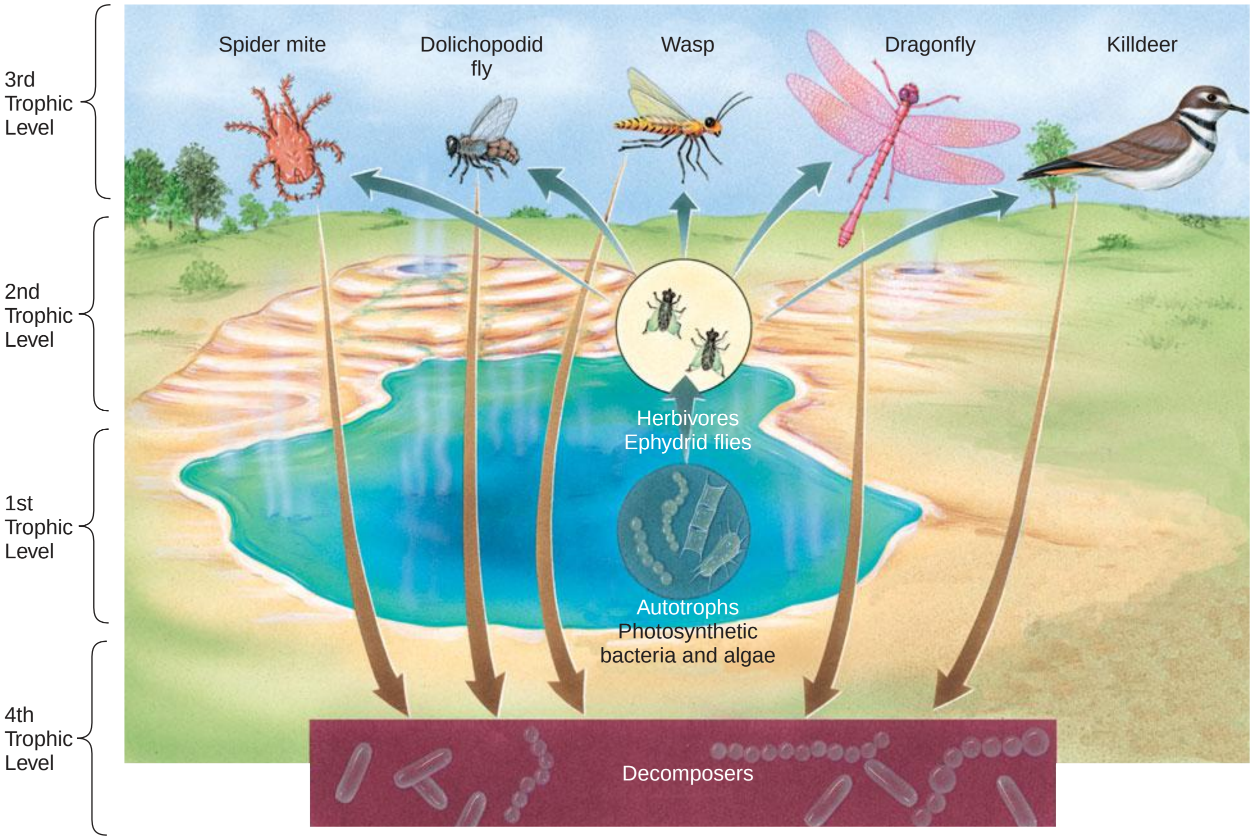


FIGURE 5.4 **Food web of a Yellowstone National Park hot spring.** Even though this is one of the simplest ecological communities in terms of the numbers of species, a fair number are found. About 20 species in all are important in this ecosystem.

tiger beetles, and one species of bird, the killdeer, that feeds on the ephydrid flies. (Note that the killdeer is a carnivore of the hot springs but also feeds widely in other ecosystems. An interesting question, little addressed in the ecological scientific literature, is how we should list this partial member of the food web: Should there be a separate category of "casual" members? What do you think?)

In addition to their other predators, the herbivorous ephydrid flies have parasites. One is a red mite that feeds on the flies' eggs and travels by attaching itself to the adult flies. Another is a small wasp that lays its eggs within the fly larvae. These are also on the third trophic level.

Wastes and dead organisms of all trophic levels are fed on by decomposers, which in the hot springs are primarily bacteria. These form the fourth trophic level.

The entire hot-springs community of organisms—photosynthetic bacteria and algae, herbivorous flies, carnivores, and decomposers—is maintained by two factors: (1) sunlight, which provides usable energy for the organisms; and (2) a constant flow of hot water, which provides a continual new supply of chemical elements required for life and a habitat in which the bacteria and algae can persist.

An Oceanic Food Chain

In oceans, food webs involve more species and tend to have more trophic levels than they do in a terrestrial ecosystem. In a typical **pelagic** (open-ocean) **ecosystem** (Figure 5.6), microscopic single-cell planktonic algae and planktonic photosynthetic bacteria are in the first trophic level. Small invertebrates called *zooplankton* and some fish feed on the algae and photosynthetic bacteria, forming the second trophic level. Other fish and invertebrates feed on these herbivores and form the third trophic level. The great baleen whales filter seawater for food, feeding primarily on small herbivorous zooplankton (mostly crustaceans), and thus the baleen whales are also in the third level. Some fish and marine mammals, such as killer whales, feed on the predatory fish and form higher trophic levels.

Food Webs Can Be Complex: The Food Web of the Harp Seal

In the abstract or in extreme environments like a hot spring, a diagram of a food web and its trophic levels may seem simple and neat. In reality, however, most food webs are complex. One reason for the complexity

A CLOSER LOOK 5.1

Land and Marine Food Webs

A Terrestrial Food Web

An example of terrestrial food webs and trophic levels is shown in Figure 5.5 for an eastern temperate woodland of North America. The first trophic level, autotrophs, includes grasses, herbs, and trees. The second trophic level, herbivores, includes mice, an insect called the pine borer, and other animals (such as deer) not shown here. The third trophic level, carnivores, includes foxes and wolves, hawks and other predatory birds, spiders, and predatory insects. People, too, are involved as **omnivores** (eaters of both plants and animals), feeding on several trophic levels. In Figure 5.5, people would be included in the fourth trophic level, the highest level in which they would take part. Decomposers, such as bacteria and fungi, feed on wastes and dead organisms of all trophic levels. Decomposers are also shown here on the fourth level. (Here's another interesting question: Should we include people *within* this ecosystem's food web? That would place us within nature. Or should we place people outside of the ecosystem, thus separate from nature?)

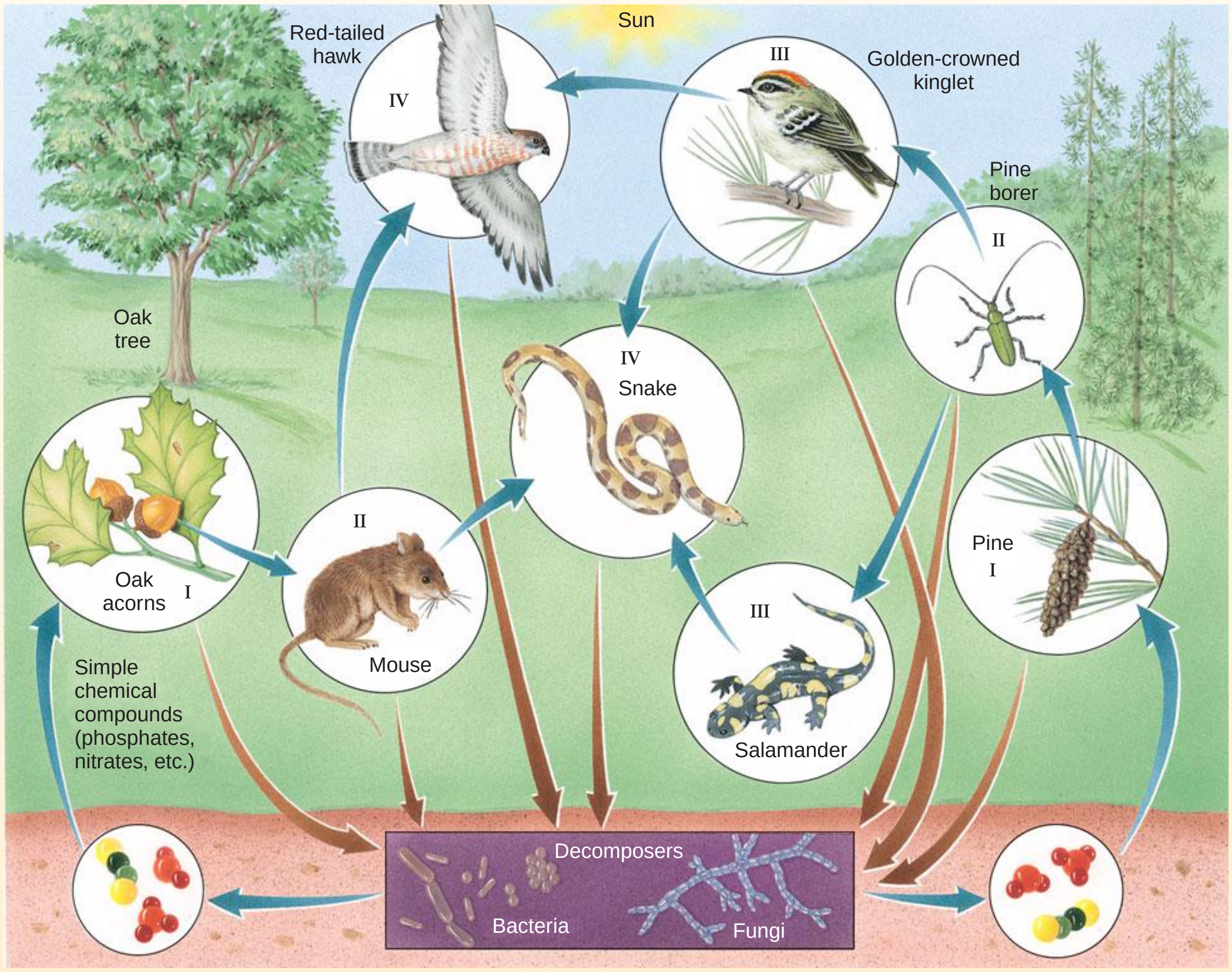


FIGURE 5.5 **A typical temperate forest food web.**

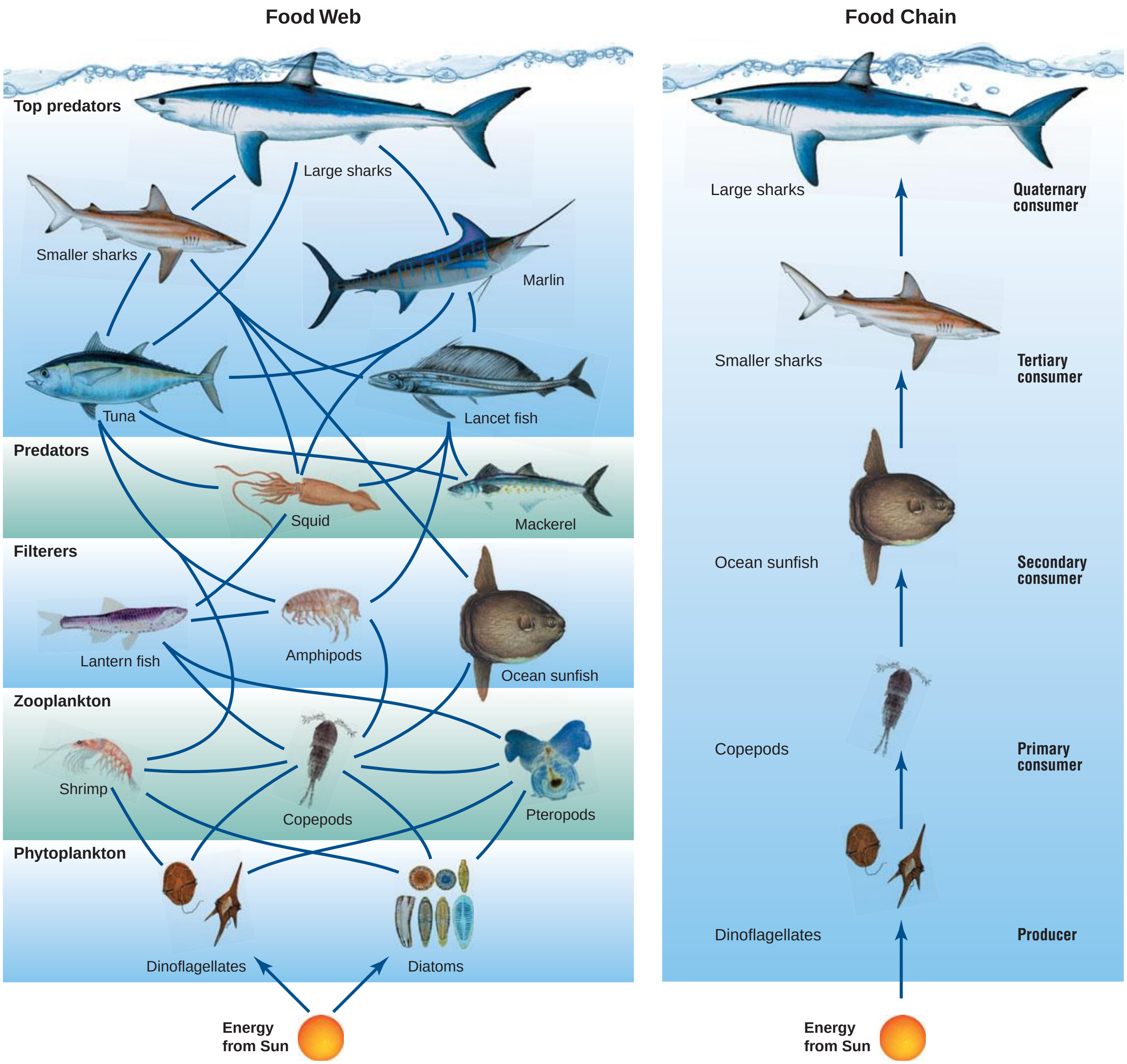


FIGURE 5.6 **An oceanic food web.** (*Source*: NOAA)

is that many creatures feed on several trophic levels. For example, consider the food web of the harp seal (Figure 5.7). This is a species of special interest because large numbers of the pups are harvested each year in Canada for their fur, giving rise to widespread controversy over the humane treatment of animals even though the species is not endangered (there are more than 5 million harp seals.)[10] This controversy is one reason that the harp seal has been well studied, so we can show its complex food web.

The harp seal is shown at the fifth level.[11] It feeds on flatfish (fourth level), which feed on sand launces (third level), which feed on euphausiids (second level), which feed on phytoplankton (first level). But the harp seal actually feeds at several trophic levels, from the second through the fourth. Thus, it feeds on predators of some of its prey and therefore competes with some of its own prey.[12] A species that feeds on several trophic levels is typically classified as belonging to the trophic level above the highest level from which it feeds. Thus, we place the harp seal on the fifth trophic level.

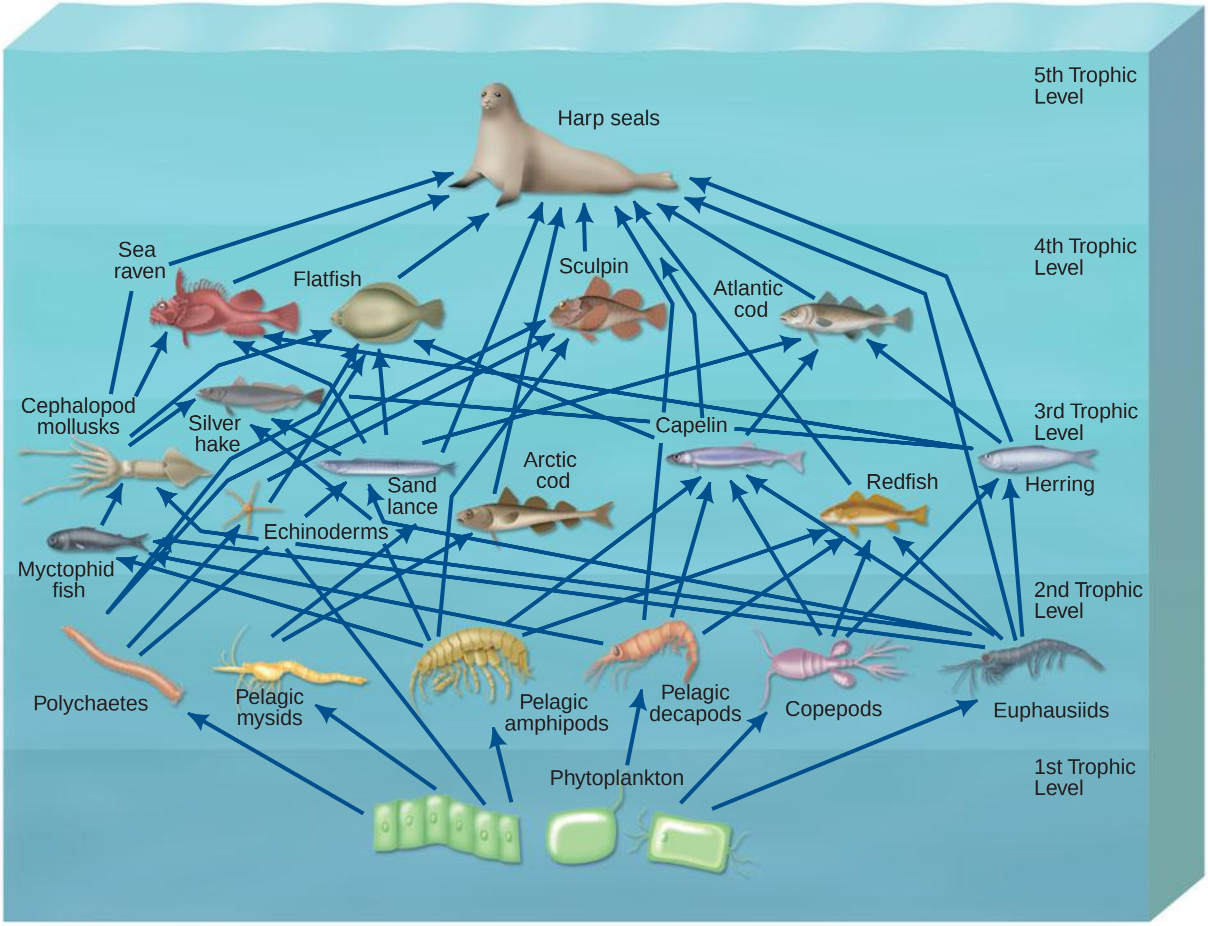


FIGURE 5.7 **Food web of the harp seal showing how complex a real food web can be.**

5.3 Ecosystems as Systems

Ecosystems are open systems: Energy and matter flow into and out of them (see Chapter 3). As we have said, an ecosystem is the minimal entity that has the properties required to sustain life. This implies that an ecosystem is real and important and therefore that we should be able to find one easily. However, ecosystems vary greatly in structural complexity and in the clarity of their boundaries. Sometimes their borders are well defined, such as between a lake and the surrounding countryside (Figure 5.8a). But sometimes the transition from one ecosystem to another is gradual—for example, the transition from deciduous to boreal forest on the slopes of Mt. Washington, N.H. (Figure 5.8b), and in the subtle gradations from grasslands to savannas in East Africa and from boreal forest to tundra in the Far North, where the trees thin out gradually and setting a boundary is difficult, and usually arbitrary.

A commonly used practical delineation of the boundary of an ecosystem on land is the **watershed**. Within a watershed, all rain that reaches the ground from any source flows out in one stream. Topography (the lay of the land) determines the watershed. When a watershed is used to define the boundaries of an ecosystem, the ecosystem is unified in terms of chemical cycling. Some classic experimental studies of ecosystems have been conducted on forested watersheds in U.S. Forest Service experimental areas, including the Hubbard Brook experimental forest in New Hampshire (Figure 5.9) and the Andrews experimental forest in Oregon. In other cases, the choice of an ecosystem's boundary may be arbitrary. For the purposes of scientific analysis, this is okay as long as this boundary is used consistently for any calculation of the exchange of chemicals and energy and the migration of organisms. Let us repeat the primary point: What all ecosystems have in common is not a particular physical size or shape but the processes we have mentioned—the flow of energy and the cycling of chemical elements, which give ecosystems the ability to sustain life.

FIGURE 5.8 **Ecosystem boundaries. (a)** Sometimes the transition from one ecosystem to another is sharp and distinct, as in the transition from lake to forest at Lake Moraine in Banff National Park, Alberta, Canada. **(b)** Sometimes the transition is indistinct and arbitrary, as in the transition from wetlands to uplands in a northern forest as seen from Mount Washington, New Hampshire. Within the distant scene are uplands and wetlands.

FIGURE 5.9 The V-shaped logged area in this picture is the site of the famous Hubbard Brook Ecosystem Study. Here, a watershed defines the ecosystem, and the V shape is an entire watershed cut as part of the experiment.

5.4 Biological Production and Ecosystem Energy Flow

All life requires energy. Energy is the ability to do work, to move matter. As anyone who has dieted knows, our weight is a delicate balance between the energy we take in through our food and the energy we use. What we do not use and do not pass on, we store. Our use of energy, and whether we gain or lose weight, follows the laws of physics. This is true not only for people but also for all populations of living things, for all ecological communities and ecosystems, and for the entire biosphere.

Ecosystem energy flow is the movement of energy through an ecosystem from the external environment through a series of organisms and back to the external environment. It is one of the fundamental processes common to all ecosystems. Energy enters an ecosystem by two pathways: energy fixed by organisms and moving through food webs within an ecosystem; and heat energy that is transferred by air or water currents or by convection through soils and sediments and warms living things. For instance, when a warm air mass passes over a forest, heat energy is transferred from the air to the land and to the organisms.

Energy is a difficult and an abstract concept. When we buy electricity, what are we buying? We cannot see it or feel it, even if we have to pay for it. At first glance, and as we think about it with our own diets, energy flow seems simple enough: We take energy in and use it, just like machines do—our automobiles, cell phones, and so on. But if we dig a little deeper into this subject, we discover a philosophical importance: We learn what distinguishes Earth's life and life-containing systems from the rest of the universe.

Although most of the time energy is invisible to us, with infrared film we can see the differences between warm and cold objects, and we can see some things about energy flow that affect life. With infrared film, warm objects appear red, and cool objects blue. Figure

5.10 shows birch trees in a New Hampshire forest, both as we see them, using standard film, and with infrared film. The infrared film shows tree leaves bright red, indicating that they have been warmed by the sun and are absorbing and reflecting energy, whereas the white birch bark remains cooler. The ability of tree leaves to absorb energy is essential; it is this source of energy that ultimately supports all life in a forest. Energy flows through life, and energy flow is a key concept.

The Laws of Thermodynamics and the Ultimate Limit on the Abundance of Life

When we discuss ecosystems, we are talking about some of the fundamental properties of life and of the ecological systems that keep life going. A question that frequently arises both in basic science and when we want to produce a lot of some kind of life—a crop,

(a) (b) (c) (d)

FIGURE 5.10 Making energy visible. Top: A birch forest in New Hampshire as we see it, using normal photographic film **(a)** and the same forest photographed with infrared film **(b)**. Red color means warmer temperatures; the leaves are warmer than the surroundings because they are heated by sunlight. Bottom: A nearby rocky outcrop as we see it, using normal photographic film **(c)** and the same rocky outcrop photographed with infrared film **(d)**. Blue means that a surface is cool. The rocks appear deep blue, indicating that they are much cooler than the surrounding trees.

WORKING IT OUT 5.1 Some Chemistry of Energy Flow

For Those Who Make Their Own Food (autotrophs)

Photosynthesis—the process by which autotrophs make sugar from sunlight, carbon dioxide, and water—is:

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

Chemosynthesis takes place in certain environments. In chemosynthesis, the energy in hydrogen sulfide (H_2S) is used by certain bacteria to make simple organic compounds. The reactions differ among species and depend on characteristics of the environment (Figure 5.11).

Net production for autotrophs is given as

$$NPP = GPP - R_a$$

where NPP is net primary production, GPP is gross primary production, and R_a is the respiration of autotrophs.

For Those Who Do Not Make Their Own Food (heterotrophs)

Secondary production of a population is given as

$$NSP = B_2 - B_1$$

where NSP is net secondary production, B_2 is the biomass (quantity of organic matter) at time 2, and B_1 is the biomass at time 1. (See discussion of biomass in Section 5.5.) The change in biomass is the result of the addition of weight of living individuals, the addition of newborns and immigrants, and loss through death and emigration. The biological use of energy occurs through respiration, most simply expressed as

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + \text{Energy}$$

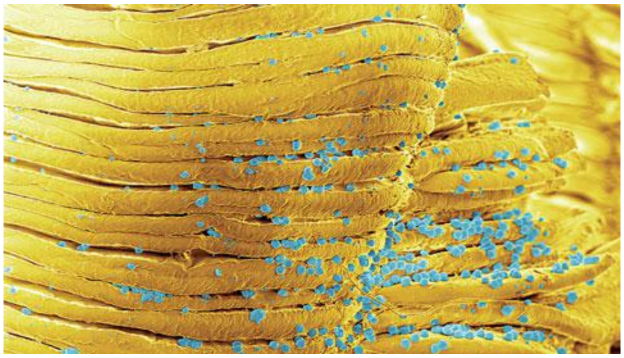


FIGURE 5.11 Deep-sea vent chemosynthetic bacteria.

biofuels, pets—is: *What ultimately limits the amount of organic matter in living things that can be produced anywhere, at any time, forever on the Earth or anywhere in the universe?*

We ask this question when we are trying to improve the production of some form of life. We want to know: How closely do ecosystems, species, populations, and individuals approach this limit? Are any of these near to being as productive as possible?

The answers to these questions, which are at the same time practical, scientifically fundamental, and philosophical, lie in the laws of thermodynamics. The **first law of thermodynamics**, known as the *law of conservation of energy* states that in any physical or chemical change, energy is neither created nor destroyed but merely changed from one form to another. (See A Closer Look 5.1.) This seems to lead us to a confusing, contradictory answer—it seems to say that we don't need to take in any energy at all! If the total amount of energy is always conserved—if it remains constant—then why can't we just recycle energy inside our bodies? The famous 20th-century physicist Erwin Schrödinger asked this question in a wonderful book entitled *What Is Life?* He wrote:

> In some very advanced country (I don't remember whether it was Germany or the U.S.A. or both) you could find menu cards in restaurants indicating, in addition to the price, the energy content of every dish. Needless to say, taken literally, this is . . . absurd. For an adult organism the energy content is as stationary as the material content. Since, surely, any calorie is worth as much as any other calorie, one cannot see how a mere exchange could help.[13]

Schrödinger was saying that, according to the first law of thermodynamics, we should be able to recycle energy in our bodies and never have to eat anything. Similarly, we can ask: Why can't energy be recycled in ecosystems and in the biosphere?

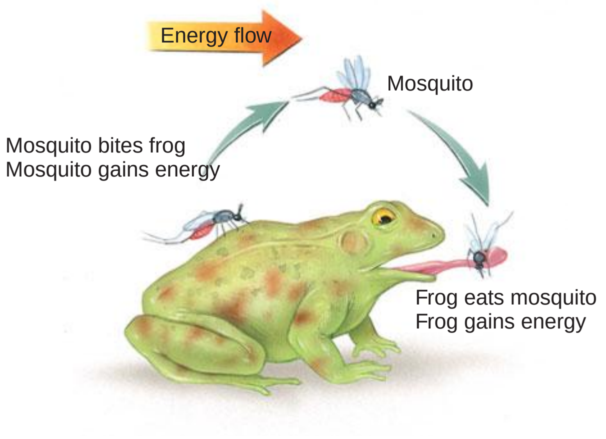


FIGURE 5.12 An impossible ecosystem. Energy always changes from a more useful, more highly organized form to a less useful, disorganized form. That is, energy cannot be completely recycled to its original state of organized, high-quality usefulness. For this reason, the mosquito–frog system will eventually stop when not enough useful energy is left. (There is also a more mundane reason: Only female mosquitoes require blood, and then only in order to reproduce. Mosquitoes are otherwise herbivorous.)

Let us imagine how that might work, say, with frogs and mosquitoes. Frogs eat insects, including mosquitoes. Mosquitoes suck blood from vertebrates, including frogs. Consider an imaginary closed ecosystem consisting of water, air, a rock for frogs to sit on, frogs, and mosquitoes. In this system, the frogs get their energy from eating the mosquitoes, and the mosquitoes get their energy from biting the frogs (Figure 5.12). Such a closed system would be a biological perpetual-motion machine. It could continue indefinitely without an input of any new material or energy. This sounds nice, but unfortunately it is impossible. Why? The general answer is found in the *second* law of thermodynamics, which addresses how energy changes in form.

To understand why we cannot recycle energy, imagine a closed system (a system that receives no input after the initial input) containing a pile of coal, a tank of water, air, a steam engine, and an engineer (Figure 5.13). Suppose the engine runs a lathe that makes furniture. The engineer lights a fire to boil the water, creating steam to run the engine. As the engine runs, the heat from the fire gradually warms the entire system.

When all the coal is completely burned, the engineer will not be able to boil any more water, and the engine will stop. The average temperature of the system is now higher than the starting temperature. The energy that was in the coal is dispersed throughout the entire system, much of it as heat in the air. Why can't the engineer recover all that energy, recompact it, put it under the boiler, and run the engine? The answer is in the **second law of thermodynamics**. Physicists have discovered that *no use of energy in the real (not theoretical) world can ever be 100% efficient.* Whenever useful work is done, some energy is inevitably converted to heat. Collecting all the energy dispersed in this closed system would require more energy than could be recovered.

Our imaginary system begins in a highly organized state, with energy compacted in the coal. It ends in a less organized state, with the energy dispersed throughout the system as heat. The energy has been degraded, and the system is said to have undergone a decrease in order. The

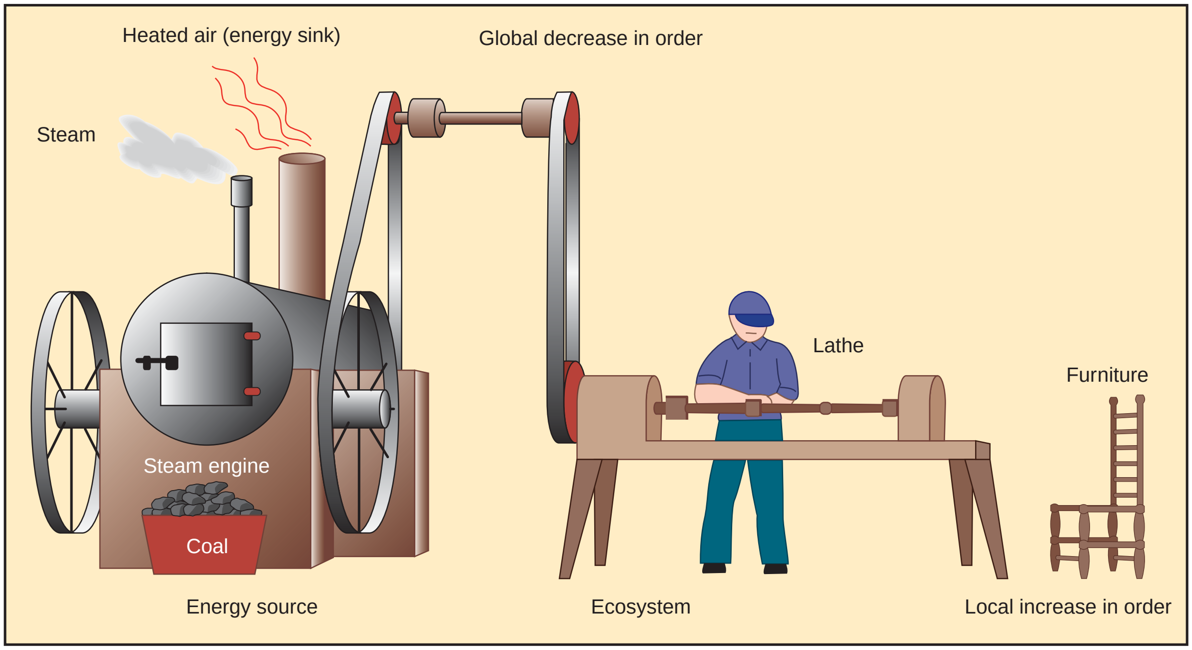


FIGURE 5.13 A system closed to the flow of energy.

measure of the decrease in order (the disorganization of energy) is called **entropy**. The engineer did produce some furniture, converting a pile of lumber into nicely ordered tables and chairs. The system had a local increase of order (the furniture) at the cost of a general increase in disorder (the state of the entire system). All energy of all systems tends to flow toward states of increasing entropy.

The second law of thermodynamics gives us a new understanding of a basic quality of life. *It is the ability to create order on a local scale that distinguishes life from its nonliving environment.* This ability requires obtaining energy in a usable form, and that is why we eat. This principle is true for every ecological level: individual, population, community, ecosystem, and biosphere. Energy must continually be added to an ecological system in a usable form. Energy is inevitably degraded into heat, and this heat must be released from the system. If it is not released, the temperature of the system will increase indefinitely. The net flow of energy through an ecosystem, then, is a one-way flow.

Based on what we have said about the energy flow through an ecosystem, we can see that an ecosystem must lie between a source of usable energy and a sink for degraded (heat) energy. The ecosystem is said to be an *intermediate system* between the energy source and the energy sink. The energy source, ecosystem, and energy sink together form a thermodynamic system. The ecosystem can undergo an increase in order, called a *local increase*, as long as the entire system undergoes a decrease in order, called a global decrease. (Note that *order* has a specific meaning in thermodynamics: Randomness is disorder; an ordered system is as far from random as possible.) To put all this simply, creating local order involves the production of organic matter. Producing organic matter requires energy; organic matter stores energy.

With these fundamentals in mind, we can turn to practical and empirical scientific problems, but this requires that we agree how to measure biological production. To complicate matters, there are several measurement units involved, depending on what people are interested in.

5.5 Biological Production and Biomass

The total amount of organic matter in any ecosystem is called its **biomass**. Biomass is increased through biological production (growth). Change in biomass over a given period is called *production*. **Biological production** is the capture of usable energy from the environment to produce organic matter (or organic compounds). This capture is often referred to as energy "fixation," and it is often said that the organism has "fixed" energy. There are two kinds of production, gross and net. **Gross production** is the increase in stored energy before any is used; **net production** is the amount of newly acquired energy stored after some energy has been used. When we use energy, we "burn" a fuel through repiration. The difference between gross and net production is like the difference between a person's gross and net income. Your gross income is the amount you are paid. Your net income is what you have left after taxes and other fixed costs. Respiration is like the expenses that are required in order for you to do your work.

Measuring Biomass and Production

Three measures are used for biomass and biological production: the quantity of organic material (biomass), energy stored, and carbon stored. We can think of these measures as the currencies of production. Biomass is usually measured as the amount per unit surface area—for example, as grams per square meter (g/m^2) or metric tons per hectare (MT/ha). Production, a rate, is the change per unit area in a unit of time—for example, grams per square meter per year. (Common units of measure of production are given in the Appendix.)

The production carried out by autotrophs is called **primary production**; that of heterotrophs is called **secondary production**. As we have said, most autotrophs make sugar from sunlight, carbon dioxide, and water in a process called photosynthesis, which releases free oxygen (see Working It Out 5.1 and 5.2). Some autotrophic bacteria can derive energy from inorganic sulfur compounds; these bacteria are referred to as **chemoautotrophs**. Such bacteria live in deep-ocean vents, where they provide the basis for a strange ecological community. Chemoautotrophs are also found in muds of marshes, where there is no free oxygen.

Once an organism has obtained new organic matter, it can use the energy in that organic matter to do things: to move, to make new compounds, to grow, to reproduce, or to store it for future uses. The use of energy from organic matter by most heterotrophic and autotrophic organisms is accomplished through respiration. In respiration, an organic compound combines with oxygen to release energy and produce carbon dioxide and water (see Working It Out 5.2). The process is similar to the burning of organic compounds but takes place within cells at much lower temperatures through enzyme-mediated reactions. *Respiration is the use of biomass to release energy that can be used to do work.* Respiration returns to the environment the carbon dioxide that had been removed by photosynthesis.

WORKING IT OUT 5.2 Gross and Net Production

The production of biomass and its use as a source of energy by autotrophs include three steps:

1. An organism produces organic matter within its body.
2. It uses some of this new organic matter as a fuel in respiration.
3. It stores some of the newly produced organic matter for future use.

The first step, production of organic matter before use, is called *gross production*. The amount left after utilization is called *net production*.

Net production = Gross production − Respiration

The gross production of a tree—or any other plant—is the total amount of sugar it produces by photosynthesis before any is used. Within living cells in a green plant, some of the sugar is oxidized in respiration. Energy is used to convert sugars to other carbohydrates; those carbohydrates to amino acids; amino acids to proteins and to other tissues, such as cell walls and new leaf tissue. Energy is also used to transport material within the plant to roots, stems, flowers, and fruits. Some energy is lost as heat in the transfer. Some is stored in these other parts of the plant for later use. For woody plants like trees, some of this storage includes new wood laid down in the trunk, new buds that will develop into leaves and flowers the next year, and new roots.

Equations for Production, Biomass, and Energy Flow

We can write a general relation between biomass (B) and net production (NP):

$$B_2 = B_1 + NP$$

where B_2 is the biomass at the end of the time period, B_1 is the amount of biomass at the beginning of the time period, and NP is the change in biomass during the time period. Thus,

$$NP = B_2 - B_1$$

General production equations are given as

$$\mathrm{GP} = \mathrm{NP} + \mathrm{R}$$

$$\mathrm{NP} = \mathrm{GP} - \mathrm{R}$$

where GP is gross production, NP is net production, and R is respiration.

Several units of measures are used in the discussion of biological production and energy flow: calories when people talk about food content; watt-hours when people talk about biofuels; and kilojoules in standard international scientific notation. To make matters even more complicated, there are two kinds of calories: the standard calorie, which is the heat required to heat one gram of water from 15.5°C to 16.5°C, and the kilocalorie, which is 1,000 of the little calories. Even more confusing, when people discuss the energy content of food and diets, they use *calorie* to mean the kilocalorie. Just remember: The calorie you see on the food package is the big calorie, the kilocalorie, equal to 1,000 little calories. Almost nobody uses the "little" calorie, regardless of what they call it. To compare, an average apple contains about 100 Kcal or 116 watt-hours. This means that an apple contains enough energy to run a 100-watt bulb for 1 hour and 9 minutes. For those of you interested in your diet and weight, a Big Mac contains 576 Kcal, which is 669 watt-hours, enough to keep that 100-watt bulb burning for 6 hours and 41 minutes.

The average energy stored in vegetation is approximately 5 Kcal/gram (21 kilojoules per gram [kJ/g]). The energy content of organic matter varies. Ignoring bone and shells, woody tissue contains the least energy per gram, about 4 Kcal/g (17 kJ/g); fat contains the most, about 9 Kcal/g (38 kJ/g); and muscle contains approximately 5–6 Kcal/g (21–25 kJ/g). Leaves and shoots of green plants have about 5 Kcal/g (21–23 kJ/g); roots have about 4.6 Kcal/g (19 kJ/g).[2]

5.6 Energy Efficiency and Transfer Efficiency

How efficiently do living things use energy? This is an important question for the management and conservation of all biological resources. We would like biological resources to use energy efficiently—to produce a lot of biomass from a given amount of energy. This is also important for attempts to sequester carbon by growing trees and other perennial vegetation to remove carbon dioxide from the atmosphere and store it in living and dead organic matter (see Chapter 20).

As you learned from the second law of thermodynamics, no system can be 100% efficient. As energy flows through a food web, it is degraded, and less and less is usable. Generally, the more energy an organism gets, the more it has for its own use. However, organisms differ in how efficiently they use the energy they obtain. A more efficient organism has an advantage over a less efficient one.

Efficiency can be defined for both artificial and natural systems: machines, individual organisms, populations, trophic levels, ecosystems, and the biosphere. **Energy efficiency** is defined as the ratio of output to input, and it is usually further defined as the amount of useful work obtained from some amount of available energy. *Efficiency* has different meanings to different users. From the point of view of a farmer, an efficient corn crop is one that converts a great deal of solar energy to sugar and uses little of that sugar to produce stems, roots, and leaves. In other words, the most efficient crop is the one that has the most harvestable energy left at the end of the season. A truck driver views an efficient truck as just the opposite: For him, an efficient truck uses as much energy as possible from its fuel and stores as little energy as possible (in its exhaust). When we view organisms as food, we define *efficiency* as the farmer does, in terms of energy storage (net production from available energy). When we are energy users, we define *efficiency* as the truck driver does, in terms of how much useful work we accomplish with the available energy.

Consider the use of energy by a wolf and by one of its principal prey, moose. The wolf needs energy to travel long distances and hunt, and therefore it will do best if it uses as much of the energy in its food as it can. For itself, a highly energy-efficient wolf stores almost nothing. But from its point of view, the best moose would be one that used little of the energy it took in, storing most of it as muscle and fat, which the wolf can eat. Thus what is efficient depends on your perspective.

A common ecological measure of energy efficiency is called *food-chain efficiency*, or *trophic-level efficiency*, which is the ratio of production of one trophic level to the production of the next-lower trophic level. This efficiency is never very high. Green plants convert only 1–3% of the energy they receive from the sun during the year to new plant tissue. The efficiency with which herbivores convert the potentially available plant energy into herbivorous energy is usually less than 1%, as is the efficiency with which carnivores convert herbivores into carnivorous energy. In natural ecosystems, the organisms in one trophic level tend to take in much less energy than the potential maximum available to them, and they use more energy than they store for the next trophic level. At Isle Royale National Park, an island in Lake Superior, wolves feed on moose in a natural wilderness. A pack of 18 wolves kills an average of one moose approximately every 2.5 days,[14] which gives wolves a trophic-level efficiency of about 0.01%.

The rule of thumb for ecological trophic energy efficiency is that more than 90% (usually much more) of all energy transferred between trophic levels is lost as heat. Less than 10% (approximately 1% in natural ecosystems) is fixed as new tissue. In highly managed ecosystems, such as ranches, the efficiency may be greater. But even in such systems, it takes an average of 3.2 kg (7 lb) of vegetable matter to produce 0.45 kg (1 lb) of edible meat. Cattle are among the least efficient producers, requiring around 7.2 kg (16 lb) of vegetable matter to produce 0.45 kg (1 lb) of edible meat. Chickens are much more efficient, using approximately 1.4 kg (3 lb) of vegetable matter to produce 0.45 kg (1 lb) of eggs or meat. Much attention has been paid to the idea that humans should eat at a lower trophic level in order to use resources more efficiently. (See Critical Thinking Issue, Should People Eat Lower on the Food Chain?)

5.7 Ecological Stability and Succession

Ecosystems are dynamic: They change over time both from external (environmental) forces and from their internal processes. It is worth repeating the point we made in Chapter 3 about dynamic systems: The classic interpretation of populations, species, ecosystems, and Earth's entire biosphere has been to assume that each is a stable, static system. But the more we study these ecological systems, the clearer it becomes that these are dynamic systems, always changing *and always requiring change.* Curiously, they persist while undergoing change. We say "curiously" because in our modern technological society we are surrounded by mechanical and electronic systems that stay the same in most characteristics and are designed to do so. We don't expect our car or television or cell phone to shrink or get larger and then smaller again; we don't expect that one component will get bigger or smaller over time. If anything like this were to happen, those systems would break.

Ecosystems, however, not only change but also then recover and overcome these changes, and life continues on. It takes some adjustment in our thinking to accept and understand such systems.

When disturbed, ecosystems can recover through **ecological succession** if the damage is not too great. We can classify ecological succession as either primary or secondary. **Primary succession** is the establishment and development of an ecosystem where one did not exist previously. Coral reefs that form on lava emitted from a volcano and cooled in shallow ocean waters are examples of primary succession. So are forests that develop on new lava flows, like those released by the volcano on the big island of Hawaii (Figure 5.14a), and forests that develop at the edges of retreating glaciers (Figure 5.14b).

Secondary succession is reestablishment of an ecosystem after disturbances. In secondary succession, there are remnants of a previous biological community, including such things as organic matter and seeds. A coral reef that has been killed by poor fishing practices, pollution, climate change, or predation, and then

(a)


(b)

FIGURE 5.14 Primary succession. (a) Forests developing on new lava flows in Hawaii and **(b)** at the edge of a retreating glacier.

recovers, is an example of secondary succession.[15] Forests that develop on abandoned pastures or after hurricanes, floods, or fires are also examples of secondary succession.

Succession is one of the most important ecological processes, and the patterns of succession have many management implications (discussed in detail in Chapter 10). We see examples of succession all around us. When a house lot is abandoned in a city, weeds begin to grow. After a few years, shrubs and trees can be found; secondary succession is taking place. A farmer weeding a crop and a homeowner weeding a lawn are both fighting against the natural processes of secondary succession.

Patterns in Succession

Succession follows certain general patterns. When ecologists first began to study succession, they focused on three cases involving forests: (1) on dry sand dunes along the shores of the Great Lakes in North America; (2) in a northern freshwater bog; and (3) in an abandoned farm field. These were particularly interesting because each demonstrated a repeatable pattern of recovery, and each tended to produce a late stage that was similar to the late stages of the others.

Dune Succession

Sand dunes are continually being formed along sandy shores and then breached and destroyed by storms. In any of the Great Lakes states, soon after a dune is formed on the shores of one of the Great Lakes, dune grass invades. This grass has special adaptations to the unstable dune. Just under the surface, it puts out runners with sharp ends (if you step on one, it will hurt). The dune grass rapidly forms a complex network of underground runners, crisscrossing almost like a coarsely woven mat. Above the ground, the green stems carry out photosynthesis, and the grasses grow. Once the dune grass is established, its runners stabilize the sand, and seeds of other plants have a better chance of germinating. The seeds germinate, the new plants grow, and an ecological community of many species begins to develop. The plants of this early stage tend to be small, grow well in bright light, and withstand the harsh environment—high temperatures in summer, low temperatures in winter, and intense storms.

Slowly, larger plants, such as eastern red cedar and eastern white pine, are able to grow on the dunes. Eventually, a forest develops, which may include species such as beech and maple. A forest of this type can persist for many years, but at some point a severe storm breaches even these heavily vegetated dunes, and the process begins again (Figure 5.15).

FIGURE 5.15 Dune succession on the shores of Lake Michigan. Dune-grass shoots appear scattered on the slope, where they emerge from underground runners.

Bog Succession

A **bog** is an open body of water with surface inlets—usually small streams—but no surface outlet. As a result, the waters of a bog are quiet, flowing slowly if at all. Many bogs that exist today originated as lakes that filled depressions in the land, which in turn were created by glaciers during the Pleistocene ice age. Succession in a northern bog, such as the Livingston Bog in Michigan (Figure 5.16), begins when a sedge (a grasslike herb) puts out floating runners (Figure 5.17a, b). These runners form a complex, matlike network similar to that formed by dune grass. The stems of the sedge grow on the runners and carry out photosynthesis. Wind blows particles onto the mat, and soil, of a kind, develops. Seeds of other plants, instead of falling into the water, land on the mat and can germinate. The floating mat becomes thicker as small shrubs and trees, adapted to wet environments, grow. In the North, these include species of the blueberry family.

FIGURE 5.16 **Livingston Bog,** a famous bog in the northern part of Michigan's lower peninsula.

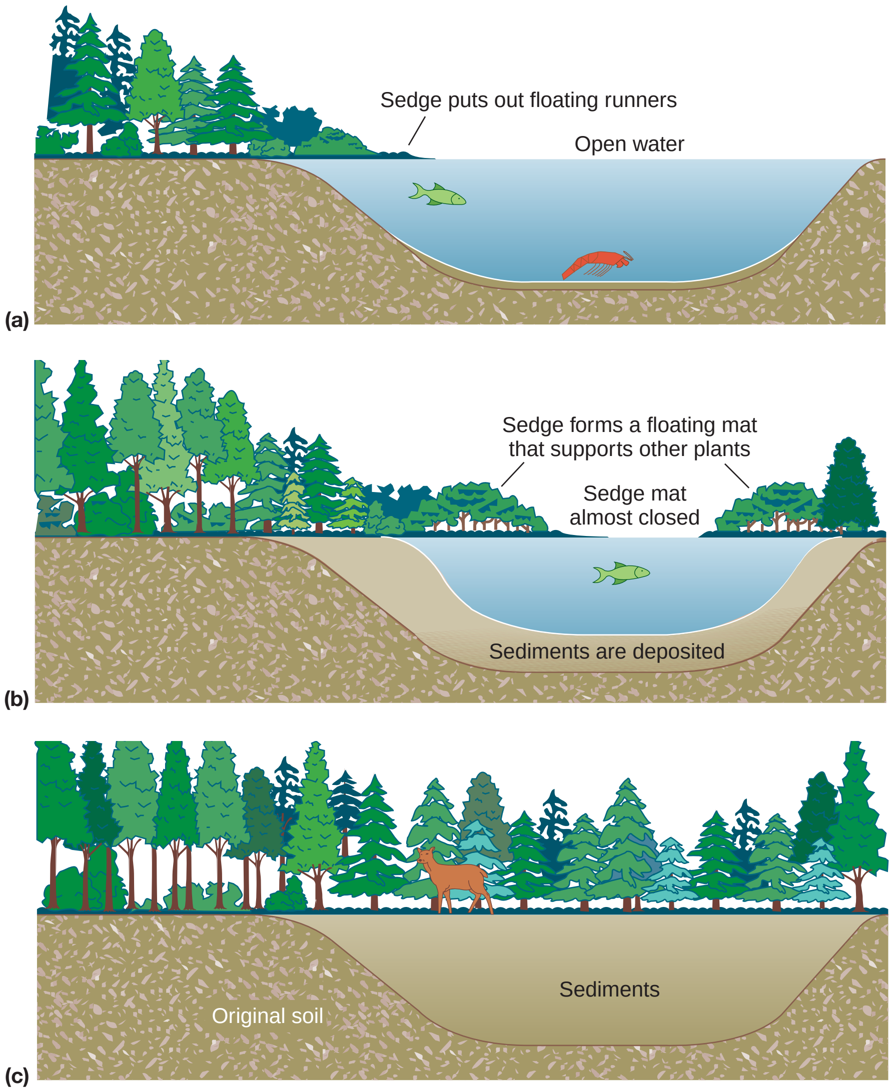


FIGURE 5.17 **Diagram of bog succession.** Open water **(a)** is transformed through formation of a floating mat of sedge and deposition of sediments **(b)** into wetland forest **(c).**

The bog also fills in from the bottom as streams carry fine particles of clay into it (Figure 5.17b, c). At the shore, the floating mat and the bottom sediments meet, forming a solid surface. But farther out, a "quaking bog" occurs. You can walk on this mat; and if you jump up and down, all the plants around you bounce and shake, because the mat is really floating. Eventually, as the bog fills in from the top and the bottom, trees grow that can withstand wetter conditions—such as northern cedar, black spruce, and balsam fir. The formerly open-water bog becomes a wetland forest. If the bog is farther south, it may eventually be dominated by beech and maple, the same species that dominate the late stages of the dunes.

Old-Field Succession

In the northeastern United States, a great deal of land was cleared and farmed in the 18th and 19th centuries. Today, much of this land has been abandoned for farming and allowed to grow back to forest (Figure 5.18). The first plants to enter the abandoned farmlands are small plants adapted to the harsh and highly variable conditions of a clearing—a wide range of temperatures and precipitation. As these plants become established, other, larger plants enter. Eventually, large trees grow, such as sugar maple, beech, yellow birch, and white pine, forming a dense forest.

Since these three different habitats—one dry (the dunes), one wet (the bog), and one in between (the old field)—tend to develop into similar forests, early ecologists believed that this late stage was in fact a steady-state condition. They referred to it as the "climatic climax," meaning that it was the final, ultimate, and permanent stage to which all land habitats would proceed if undisturbed by people. Thus, the examples of succession were among the major arguments in the early 20th century that nature did in fact achieve a constant condition, a steady state, and there actually was a balance of nature. We know today that this is not true, a point we will return to later.

Coral Reef Succession

Coral reefs (Figure 5.19) are formed in shallow warm waters by corals, small marine animals that live in colonies and are members of the phylum Coelenterata, which also includes sea anemones and jellyfishes. Corals have a whorl of tentacles surrounding the mouth, and feed by catching prey, including planktonic algae, as it passes by. The corals settle on a solid surface and produce a hard polyp of calcium carbonate (in other words, limestone). As old individuals die, this hard material becomes the surface on which new individuals establish themselves. In addition to the coelenterates, other limestone-shell-forming organisms—algae, corals, snails, urchins—live and die on the reef and are glued together primarily by a kind of algae.[16] Eventually a large and complex structure results involving many other species, including autotrophs and heterotrophs, creating one of the most species-diverse of all kinds of ecosystems. Highly valued for this diversity, for production of many edible fish, for the coral itself (used in various handicrafts and arts), and for recreation, coral reefs attract lots of attention.

Succession, in Sum

Even though the environments are very different, these four examples of ecological succession—dune, bog, old field, and coral reef—have common elements found in most ecosystems:

1. An initial kind of autotroph (green plants in three of the examples discussed here; algae and photosynthetic bacteria in marine systems; algae and photosynthetic bacteria, along with some green plants in some freshwater and near-shore marine systems). These are typically small in stature and specially adapted to the unstable conditions of their environment.

FIGURE 5.18 Old-growth eastern deciduous forest.

FIGURE 5.19 Hawaiian coral reef.

2. A second stage with autotrophs still of small stature, rapidly growing, with seeds or other kinds of reproductive structures that spread rapidly.
3. A third stage in which larger autotrophs—like trees in forest succession—enter and begin to dominate the site.
4. A fourth stage in which a mature ecosystem develops.

Although we list four stages, it is common practice to combine the first two and speak of early-, middle-, and late-successional stages. The stages of succession are described here in terms of autotrophs, but similarly adapted animals and other life-forms are associated with each stage. We discuss other general properties of succession later in this chapter.

Species characteristic of the early stages of succession are called pioneers, or **early-successional species**. They have evolved and are adapted to the environmental conditions in early stages of succession. In terrestrial ecosystems, vegetation that dominates late stages of succession, called **late-successional species**, tends to be slower-growing and longer-lived, and can persist under intense competition with other species. For example, in terrestrial ecosystems, late-successional vegetation tends to grow well in shade and have seeds that, though not as widely dispersing, can persist a rather long time. Typical **middle-successional species** have characteristics in between the other two types.

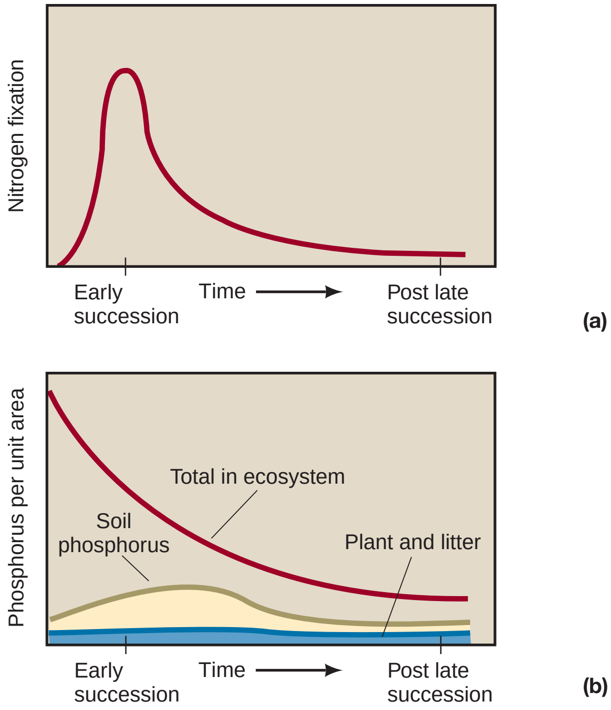


FIGURE 5.20 **(a)** Hypothesized changes in soil nitrogen during the course of soil development. **(b)** Change in total soil phosphorus over time with soil development. (P.M. Vitousek and P.S. White, Process studies in forest succession, in D.C. West, H.H. Shugart, and D.B. Botkin, eds., [New York: Springer-Verlag, 1981], Figure 17.1, p. 269.)

5.8 Chemical Cycling and Succession

One of the important effects of succession is a change in the storage of chemical elements necessary for life. On land, the storage of chemical elements essential for plant growth and function (including nitrogen, phosphorus, potassium, and calcium) generally increases during the progression from the earliest stages of succession to middle succession (Figure 5.20). There are three reasons for this:

Increased storage. Organic matter, living or dead, stores chemical elements. As long as there is an increase in organic matter within the ecosystem, there will be an increase in the storage of chemical elements.

Increased rate of uptake. For example, in terrestrial ecosystems. many plants have root nodules containing bacteria that can assimilate atmospheric nitrogen, which is then used by the plant in a process known as *nitrogen fixation.*

Decreased rate of loss. The presence of live and dead organic matter helps retard erosion. Both organic and inorganic soil can be lost to erosion by wind and water. Vegetation and, in certain marine and freshwater ecosystems, large forms of algae tend to prevent such losses and therefore increase total stored material.

Ideally, chemical elements could be cycled indefinitely in ecosystems, but in the real world there is always some loss as materials are moved out of the system by wind and water. As a result, ecosystems that have persisted continuously for the longest time are less fertile than those in earlier stages. For example, where glaciers melted back thousands of years ago in New Zealand, forests developed, but the oldest areas have lost much of their fertility and have become shrublands with less diversity and biomass. The same thing happened to ancient sand dune vegetation in Australia.[17]

5.9 How Species Change Succession

Early-successional species can affect what happens later in succession in three ways: through (1) facilitation, (2) interference, or (3) life history differences (Figure 5.21).[18,19]

Facilitation

In facilitation, an earlier-successional species changes the local environment in ways that make it suitable for another species that is characteristic of a later successional stage. Dune and bog succession illustrate facilitation. The first plant species—dune grass and floating sedge—prepare the way for other species to grow. Facilitation is common in tropical rain forests,[20] where early-successional species

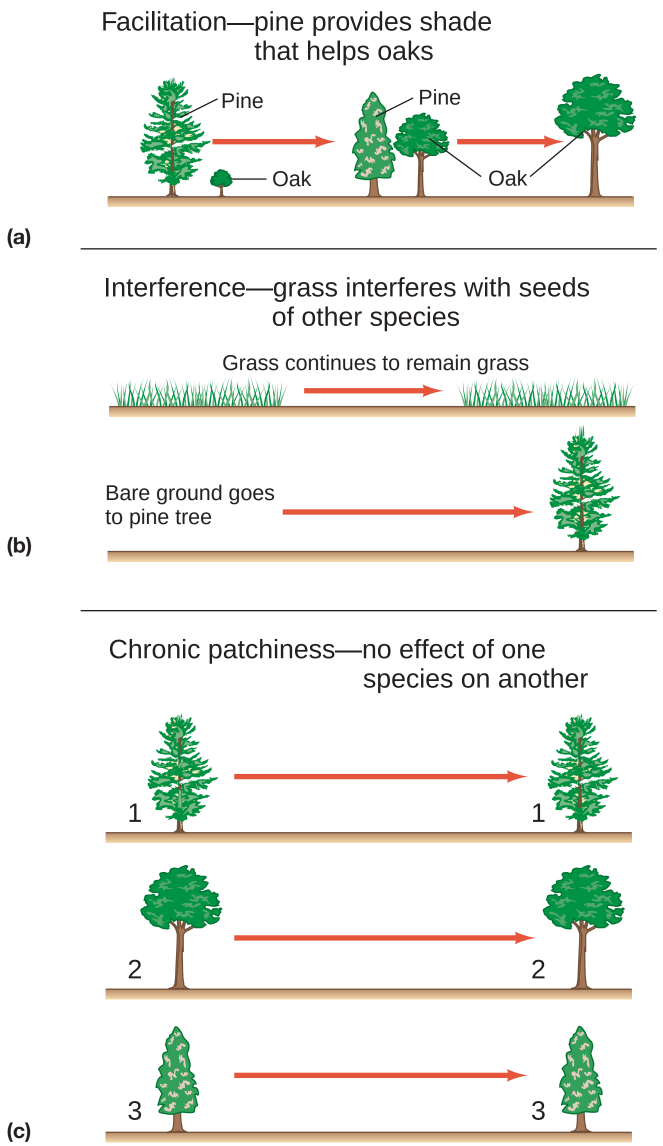


FIGURE 5.21 Interaction among species during ecological succession. (a) Facilitation. As Henry David Thoreau observed in Massachusetts more than 100 years ago, pines provide shade and act as "nurse trees" for oaks. Pines do well in openings. If there were no pines, few or no oaks would survive. Thus the pines facilitate the entrance of oaks. **(b) Interference.** Some grasses that grow in open areas form dense mats that prevent seeds of trees from reaching the soil and germinating. **(c) Chronic patchiness.** Earlier-entering species neither help nor interfere with other species; instead, as in a desert, the physical environment dominates.

speed the reappearance of the microclimatic conditions that occur in a mature forest. Because of the rapid growth of early-successional plants, after only 14 years the temperature, relative humidity, and light intensity at the soil surface in tropical forests can approximate those of a mature rain forest.[21] Once these conditions are established, species adapted to deep forest shade can germinate and persist.

Facilitation also occurs in coral reefs, mangrove swamps along ocean shores, kelp beds along cold ocean shores such as the Pacific coast of the United States and Canada's Pacific Northwest, and in shallow marine benthic areas where the water is relatively calm and large algae can become established.

Knowing the role of facilitation can be useful in the restoration of damaged areas. Plants that facilitate the presence of others should be planted first. On sandy areas, for example, dune grasses can help hold the soil before we attempt to plant shrubs or trees.

Interference

In contrast to facilitation, interference refers to situations where an earlier-successional species changes the local environment so it is *unsuitable* to another species characteristic of a later-successional stage. Interference is common, for example, in American tall-grass prairies, where prairie grasses like little bluestem form a mat of living and dead stems so dense that seeds of other plants cannot reach the ground and therefore do not germinate. Interference does not last forever, however. Eventually, some breaks occur in the grass mat—perhaps from surface-water erosion, the death of a patch of grass from disease, or removal by fire. Breaks in the grass mat allow seeds of trees to germinate. For example, in the tall-grass prairie, seeds of red cedar can then reach the ground. Once started, red cedar soon grows taller than the grasses, shading them so much that they cannot grow. More ground is open, and the grasses are eventually replaced.

The same pattern occurs in some Asian tropical rain forests. The grass, *Imperata*, forms stands so dense that seeds of later-successional species cannot reach the ground. *Imperata* either replaces itself or is replaced by bamboo, which then replaces itself. Once established, *Imperata* and bamboo appear able to persist for a long time. Once again, when and if breaks occur in the cover of these grasses, other species can germinate and grow, and a forest eventually develops.

Life History Differences

In this case, changes in the time it takes different species to establish themselves give the appearance of a succession caused by species interactions, but it is not. In cases where no species interact through succession, the result is termed **chronic patchiness**. Chronic patchiness is characteristic of highly disturbed environments and highly stressful ones in terms of temperature, precipitation, or chemical availability, such as deserts. For example, in the warm deserts of California, Arizona, and Mexico, the major shrub species grow in patches, often consisting of mature individuals with few seedlings. These patches tend to persist for long periods until there is a disturbance.[22] Similarly, in highly polluted environments, a sequence of species replacement may not occur. Chronic patchiness also describes planktonic ecological communities and their ecosystems, which occur in the constantly moving waters of the upper ocean and the upper waters of ponds, lakes, rivers, and streams.

CRITICAL THINKING ISSUE

Should People Eat Lower on the Food Chain?

The energy content of a food chain is often represented by an energy pyramid, such as the one shown here in Figure 5.22a for a hypothetical, idealized food chain. In an energy pyramid, each level of the food chain is represented by a rectangle whose area is more or less proportional to the energy content of that level. For the sake of simplicity, the food chain shown here assumes that each link in the chain has only one source of food.

Assume that if a 75 kg (165 lb) person ate frogs (and some people do!), he would need 10 a day, or 3,000 a year (approximately 300 kg, or 660 lb). If each frog ate 10 grasshoppers a day, the 3,000 frogs would require 9 million grasshoppers a year to supply their energy needs, or approximately 9,000 kg (19,800 lb) of grasshoppers. A horde of grasshoppers of that size would require 333,000 kg (732,600 lb) of wheat to sustain them for a year.

As the pyramid illustrates, the energy content decreases at each higher level of the food chain. The result is that the amount of energy at the top of a pyramid is related to the number of layers the pyramid has. For example, if people fed on grasshoppers rather than frogs, each person could probably get by on 100 grasshoppers a day. The 9 million grasshoppers could support 300 people for a year, rather than only one. If, instead of grasshoppers, people ate wheat, then 333,000 kg of wheat could support 666 people for a year.

This argument is often extended to suggest that people should become herbivores (vegetarians) and eat directly from the lowest level of all food chains, the autotrophs. Consider, however, that humans can eat only parts of some plants. Herbivores can eat some parts of plants that humans cannot eat, and some plants that humans cannot eat at all. When people eat these herbivores, more of the energy stored in plants becomes available for human consumption.

The most dramatic example of this is in aquatic food chains. Because people cannot digest most kinds of algae, which are the base of most aquatic food chains, they depend on eating fish that eat algae and fish that eat other fish. So if people were to become entirely herbivorous, they would be excluded from many food chains. In addition, there are major areas of Earth where crop production damages the land but grazing by herbivores does not. In those cases, conservation of soil and biological diversity lead to arguments that support the use of grazing animals for human food. This creates an environmental issue: How low on the food chain should people eat?

Critical Thinking Questions

1. Why does the energy content decrease at each higher level of a food chain? What happens to the energy lost at each level?
2. The pyramid diagram uses mass as an indirect measure of the energy value for each level of the pyramid. Why is it appropriate to use mass to represent energy content?
3. Using the average of 21 kilojoules (kJ) of energy to equal 1 g of completely dried vegetation (see Working It Out 5.2) and assuming that wheat is 80% water, what is the energy content of the 333,000 kg of wheat shown in the pyramid?
4. Make a list of the environmental arguments for and against an entirely vegetarian diet for people. What might be the consequences for U.S. agriculture if everyone in the country began to eat lower on the food chain?
5. How low do you eat on the food chain? Would you be willing to eat lower? Explain.

FIGURE 5.22 **(a)** Energy pyramid. **(b)** Grasshoppers. **(c)** Frogs that eat grasshoppers.

SUMMARY

- An ecosystem is the simplest entity that can sustain life. At its most basic, an ecosystem consists of several species and a fluid medium (air, water, or both). The ecosystem must sustain two processes—the cycling of chemical elements and the flow of energy.
- The living part of an ecosystem is the ecological community, a set of species connected by food webs and trophic levels. A food web or food chain describes who feeds on whom. A trophic level consists of all the organisms that are the same number of feeding steps from the initial source of energy.
- Community-level effects result from indirect interactions among species, such as those that occur when sea otters influence the abundance of sea urchins.
- Ecosystems are real and important, but it is often difficult to define the limits of a system or to pinpoint all the interactions that take place. Ecosystem management is considered key to the successful conservation of life on Earth.
- Energy flows one way through an ecosystem; the second law of thermodynamics places a limit on the abundance of productivity of life and requires the one-way flow.
- Chemical elements cycle, and in theory could cycle forever, but in the real world there is always some loss.
- Ecosystems recover from changes through ecological succession, which has repeatable patterns.
- Ecosystems are non-steady-state systems, undergoing changes all the time and requiring change.

REEXAMINING THEMES AND ISSUES

Human Population

The human population depends on many ecosystems that are widely dispersed around the globe. Modern technology may appear to make us independent of these natural systems. In fact, though, the more connections we establish through modern transportation and communication, the more kinds of ecosystems we depend on. Therefore, the ecosystem concept is one of the most important we will learn about in this book.

Sustainability

The ecosystem concept is at the heart of managing for sustainability. When we try to conserve species or manage living resources so that they are sustainable, we must focus on their ecosystem and make sure that it continues to function.

Global Perspective

Our planet has sustained life for approximately 3.5 billion years. To understand how Earth as a whole has sustained life for such a long time, we must understand the ecosystem concept because the environment at a global level must meet the same basic requirements as those of any local ecosystem.

Urban World

Cities are embedded in larger ecosystems. But like any life-supporting system, a city must meet basic ecosystem needs. This is accomplished through connections between cities and surrounding environments. Together, these function as ecosystems or sets of ecosystems. To understand how we can create pleasant and sustainable cities, we must understand the ecosystem concept.

People and Nature

The feelings we get when we hike through a park or near a beautiful lake are as much a response to an ecosystem as to individual species. This illustrates the deep connection between people and ecosystems. Also, many effects we have on nature are at the level of an ecosystem, not just on an individual species.

Science and Values

The introductory case study about sea otters, sea urchins, and kelp illustrates the interactions between values and scientific knowledge about ecosystems. Science can tell us how organisms interact. This knowledge confronts us with choices. Do we want abalone to eat, sea otters to watch, kelp forests for biodiversity? The choices we make depend on our values.

KEY TERMS

STUDY QUESTIONS

1. Farming has been described as managing land to keep it in an early stage of succession. What does this mean, and how is it achieved?
2. Redwood trees reproduce successfully only after disturbances (including fire and floods), yet individual redwood trees may live more than 1,000 years. Is redwood an early- or late-successional species?
3. What is the difference between an ecosystem and an ecological community?
4. What is the difference between the way energy puts limits on life and the way phosphorus does so?
5. Based on the discussion in this chapter, would you expect a highly polluted ecosystem to have many species or few species? Is our species a keystone species? Explain.
6. Keep track of the food you eat during one day and make a food chain linking yourself with the sources of those foods. Determine the biomass (grams) and energy (kilocalories) you have eaten. Using an average of 5 kcal/g, then using the information on food packaging or assuming that your net production is 10% efficient in terms of the energy intake, how much additional energy might you have stored during the day? What is your weight gain from the food you have eaten?
7. Which of the following are ecosystems? Which are ecological communities? Which are neither?
   (a) Chicago
   (b) A 1,000-ha farm in Illinois
   (c) A sewage-treatment plant
   (d) The Illinois River
   (e) Lake Michigan

FURTHER READING

Modern Studies

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Odum, Eugene, and G.W. Barrett, ***Fundamentals of Ecology*** (Duxbury, MA: Brooks/Cole, 2004). Odum's original textbook was a classic, especially in providing one of the first serious introductions to ecosystem ecology. This is the latest update of the late author's work, done with his protégé.

Schrödinger, E. (ed. Roger Penrose), ***What Is Life?: With Mind and Matter and Autobiographical Sketches (Canto)*** (Cambridge: Cambridge University Press, 1992). The original statement about how the use of energy differentiates life from other phenomena in the universe. Easy to read and a classic.

CHAPTER 6

The Biogeochemical Cycles

As a result of biogeochemical cycles marine life is plentiful in the Santa Barbara Channel of southern California.

LEARNING OBJECTIVES

Life is composed of many chemical elements, which have to be available in the right amounts, the right concentrations, and the right ratios to one another. If these conditions are not met, then life is limited. The study of chemical availability and biogeochemical cycles—the paths chemicals take through Earth's major systems—is important in solving many environmental problems. After reading this chapter, you should understand . . .

- What the major biogeochemical cycles are;
- How life, over the Earth's history, has greatly altered chemical cycles;
- The major factors and processes that control biogeochemical cycles;
- Why some chemical elements cycle quickly and some slowly;
- How each major component of Earth's global system (the atmosphere, waters, solid surfaces, and life) is involved and linked with biogeochemical cycles;
- How the biogeochemical cycles most important to life, especially the carbon cycle, generally operate;
- How humans affect biogeochemical cycles.

CASE STUDY

Methane and Oil Seeps: Santa Barbara Channel

The Santa Barbara Channel off the shore of southern and central California is home to numerous species, including such marine mammals as dolphins, sea otters, elephant seals, sea lions, harbor seals, and blue, humpback, and gray whales; many birds, including brown pelicans; and a wide variety of fish. The channel is also a region with large oil and gas resources that have been exploited by people for thousands of years.[1,2,3] For centuries, Native Americans who lived along the shoreline collected tar from oil seeps to seal baskets and the planks of their seagoing canoes. During the last century, oil wells on land and from platforms anchored on the seabed have been extracting oil and gas. Oil and gas are hydrocarbons, and as such are part of the global carbon cycle that involves physical, geological, biological, and chemical processes.

The story of oil and gas in the Santa Barbara Channel begins 6–18 million years ago with the deposition of a voluminous amount of fine sediment, enriched with planktonic microorganisms whose bodies sank to the ocean floor and were buried. (*Planktonic* refers to small floating algae and animals.) Over geologic time, the sediment was transformed into sedimentary rock, and the organic material was transformed by heat and pressure into oil and gas. About a million or so years ago, tectonic uplift and fracturing forced the oil and gas toward the surface. Oil and gas seepage has reached the surface for at least 120,000 years and perhaps more than half a million years.

Some of the largest seeps of oil and natural gas (primarily methane) are offshore of the University of California, Santa Barbara, at Coal Oil Point, where about 100 barrels of oil and approximately 57,000 m^3 (2 million cubic feet) of gas are released per day (Figures 6.1 and 6.2). To put the amount of oil in perspective, the 1989 *Exxon Valdez* tanker accident in Prince William Sound released about 250,000 barrels of oil. Thus, the oil seeping from the Coal Oil Point area alone equals one *Exxon Valdez* accident every seven years. This is a tremendous amount of oil to be added to the marine environment.

Sudden emissions of gases create small pits on the seafloor. The gas rises as clouds of bubbles clearly visible at the surface (Figure 6.2b and c). Once at the surface, the oil and gas form slicks that are transported by marine currents and wind. On the seafloor, the heaviest materials form mounds of tar several meters or more in diameter.[3] Some of the thicker tar washes up on local beaches, sometimes covering enough of the water and beach to stick to the bare skin of walkers and swimmers. Tar may be found on beaches for several kilometers to the east.

FIGURE 6.1 **Coal Oil Point, Santa Barbara**, the location of large offshore oil and gas seeps on one of America's most beautiful coastlines. Active oil and gas seeps are located from near the shore to just past offshore platform Holly that has many pumping oil wells.

The emitted hydrocarbon gases contribute to air pollution in the Santa Barbara area. Once in the atmosphere, they interact with sunlight to produce smog, much like the smog produced by hydrocarbon emissions from automobiles in Los Angeles. If all the methane ended up in the atmosphere as hydrocarbons, the contribution to air pollution in Santa Barbara County would be about double the emission rate from all on-road vehicles in Santa Barbara County.

Fortunately for us, seawater has a tremendous capacity to take up the methane, and bacteria in the ocean feed on the methane, releasing carbon dioxide (Figure 6.2a). The ocean and its bacteria thus take care of about half the methane moving up from the seeps. Thanks to microbial decomposition of the methane, only about 1% of the methane that is dissolved in the seawater is emitted into the atmosphere.[1, 2]

Even so, in recent years people have taken action to further control the oil and gas seeps at Coal Oil Point. Two steel seep tents (each 30 m by 30 m) have been placed over some of the methane seeps, and the gas is collected and moved to the shore through pipelines, for use as natural gas. Furthermore, the pumping of oil from a single well from a nearby platform with many wells apparently has reduced emissions of methane and oil from the seeps. What drives methane emission is pressure from below, and pumping from the wells evidently reduces that pressure.

The lesson from the methane and oil seeps at Coal Oil Point is twofold: first, that this part of the carbon cycle is a complex linkage of physical, biological, and chemical processes; and second, that human activity may also play a role. These two concepts will be a recurring theme in our discussion of the major biogeochemical cycles that concern us today.

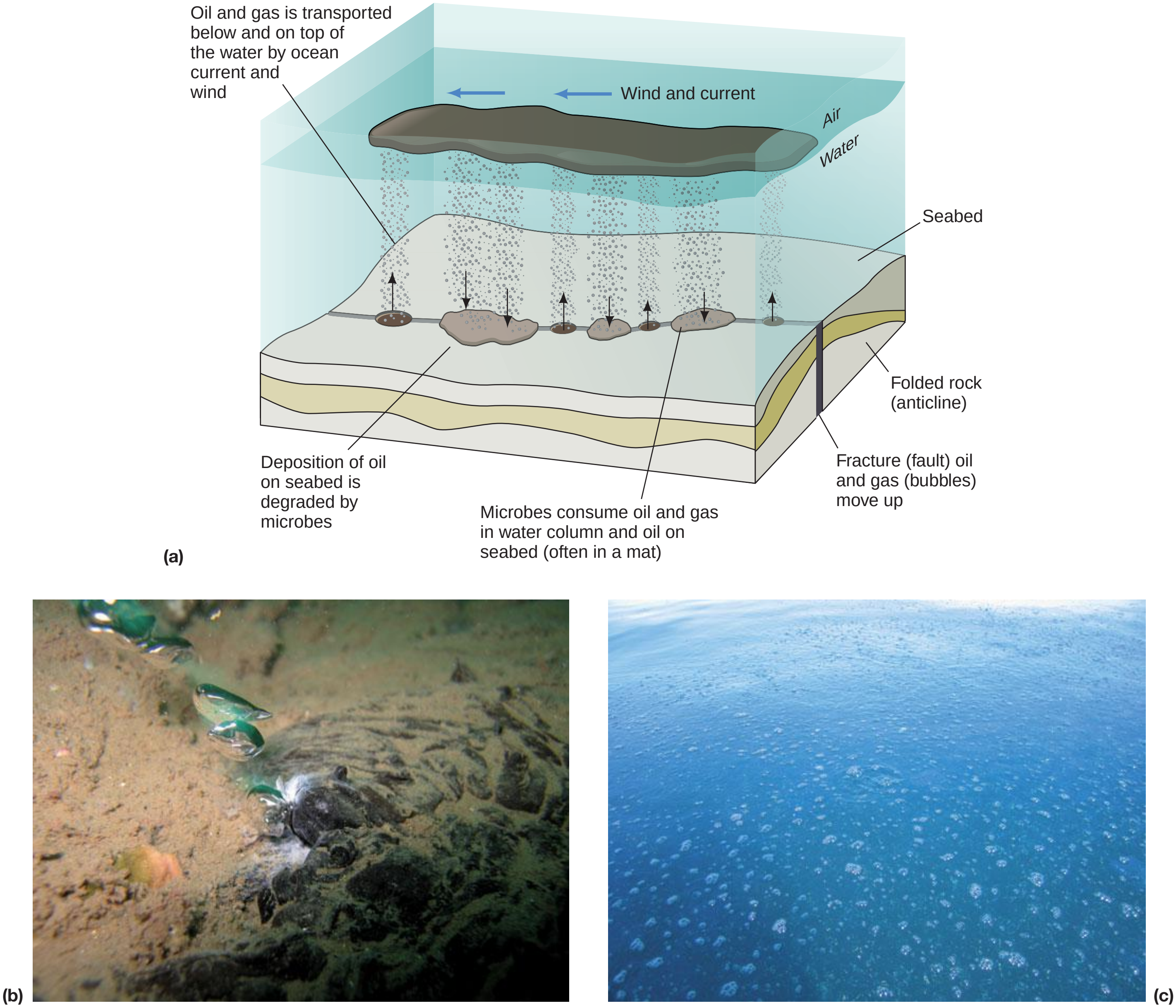
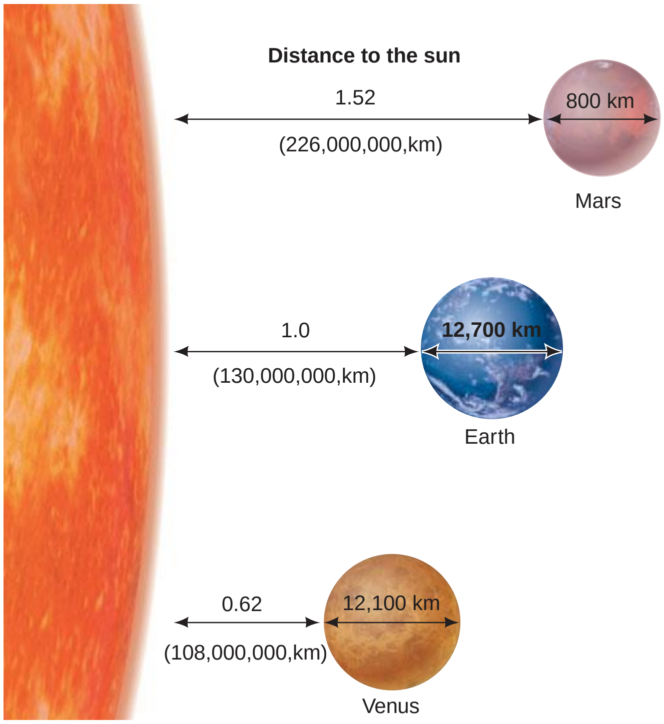


FIGURE 6.2 **(a)** Idealized diagram of physical, chemical, and biological processes with shallow methane and oil seeps; **(b)** small bubbles of methane (~1 cm) from a seep at Coal Oil Point on the seabed; and **(c)** methane bubbles (~1 cm) at the surface. (*Photographs courtesy of David Valentine.*)

6.1 Earth Is a Peculiar Planet

Our planet, Earth, is unique, at least to the extent that we have explored the cosmos. In our solar system, and in the Milky Way galaxy to the extent that we have observed it, Earth is the only body that has the combination of four characteristics: liquid water; water at its triple point (gas, liquid, and solid phases at the same time); plate tectonics; and life (Figure 6.3). (Recent space probes to the moons of Jupiter and Saturn suggest that there may be liquid water on a few of these and perhaps also an equivalent of plate tectonics. And recent studies of Mars suggest that liquid water has broken through to the surface on occasion in the past, causing Earthlike water erosion.)

The above discussion leads to consideration of the history of Earth over billions of years. This has prompted some geologists to propose "big history"—to link contemporary history with geologic history, perhaps even going back all the way to the *Big Bang*



Atmosphere	Venus	Earth	Mars
Carbon dioxide	98%	0.03%	96%
Hydrogen	1.9%	73%	2.7%
Oxygen	Trace	21%	0.13%
Argon	0.1%	1%	2%
Total Pressure (bars)	90	1	0.00
Surface temperature	447°C	13°C	−53°C

FIGURE 6.3 Venus, Earth, and Mars. These three planets had a common origin and should be similar. They are within a factor of 2 in size and distance from the sun, and the atmospheres of Mars and Venus are similar in chemical makeup. Earth's atmosphere, however, is very different.

12 billion years ago, when our universe was born.[4,5] The main regimes of big history include cosmos, Earth, and life. To this, in the context of environmental science, we add human history.[4,5]

Space Travelers and Our Solar System

Life changes the cycling of chemical elements on Earth and has done so for several billion years.[6] To begin to examine this intriguing effect of life at a global level, it is useful to imagine how travelers from another solar system might perceive our planet. Imagine these space travelers approaching our solar system. They find that their fuel is limited and that of the four inner planets, only two, the second (Venus) and the fourth (Mars), are on their approach path. By chance, and because of differences in the orbits of the planets, the first (Mercury) and the third (Earth) are both on the opposite side of the sun, not easily visible for their instruments to observe or possible for their spacecraft to approach closely. However, they can observe Mars and Venus as they fly by them, and from those observations hypothesize about the characteristics of the planet whose orbit is between those two—Earth (Figure 6.4).

The space travelers' instruments tell them that the atmospheres of Venus and Mars are primarily carbon dioxide, with some ammonia (nitrogen combined with hydrogen) and trace amounts of nitrogen, oxygen, argon, and the other "noble gases"—that is, elements like argon that form few compounds. Since the space travelers understand how solar systems originate, they know that the inner planets are formed by the gathering together of particles as a result of gravitational force. Therefore, they believe that the second, third, and fourth planets should have a similar composition, and this leads them to believe that it is reasonable to assume the third planet will have an atmosphere much like that of Venus and Mars.

Suppose a later space flight from the same solar system visits ours once again, but this time it is able to approach Earth. Knowing the results of the previous voyage, the new travelers are surprised to discover that Earth's atmosphere is entirely different from those of Venus and Mars. It is composed primarily (78%) of free (molecular) nitrogen (N_2), with about 20% oxygen, a trace of

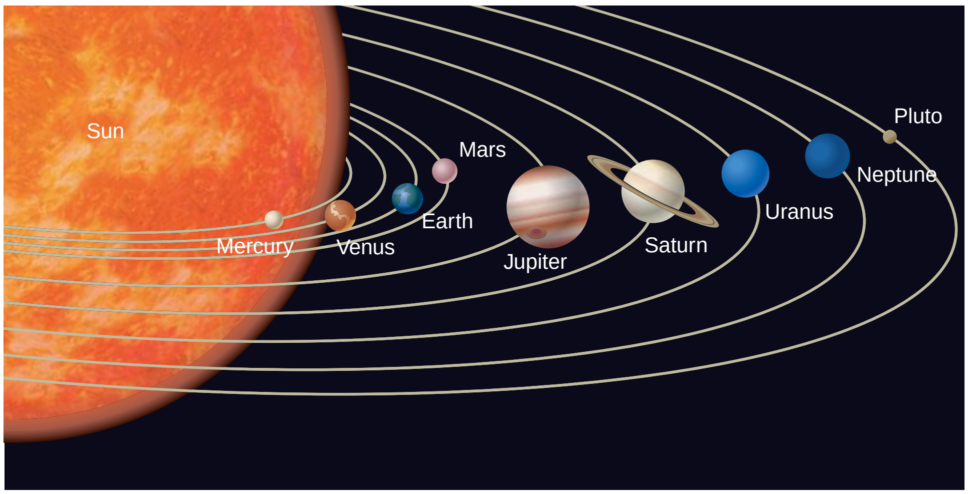


FIGURE 6.4 Our solar system with the planets (Pluto is not classified as a planet) shown from NASA space probes. Imagine travel to this system from another and wondering what the third planet was like.

carbon dioxide and other gases, and some argon. What has caused this great difference? Because they are trained in science and in the study of life in the universe, and because they come from a planet that has life, these space travelers recognize the cause immediately: *Earth must contain life.* Life changes its planet's atmosphere, oceans, and upper surfaces. Even without seeing life directly, they know from its atmosphere that Earth is a "living" planet.

The great 20th-century ecologist G. Evelyn Hutchinson described this phenomenon succinctly. The strangest characteristic of Earth's surface, he wrote, is that it is not in thermodynamic equilibrium, which is what would happen if you were able to carry out a giant experiment in which you took Earth, with its atmosphere, oceans, and solid surfaces, and put it into a closed container sealed against the flow of energy and matter. Eventually the chemistry of the air, water, and rocks would come into a chemical and physical fixed condition where the energy was dispersed as heat and there would be no new chemical reactions. Physicists will tell you that everything would be at the lowest energy level, that matter and energy would be dispersed randomly, and nothing would be happening. This is called the **thermodynamic equilibrium**. In this giant experiment, this equilibrium would resemble that in the atmospheres of Mars and Venus, and Earth's atmosphere would be very different from the way it is now.

Life on Earth acts as a pump to keep the atmosphere, ocean, and rocks far from a thermodynamic equilibrium. The highly oxygenated atmosphere is so far from a thermodynamic equilibrium that it is close to an explosive combination with the organic matter on the Earth. James Lovelock, the originator of the Gaia hypothesis, has written that if the oxygen concentration in the atmosphere rose a few percentage points, to around 22% or higher, fires would break out spontaneously in dead wood on Earth's surface.[6] It's a controversial idea, but it suggests how close the present atmosphere is to a violent disequilibrium.[7]

The Fitness of the Environment[8]

Early in the 20th century, a scientist named Lawrence Henderson wrote a book with a curious title: *The Fitness of the Environment.*[9] In this book, Henderson observed that the environment on Earth was peculiarly suited to life. The question was, how did this come about? Henderson sought to answer this question in two ways: first, by examining the cosmos and seeking an answer in the history of the universe and in fundamental characteristics of the universe; second, by examining the properties of Earth and trying to understand how these may have come about.

"In the end there stands out a perfectly simple problem which is undoubtedly soluble," Henderson wrote. "In what degree are the physical, chemical, and general meteorological characteristics of water and carbon dioxide and of the compounds of carbon, hydrogen, and oxygen favorable to a mechanism which must be physically, chemically, and physiologically complex, which must be itself well regulated in a well-regulated environment, and which must carry on an active exchange of matter and energy with that environment?" In other words, to what extent are the nonbiological properties of the global environment favorable to life? And why is Earth so fit for life?

Today, we can give partial answers to Henderson's question. The answers involve recognizing that "environmental fitness" is the result of a two-way process. Life evolved in an environment conducive for that to occur, and then, over time, life altered the environment at a global level. These global alterations were originally problems for existing organisms, but they also created opportunities for the evolution of new life-forms adapted to the new conditions.

The Rise of Oxygen

The fossil record provides evidence that before about 2.3 billion years ago Earth's atmosphere was very low in oxygen (anoxic), much closer to the atmospheres of Mars and Venus. The evidence for this exists in water-worn grains of pyrite (iron sulfide, FeS_2), which appear in sedimentary rocks formed before 2.3 billion years ago. Today, when pure iron gets into streams, it is rapidly oxidized because there is so much oxygen in the atmosphere, and the iron forms sediments of iron oxides (what we know familiarly as rusted iron). If there were similar amounts of oxygen in the ancient waters, these ancient deposits would not have been pyrite—iron combined with sulfur—but would have been oxidized, just as they are today. This tells us that Earth's ancient Precambrian atmosphere and oceans were low in oxygen.

The ancient oceans had a vast amount of dissolved iron, which is much more soluble in water in its unoxidized state. Oxygen released into the oceans combined with the dissolved iron, changing it from a more soluble to a less soluble form. No longer dissolved in the water, the iron settled (precipitated) to the bottom of the oceans and became part of deposits that slowly were turned into rock. Over millions of years, these deposits formed the thick bands of iron ore that are mined today all around Earth, with notable deposits found today from Minnesota to Australia. That was the major time when the great iron ore deposits, now mined, were formed. It is intriguing to realize that very ancient Earth history affects our economic and environmental lives today.

FIGURE 6.5 Banded-iron formations. Photograph of the Grand Canyon showing red layers that contain oxidized iron below layers of other colors that lack the deposited iron.

The most convincing evidence of an oxygen-deficient atmosphere is found in ancient chemical sediments called *banded-iron formations* (Figure 6.5).

These sediments were laid down in the sea, a sea that must have been able to carry dissolved iron—something it can't do now because oxygen precipitates the iron. If the ancient sea lacked free oxygen, then oxygen must also have been lacking in the atmosphere; otherwise, simple diffusion would have brought free oxygen into the ocean from the atmosphere.

How did the atmosphere become high enough in oxygen to change iron deposits from unoxidized to oxidized? The answer is that life changed the environment at a global level, adding free oxygen and removing carbon dioxide, first within the oceans, then in the atmosphere. This came about as a result of the evolution of photosynthesis. In photosynthesis, you will recall, carbon dioxide and water are combined, in the presence of light, to form sugar and free oxygen. But in early life, oxygen was a toxic waste that was eliminated from the cell and emitted into the surrounding environment. Scientists calculate that before oxygen started to accumulate in the air, 25 times the present-day amount of atmospheric oxygen had been neutralized by reducing agents such as dissolved iron. It took about 2 billion years for the unoxidized iron in Earth's oceans to be used up.

Life Responds to an Oxygen Environment

Early in Earth's history, from 4.6 billion years ago until about 2.3 billion years ago, was the oxygen-deficient phase of life's history. Some of the earliest photosynthetic organisms (3.4 billion years ago) were ancestors of bacteria that formed mats in shallow water (Figure 6.6). Photosynthesis became well established by about 1.9 billion years ago, but until sufficient free oxygen was in the atmosphere, organisms could get their energy only by

(a)

(b)

FIGURE 6.6 Stromatolites. Among the earliest photosynthetic organisms were bacteria that formed these large mounds called stromatolites **(a)**, fossils of which, shown here, have been dated as old as 3.4 billion years. The bacteria grew in long filaments—cells connected to one another in a line—and these formed layers that were infiltrated by sand and clay that washed down from the land into the shallow waters of the bays where this kind of photosynthetic bacteria lived (they took oxygen from water). Over time, the combination of sediments and living and dead bacterial cells formed large mounds. Similar bacteria, if not exactly the same species, still live, and form the same kind of mounds shown here in Shark Bay, Australia **(b)**. The ancient stromatolites were among the organisms that eventually created an oxygen-rich atmosphere.

fermentation, and the only kinds of organisms were bacteria and their relatives called **prokaryotes**. These have a simpler internal cell structure than that of the cells of our bodies and other familiar forms of life, known as **eukaryotes** (Figure 6.7).

Without oxygen, organisms cannot completely "burn" organic compounds. Instead, they can get some energy from what we call fermentation, whose waste products are carbon dioxide and alcohol. Alcohol is a high-energy compound that, for the cell in an oxygenless atmosphere, is a waste product that has to be gotten rid of. Fermentation's low-energy yield to the organism puts limitations on the anaerobic cell. For example:

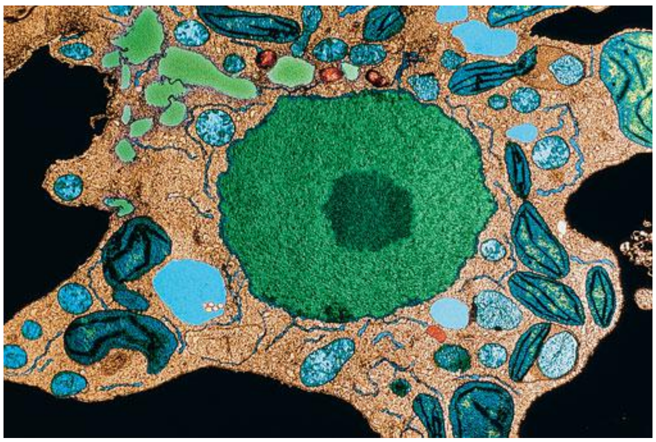
- Anaerobic cells must be small because a large surface-to-volume ratio is required to allow rapid diffusion of food in and waste out.
- Anaerobic cells have trouble keeping themselves supplied with energy. They cannot afford to use energy to maintain **organelles**—specialized cell parts that function like the organs of multicelled organisms. This means that all anaerobic bacteria were prokaryotes lacking specialized organelles, including a nucleus.
- Prokaryotes need free space around them; crowding interferes with the movement of nutrients and water into and out of the cell. Therefore, they live singly or strung end-to-end in chains. They cannot form three-dimensional structures. They are life restricted to a plane.

For other forms of life to evolve and persist, bacteria had to convert Earth's atmosphere to one high in oxygen. Once the atmosphere became high in oxygen, complete respiration was possible, and organisms could have much more complex structures, with three-dimensional bodies, and could use energy more efficiently and rapidly. Thus the presence of free oxygen, a biological product, made possible the evolution of eukaryotes, organisms with more structurally complex cells and bodies, including the familiar animals and plants. Eukaryotes can do the following:

- Use oxygen for respiration, and because oxidative respiration is much more efficient (providing more energy) than fermentation, eukaryotes do not require as large a surface-to-volume ratio as anaerobic cells do, so eukaryote cells are larger.
- Maintain a nucleus and other organelles because of their superior metabolic efficiency.
- Form three-dimensional colonies of cells. Unlike prokaryotes, aerobic eukaryotes are not inhibited by crowding, so they can exist close to each other. This made possible the complex, multicellular body structures of animals, plants, and fungi.

Animals, plants, and fungi first evolved about 700 million to 500 million years ago. Inside their cells, DNA, the genetic material, is concentrated in a nucleus rather than distributed throughout the cell, and the cell contains organelles such as mitochondria which process energy. With the appearance of eukaryotes and the growth of an oxygenated atmosphere, the **biosphere**—our planet's system that includes and sustains all life—started to change rapidly and to influence more processes on Earth.

In sum, life affected Earth's surface—not just the atmosphere, but the oceans, rocks, and soils—and it still does so today. Billions of years ago, Earth presented a habitat where life could originate and flourish. Life, in turn, fundamentally changed the characteristics of the planet's surface, providing new opportunities for life and ultimately leading to the evolution of us.

(a)


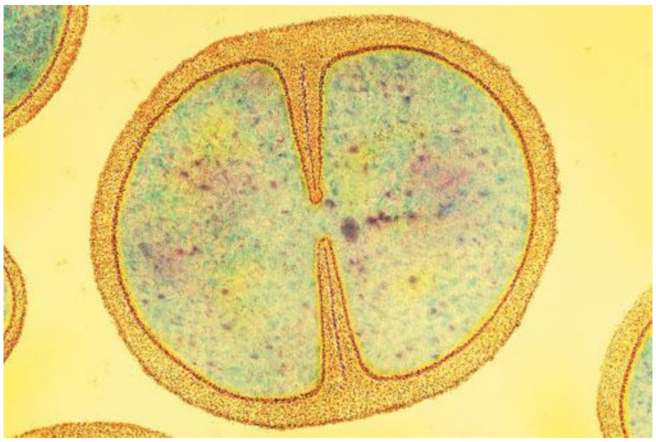

(b)

FIGURE 6.7 **Prokaryotes and eukaryotes.** Photomicrograph of **(a)** bacterial (Prokaryote)cell and **(b)** a bacterial (prokaryote) cell. From these images you can see that the eukaryotic cell has a much more complex structure, including many organelles.

6.2 Life and Global Chemical Cycles

All living things are made up of chemical elements (see Appendix D for a discussion of matter and energy), but of the more than 103 known chemical elements, only 24 are required by organisms (see Figure 6.8). These 24 are divided into the **macronutrients**, elements required in large amounts by all life, and **micronutrients**, elements required either in small amounts by all life or in moderate amounts by some forms of life and not at all by others. (*Note*: For those of you unfamiliar with the basic chemistry of the elements, we have included an introduction in Appendix E, which you might want to read now before proceeding with the rest of this chapter.)

The macronutrients in turn include the "big six" elements that are the fundamental building blocks of life: carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur. Each one plays a special role in organisms. Carbon is the basic building block of organic compounds; along with oxygen and hydrogen, carbon forms carbohydrates. Nitrogen, along with these other three, makes proteins. Phosphorus is the "energy element"—it occurs in compounds called ATP and ADP, important in the transfer and use of energy within cells.

Other macronutrients also play specific roles. Calcium, for example, is the structure element, occurring in bones and teeth of vertebrates, shells of shellfish, and wood-forming cell walls of vegetation. Sodium and potassium are important to nerve-signal transmission. Many of the metals required by living things are necessary for specific enzymes. (An enzyme is a complex organic compound that acts as a catalyst—it causes or speeds up chemical reactions, such as digestion.)

For any form of life to persist, chemical elements must be available at the right times, in the right amounts, and in the right concentrations. When this does not happen, a chemical can become a **limiting factor**, preventing the growth of an individual, a population, or a species, or even causing its local extinction.

Chemical elements may also be toxic to some life-forms and ecosystems. Mercury, for example, is toxic even in low concentrations. Copper and some other

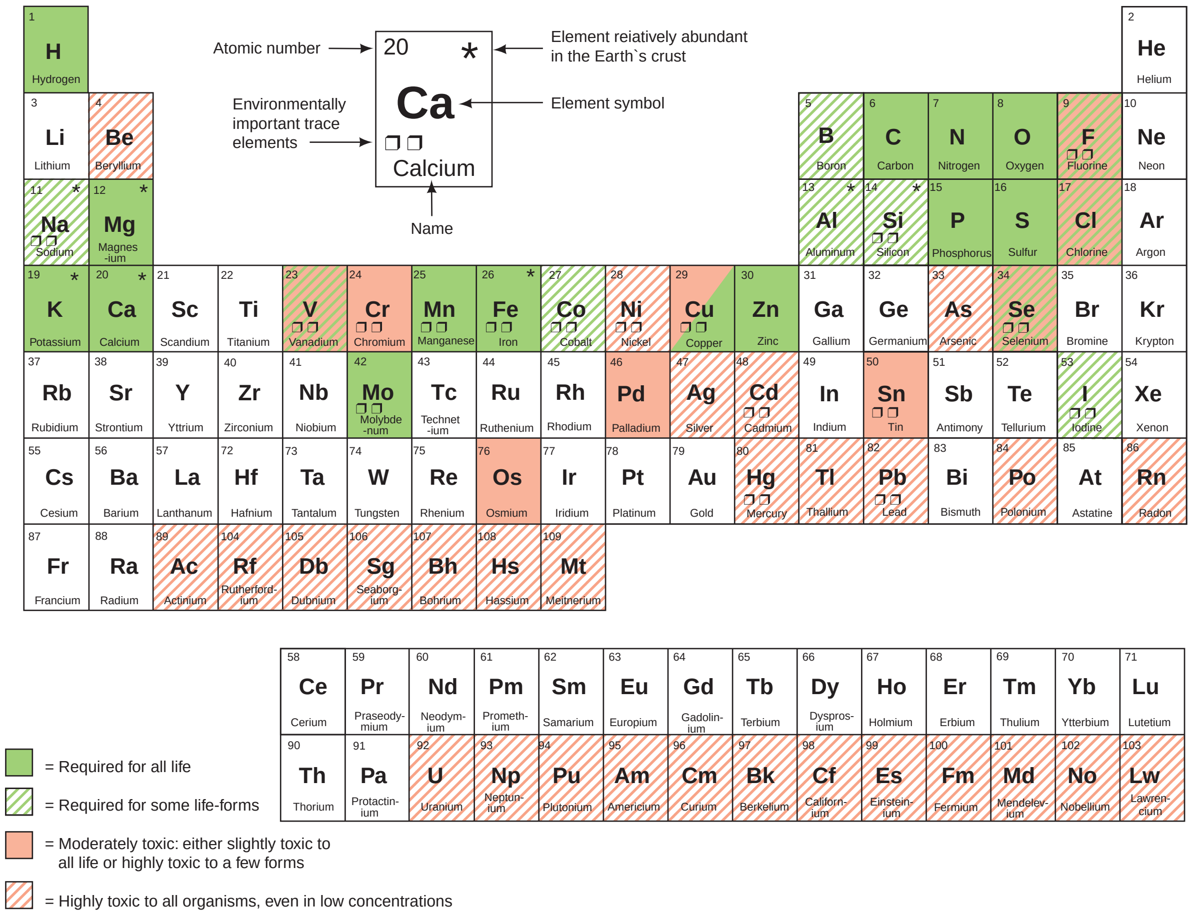


FIGURE 6.8 The Periodic Table of the Elements. The elements in green are required by all life; those in hatched green are micronutrients—required in very small amounts by all life-forms or required by only some forms of life. Those that are moderately toxic are in hatched red, and those that are highly toxic are solid red.

elements are required in low concentrations for life processes but are toxic in high concentrations.

Finally, some elements are neutral for life. Either they are chemically inert, such as the noble gases (for example, argon and neon), which do not react with other elements, or they are present on Earth in very low concentrations.

6.3 General Aspects of Biogeochemical Cycles

A **biogeochemical cycle** is the complete path a chemical takes through the four major components, or reservoirs, of Earth's system: atmosphere, hydrosphere (oceans, rivers, lakes, groundwaters, and glaciers), lithosphere (rocks and soils), and biosphere (plants and animals). A biogeochemical cycle is *chemical* because it is chemicals that are cycled, *bio-* because the cycle involves life, and *geo-* because a cycle may include atmosphere, water, rocks, and soils. Although there are as many biogeochemical cycles as there are chemicals, certain general concepts hold true for these cycles.

- Some chemical elements, such as oxygen and nitrogen, cycle quickly and are readily regenerated for biological activity. Typically, these elements have a gas phase and are present in the atmosphere and/or easily dissolved in water and carried by the hydrologic cycle (discussed later in the chapter).
- Other chemical elements are easily tied up in relatively immobile forms and are returned slowly, by geologic processes, to where they can be reused by life. Typically, they lack a gas phase and are not found in significant concentrations in the atmosphere. They also are relatively insoluble in water. Phosphorus is an example.
- Most required nutrient elements have a light atomic weight. The heaviest required micronutrient is iodine, element 53.
- Since life evolved, it has greatly altered biogeochemical cycles, and this alteration has changed our planet in many ways.
- The continuation of processes that control biogeochemical cycles is essential to the long-term maintenance of life on Earth.

Through modern technology, we have begun to transfer chemical elements among air, water, and soil, in some cases at rates comparable to natural processes. These transfers can benefit society, as when they improve crop production, but they can also pose environmental dangers, as illustrated by the opening case study. To live wisely with our environment, we must recognize the positive and negative consequences of altering biogeochemical cycles.

The simplest way to visualize a biogeochemical cycle is as a box-and-arrow diagram of a system (see the discussion of systems in Chapter 3), with the boxes representing places where a chemical is stored (*storage compartments*) and the arrows representing pathways of transfer (Figure 6.9a). In this kind of diagram, the **flow** is the amount moving from one compartment to another, whereas the **flux** is the rate of transfer—the amount per unit time—of a chemical that enters or leaves a storage compartment. The **residence time** is the average time that an atom is stored in a compartment. The donating compartment is a **source**, and the receiving compartment is a **sink**.

A biogeochemical cycle is generally drawn for a single chemical element, but sometimes it is drawn for a compound—for example, water (H_2O). Figure 6.9b shows the basic elements of a biogeochemical cycle for water, represented about as simply as it can be, as three compartments: water stored temporarily in a lake (compartment B); entering the lake from the atmosphere (compartment A) as precipitation and from the land around the lake as runoff (compartment C). It leaves the lake through evaporation to the atmosphere or as runoff via a surface stream or subsurface flows. We diagrammed the Missouri River in the opening case study of Chapter 3 in this way.

As an example, consider a salt lake with no transfer out except by evaporation. Assume that the lake contains 3,000,000 m^3 (106 million ft^3) of water and the evaporation is 3,000 m^3/day (106,000 ft^3/day). Surface runoff into the lake is also 3,000 m^3/day, so the volume of water in the lake remains constant (input = output). We can calculate the average residence time of the water in the lake as the volume of the lake divided by the evaporation rate (rate of transfer), or 3,000,000 m^3 divided by 3,000 m^3/day, which is 1,000 days (or 2.7 years).

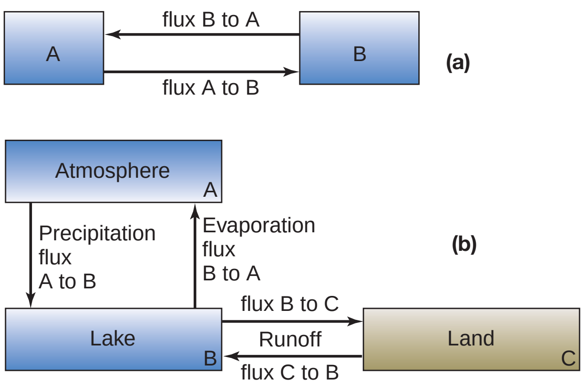


FIGURE 6.9 **(a)** A unit of a biogeochemical cycle viewed as a systems diagram; **(b)** a highly simplified systems diagram of the water cycle.

6.4 The Geologic Cycle

Throughout the 4.6 billion years of Earth's history, rocks and soils have been continuously created, maintained, changed, and destroyed by physical, chemical, and biological processes. This is another illustration that the biosphere is a dynamic system, not in steady state. Collectively, the processes responsible for formation and change of Earth materials are referred to as the **geologic cycle** (Figure 6.10). The geologic cycle is best described as a group of cycles: tectonic, hydrologic, rock, and biogeochemical. (We discuss the last cycle separately because it requires lengthier examination.)

The Tectonic Cycle

The **tectonic cycle** involves the creation and destruction of Earth's solid outer layer, the *lithosphere*. The lithosphere is about 100 km (60 mi) thick on average and is broken into several large segments called *plates*, which are moving relative to one another (Figure 6.11). The slow movement of these large segments of Earth's outermost rock shell is referred to as **plate tectonics**. The plates "float" on denser material and move at rates of 2 to 15 cm/year (0.8 to 6.9 in./year), about as fast as your fingernails grow. The tectonic cycle is driven by forces originating deep within the earth. Closer to the surface, rocks are deformed by spreading plates, which produce ocean basins, and by collisions of plates, which produce mountain ranges and island-arc volcanoes.

Plate tectonics has important environmental effects. Moving plates change the location and size of continents, altering atmospheric and ocean circulation and thereby altering climate. Plate movement has also created ecological islands by breaking up continental areas. When this happens, closely related life-forms are isolated from one another for millions of years, leading to the evolution of new species. Finally, boundaries

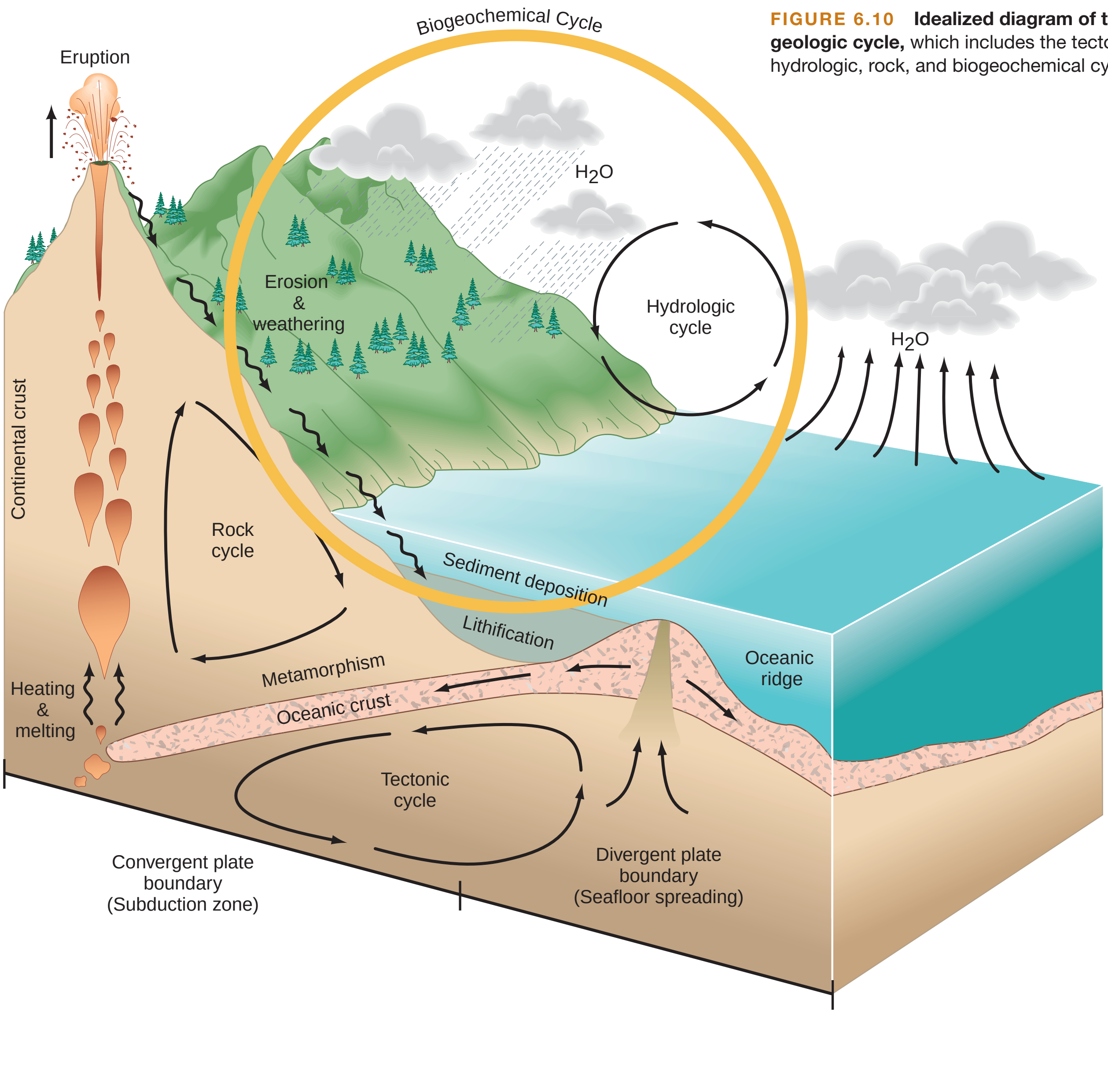


FIGURE 6.10 Idealized diagram of the geologic cycle, which includes the tectonic, hydrologic, rock, and biogeochemical cycles.

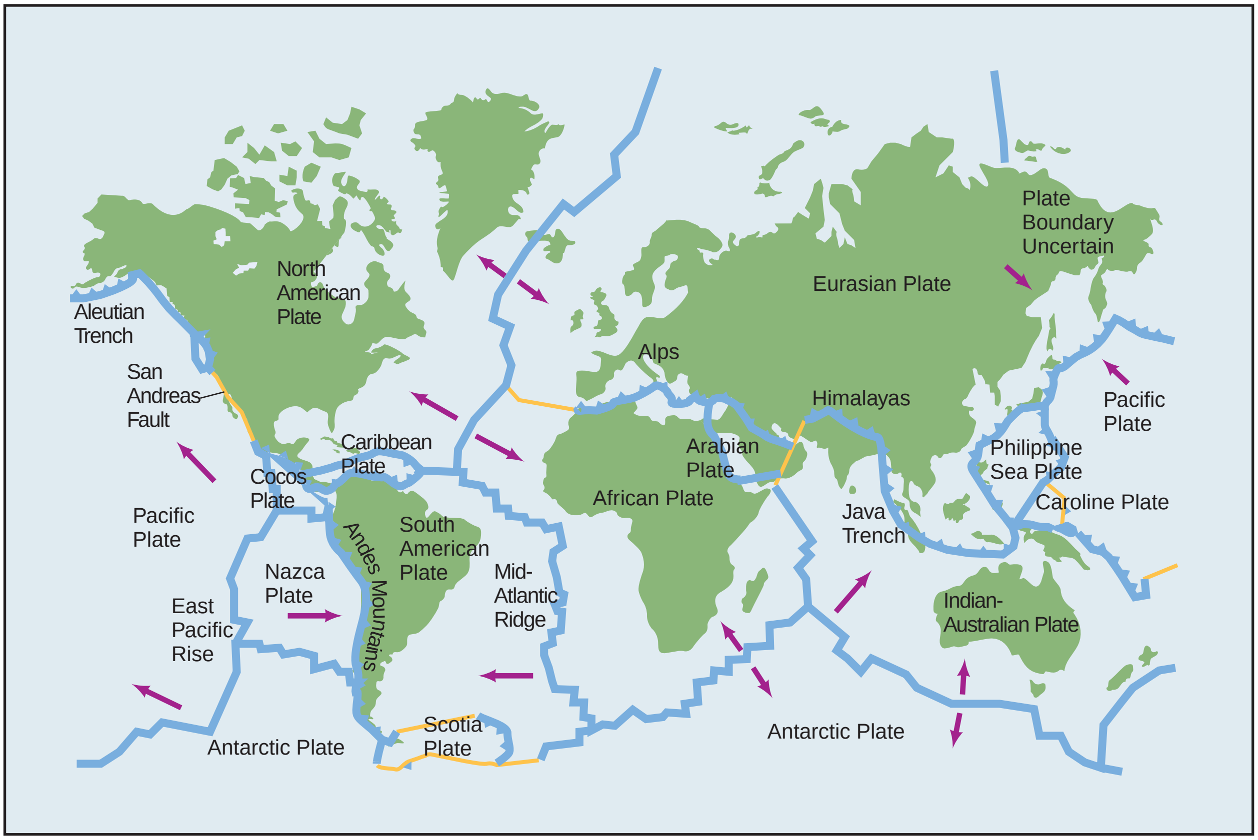


FIGURE 6.11 Generalized map of Earth's lithospheric plates. Divergent plate boundaries are shown as heavy lines (for example, the Mid-Atlantic Ridge). Convergent boundaries are shown as barbed lines (for example, the Aleutian trench). Transform fault boundaries are shown as yellow, thinner lines (for example, the San Andreas Fault). Arrows indicate directions of relative plate motions. (*Source*: Modified from B.C. Burchfiel, R.J. Foster, E.A. Keller, W.N. Melhorn, D.G. Brookins, L.W. Mintz, and H.V. Thurman, *Physical Geology: The Structures and Processes of the Earth* [Columbus, Ohio: Merrill, 1982].)

between plates are geologically active areas, and most volcanic activity and earthquakes occur there. Earthquakes occur when the brittle upper lithosphere fractures along faults (fractures in rock within the Earth's crust). Movement of several meters between plates can occur within a few seconds or minutes, in contrast to the slow, deeper plate movement described above.

Three types of plate boundaries occur: divergent, convergent, and transform faults.

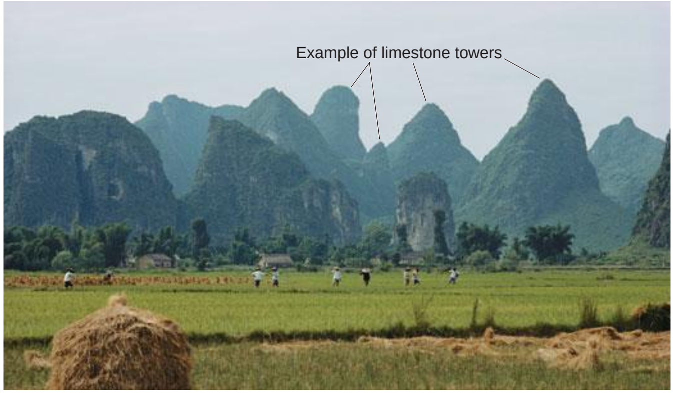
A divergent plate boundary occurs at a spreading ocean ridge, where plates are moving away from one another and new lithosphere is produced. This process, known as *seafloor spreading*, produces ocean basins.

A convergent plate boundary occurs when plates collide. When a plate composed of relatively heavy ocean-basin rocks dives (subducts) beneath the leading edge of a plate composed of lighter continental rocks, a subduction zone is present. Such a convergence may produce linear coastal mountain ranges, such as the Andes in South America. When two plates that are both composed of lighter continental rocks collide, a continental mountain range may form, such as the Himalayas in Asia.

A transform fault boundary occurs where one plate slides past another. An example is the San Andreas Fault in California, which is the boundary between the North American and Pacific plates. The Pacific plate is moving north, relative to the North American plate, at about 5 cm/year (2 in./year). As a result, Los Angeles is moving slowly toward San Francisco, about 500 km (300 mi) north. If this continues, in about 10 million years San Francisco will be a suburb of Los Angeles.

Uplift and subsidence of rocks, along with erosion, produce Earth's varied topography. The spectacular Grand Canyon of the Colorado River in Arizona (Figure 6.12a), sculpted from mostly sedimentary rocks, is one example. Another is the beautiful tower karst in China (Figure 6.12b). These resistant blocks of limestone have survived chemical weathering and erosion that removed the surrounding rocks.

(a)



(b)

FIGURE 6.12 Plate tectonics and landscapes. (a) In response to slow tectonic uplift of the region, the Colorado River has eroded through the sedimentary rocks of the Colorado plateau to produce the spectacular Grand Canyon. The river in recent years has been greatly modified by dams and reservoirs above and below the canyon. Sediment once carried to the Gulf of California is now deposited in reservoirs. The dam stores sediments, and some of the water released is from the deeper and thus cooler parts of the reservoir, so water flowing out of the dam and down through the Grand Canyon is clearer and colder than it used to be. Fewer sandbars are created; this and the cooler water change which species of fish are favored. Thus this upstream dam has changed the hydrology and environment of the Colorado River in the Grand Canyon. **(b)** This landscape in the People's Republic of China features tower karst, steep hills or pinnacles composed of limestone. The rock has been slowly dissolving through chemical weathering. The pinnacles and hills are remnants of the weathering and erosion processes.

The Hydrologic Cycle

The **hydrologic cycle** (Figure 6.13) is the transfer of water from the oceans to the atmosphere to the land and back to the oceans. It includes evaporation of water from the oceans; precipitation on land; evaporation from land; transpiration of water by plants; and runoff from streams, rivers, and subsurface groundwater. Solar energy drives the hydrologic cycle by evaporating water from oceans, freshwater bodies, soils, and vegetation. Of the total 1.3 billion km^3 of water on Earth, about 97% is in oceans and about 2% is in glaciers and ice caps; 0.76% is shallow groundwater: 0.013% is in lakes and rivers; and only 0.001% is in the atmosphere. Although water on land and in the atmosphere accounts for only a small fraction of the water on Earth, this water is important in moving chemicals,

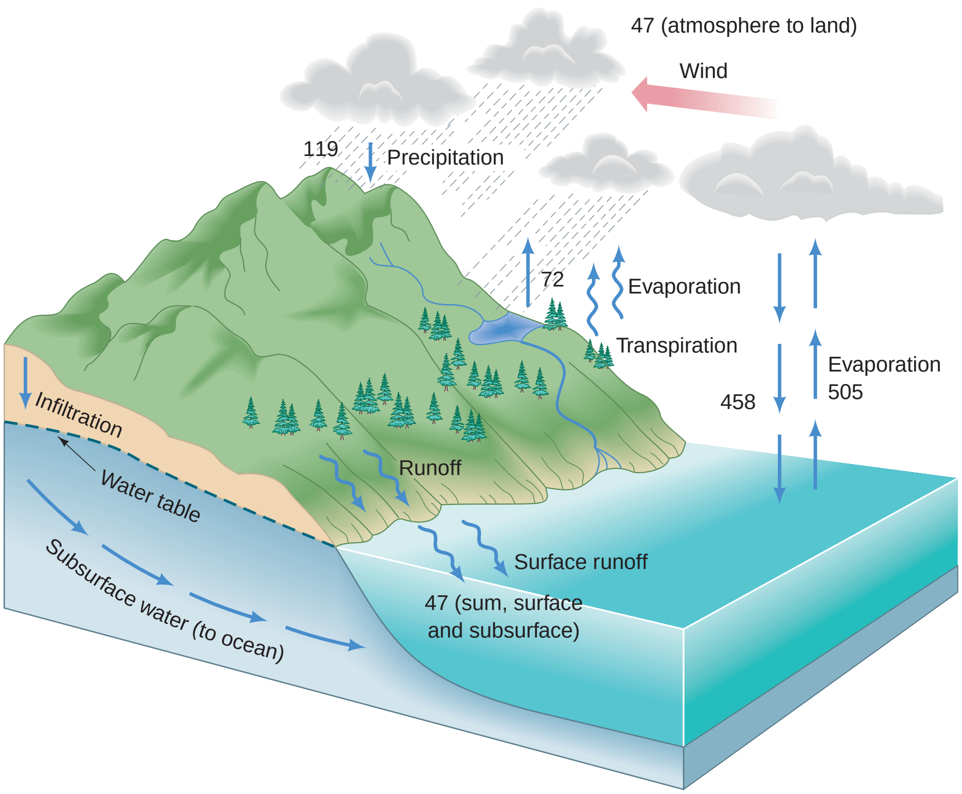


FIGURE 6.13 The hydrologic cycle, showing the transfer of water (thousands of km^3/yr) from the oceans to the atmosphere to the continents and back to the oceans again. (*Source*: From P.H. Gleick, *Water in Crisis* [New York: Oxford University Press, 1993].)

sculpting landscape, weathering rocks, transporting sediments, and providing our water resources.

The rates of transfer of water from land to the ocean are relatively low, and the land and oceans are somewhat independent in the water cycle because most of the water that evaporates from the ocean falls back into the ocean as precipitation, and most of the water that falls as precipitation on land comes from evaporation of water from land, as shown in Figure 6.13. Approximately 60% of precipitation on land evaporates each year back to the atmosphere, while the rest, about 40%, returns to the ocean as surface and subsurface runoff. The distribution of water is far from uniform on the land, and this has many environmental and ecological effects, which we discuss in Chapter 8 (on biological diversity), Chapters 19 and 20 (on water and climate), and Chapter 22 (urban environments).

At the regional and local levels, the fundamental hydrologic unit of the landscape is the *drainage basin* (also called a *watershed* or *catchment*). As explained in Chapter 5, a watershed is the area that contributes surface runoff to a particular stream or river. The term is used in evaluating the hydrology of an area (such as the stream flow or runoff from slopes) and in ecological research and biological conservation. Watersheds are best categorized by drainage basin area, and further by how many streams flow into the final, main channel. A first-order watershed is drained by a single small stream; a second-order watershed includes streams from first-order watersheds, and so on. Drainage basins vary greatly in size, from less than a hectare (2.5 acres) for a first-order watershed to millions of square kilometers for major rivers like the Missouri, Amazon, and Congo. A watershed is usually named for its main stream or river, such as the Mississippi River drainage basin.

The Rock Cycle

The **rock cycle** consists of numerous processes that produce rocks and soils. The rock cycle depends on the tectonic cycle for energy, and on the hydrologic cycle for water. As shown in Figure 6.14, rock is classified as igneous, sedimentary, or metamorphic. These three types of rock are involved in a worldwide recycling process. Internal heat from the tectonic cycle produces *igneous rocks* from molten material (magma) near the surface, such as lava from volcanoes. When magma crystalized deep in the earth the igneous rock granite was formed. These new rocks weather when exposed at the surface. Water in cracks of rocks expands when it freezes, breaking the rocks apart. This physical weathering makes smaller particles of rock from bigger ones, producing sediment, such as gravel, sand, and silt. Chemical weathering occurs, too, when the weak acids in water dissolve chemicals from rocks. The sediments and dissolved chemicals are then transported by water, wind, or ice (glaciers).

Weathered materials that accumulate in *depositional basins*, such as the oceans, are compacted by overlying sediments and converted to *sedimentary rocks.* The process of creating rock by compacting and cementing particles is called *lithification.* Sedimentary rocks buried at sufficient depths (usually tens to hundreds of kilometers) are altered by heat, pressure, or chemically active fluids and transformed into *metamorphic rocks.* Later, plate tectonics uplift may bring these deeply buried rocks to the surface, where they, too, are subjected to weathering, producing new sediment and starting the cycle again.

You can see in Figure 6.14 that life processes play an important role in the rock cycle by adding organic carbon to rocks. The addition of organic carbon produces rocks such as limestone, which is mostly calcium carbonate (the material of seashells and bones), as well as fossil fuels, such as coal.

Our discussion of geologic cycles has emphasized tectonic, hydrologic, and rock-forming processes. We can now begin to integrate biogeochemical processes into the picture.

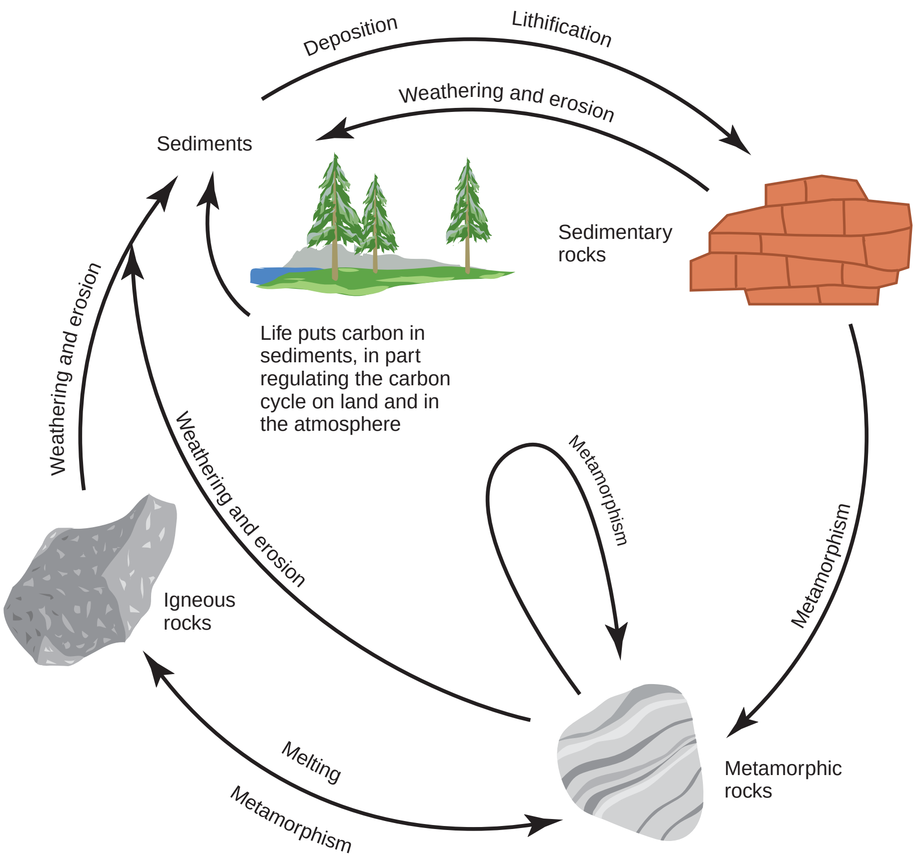


FIGURE 6.14 **The rock cycle** and major paths of material transfer as modified by life.

6.5 Some Major Global Biogeochemical Cycles

With Figure 6.14's basic diagram in mind, we can now consider complete chemical cycles, though still quite simplified. Each chemical element has its own specific cycle, but all the cycles have certain features in common (Figure 6.15).

The Carbon Cycle

Carbon is the basic building block of life and the element that anchors all organic substances, from coal and oil to DNA (deoxyribonucleic acid), the compound that carries genetic information. Although of central importance to life, carbon is not one of the most abundant elements in Earth's crust. It contributes only 0.032% of the weight of the crust, ranking far behind oxygen (45.2%), silicon (29.5%), aluminum (8.0%), iron (5.8%), calcium (5.1%), and magnesium (2.8%).[10, 11]

The major pathways and storage reservoirs of the **carbon cycle** are shown in Figure 6.16. This diagram is simplified to show the big picture of the carbon cycle. Details are much more complex. [12]

- **Oceans and land ecosystems:** In the past half-century, ocean and land ecosystems have removed about 3.1 ± 0.5 GtC/yr, which is approximately 45% of the carbon emitted from burning fossil fuels during that period.
- **Land-use change:** Deforestation and decomposition of what is cut and left, as well as burning of forests to make room for agriculture in the tropics, are the main reasons 2.2 ± 0.8 GtC/yr is added to the atmosphere. A small flux of carbon (0.2 ± 0.5 GtC/yr) from hot tropical areas is pulled from the atmosphere by growing forests. In other words, when considering land-use change, deforestation is by far the dominant process.
- **Residual land sink:** The observed net uptake of CO_2 from the atmosphere (see Figure 6.16) by land ecosystems suggests there must be a sink for carbon in land ecosystems that has not been adequately identified. The sink is large, at 2 to 3 GtC/yr, with large uncertainty ($\pm$ 1.7GtC/yr). Thus, our understanding of the carbon cycle is not yet complete.

Carbon has a gaseous phase as part of its cycle, occurring in the atmosphere as carbon dioxide (CO_2) and methane (CH_4), both greenhouse gases. Carbon enters

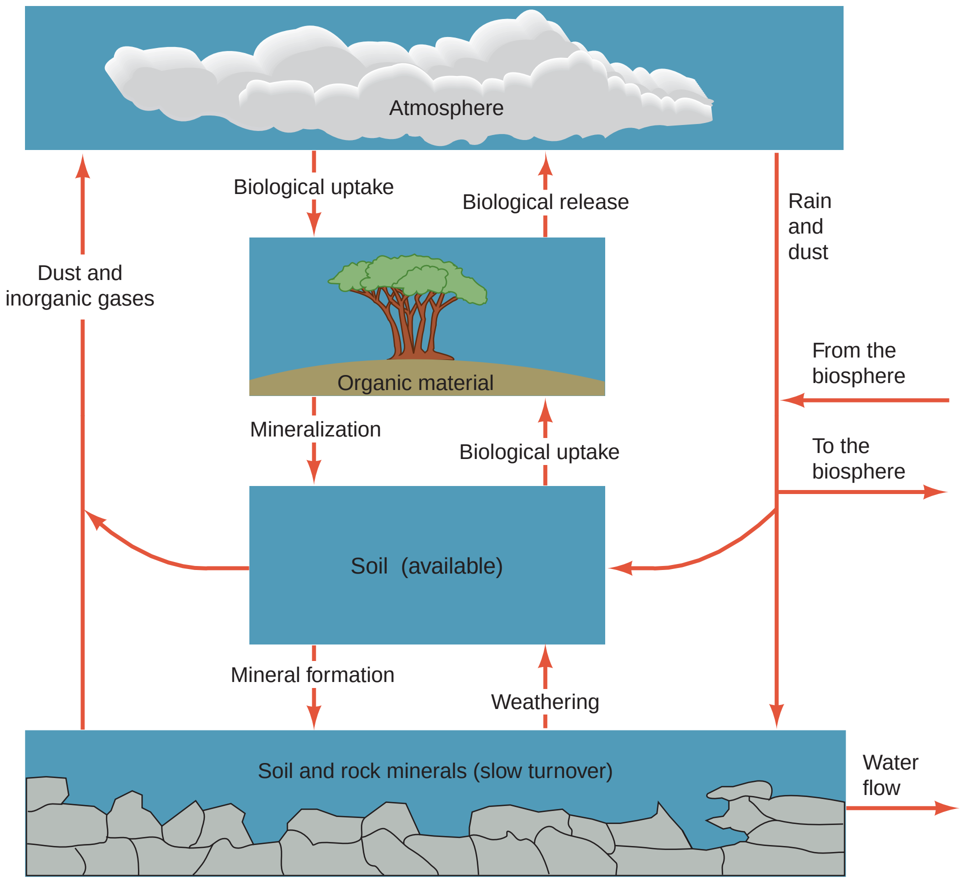
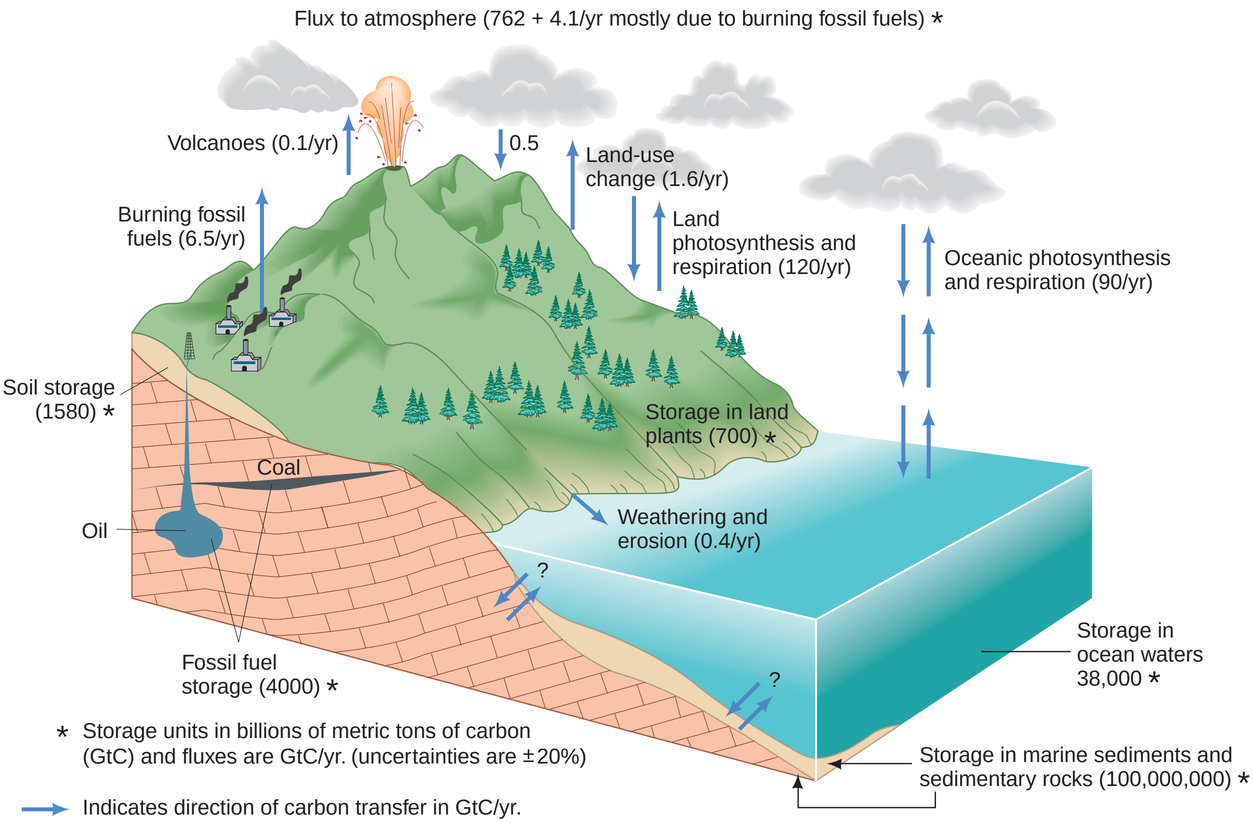


FIGURE 6.15 Basic biogeochemical cycle.

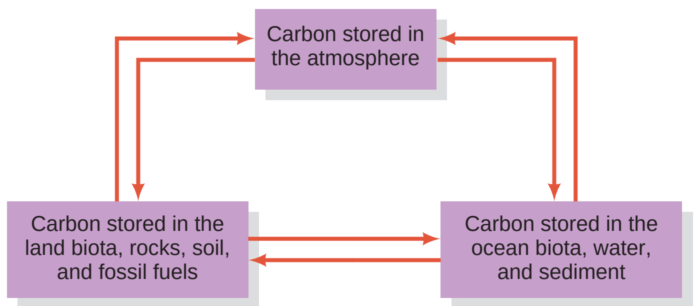
the atmosphere through the respiration of living things, through fires that burn organic compounds, and by diffusion from the ocean. It is removed from the atmosphere by photosynthesis of green plants, algae, and photosynthetic bacteria and enters the ocean from the atmosphere by the simple diffusion of carbon dioxide. The carbon dioxide then dissolves, some of it remaining in that state and the rest converting to carbonate ($CO_3^{=}$) and bicarbonate (HCO_3^{-}). Marine algae and photosynthetic bacteria obtain the carbon dioxide they use from the water in one of these three forms.

Carbon is transferred from the land to the ocean in rivers and streams as dissolved carbon, including organic compounds, and as organic particulates (fine particles of organic matter) and seashells and other forms of calcium carbonate ($CaCO_3$). Winds, too, transport small organic particulates from the land to the ocean. Rivers and streams transfer a relatively small fraction of the total global carbon flux to the oceans. However, on the local and regional scale, input of carbon from rivers to nearshore areas, such as deltas and salt marshes, which are often highly biologically productive, is important.

Carbon enters the **biota**—the term for all life in a region—through photosynthesis and is returned to the atmosphere or waters by respiration or by wildfire. When an organism dies, most of its organic material decomposes into inorganic compounds, including carbon dioxide. Some carbon may be buried where there is not sufficient



(a)



(b)

FIGURE 6.16 The carbon cycle. (a) Generalized global carbon cycle. **(b)** Parts of the carbon cycle simplified to illustrate the cyclic nature of the movement of carbon. (*Source*: Modified from G. Lambert, *La Recherche* 18 [1987]:782–83, with some data from R. Houghton, *Bulletin of the Ecological Society of America* 74, no. 4 [1993]: 355–356, and R. Houghton, *Tellus* 55B, no. 2 [2003]: 378–390), and IPCC, The Physical Science Basis: Working Group I. Contribution to the *Fourth Assessment Report* [New York: Cambridge University Press, 2007].)

oxygen to make this conversion possible or where the temperatures are too cold for decomposition. In these locations, organic matter is stored. Over years, decades, and centuries, storage of carbon occurs in wetlands, including parts of floodplains, lake basins, bogs, swamps, deep-sea sediments, and near-polar regions. Over longer periods (thousands to several million years), some carbon may be buried with sediments that become sedimentary rocks. This carbon is transformed into fossil fuels. Nearly all of the carbon stored in the lithosphere exists as sedimentary rocks, mostly carbonates, such as limestone, much of which has a direct biological origin.

The cycling of carbon dioxide between land organisms and the atmosphere is a large flux. Approximately 15% of the total carbon in the atmosphere is taken up by photosynthesis and released by respiration on land annually. Thus, as noted, life has a large effect on the chemistry of the atmosphere.

Because carbon forms two of the most important greenhouse gases—carbon dioxide and methane—much research has been devoted to understanding the carbon cycle, which will be discussed in Chapter 20 about the atmosphere and climate change.

The Carbon–Silicate Cycle

Carbon cycles rapidly among the atmosphere, oceans, and life. However, over geologically long periods, the cycling of carbon becomes intimately involved with the cycling of silicon. The combined carbon–silicate cycle is therefore of geologic importance to the long-term stability of the biosphere over periods that exceed half a billion years.[12]

The **carbon–silicate cycle** begins when carbon dioxide in the atmosphere dissolves in the water to form weak carbonic acid (H_2CO_3) that falls as rain (Figure 6.17). As the mildly acidic water migrates through the ground, it chemically weathers (dissolves) rocks and facilitates the erosion of Earth's abundant silicate-rich rocks. Among other products, weathering and erosion release calcium ions (Ca^{++}) and bicarbonate ions (HCO_3^-). These ions enter the groundwater and surface waters and eventually are transported to the ocean. Calcium and bicarbonate ions make up a major portion of the chemical load that rivers deliver to the oceans.

Tiny floating marine organisms use the calcium and bicarbonate to construct their shells. When these organisms die, the shells sink to the bottom of the ocean, where they accumulate as carbonate-rich sediments. Eventually, carried by moving tectonic plates, they enter a subduction zone (where the edge of one continental plate slips under the edge of another). There they are subjected to increased heat, pressure, and partial melting. The resulting magma releases carbon dioxide, which rises in volcanoes and is released into the atmosphere. This process provides a lithosphere-to-atmosphere flux of carbon.

The long-term carbon–silicate cycle (Figure 6.17) and the short-term carbon cycle (Figure 6.16) interact to affect levels of CO_2 and O_2 in the atmosphere. For example, the burial of organic material in an oxygen-poor environment amounts to a net increase of photosynthesis (which produces O_2) over respiration (which produces CO_2). Thus, if burial of organic carbon in oxygen-poor environments increases, the concentration of atmospheric

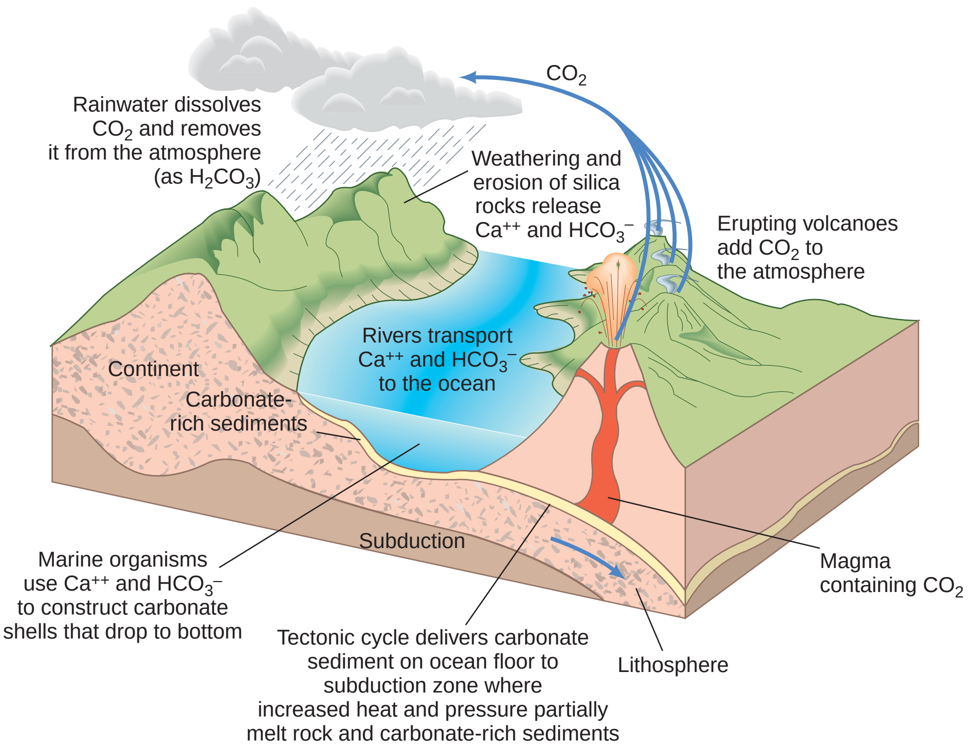


FIGURE 6.17 An idealized diagram showing the carbon–silicate cycle. (*Source*: Modified from J.E. Kasting, O.B. Toon, and J.B. Pollack, How climate evolved on the terrestrial planets, *Scientific American* 258 [1988]:2.)

oxygen will increase. Conversely, if more organic carbon escapes burial and is oxidized to produce CO_2, then the CO_2 concentration in the atmosphere will increase.[13]

The Nitrogen Cycle

Nitrogen is essential to life in proteins and DNA. As we discussed at the beginning of this chapter, free or diatonic nitrogen (N_2 uncombined with any other element) makes up approximately 78% of Earth's atmosphere. However, no organism can use molecular nitrogen directly. Some organisms, such as animals, require nitrogen in an organic compound. Others, including plants, algae, and bacteria, can take up nitrogen either as the nitrate ion (NO_3^-) or the ammonium ion (NH_4^+). Because nitrogen is a relatively unreactive element, few processes convert molecular nitrogen to one of these compounds. Lightning oxidizes nitrogen, producing nitric oxide. In nature, essentially all other conversions of molecular nitrogen to biologically useful forms are conducted by bacteria.

The **nitrogen cycle** is one of the most important and most complex of the global cycles (Figure 6.18). The process of converting inorganic, molecular nitrogen in the atmosphere to ammonia or nitrate is called **nitrogen fixation**. Once in these forms, nitrogen can be used on land by plants and in the oceans by algae. Bacteria, plants, and algae then convert these inorganic nitrogen compounds into organic ones through chemical reactions, and the nitrogen becomes available in ecological food chains. When organisms die, bacteria convert the organic compounds containing nitrogen back to ammonia, nitrate, or molecular nitrogen, which enters the atmosphere. The process of releasing fixed nitrogen back to molecular nitrogen is called **denitrification**.

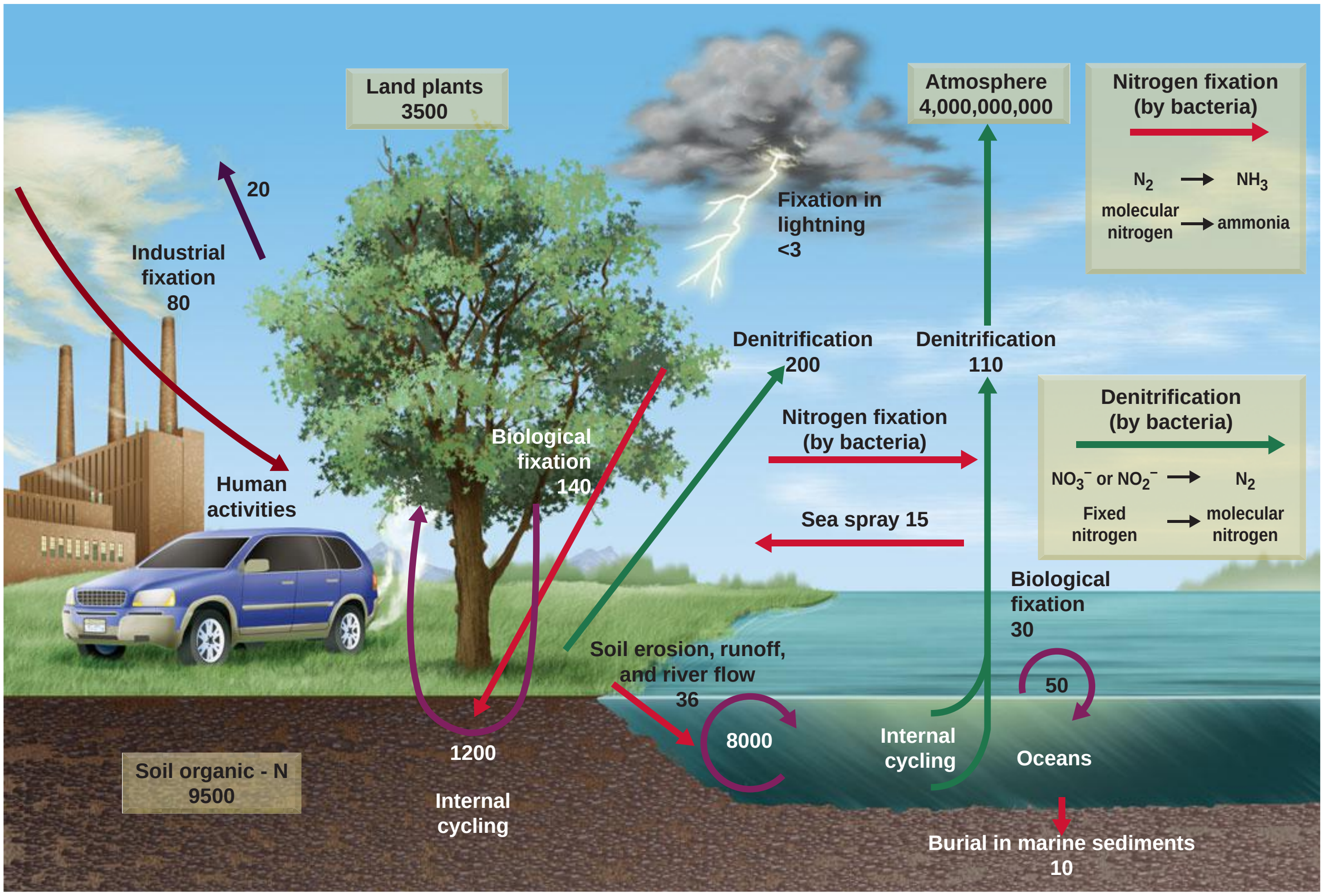


FIGURE 6.18 The global nitrogen cycle. Numbers in boxes indicate amounts stored, and numbers with arrows indicate annual flux, in millions of metric tons of nitrogen. Note that the industrial fixation of nitrogen is nearly equal to the global biological fixation. (*Source*: Data from R. Söderlund and T. Rosswall, in *The Handbook of Environmental Chemistry*, Vol. 1, Pt. B, O. Hutzinger, ed. [New York: Springer-Verlag, 1982]; W.H. Schlosinger, *Biogeochemistry: An Analysis of Global Change* [San Diego: Academic Press, 1997], p. 386; and Peter M. Vitousek, Chair, John Aber, Robert W. Howarth, Gene E. Likens, Pamela A. Matson, David W. Schindler, William H. Schlesinger, and G. David Tilman, Human alteration of the global nitrogen cycle: Causes and consequences, *Issues in Ecology—Human Alteration of the Global Nitrogen Cycle*, Ecological Society of America publication http://esa.sdsc.edu/tilman.htm 30/08/2000.)

Thus, all organisms depend on nitrogen-converting bacteria. Some organisms, including termites and ruminant (cud-chewing) mammals, such as cows, goats, deer, and bison, have evolved symbiotic relationships with these bacteria. For example, the roots of the pea family have nodules that provide a habitat for the bacteria. The bacteria obtain organic compounds for food from the plants, and the plants obtain usable nitrogen. Such plants can grow in otherwise nitrogen-poor environments. When these plants die, they contribute nitrogen-rich organic matter to the soil, improving the soil's fertility. Alder trees, too, have nitrogen-fixing bacteria in their roots. These trees grow along streams, and their nitrogen-rich leaves fall into the streams and increase the supply of organic nitrogen to freshwater organisms.

In terms of availability for life, nitrogen lies somewhere between carbon and phosphorus. Like carbon, nitrogen has a gaseous phase and is a major component of Earth's atmosphere. Unlike carbon, however, it is not very reactive, and its conversion depends heavily on biological activity. Thus, the nitrogen cycle is not only essential to life but also primarily driven by life.

In the early part of the 20th century, scientists invented industrial processes that could convert molecular nitrogen into compounds usable by plants. This greatly increased the availability of nitrogen in fertilizers. Today, industrial fixed nitrogen is about 60% of the amount fixed in the biosphere and is a major source of commercial nitrogen fertilizer.[14]

Although nitrogen is required for all life, and its compounds are used in many technological processes and in modern agriculture, nitrogen in agricultural runoff can pollute water, and many industrial combustion processes and automobiles that burn fossil fuels produce nitrogen oxides that pollute the air and play a significant role in urban smog (see Chapter 21).

The Phosphorus Cycle

Phosphrus, one of the "big six" elements required in large quantities by all forms of life, is often a limiting nutrient for plant and algae growth. We call it the "energy element" because it is fundamental to a cell's use of energy, and therefore to the use of energy by all living things. Phosphorus is in DNA, which carries the genetic material of life. It is an important ingredient in cell membranes.

The **phosphorus cycle** is significantly different from the carbon and nitrogen cycles. Unlike carbon and nitrogen, phosphorus does not have a gaseous phase on Earth; it is found in the atmosphere only in small particles of dust (Figure 6.19). In addition, phosphorus tends to form compounds that are relatively insoluble in water, so phosphorus is not readily weathered chemically. It does occur commonly in an oxidized state as phosphate, which combines with calcium, potassium, magnesium, or iron to form minerals. All told, however, the rate of transfer of phosphorus in Earth's system is slow compared with that of carbon or nitrogen.

Phosphorus enters the biota through uptake as phosphate by plants, algae, and photosynthetic bacteria. It is recycled locally in life on land nearly 50 times before being transported by weathering and runoff. Some phosphorus is inevitably lost to ecosystems on the land. It is transported by rivers to the oceans, either in a water-soluble form or as suspended particles. When it finally reaches the ocean, it may be recycled about 800 times before entering marine sediments to become part of the rock cycle. Over tens to hundreds of millions of years, the sediment is transformed into sedimentary rocks, after which it may eventually be returned to the land by uplift, weathering, and erosion.[15]

Ocean-feeding birds, such as the brown pelican, provide an important pathway in returning phosphrus from the ocean to the land. These birds feed on small fish, especially anchovies, which in turn feed on tiny ocean plankton. Plankton thrive where nutrients, such as phosphorus, are present. Areas of rising oceanic currents known as upwellings are such places. Upwellings occur near continents where the prevailing winds blow offshore, pushing surface waters away from the land and allowing deeper waters to rise and replace them. Upwellings carry nutrients, including phosphorus, from the depths of the oceans to the surface.

The fish-eating birds nest on offshore islands, where they are protected from predators. Over time, their nesting sites become covered with their phosphorus-laden excrement, called guano. The birds nest by the thousands, and deposits of guano accumulate over centuries. In relatively dry climates, guano hardens into a rocklike mass that may be up to 40 m (130 ft) thick. The guano results from a combination of biological and nonbiological processes. Without the plankton, fish, and birds, the phosphorus would have remained in the ocean. Without the upwellings, the phosphorus would not have been available.

Guano deposits were once major sources of phosphorus for fertilizers. In the mid-1800s, as much as 9 million metric tons per year of guano deposits were shipped to London from islands near Peru (Figure 6.20). Today, most phosphorus fertilizers come from the mining of phosphate-rich sedimentary rocks containing fossils of marine animals. The richest phosphate mine in the world is Bone Valley, 40 km east of Tampa, Florida. But 10–15 million years ago Bone Valley was the bottom of a shallow sea where marine invertebrates lived and died.[16]

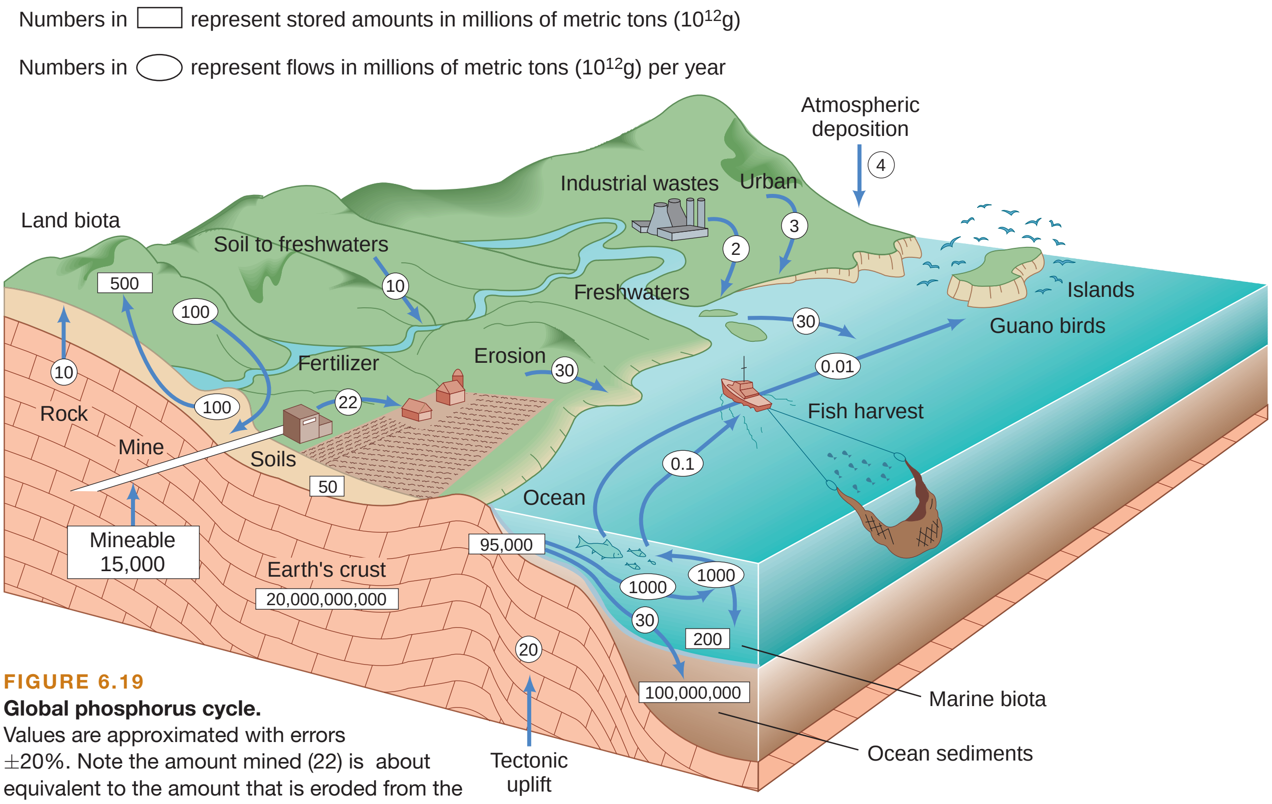


FIGURE 6.19
Global phosphorus cycle.
Values are approximated with errors ±20%. Note the amount mined (22) is about equivalent to the amount that is eroded from the land and enters the oceans by runoff (25).
(*Sources*: Data from 5 mil, 2000 *Phosphorus in the environment: Natural flows and human interference*. Annual Review of Environment and Resources 25:53–88.)

(a)

(b)

FIGURE 6.20 **Guano Island**, Peru. For centuries the principal source of phosphorus fertilizer was guano deposits from seabirds. The birds feed on fish and nest on small islands. Their guano accumulates in this dry climate over centuries, forming rocklike deposits that continue to be mined commercially for phosphate fertilizers. On the Peruvian Ballestas Islands **(a)** seabirds (in this case, Incan terns) nest, providing some of the guano, and **(b)** sea lions haul out and rest on the rocklike guano.

Through tectonic processes, the valley was slowly uplifted, and in the 1880s and 1890s phosphate ore was discovered there. Today, Bone Valley provides about 20% of the world's phosphate (Figure 6.21).

About 80% of phosphorus is produced in four countries: the United States, China, South Africa, and Morocco.[17,18] The global supply of phosphorus that can be extracted economically is about 15 billion tons (15,000 million tons). Total U.S. reserves are estimated at 1.2 billion metric tons. In 2009, in the United States, approximately 30.9 million tons of marketable phosphorus rocks valued at $3.5 billion were obtained by removing more than 120 million tons of rocks from mines. Most of the U.S. phosphorus, about 85%, came from Florida and North Carolina, the rest from Utah and Idaho.[19] All of our industrialized agriculture—most of the food produced in the United States—depends on phosphorus for fertilizers that comes from just four states!

Phosphorus may become much more difficult to obtain in the next few decades. According to the U.S. Geological Survey, in 2007 the price of phosphate rock "jumped dramatically worldwide owing to increased agricultural demand and tight supplies," and by 2009 "the average U.S. price was more than double that of 2007," reaching as much as $500 a ton in some parts of the world.[20]

One fact is clear: Without phosphorus, we cannot produce food. Thus, declining phosphorus resources will harm the global food supply and affect all of the world's economies. Extraction continues to increase as the expanding human population demands more food and as we grow more corn for biofuel. However, if the price of phosphorus rises as high-grade deposits dwindle, phosphorus from lower-grade deposits can be mined at a profit. Florida is thought to have as much as 8 billion metric tons of phosphorus that might eventually be recovered if the price is right.

Mining, of course, may have negative effects on the land and ecosystems. For example, in some phosphorus mines, huge pits and waste ponds have scarred the landscape, damaging biologic and hydrologic resources. Balancing the need for phosphorus with the adverse environmental impacts of mining is a major environmental issue. Following phosphate extraction, land disrupted by open-pit phosphate mining, shown in Figure 6.21 is reclaimed to pastureland, as mandated by law.

As with nitrogen, an overabundance of phosphorus causes environmental problems. In bodies of water, from ponds to lakes and the ocean, phosphorus can promote unwanted growth of photosynthetic bacteria. As the algae proliferate, oxygen in the water may be depleted. In oceans, dumping of organic materials high in nitrogen and phosphorus has produced several hundred "dead zones." collectively covering about 250,000 km^2. Although this is an area almost as large as Texas, it represents less than 1% of the area of the Earth's oceans (335,258,000 km^2).

What might we do to maintain our high agriculture production but reduce our need for newly mined phosphate? Among the possibilities:

- Recycle human waste in the urban environment to reclaim phosphorus and nitrogen.
- Use wastewater as a source of fertilizer, rather than letting it end up in waterways.
- Recycle phosphorus-rich animal waste and bones for use in fertilizer.
- Further reduce soil erosion from agricultural lands so that more phosphorus is retained in the fields for crops.
- Apply fertilizer more efficiently so less is immediately lost to wind and water erosion.
- Find new phosphorus sources and more efficient and less expensive ways to mine it.
- Use phosphorus to grow food crops rather than biofuel crops.

We have focused on the biogeochemical cycles of three of the macronutrients, illustrating the major kinds of biogeochemical cycles—those with and those without an atmospheric component—but obviously this is just an introduction about methods that can be applied to all elements required for life and especially in agriculture.

FIGURE 6.21 **A large open-pit phosphate mine in Florida (similar to Bone Valley), with piles of waste material.** The land in the upper part of the photograph has been reclaimed and is being used for pasture.

CRITICAL THINKING ISSUE

How Are Human Activities Linked to the Phosphorus and Nitrogen Cycles?

Scientists estimate that nitrogen deposition to Earth's surface will double in the next 25 years and that the use of phosphorus will also increase greatly as we attempt to feed a few billion more people in coming decades. The natural rate of nitrogen fixation is estimated to be 140 teragrams (Tg) of nitrogen a year (1 teragram = 1 million metric tons). Human activities—such as the use of fertilizers, draining of wetlands, clearing of land for agriculture, and burning of fossil fuels—are causing additional nitrogen to enter the environment. Currently, human activities are responsible for more than half of the fixed nitrogen that is deposited on land. Before the 20th century, fixed nitrogen was recycled by bacteria, with no net accumulation. Since 1900, however, the use of commercial fertilizers has increased exponentially (Figure 6.22). Nitrates and ammonia from burning fossil fuels have increased about 20% in the last decade or so. These inputs have overwhelmed the denitrifying part of the nitrogen cycle and the ability of plants to use fixed nitrogen.

Nitrate ions, in the presence of soil or water, may form nitric acid. With other acids in the soil, nitric acid can leach out chemicals important to plant growth, such as magnesium and potassium. When these chemicals are depleted, more toxic ones, such as aluminum, may be released, damaging tree roots. Acidification of soil by nitrate ions is also harmful to organisms. When toxic chemicals wash into streams, they can kill fish. Excess nitrates in rivers and along coasts can cause algae to overgrow, damaging ecosystems. High levels of nitrates in drinking water from streams or groundwater contaminated by fertilizers are a health hazard.[21, 22, 23, 24]

The nitrogen, phosphorus, and carbon cycles are linked because nitrogen is a component of chlorophyll, the molecule that plants use in photosynthesis. Phosphorus taken up by plants enters the food chain and, thus, the carbon cycle. It is an irreplaceable ingredient in life. Because nitrogen is a limiting factor on land, it has been predicted that rising levels of global nitrogen may increase plant growth. Recent studies have suggested, however, that a beneficial effect from increased nitrogen would be short-lived. As plants use additional nitrogen, some other factor, such as phosphorus, will become limiting. When that occurs, plant growth will slow, and so will the uptake of carbon dioxide. More research is needed to understand the interactions between carbon and the phosphorus and nitrogen cycles and to be able to predict the long-term effects of human activities.

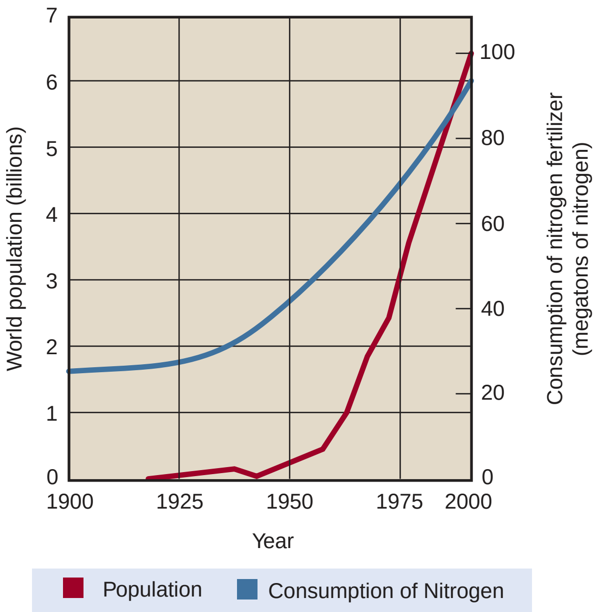


FIGURE 6.22 The use of nitrogen fertilizers has increased greatly. (*Source*: Modified from Rhodes, D. 2009. Purdue University Department of Horticulture & Landscape Architecture.)

Critical Thinking Questions

1. The supply of phosphorus from mining is a limited resource. In the U.S., extraction is decreasing, and the price is rising dramatically. Do you think phosphorus can be used sustainably? How? If not, what are the potential consequences for agriculture?
2. Do you think phosphorus use should be governed by an international body? Why? Why not?
3. Compare the rate of human contributions to nitrogen fixation with the natural rate.
4. How does the change in fertilizer use relate to the change in world population? Why?
5. Develop a diagram to illustrate the links between the phosphorus, nitrogen, and carbon cycles.
6. Make a list of ways in which we could modify our activities to reduce our contributions to the phosphorus and nitrogen cycles.
7. Should phosphorus and nitrogen be used to produce corn as a biofuel (alcohol)? Why? Why not?

SUMMARY

- Biogeochemical cycles are the major way that elements important to Earth processes and life are moved through the atmosphere, hydrosphere, lithosphere, and biosphere.
- Biogeochemical cycles can be described as a series of reservoirs, or storage compartments, and pathways, or fluxes, between reservoirs.
- In general, some chemical elements cycle quickly and are readily regenerated for biological activity. Elements whose biogeochemical cycles include a gaseous phase in the atmosphere tend to cycle more rapidly.
- Life on Earth has greatly altered biogeochemical cycles, creating a planet with an atmosphere unlike those of any others known, and especially suited to sustain life.
- Every living thing, plant or animal, requires a number of chemical elements. These chemicals must be available at the appropriate time and in the appropriate form and amount.
- Chemicals can be reused and recycled, but in any real ecosystem some elements are lost over time and must be replenished if life in the ecosystem is to persist. Change and disturbance of natural ecosystems are the norm. A steady state, in which the net storage of chemicals in an ecosystem does not change with time, cannot be maintained.
- Our modern technology has begun to alter and transfer chemical elements in biogeochemical cycles at rates comparable to those of natural processes. Some of these activities are beneficial to society, but others create problems, such as pollution by nitrogen and phosphorus
- To be better prepared to manage our environment, we must recognize both the positive and the negative consequences of activities that transfer chemical elements, and we must deal with them appropriately.
- Biogeochemical cycles tend to be complex, and Earth's biota has greatly altered the cycling of chemicals through the air, water, and soil. Continuation of these processes is essential to the long-term maintenance of life on Earth.
- There are many uncertainties in measuring either the amount of a chemical in storage or the rate of transfer between reservoirs.

REEXAMINING THEMES AND ISSUES

Human Population

Through modern technology, we are transferring some chemical elements through the air, water, soil, and biosphere at rates comparable to those of natural processes. As our population increases, so does our use of resources and so do these rates of transfer. This is a potential problem because eventually the rate of transfer for a particular chemical may become so large that pollution of the environment results.

Sustainability

If we are to sustain a high-quality environment, the major biogeochemical cycles must transfer and store the chemicals necessary to maintain healthy ecosystems. That is one reason why understanding biogeochemical cycles is so important. For example, the release of sulfur into the atmosphere is degrading air quality at local to global levels. As a result, the United States is striving to control these emissions.

Global Perspective

The major biogeochemical cycles discussed in this chapter are presented from a global perspective. Through ongoing research, scientists are trying to better understand how major biogeochemical cycles work. For example, the carbon cycle and its relationship to the burning of fossil fuels and the storage of carbon in the biosphere and oceans are being intensely investigated. Results of these studies are helping us to develop strategies for reducing carbon emissions. These strategies are implemented at the local level, at power plants, and in cars and trucks that burn fossil fuels.

Urban World

Our society has concentrated the use of resources in urban regions. As a result, the release of various chemicals into the biosphere, soil, water, and atmosphere is often greater in urban centers, resulting in biogeochemical cycles that cause pollution problems.

People and Nature

Humans, like other animals, are linked to natural processes and nature in complex ways. We change ecosystems through land-use changes and the burning of fossil fuels, both of which change biogeochemical cycles, especially the carbon cycle that anchors life and affects Earth's climate.

Science and Values

Our understanding of biogeochemical cycles is far from complete. There are large uncertainties in the measurement of fluxes of chemical elements—nitrogen, carbon, phosphorus, and others. We are studying biogeochemical cycles because understanding them will help us to solve environmental problems. Which problems we address first will reflect the values of our society.

KEY TERMS

biogeochemical cycle **112**
biosphere **110**
biota **118**
carbon cycle **117**
carbon–silicate cycle **119**
denitrification **120**
eukaryote **110**
flow **112**
flux **112**
geologic cycle **113**
hydrologic cycle **115**
limiting factor **111**
macronutrients **111**
micronutrients **111**
nitrogen cycle **120**
nitrogen fixation **120**
organelle **110**
phosphorus cycle **121**
plate tectonics **113**
prokaryote **110**
residence time **112**
rock cycle **116**
sink **112**
source **112**
tectonic cycle **113**
thermodynamic equilibrium **108**

STUDY QUESTIONS

1. Why is an understanding of biogeochemical cycles important in environmental science? Explain your answer, using two examples.

2. What are some of the general rules that govern biogeochemical cycles, especially the transfer of material?

3. Identify the major aspects of the carbon cycle and the environmental concerns associated with it.

4. What are the differences in the geochemical cycles for phosphorus and nitrogen, and why are the differences important in environmental science?

5. What are the major ways that people have altered biogeochemical cycles?

6. If all life ceased on Earth, how quickly would the atmosphere become like that of Venus and Mars? Explain.

FURTHER READING

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Lovelock, J., ***The Ages of Gaia: A Biography of the Earth*** (Oxford: Oxford University Press, 1995).

Schlesinger, W.H., ***Biogeochemistry: An Analysis of Global Change,*** **2nd ed.** (San Diego: Academic Press, 1997). This book provides a comprehensive and up-to-date overview of the chemical reactions on land, in the oceans, and in the atmosphere of Earth.

CHAPTER 7

Dollars and Environmental Sense: Economics of Environmental Issues

A New England common illustrates the tragedy of the Commons, one of the key ideas of Environmental Economics.

LEARNING OBJECTIVES

Why do people value environmental resources? To what extent are environmental decisions based on economics? Other chapters in this text explain the causes of environmental problems and discuss technical solutions. The scientific solutions, however, are only part of the answer. This chapter introduces some basic concepts of environmental economics and shows how these concepts help us understand environmental issues. After reading this chapter, you should understand . . .

- How the perceived future value of an environmental benefit affects our willingness to pay for it now;
- What "externalities" are and why they matter;
- How much risk we should be willing to accept for the environment and ourselves;
- How we can place a value on environmental intangibles, such as landscape beauty.

CASE STUDY

Cap, Trade, and Carbon Dioxide

We hear a lot in the news these days about a public and congressional debate over "cap-and-trade" and the control of carbon dioxide emissions. The question our society is wrestling with is this: Assuming that carbon dioxide, as a greenhouse gas, can be treated like any other air pollutant legally and economically, how can its emissions best be controlled? "Best" in this context means reducing human-induced carbon dioxide emissions as much as possible, doing so in the least expensive way, and in a way that is fair to all participants. Among the most commonly discussed methods are the following:

Tax on emitters: The government levies a tax based on the quantity of pollution emitted.

Legal emissions limit: The law will limit the amount of emissions allowed from each source—individual, corporation, facility (e.g., a single power plant), or government organization. The control is applied individually, emitter by emitter, with each assigned a maximum.

Cap-and-trade: First, the government decides how much of a particular pollutant will be permitted, either as a *total amount* in the environment or as the *total amount emitted into the environment per year*. (This is one way that cap-and-trade differs from legal emissions limits, which are set per emitter.) Next, the limit is divided up among the sources of the pollutant, but the owners of those sources can trade among themselves. (In contrast, legal emissions limits allow no trading among participants.)

The rationale behind the tax on emitters is twofold. First of all, it raises tax money, which in theory could be used to find ways to reduce and better control the pollution. Second, it is supposed to discourage businesses from emitting pollution. But critics of a direct tax on emitters say it doesn't work and is bad for business. They say businesses simply pass on the cost of the taxes in their prices, so the tax burden is on the consumer but the likely economic result is fewer sales.

Critics of legal emissions limits say that since government sets the limits, this could be arbitrary and place an unfair burden on certain businesses. It also requires extensive, costly monitoring, placing a further burden on society's economics.

The potential problems of direct taxes and emissions limits led to the idea of cap-and-trade. Here's how it works. Suppose you own a coal-fired power plant and the government gives you a certain number of carbon allowances—tons of carbon dioxide you will be allowed to emit into the air each year. These allowances come to you as "ration coupons," something like food stamps, and you can either "spend" them yourself by emitting the amount of pollutant each stamp permits, or sell them to someone else. If you decide to build a solar power plant that replaces your coal plant, you can sell your pollution allowances to a power company that is still using coal and is emitting more than its allowed amount. That company could then increase its emissions. In theory, both you and the other company make money—you by simply selling your credits, the other company by not having to build a completely new power plant.

Does cap-and-trade work? The Environmental Protection Agency (EPA) now has three decades of experience with attempts to control air pollutants and has found that cap-and-trade works very well—for example, in reducing acid rain resulting from sulfur dioxide emissions from power plants (Figure 7.1).[1] Proponents of cap-and-trade argue that it places the benefits and disbenefits of pollution control directly in the hands of the polluters, rather than passing them on to consumers (which a tax usually ends up doing). Also, it keeps the activity in a kind of free market, rather than forcing specific actions on individuals, and in this way minimizes government interference.

Opponents of cap-and-trade argue that it is really just a tax in disguise, that its end result is the same as a direct tax—the corporations that produce electricity from fossil fuel will be burdened with a huge tax and put at a disadvantage versus corporations that turn to alternative energy sources. Advocates of cap-and-trade say that this is just the point—that the whole idea is to encourage our society to move away from fossil fuels, and that this has proved to be an efficient way to do it. Opponents counter that the net result will be a burden on everybody and that the average family's energy bill could go up an estimated $1,500 a year.[2] Proponents of cap-and-trade cite its success with acid rain from sulfur dioxide emissions (Figure 7.1), but critics say that, unlike sulfur dioxide, carbon dioxide isn't really a pollutant in the usual legal sense, and that because carbon dioxide is a global problem, cap-and-trade can't work without unusual treaties among nations.

You can see from the cap-and-trade example that what seems at first glance a simple and straightfor-

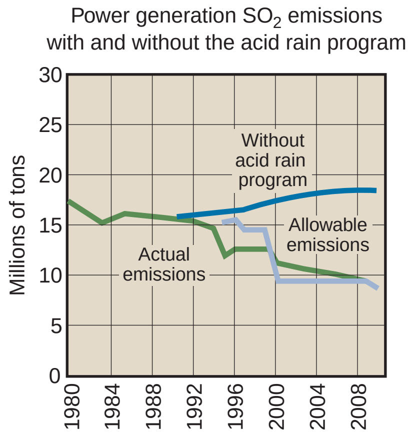

FIGURE 7.1 **Cap-and-trade helped the EPA reduce acid rain caused by sulfur dioxide emissions (a) from power plants like this coal-fired power plant in Arizona (b).**

ward solution can turn out to be much more difficult. Deciding whether cap-and-trade can be a good way to reduce carbon dioxide emissions into the atmosphere depends in part on scientific knowledge, but also on economic analyses. So it is with most environmental issues.

7.1 Overview of Environmental Economics

The history of modern environmental law can be traced back to the 1960s and the beginnings of the modern social and political movement we know as environmentalism. Its foundation is the "three E's": ecology, engineering, and economics.[3] Although in this environmental science textbook we will devote most of our time to the scientific basis—ecology, geology, climatology, and all the other sciences involved in environmental analysis—economics underlies much of the discussion. It is always a factor in finding solutions that work, are efficient, and are fair. This is why we are devoting one of our early overview chapters to environmental economics.

Environmental economics is not simply about money; it is about how to persuade people, organizations, and society at large to act in a way that benefits the environment, keeping it as free as possible of pollution and other damage, keeping our resources sustainable, and accomplishing these goals within a democratic framework. Put most simply, environmental economics focuses on two broad areas: controlling pollution and environmental damage in general, and sustaining renewable resources—forests, fisheries, recreational lands, and so forth. Environmental economists also explore the reasons why people don't act in their own best interests when it comes to the environment. Are there rational explanations for what seem to be irrational choices? If so, and if we can understand them, perhaps we can do something about them. What we do, what we can do, and how we do it are known collectively as **policy instruments**.

Environmental decision-making often, perhaps even usually, involves analysis of tangible and intangible factors. In the language of economics, a **tangible factor** is one you can touch, buy, and sell. A house lost in a mudslide due to altering the slope of the land is an example of a tangible factor. For economists, an **intangible factor** is one you can't touch directly, but you value it, as with the beauty of the slope before the mudslide. Of the two, the intangibles are obviously more difficult to deal with because they are harder to measure and to value economically. Nonetheless, evaluation of intangibles is becoming more important. As you will see in later chapters, huge amounts of money and resources are involved in economic decisions about both tangible and intangible aspects of the environment: There are the costs of pollution and the loss of renewable resources, and there are the costs of doing something about these problems.

In every environmental matter, there is a desire on the one hand to maintain individual freedom of choice, and on the other to achieve a specific social goal. In ocean fishing, for example, we want to allow every individual to choose whether or not to fish, but we want to prevent everyone from fishing at the same time and bringing fish species to extinction. This interplay between private good and public good is at the heart of environmental issues.

In this chapter we will examine some of the basic issues in environmental economics: the environment as a commons; risk-benefit analysis; valuing the future; and why people often do not act in their own best interest.

7.2 Public-Service Functions of Nature

A complicating factor in maintaining clean air, soils, and water, and sustaining our renewable resources is that ecosystems do some of this without our help. Forests absorb particulates, salt marshes convert toxic compounds to nontoxic forms, wetlands and organic soils treat sewage. These are called the **public-service functions** of nature. Economists refer to the ecological systems that provide these benefits as **natural capital**.

The atmosphere performs a public service by acting as a large disposal site for toxic gases. And carbon monoxide is eventually converted to nontoxic carbon dioxide either by inorganic chemical reactions or by soil bacteria. Bacteria also clean water in the soil by decomposing toxic chemicals, and bacteria fix nitrogen in the oceans, lakes, rivers, and soils. If we replaced this function by producing nitrogen fertilizers artificially and transporting them ourselves, the cost would be immense—but, again, we rarely think about this activity of bacteria.

FIGURE 7.2 **Public-service functions of living things.** Wild creatures and natural ecosystems carry out tasks that are important for our survival and would be extremely expensive for us to accomplish by ourselves. For example, bees pollinate millions of flowers important for food production, timber supply, and aesthetics. As a result, beekeeping is a commercial enterprise, with rewards and risks, as shown in this photograph.

Among the most important public-service providers are the pollinators, which include birds, bats, ants, bees, wasps, beetles, butterflies, moths, flies, mosquitoes, and midges. It is estimated that pollinating animals pollinate about $15 billion worth of crops grown on 2 million acres in the United States,[4, 5] that about one bite in three of the food you eat depends on pollinators, and that their total economic impact can reach $40 billion a year (Figure 7.2).[6] The cost of pollinating these crops by hand would be exorbitant, so a pollutant that eliminated bees would have large indirect economic consequences. We rarely think of this benefit of bees, but it has received wide attention in recent years because of a disease called Colony Collapse Disorder (CCD), which affected food costs, agricultural practices, and many companies that provide bees to pollinate crops.[7]

Public-service functions of living things are estimated to provide between $3 trillion and $33 trillion in benefits to human beings and other forms of life per year.[8] However, current estimates are only rough approximations because the value is difficult to measure.

7.3 The Environment as a Commons

Often people use a natural resource without regard for maintaining that resource and its environment in a renewable state—that is, they don't concern themselves with that resource's sustainability. At first glance, this seems puzzling, but economic analysis suggests that the profit motive, by itself, will not always lead a person to act in the best interests of the environment.

One reason has to do with what the ecologist Garrett Hardin called "the tragedy of the commons."[9] When a resource is shared, an individual's personal share of profit from its exploitation is usually greater than his or her share of the resulting loss. A second reason has to do with the low growth rate, and therefore low productivity, of a resource.

A **commons** is land (or another resource) owned publicly, with public access for private uses. The term *commons* originated from land owned publicly in

English and New England towns and set aside so that all the farmers of the town could graze their cattle. Sharing the grazing area worked as long as the number of cattle was low enough to prevent overgrazing. It would seem that people of goodwill would understand the limits of a commons. But take a dispassionate view and think about the benefits and costs to each farmer as if it were a game. Phrased simply, each farmer tries to maximize personal gain and must periodically consider whether to add more cattle to the herd on the commons. The addition of one cow has both a positive and a negative value. The positive value is the benefit when the farmer sells that cow. The negative value is the additional grazing by the cow. The personal profit from selling a cow is greater than the farmer's share of the loss caused by the degradation of the commons. Therefore, the short-term successful game plan is always to add another cow.

Since individuals will act to increase use of the common resource, eventually the common grazing land is so crowded with cattle that none can get adequate food and the pasture is destroyed. In the short run, everyone seems to gain, but in the long run, everyone loses. This applies generally: Complete freedom of action in a commons inevitably brings ruin to all. The implication seems clear: Without some management or control, all natural resources treated like a commons will inevitably be destroyed.

How can we deal with the tragedy of the commons? It is only a partially solved problem. As several scientists wrote recently, "No single broad type of ownership—government, private or community—uniformly succeeds or fails to halt major resource deterioration." Still, in trying to solve this puzzle, economic analysis can be helpful.

There are many examples of commons, both past and present. In the United States, 38% of forests are on publicly owned lands; as such, these forests are commons. Resources in international regions, such as ocean fisheries away from coastlines, and the deep-ocean seabed, where valuable mineral deposits lie, are international commons not controlled by any single nation.

The Arctic sea ice is a commons (Figure 7.3), as is most of the continent of Antarctica, although there are some national territorial claims, and international negotiations have continued for years about conserving Antarctica and about the possible use of its resources.

The atmosphere, too, is a commons, both nationally and internationally. Consider the possibility of global warming. Individuals, corporations, public utilities, motor vehicles, and nations add carbon dioxide to the air by burning fossil fuels. Just as Garrett Hardin suggested, people tend to respond by benefiting themselves (burning more fossil fuel) rather than by benefiting the commons (burning less fossil fuel). The picture here is quite mixed, however, with much ongoing effort to bring cooperation to this common issue.

FIGURE 7.3 Arctic sea ice and polar bears, which live in many areas of the Arctic, are part of a commons.

In the 19th century, burning wood in fireplaces was the major source of heating in the United States (and fuel wood is still the major source of heat in many nations). Until the 1980s, a wood fire in a fireplace or woodstove was considered a simple good, providing warmth and beauty. People enjoyed sitting around a fire and watching the flames—an activity with a long history in human societies. But in the 1980s, with increases in populations and vacation homes in states such as Vermont and Colorado, home burning of wood began to pollute air locally. Especially in valley towns surrounded by mountains, the air became fouled, visibility declined, and there was a potential for ill effects on human health and the environment. Several states, including Vermont, have had programs offering rebates to buyers of newer, lower-polluting woodstoves.[10] The local air is a commons, and its overuse required a societal change.

Recreation is a problem of the commons—overcrowding of national parks, wilderness areas, and other nature–recreation areas. An example is Voyageurs National Park in northern Minnesota. The park, within North America's boreal-forest biome, includes many lakes and islands and is an excellent place for fishing, hiking, canoeing, and viewing wildlife. Before the area became a national park, it was used for motorboating, snowmobiling, and hunting; a number of people in the region made their living from tourism based on these kinds of recreation. Some environmental groups argue that Voyageurs National Park is ecologically fragile and needs to be legally designated a U.S. wilderness area to protect it from overuse and from the adverse effects of motorized vehicles. Others argue that the nearby million-acre Boundary Waters Canoe Area provides ample wilderness, that Voyageurs can withstand a moderate level of hunting and motorized transportation,

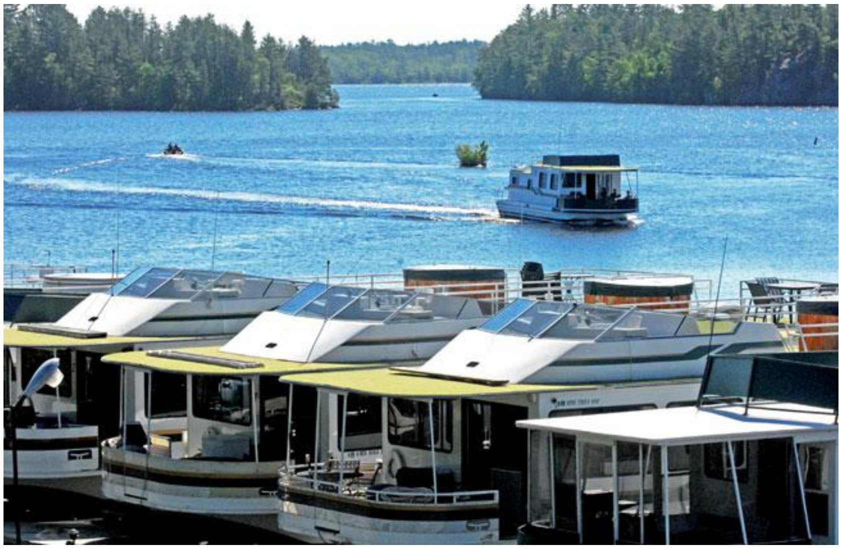

FIGURE 7.4 Voyageurs National Park in northern Minnesota has many lakes well suited to recreational boating. But what kind of boating—what kinds of motors, what size boats—is a long-running controversy. In a commons such as a national park, these are the kinds of conflicts that arise over intangible value (such as scenic beauty) and tangible value (such as the opportunity for boat owners and guides to make a living). Here we see a guided tour on a motorized boat.

and that these uses should be allowed. At the heart of this conflict is the problem of the commons, which in this case can be summed up as follows:

- What is the appropriate public use of public lands?
- Should all public lands be open to all public uses?
- Should some public lands be protected from people?

At present, the United States has a policy of different uses for different lands. In general, national parks are open to the public for many kinds of recreation, whereas designated wildernesses have restricted visitorship and kinds of uses (Figure 7.4).

7.4 Low Growth Rate and Therefore Low Profit as a Factor in Exploitation

We said earlier that the second reason individuals tend to overexploit natural resources held in common is the low growth rate of many biological resources.[11] For example, one way to view whales economically is to consider them solely in terms of whale oil. Whale oil, a marketable product, and the whales alive in the ocean, can be thought of as the capital investment of the industry.

From an economic point of view, how can whalers get the best return on their capital? Keeping in mind that whale populations, like other populations, increase only if there are more births than deaths, we will examine two approaches: *resource sustainability* and *maximum profit*. If whalers adopt a simple, one-factor resource-sustainability policy, they will harvest only the net biological productivity each year (the number by which the population increased). Barring disease or disaster, this will maintain the total abundance of whales at its current level and keep the whalers in business indefinitely. If, on the other hand, they choose to simply maximize immediate profit, they will harvest all the whales now, sell the oil, get out of the whaling business, and invest their profits.

Suppose they adopt the first policy. What is the maximum gain they can expect? Whales, like other large, long-lived creatures, reproduce slowly, with each female typically giving birth to a calf every three or four years. Thus, the total net growth of a whale population is likely to be no more than 5% per year and probably more like 3%. This means that if all the oil in the whales in the oceans today represented a value of $100 million, then the most the whalers could expect to take in each year would be no more than 5% of this amount, or $5 million. Until the 2008 economic recession, 5% interest was considered a modest, even poor, rate of return on one's money. And meanwhile the whalers would have to pay for the upkeep of ships and other equipment, salaries of employees, and interest on loans—all of which would decrease profit.

However, if whalers opted for the second policy and harvested all the whales, they could invest the money from the oil. Although investment income varies, even a conservative return on their investment of $100 million would likely yield millions of dollars annually, and since they would no longer be hunting whales, this would be clear profit, without the costs of paying a crew, maintaining ships, buying fuel, marketing the oil, and so on.

Clearly, if one considers only direct profit, it makes sense to adopt the second policy: Harvest all the whales, invest the money, and relax. And this seems to have been the case for those who hunted bowhead whales in the 19th and early 20th centuries (Figures 7.5 and 7.6).[12] Whales simply are not a highly profitable long-term investment under the resource-sustainability policy. From a

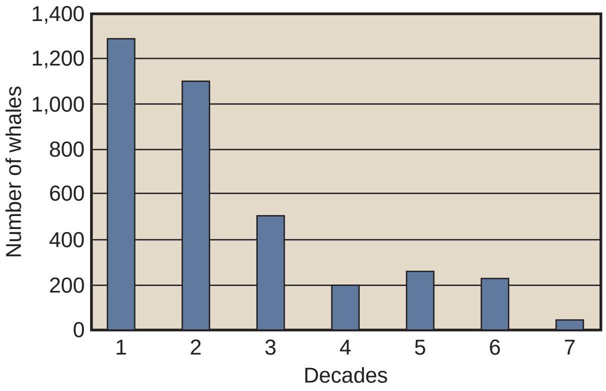

FIGURE 7.5 Bowhead whales caught and killed by Yankee whalers from 1849 to 1914. The number killed, shown for each decade, declined rapidly, indicating that the whale population was unable to reproduce at a rate that could replace the initial large catches, yet the whalers kept killing at a nonsustainable rate, as economics would predict. (*Source*: Redrawn from J.R. Bockstoce and D.B. Botkin, *The Historical Status and Reduction of the Western Arctic Bowhead Whale* (Balaena mysticetus) *Population by the Pelagic Whaling Industry, 1849–1914*. Final report to the U.S. National Marine Fisheries Service by the Old Dartmouth Historical Society, 1980; and J.R. Bockstoce, D.B. Botkin, A. Philp, B.W. Collins, and J.C. George, The geographic distribution of bowhead whales in the Bering, Chukchi, and Beaufort seas: Evidence from whaleship records, 1849–1914, *Marine Fisheries Review* 67(3) [2007]:1–43.)

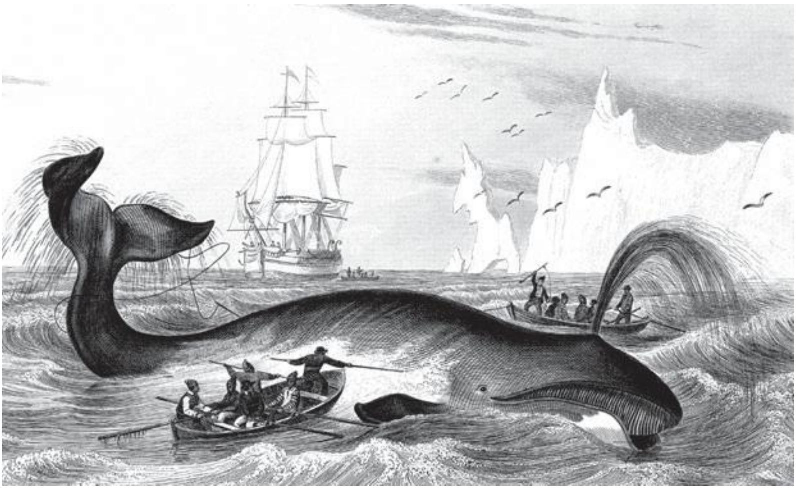

FIGURE 7.6 Bowhead whale baleen (their modified teeth) on a dock in San Francisco in the late 19th century, when these flexible plates were needed for women's corsets and other uses where strength and flexibility were important. Baleen and whale oil were the two commercial products obtained from bowheads. When baleen was replaced by new forms of steel, the baleen market disappeared. Commercial bowhead whale hunting ended with the beginning of World War I. However, whale oil remained listed as a strategic material by the U.S. Department of Defense for decades afterward because of its lubricating qualities.

tangible economic perspective, without even getting into the intangible ethical and environmental concerns, it is no wonder that there are fewer and fewer whaling companies and that companies left the whaling business when their ships became old and inefficient. Few nations support whaling; those that do have stayed with whaling for cultural reasons. For example, whaling is important to the Eskimo culture, so some harvest of bowheads takes place in Alaska; and whale meat is a traditional Japanese and Norwegian food, so these countries continue to harvest whales for this reason.

Scarcity Affects Economic Value

The relative scarcity of a necessary resource is another factor to consider in resource use, because this affects its value and therefore its price. For example, if a whaler lived on an isolated island where whales were the only food and he had no communication with other people, then his primary interest in whales would be as a way for him to stay alive. He couldn't choose to sell off all whales to maximize profit, since he would have no one to sell them to. He might harvest at a rate that would maintain the whale population. Or, if he estimated that his own life expectancy was only about ten years, he might decide that he could take a chance on consuming whales beyond their ability to reproduce. Cutting it close to the line, he might try to harvest whales at a rate that would cause them to become extinct at the same time that he would. "You can't take it with you" would be his attitude.

If ships began to land regularly at this island, he could leave, or he could trade and begin to benefit from some of the future value of whales. If ocean property rights existed, so he could "own" the whales that lived within a certain distance of his island, then he might consider the economic value of owning this right to the whales. He could sell rights to future whales, or mortgage against them, and thus reap the benefits during his lifetime from whales that could be caught after his death. Causing the extinction of whales would not be necessary.

From this example, we see that policies that seem ethically good may not be the most profitable for an individual. We must think beyond the immediate, direct economic advantages of harvesting a resource. Economic analysis clarifies how an environmental resource should be used, what is perceived as its intrinsic value and therefore its price. And this brings us to the question of externalities.

7.5 Externalities

One gap in our thinking about whales, an environmental economist would say, is that we must be concerned with externalities in whaling. An **externality**, also called an **indirect cost**, is often not recognized by producers as part of their costs and benefits, and therefore not normally accounted for in their cost-revenue analyses.[11] Put simply, externalities are costs or benefits that don't show up in the price tag.[13] In the case of whaling, externalities include the loss of revenue to whale-watching tourist boats and the loss of the ecological role that whales play in marine ecosystems. Classically, economists agree that the only way for a consumer to make a rational decision is by comparing the true costs—including externalities—against the benefits the consumer seeks.

Air and water pollution provide good examples of externalities. Consider the production of nickel from ore at the Sudbury, Ontario, smelters, which has serious environmental effects. Traditionally, the economic costs associated with producing commercially usable nickel from an ore were only the **direct costs**—that is, those borne by the producer in obtaining, processing, and distributing a product—passed directly on to the user or purchaser. In this case, direct costs include purchasing the ore, buying energy to run the smelter, building the plant, and paying employees. The externalities, however, include costs associated with degradation of the environment from the plant's emissions. For example, prior to implementation of pollution control, the Sudbury smelter destroyed vegetation over a wide area, which led to increased erosion. Although air emissions from smelters have been substantially reduced and restoration efforts have initiated a slow recovery of the area, pollution remains a problem, and total recovery of the local ecosystem may take a century or more.[14] There are costs associated with the value of trees and soil, with restoring vegetation and land to a productive state.

Problem number one: What is the true cost of clean air over Sudbury? Economists say that there is plenty of disagreement about the cost, but that everyone agrees that it is larger than zero. In spite of this, clean air and water are traded and dealt with in today's world as if their value were zero. How do we get the value of clean air and water and other environmental benefits to be recognized socially as greater than zero? In some cases, we can determine the dollar value. We can evaluate water resources for power or other uses based on the amount of flow of the rivers and the quantity of water storage in rivers and lakes. We can evaluate forest resources based on the number, types, and sizes of trees and their subsequent yield of lumber. We can evaluate mineral resources by estimating how many metric tons of economically valuable mineral material exist at particular locations. Quantitative evaluation of the tangible natural resources—such as air, water, forests, and minerals—prior to development or management of a particular area is now standard procedure.

Problem number two: Who should bear the burden of these costs? Some suggest that environmental and ecological costs should be included in costs of production through taxation or fees. The expense would be borne by the corporation that benefits directly from the sale of the resource (nickel in the case of Sudbury) or would be passed on in higher sales prices to users (purchasers) of nickel. Others suggest that these costs be shared by the entire society and paid for by general taxation, such as a sales tax or income tax. The question is whether it is better to finance pollution control using tax dollars or a "polluter pays" approach.

7.6 Valuing the Beauty of Nature

The beauty of nature—often termed *landscape aesthetics*—is an environmental intangible that has probably been important to people as long as our species has existed. We know it has been important since people have written, because the beauty of nature is a continuous theme in literature and art. Once again, as with forests cleaning the air, we face the difficult question: How do we arrive at a price for the beauty of nature? The problem is even more complicated because among the kinds of scenery we enjoy are many modified by people. For example, the open farm fields in Vermont improved the view of the mountains and forests in the distance, so when farming declined in the 1960s, the state began to provide tax incentives for farmers to keep their fields open and thereby help the tourism economy (Figure 7.7).

One of the perplexing problems of aesthetic evaluation is personal preference. One person may appreciate a high mountain meadow far removed from civilization; a second person may prefer visiting with others on a patio at a trailhead lodge; a third may prefer to visit a city park; and a fourth may prefer the austere beauty of a desert. If we are going to consider aesthetic factors in environmental analysis, we must develop a method of aesthetic evaluation that allows for individual differences—another yet unsolved topic.

One way the intangible value of landscape beauty is determined is by how much people are willing to pay for it, and how high a price people will pay for land with a beautiful view, compared with the price of land without a view. As apartment dwellers in any big city will tell you,

FIGURE 7.7 How much is a beautiful scene worth? Consider, for example, this view in New Hampshire looking west to the Connecticut River and Vermont. Is landscape beauty an externality?

the view makes a big difference in the price of their unit. For example, in mid-2009, the *New York Times* listed two apartments, both with two bedrooms, for sale in the same section of Manhattan, one without a view for $850,000 and one with a wonderful view of the Hudson River estuary for $1,315,000 (Figure 7.8).

Some philosophers suggest that there are specific characteristics of landscape beauty and that we can use these characteristics to help us set the value of intangibles. Some suggest that the three key elements of landscape beauty are coherence, complexity, and mystery—mystery in the form of something seen in part but not completely, or not completely explained. Other philosophers suggest that the primary aesthetic qualities are unity vividness, and variety.[15] *Unity* refers to the quality or wholeness of the perceived landscape—not as an assemblage but as a single, harmonious unit. *Vividness* refers to that quality of landscape that makes a scene visually striking; it is related to intensity, novelty, and clarity. People differ in what they believe are the key qualities of landscape beauty, but again, almost everyone would agree that the value is greater than zero.

FIGURE 7.8 A view from a New York City apartment greatly increased its price compared with similar apartments without a view.

7.7 How Is the Future Valued?

The discussion about whaling—explaining why whalers may not find it advantageous to conserve whales—reminds us of the old saying "A bird in the hand is worth two in the bush." In economic terms, a profit now is worth much more than a profit in the future. This brings up another economic concept important to environmental issues: the future value of anything compared with its present value.

Suppose you are dying of thirst in a desert and meet two people. One offers to sell you a glass of water now, and the other offers to sell you a glass of water if you can be at the well tomorrow. How much is each glass worth? If you believe you will die today without water, the glass of water today is worth all your money, and the glass tomorrow is worth nothing. If you believe you can live another day without water, but will die in two days, you might place more value on tomorrow's glass than on today's, since it will gain you an extra day—three rather than two.

In practice, things are rarely so simple and distinct. We know we aren't going to live forever, so we tend to value personal wealth and goods more if they are available now than if they are promised in the future. This evaluation is made more complex, however, because we are accustomed to thinking of the future—to planning a nest egg for retirement or for our children. Indeed, many people today argue that we have a debt to future generations and must leave the environment in at least as good a condition as we found it. These people would argue that the future environment is not to be valued less than the present one (Figure 7.9).

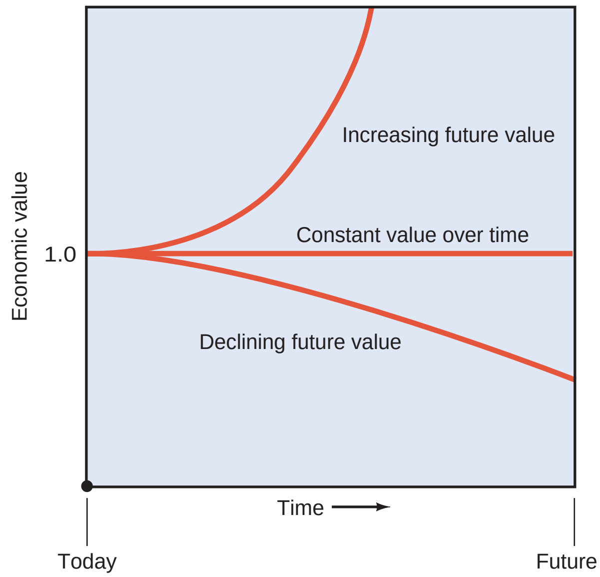

FIGURE 7.9 Economic value as a function of time—a way of comparing the value of having something now with the value of having it in the future. A negative value means that there is more value attached to having something in the present than having it in the future. A positive value means that there is more value attached to having something in the future than having it today.

Since the future existence of whales and other endangered species has value to those interested in biological conservation, the question arises: Can we place a dollar value on the *future* existence of anything? The future value depends on how far into the future you are talking about. The future times associated with some important global environmental topics, such as stratospheric ozone depletion and global warming, extend longer than a century. This is because chlorofluorocarbons (CFCs) have such a long residence time in the atmosphere and because of the time necessary to realize benefits from changing energy policy to offset global climate change.

Another aspect of future versus present value is that spending on the environment can be viewed as diverting resources from alternative forms of productive investment that will be of benefit to future generations. (This assumes that spending on the environment is not itself a productive investment.)

A further issue is that as we get wealthier, the value we place on many environmental assets (such as wilderness areas) increases dramatically. Thus, if society continues to grow in wealth over the next century as it has over the past century, the environment will be worth far more to our great-grandchildren than it was to our great-grandparents, at least in terms of willingness to pay to protect it. The implication—which complicates this topic even more—is that conserving resources and environment for the future is tantamount to taking from the poor today and giving to the possibly rich in the future. To what extent should we ask the average American today to sacrifice now for richer great-great-grandchildren? How can we know the future usefulness of today's sacrifices? Put another way, what would you have liked your ancestors in 1900 to have sacrificed for our benefit today? Should they have increased research and development on electric transportation? Should they have saved more tall-grass prairie or restricted whaling?

Economists observe that it is an open question whether something promised in the future will have more value then than it does today. Future economic value is difficult enough to predict because it is affected by how future consumers view consumption. But if, in addition, something has greater value in the future than it does today, then that leads to the mathematical conclusion that in the very long run, the future value will become infinite, which of course is impossible. So in terms of the future, the basic issues are (1) that since we are so much richer and better off than our ancestors, their sacrificing for us might have been inappropriate; and (2) even if they had wanted to sacrifice, how would they have known what sacrifices would be important to us?

As a general rule, one answer to the thorny questions about future value is: Do not throw away or destroy something that cannot be replaced if you are not sure of its future value. For example, if we do not fully understand the value of the wild relatives of potatoes that grow in Peru but do know that their genetic diversity might be helpful in developing future strains of potatoes, then we ought to preserve those wild strains.

7.8 Risk-Benefit Analysis

Death is the fate of all individuals, and almost every activity in life involves some risk of death or injury. How, then, do we place a value on saving a life by reducing the level of a pollutant? This question raises another important area of environmental economics: **risk-benefit analysis**, in which the riskiness of a present action in terms of its possible outcomes is weighed against the benefit, or value, of the action. Here, too, difficulties arise.

With some activities, the relative risk is clear. It is much more dangerous to stand in the middle of a busy highway than to stand on the sidewalk, and hang gliding has a much higher mortality rate than hiking. The effects of pollutants are often more subtle, so the risks are harder to pinpoint and quantify. Table 7.1 gives the lifetime risk of death associated with a variety of activities and some forms of pollution. In looking at the table, remember that since the ultimate fate of everyone is death, the total lifetime risk of death from all causes must be 100%. So if you are going to die of something and you smoke a pack of cigarettes a day, you have 8 chances in 100 that your death will be a result of smoking. At the same time, your risk of death from driving an automobile is 1 in 100. Risk tells you the chance of an event but not its timing. So you might smoke all you want and die from the automobile risk first.

One of the striking things about Table 7.1 is that death from outdoor environmental pollution is comparatively low—even compared to the risks of drowning or of dying in a fire. This suggests that the primary reason we value lowering air pollution is not to lengthen our lives but to improve the quality of our lives. Considering people's great interest in air pollution today, the quality of life must be much more important than is generally recognized. We are willing to spend money on improving that quality rather than just extending our lives. Another striking observation in this table is that natural *indoor* air pollution is much more deadly than most outdoor air pollution—unless, of course, you live at a toxic-waste facility.

It is commonly believed that future discoveries will help to decrease various risks, perhaps eventually allowing us to approach a zero-risk environment. But complete elimination of risk is generally either technologically impossible or prohibitively expensive. Societies differ in their views of what constitutes socially, psychologically, and ethically acceptable levels of risk for any cause of death or injury, but we can make some generalizations about the acceptability of various risks. One factor is the number of people affected. Risks that affect a small population (such as employees at nuclear power plants) are usually more

Table 7.1 RISK OF DEATH FROM VARIOUS CAUSES

CAUSE	RESULT	RISK OF DEATH (PER LIFETIME)	LIFETIME RISK OF DEATH (%)	COMMENT
Cigarette smoking (pack a day)	Cancer, effect on heart, lungs, etc.	8 in 100	8.0%	
Breathing radon-containing air in the home	Cancer	1 in 100	1.0%	Naturally occurring
Automobile driving		1 in 100	1.0%	
Death from a fall		4 in 1,000	0.4%	
Drowning		3 in 1,000	0.3%	
Fire		3 in 1,000	0.3%	
Artificial chemicals in the home	Cancer	2 in 1,000	0.2%	Paints, cleaning agents, pesticides
Sunlight exposure	Melanoma	2 in 1,000	0.2%	Of those exposed to sunlight
Electrocution		4 in 10,000	0.04%	
Air outdoors in an industrial area		1 in 10,000	0.01%	
Artificial chemicals in water		1 in 100,000	0.001%	
Artificial chemicals in foods		less than 1 in 100,00	0.001%	
Airplane passenger (commercial airline)		less than 1 in 1,000,000	0.00010%	

Source: From *Guide to Environmental Risk* (1991), U.S. EPA Region 5 Publication Number 905/91/017.

acceptable than those that involve all members of a society (such as risk from radioactive fallout).

In addition, novel risks appear to be less acceptable than long-established or natural risks, and society tends to be willing to pay more to reduce such risks. For example, in the late part of the 20th century, France spent about \$1 million each year to reduce the likelihood of one air-traffic death but only \$30,000 for the same reduction in automobile deaths.[16] Some argue that the greater safety of commercial air travel versus automobile travel is in part due to the relatively novel fear of flying compared with the more ordinary fear of death from a road accident. That is, because the risk is newer to us and thus less acceptable, we are willing to spend more per life to reduce the risk from flying than to reduce the risk from driving.

People's willingness to pay for reducing a risk also varies with how essential and desirable the activity associated with the risk is. For example, many people accept much higher risks for athletic or recreational activities than they would for transportation- or employment-related activities (see Table 7.1). People volunteer to climb Mt. Everest even though many who have attempted it have died, but the same people could be highly averse to risking death in a train wreck or commercial airplane crash. The risks associated with playing a sport or using transportation are assumed to be inherent in the activity. The risks to human health from pollution may be widespread and linked to a large number of deaths. But although risks from pollution are often unavoidable and unseen, people want a lesser risk from pollution than from, say, driving a car or playing a sport.

In an ethical sense, it is impossible to put a value on a human life. However, it is possible to determine how much people are willing to pay for a certain amount of risk reduction or a certain probability of increased longevity. For example, a study by the Rand Corporation considered measures that would save the lives of heart-attack victims, including increasing ambulance services and initiating pretreatment screening programs. According to the study, which identified the likely cost per life saved and people's willingness to pay, people favored government spending of about \$32,000 per life saved, or \$1,600 per year of longevity. Although information is incomplete, it is possible to estimate the cost of extending lives in terms of dollars per person per year for various actions (Figure 7.10 and Table 7.1). For example, on the basis of direct effects on human health, it costs more to increase longevity by reducing air pollution than to directly reduce deaths by adding a coronary-ambulance system.

Such a comparison is useful as a basis for decision-making. Clearly, though, when a society chooses to reduce air pollution, many factors beyond the direct, measurable health benefits are considered. Pollution not only directly affects our health but also causes ecological and aesthetic damage, which can indirectly affect human health (see Section 7.4). We might want to choose a slightly higher risk of death in a more pleasant environment rather than increase the chances of living longer in a poor environment—spend money to clean up the air rather than increase ambulance services to reduce deaths from heart attacks.

Comparisons like these may make you uncomfortable. But like it or not, we cannot avoid making choices of this kind. The issue boils down to whether we should improve the quality of life for the living or extend life expectancy regardless of the quality of life.[17]

The degree of risk is an important concept in our legal processes. For example, the U.S. Toxic Substances Control Act states that no one may manufacture a new chemical substance or process a chemical substance for a new use without obtaining clearance from the EPA. The Act establishes procedures for estimating the hazard to the environment and to human health of any new chemical before its use becomes widespread. The EPA examines the data provided and judges the degree of risk associated with all aspects of the production of the new chemical or process, including extraction of raw materials, manufacturing, distribution, processing, use, and disposal. The chemical can be banned or restricted in either manufacturing or use if the evidence suggests that it will pose an unreasonable risk to human health or to the environment.

But what is unreasonable?[18] This question brings us back to Table 7.1 and makes us realize that deciding what is "unreasonable" involves judgments about the quality of life as well as the risk of death. The level of acceptable pollution (and thus risk) is a social-economic-environmental trade-off. Moreover, the level of acceptable risk changes over time in society, depending on changes in scientific knowledge, comparison with risks from other causes, the expense of decreasing the risk, and the social and psychological acceptability of the risk.

When adequate data are available, it is possible to take scientific and technological steps to estimate the level of risk and, from this, to estimate the cost of reducing risk and compare the cost with the benefit. However, what constitutes an acceptable risk is more than a scientific or technical issue. The acceptability of a risk involves ethical and psychological attitudes of individuals and society. We must therefore ask several questions: What risk from a particular pollutant is acceptable? How much is a given reduction in risk from that pollutant worth to us? How much will each of us, as individuals or collectively as a society, be willing to pay for a given reduction in that risk?

The answers depend not only on facts but also on societal and personal values. What must also be factored into the equation is that the costs of cleaning up pollutants and polluted areas and the costs of restoration programs can be minimized, or even eliminated, if a recognized pollutant is controlled initially. The total cost of pollution control need not increase indefinitely.

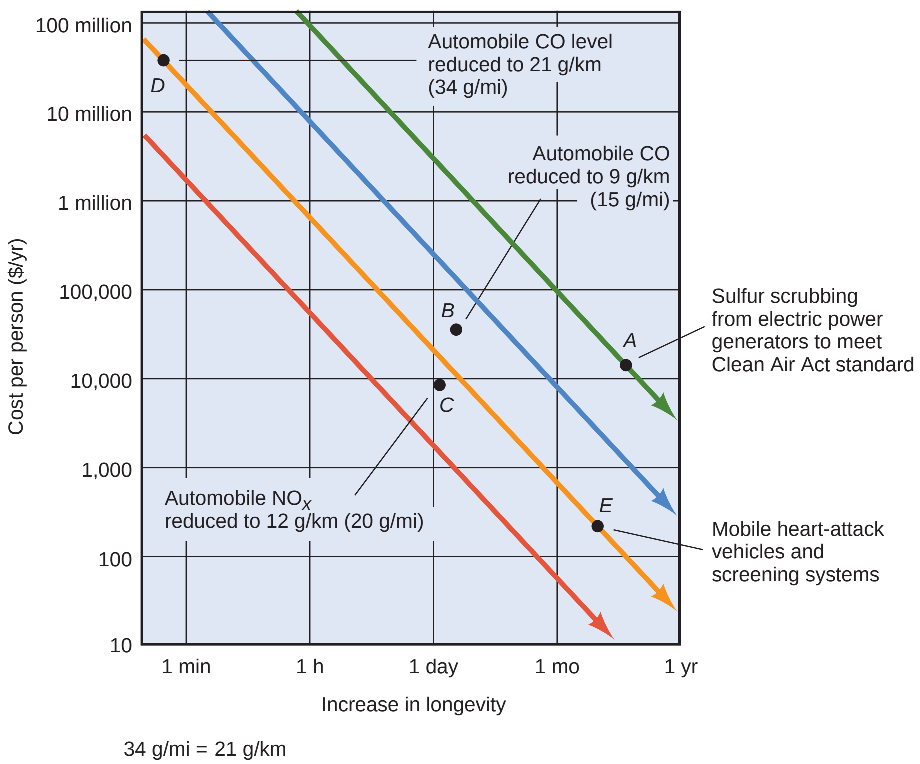

FIGURE 7.10 The cost of extending a life in dollars per year is one way to rank the effectiveness of various efforts to reduce pollutants. This graph shows that reducing sulfur emissions from power plants to the Clean Air Act level **(A)** would extend a human life 1 year at a cost of about $10,000. Similar restrictions applied to automobile emissions **(B, C)** would increase lifetimes by 1 day. More stringent automobile controls would be much more expensive **(D)**; mobile units and screening programs for heart problems would be much cheaper **(E)**. This graph represents only one step in an environmental analysis. (*Source:* Based on R. Wilson, Risk-benefit analysis for toxic chemicals, *Ecotoxicology and Environmental Safety* 4 [1980]: 370–83.)

CRITICAL THINKING ISSUE

Georges Bank: How Can U.S. Fisheries Be Made Sustainable?

The opening case study discussed several ways that economists help make policy. Ocean fishing in Georges Bank—a large, shallow area between Cape Cod, Massachusetts, and Cape Sable Island in Nova Scotia, Canada—illustrates different ways of making a policy work. Both overfishing and pollution have been blamed for the alarming decline in groundfish (cod, haddock, flounder, redfish, pollack, hake) off the northeastern coast of the United States and Canada. Governments' attempts to regulate fishing have generated bitter disputes with fishermen, many of whom contend that restrictions on fishing make them scapegoats for pollution problems. The controversy has become a classic battle between short-term economic interests and long-term environmental concerns.

The oceans outside of national territorial waters are *commons*—open to free use by all—and thus the fish and mammals that live in them are common resources. What is a common resource may change over time, however. The move by many nations to define international waters as beginning 325 kilometers (200 miles) from their coasts has turned some fisheries that used to be completely open common resources into national resources open only to domestic fishermen.

In fisheries, there have been four main management options:

1. Establish total catch quotas for the entire fishery and allow anybody to fish until the total is reached.
2. Issue a restricted number of licenses but allow each licensed fisherman to catch many fish. (This is equivalent to the ***legal emissions limit*** explained in the opening case study.)
3. Tax the catch (the fish brought in) or the effort (the cost of ships, fuel, and other essential items). (This is equivalent to the ***tax on emitters*** in the opening case study.)
4. Allocate fishing rights—that is, assign each fisherman a transferable and salable quota (see the ***cap-and-trade*** option in the opening case study.)

With total-catch quotas, the fishery is closed when the quota is reached. Whales, Pacific halibut, tropical tuna, and anchovies have been regulated in this way. Although regulating the total catch can be done in a way that helps the fish, it tends to increase the number of fishermen and encourage them to buy larger and larger boats. The end result is a hardship for fishermen—huge boats usable for only a brief time each year. When Alaska tried this, all of the halibut were caught in a few days, with the result that restaurants no longer had halibut available for most of the year. This undesirable result led to a change in policy: The total-catch approach was replaced by the sale of licenses.

Issues relating to U.S. fisheries are hardly new. In the early 1970s, fishing was pretty open, but in 1977, in response to concerns about overfishing in U.S. waters by foreign factory ships, the U.S. government extended the nation's coastal waters from 12 to 200 miles (from 19 to 322 km). To encourage domestic fishermen, the National Marine Fisheries Service provided loan guarantees for replacing older vessels and equipment with newer boats carrying high-tech equipment for locating fish. During this same period, demand for fish increased as Americans became more concerned about cholesterol in red meat. Consequently, the number of fishing boats, the number of days at sea, and fishing efficiency increased sharply, and 50–60% of the populations of some species were landed each year.

The international battle over Georges Bank led to a consideration by the International Court of Justice in The Hague. This court's 1984 decision intensified competition. Overfishing continued, and in 1992 Canada was forced to suspend all cod fishing to save the stock from complete annihilation. Later that year, Canada prohibited fishing at certain times and in certain areas on Georges Bank, mandated minimum net sizes, and set quotas on the catch.

These measures were intended to cut the fishing effort in half by 1997. A limited number of fishing permits were issued, limiting the number of days at sea and number of trips for harvesting certain species. High-tech monitoring equipment ensured compliance. Still, things got worse. Recently, portions of Georges Bank were closed indefinitely to fishing for some fish species, including yellowtail, cod, and haddock.

In the spring of 2009, fishermen suggested that the limit on individual fishermen be replaced by a group quota, a variation on Management Option 4 (above). Fishermen would work together in groups called "sectors," and each sector could take a set percentage of the annual catch of one species. This approach is being used elsewhere in U.S. waters. It places fewer restrictions on individual fishermen, such as limiting each one's number of trips or days at sea.

Recent economic analysis suggests that taxes taking into account the cost of externalities (such as water pollution from motorboat oil) can work to the best advantage of fishermen and fish. Allocating a transferable and salable quota to each fisherman produces similar results. However, after decades of trying to find a way to regulate fishing so that Georges Bank becomes a sustainable fishery, nothing has worked well. The fisheries remain in trouble.

Critical Thinking Questions

1. Which of the policy options described above attempt to convert the fishing industry from a commons system to private ownership? How might these measures help prevent overfishing? Is it right to institute private ownership of public resources?

2. Thinking over the choices discussed in this chapter, what policy option do you think has the best chance of sustaining the fisheries on Georges Bank? Explain your answer.
3. What approach to future value (approximately) do each of the following people assume for fish?

   Fisherman: If you don't get it now, someone else will.
   Fisheries manager: By sacrificing now, we can do something to protect fish stocks.
4. Develop a list of the environmental and economic advantages and disadvantages of ITQs. Would you support instituting ITQs in New England? Explain why or why not.
5. Do you think it is possible to reconcile economic and environmental interests in the case of the New England fishing industry? If so, how? If not, why not?

SUMMARY

- Economic analysis can help us understand why environmental resources have been poorly conserved in the past and how we might more effectively achieve conservation in the future.
- Economic analysis is applied to two different kinds of environmental issues: the use of desirable resources (fish in the ocean, oil in the ground, forests on the land) and the minimization of pollution.
- Resources may be common property or privately controlled. The kind of ownership affects the methods available to achieve an environmental goal. There is a tendency to overexploit a common-property resource and to harvest to extinction nonessential resources whose innate growth rate is low, as suggested in Hardin's "tragedy of the commons."
- Future worth compared with present worth can be an important determinant of the level of exploitation.
- The relation between risk and benefit affects our willingness to pay for an environmental good.
- Evaluation of environmental intangibles, such as landscape aesthetics, is becoming more common in environmental analysis. Such evaluation can be used to balance the more traditional economic evaluation and to help separate facts from emotion in complex environmental problems.
- Societal methods to achieve an environmental goal include moral suasion, direct controls, market processes, and government investment. Many kinds of controls have been applied to pollution and the use of desirable resources.

REEXAMINING THEMES AND ISSUES

Human Population

The tragedy of the commons will worsen as human population density increases because more and more individuals will seek personal gain at the expense of community values. For example, more and more individuals will try to make a living from harvesting natural resources. How people can use resources while at the same time conserving them requires an understanding of environmental economics.

Sustainability

From this chapter, we learn why people sometimes are not interested in sustaining an environmental resource from which they make a living. When the goal is simply to maximize profits, it is sometimes a rational decision to liquidate an environmental resource and put the money gained into a bank or another investment, to avoid such liquidation, we need to understand economic externalities and intangible values.

Global Perspective

Solutions to global environmental issues, such as global warming, require that we understand the different economic interests of developed and developing nations. These can lead to different economic policies and different valuation of global environmental issues.

Urban World

The tragedy of the commons began with grazing rights in small villages. As the world becomes increasingly urbanized, the pressure to use public lands for private economic gain is likely to increase. An understanding of environmental economics can help us find solutions to urban environmental problems.

People and Nature

This chapter brings us to the heart of the matter: How do we value the environment, and when can we attach a monetary value to the benefits and costs of environmental actions? People are intimately involved with nature. While we seek rational methods to put a value on nature, the values we choose often derive from intangible benefits, such as an appreciation of the beauty of nature.

Science and Values

One of the central questions of environmental economics concerns how to develop equivalent economic valuation for tangible and intangible factors. For example, how can we compare the value of timber with the beauty people attach to the scenery, trees intact? How can we compare the value of a dam that provides irrigation water and electrical power on the Columbia River with the scenery without the dam, and the salmon that could inhabit that river?

KEY TERMS

commons **130**
direct costs **134**
environmental economics **129**
externality **133**
indirect cost **133**
intangible factor **129**
natural capital **130**
policy instruments **129**
public-service functions **130**
risk-benefit analysis **136**
tangible factor **129**

STUDY QUESTIONS

1. What is meant by the term *the tragedy of the commons?* Which of the following are the result of this tragedy?
(a) The fate of the California condor
(b) The fate of the gray whale
(c) The high price of walnut wood used in furniture

2. What is meant by risk-benefit analysis?

3. Cherry and walnut are valuable woods used to make fine furniture. Basing your decision on the information in the following table, which would you invest in? (*Hint:* Refer to the discussion of whales in this chapter.)
(a) A cherry plantation
(b) A walnut plantation
(c) A mixed stand of both species
(d) An unmanaged woodland where you see some cherry and walnut growing

Species	*Longevity*	*Maximum Size*	*Maximum Value*
Walnut	400 years	1 m	$15,000/tree
Cherry	100 years	1 m	$10,000/tree

4. Bird flu is spread in part by migrating wild birds. How would you put a value on (a) the continued existence of one species of these wild birds; (b) domestic chickens important for food but also a major source of the disease; (c) control of the disease for human health? What relative value would you place on each (that is, which is most important and which least)? To what extent would an economic analysis enter into your valuation?

5. Which of the following are intangible resources? Which are tangible?
(a) The view of Mount Wilson in California
(b) A road to the top of Mount Wilson
(c) Porpoises in the ocean
(d) Tuna in the ocean
(e) Clean air

6. What kind of future value is implied by the statement "Extinction is forever"? Discuss how we might approach providing an economic analysis for extinction.

7. Which of the following can be thought of as commons in the sense meant by Garrett Hardin? Explain your choice.
   (a) Tuna fisheries in the open ocean
   (b) Catfish in artificial freshwater ponds
   (c) Grizzly bears in Yellowstone National Park
   (d) A view of Central Park in New York City
   (e) Air over Central Park in New York City

FURTHER READING

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Goodstein, E.S., *Economics and the Environment*, 3rd ed. (New York: Wiley, 2000).

Hanley, Nick, Jason Shogren, and Ben White, *Environmental Economics in Theory and Practice,* 2nd ed., paperback (New York: Macmillan, 2007).

Hardin, G., Tragedy of the Commons, *Science* 162: 1243–1248, 1968. One of the most cited papers in both science and social science, this classic work outlines the differences between individual interest and the common good.

CHAPTER 8

Biological Diversity and Biological Invasions

Yellow dragon disease—*huanglongbing* in Chinese, "citrus greening" in the United States, represented in China by this iconic symbol for the disease, is a growing threat worldwide to citrus crops. The reason this is a threat has to do with patterns of biodiversity and how people interface with these.

LEARNING OBJECTIVES

Biological diversity has become one of the "hot-button" environmental topics—there is a lot of news about endangered species, loss of biodiversity, and its causes. This chapter provides a basic scientific introduction that will help you understand the background to this news, the causes of and solutions to species loss, and the problems that arise when we move species around the globe. Interest in the variety of life on Earth is not new; people have long wondered how the amazing diversity of living things on Earth came to be. This diversity has developed through biological evolution and is affected by interactions among species and by the environment. After reading this chapter, you should understand . . .

- How biological evolution works—how mutation, natural selection, migration, and genetic drift lead to evolution of new species;
- Why people value biological diversity;
- How people affect biological diversity: by eliminating, reducing, or altering habitats; harvesting; introducing new species where they had not lived before; and polluting the environment;
- When and how biological diversity is important to ecosystems—how it may affect biological production, energy flow, chemical cycling, and other ecosystem processes;
- What major environmental problems are associated with biological diversity;
- Why so many species have been able to evolve and persist;
- The concepts of the ecological niche and habitat;
- The theory of island biogeography;
- How species invade new habitats, and when this can be beneficial and when harmful.

CASE STUDY

Citrus Greening

In 2005 a tiny fruit fly that carries and disperses a bacterial disease of citrus plants arrived in the United States from China (Figure 8.1). This disease, known as "citrus greening" or Chinese *huanglongbing* (yellow dragon disease) had been extending its range and had reached India, many African countries, and Brazil (Figure 8.2). Wherever the fly and the bacteria have gone, citrus crops have failed. The bacteria interfere with the flow of organic compounds in the phloem (the living part of the plant's bark). The larvae of the fruit fly sucks juices from the tree, inadvertently injecting the bacteria. Winds blow the adult flies from one tree to another, making control of the fly difficult. According to the U.S. Department of Agriculture (USDA), citrus greening is the most severe new threat to citrus plants in the United States and might end commercial orange production in Florida. Many Florida counties are under a quarantine that prevents citrus plants from being moved from one area to another.[1]

Introductions of new species into new habitats have occurred as long as life has existed on Earth. And beginning with the earliest human travelers, our ancestors have moved species around the world, sometimes on purpose, sometimes unknowingly. Polynesians brought crops, pigs, and many other animals and plants from one Pacific Island to another as they migrated and settled widely before A.D. 1000. The intentional spread of crop plants around the world has been one of the primary reasons that our species has been able to survive in so many habitats and has grown to such a huge number. But if invasion by species is as old as life, and often beneficial to people, why is it also the source of so many environmental problems? The answers lie in this chapter.

(a) (b)

FIGURE 8.1 **(a) *Larvae of Diaphorina citri*, the tiny fly that spreads citrus greening bacteria (*Candidatus* Liberibacter *asiaticus*); (b) the disease yellows leaves, turns fruit greenish brown, and eventually kills the tree.**

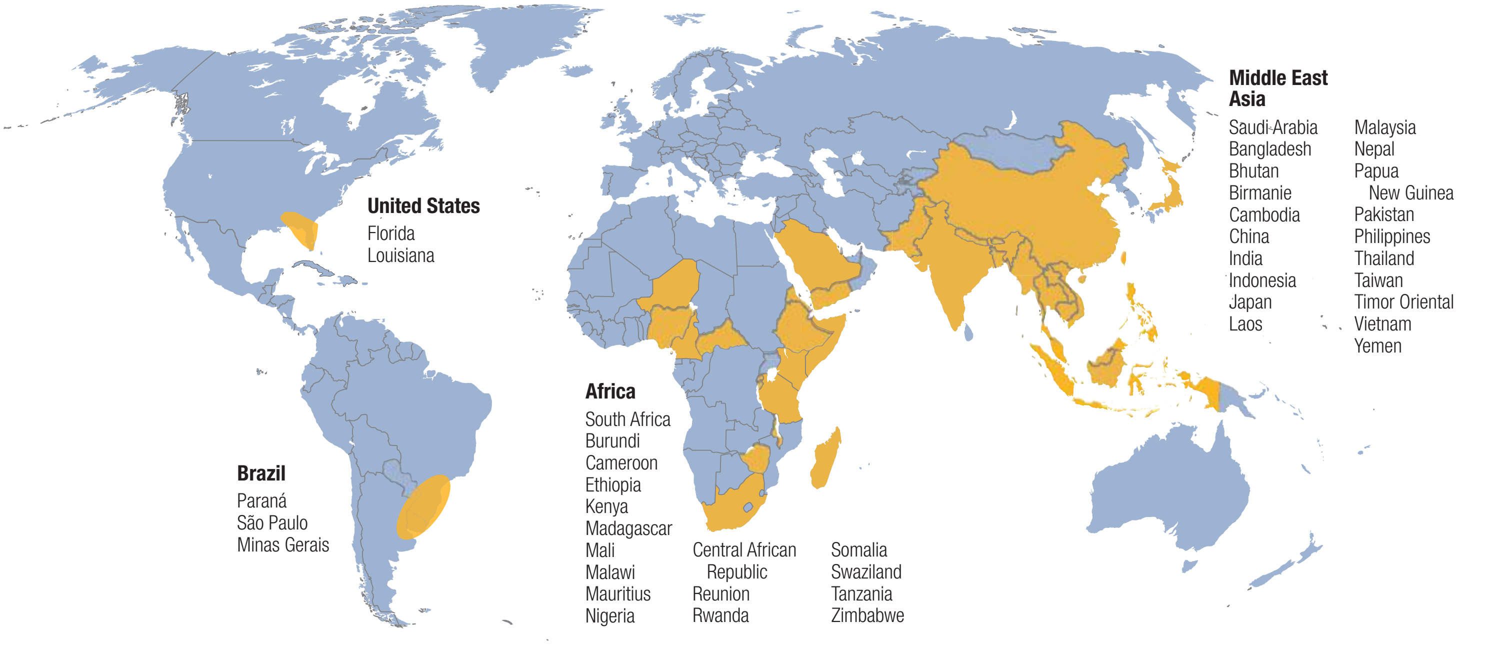


FIGURE 8.2 **Where citrus greening has spread from its origin in China.** The yellow shows the disease locations. (*Source*: USDA.)

8.1 What Is Biological Diversity?

Biological diversity refers to the variety of life-forms, commonly expressed as the number of species or the number of genetic types in an area. (We remind you of the definitions of *population* and *species* in Chapter 4: A **population** is a group of individuals of the same species living in the same area or interbreeding and sharing genetic information. A **species** is all individuals that are capable of interbreeding. A species is made up of populations.)

Conservation of biological diversity gets lots of attention these days. One day we hear about polar bears on the news, the next day something about wolves or salmon or elephants or whales. What should we do to protect these species that mean so much to people? What do we need to do about biological diversity in general—all the life-forms, whether people enjoy them or not? And is this a scientific issue or not? Is it even partially scientific?

That's what this chapter is about. It introduces the scientific concepts concerning biological diversity, explains the aspects of biological diversity that have a scientific base, distinguishes the scientific aspects from the nonscientific ones, and thereby provides a basis for you to evaluate the biodiversity issues you read about.

Why Do People Value Biodiversity?

Before we discuss the scientific basis of biodiversity and the role of science in its conservation, we should consider why people value it. There are nine primary reasons: utilitarian; public-service; ecological; moral; theological; aesthetic; recreational; spiritual; and creative.[2]

Utilitarian means that a species or group of species provides a product that is of direct value to people. *Public-service* means that nature and its diversity provide some service, such as taking up carbon dioxide or pollinating flowers, that is essential or valuable to human life and would be expensive or impossible to do ourselves. *Ecological* refers to the fact that species have roles in their ecosystems, and that some of these are necessary for the persistence of their ecosystems, perhaps even for the persistence of all life. Scientific research tells us which species have such ecosystem roles. The *moral* reason for valuing biodiversity is the belief that species have a right to exist, independent of their value to people. The *theological* reason refers to the fact that some religions value nature and its diversity, and a person who subscribes to that religion supports this belief.

The last four reasons for valuing nature and its diversity—aesthetic, recreational, spiritual, and creative—have to do with the intangible (nonmaterial) ways that nature and its diversity benefit people (see Figure 8.3). These four are often lumped together, but we separate them here. *Aesthetic* refers to the beauty of nature, including the variety of life. *Recreational* is self-explanatory—people enjoy getting out into nature, not just because it is beautiful to look at but because it provides us with healthful activities that we enjoy. *Spiritual* describes the way contact with nature and its diversity often moves people, an uplifting often perceived as a religious experience. *Creative* refers to the fact that artists, writers, and musicians find stimulation for their creativity in nature and its diversity.

Science helps us determine what are utilitarian, public-service, and ecosystem functions of biological diversity, and scientific research can lead to new utilitarian benefits from biological diversity. For example, medical research led to the discovery and development of paclitaxel (trade name Taxol), a chemical found in the Pacific yew and now used widely in chemotherapy treatment of certain cancers. (Ironically, this discovery led at first to the harvest of this endangered tree species, creating an environmental controversy until the compound could be made artificially.)

The rise of the scientific and industrial age brought a great change in the way that people valued nature. Long ago, for example, when travel through mountains was arduous, people struggling to cross them were probably not particularly interested in the scenic vistas. But around the time of the Romantic poets, travel through the Alps became easier, and suddenly poets began to appreciate the "terrible joy" of mountain scenery. Thus scientific knowledge indirectly influences the nonmaterial ways that people value biological diversity.

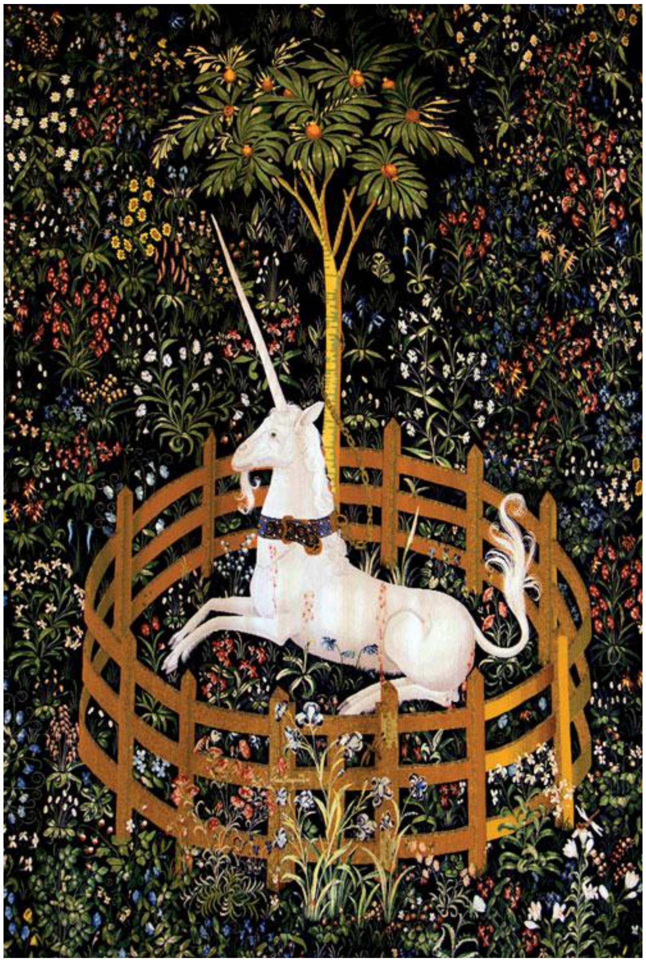


FIGURE 8.3 People have long loved the diversity of life. Here, a late-15th-century Dutch medieval tapestry, *The Hunting of the Unicorn* (now housed in The Cloisters, part of the New York City's Metropolitan Museum of Art), celebrates the great diversity of life. Except for the mythological unicorn, all the plants and animals shown, including frogs and insects, are familiar to naturalists today and are depicted with great accuracy.

8.2 Biological Diversity Basics

Biological diversity involves the following concepts:

- ***Genetic diversity***: the total number of genetic characteristics of a specific species, subspecies, or group of species. In terms of genetic engineering and our new understanding of DNA, this could mean the total base-pair sequences in DNA; the total number of genes, active or not; or the total number of active genes.
- ***Habitat diversity***: the different kinds of habitats in a given unit area.
- ***Species diversity***, which in turn has three qualities:
  species richness—the total number of species;
  species evenness—the relative abundance of species; and
  species dominance—the most abundant species.

To understand the differences between species richness, species evenness, and species dominance, imagine two ecological communities, each with 10 species and 100 individuals, as illustrated in Figure 8.4. In the first community (Figure 8.4a), 82 individuals belong to a single species, and the remaining nine species are represented by two individuals each. In the second community (Figure 8.4b), all the species are equally abundant; each therefore has 10 individuals. Which community is more diverse?

At first, one might think that the two communities have the same species diversity because they have the same number of species. However, if you walked through both communities, the second would appear more diverse. In the first community, most of the time you would see individuals only of the dominant species (elephants in Figure 8.4a); you probably wouldn't see many of the other species at all.

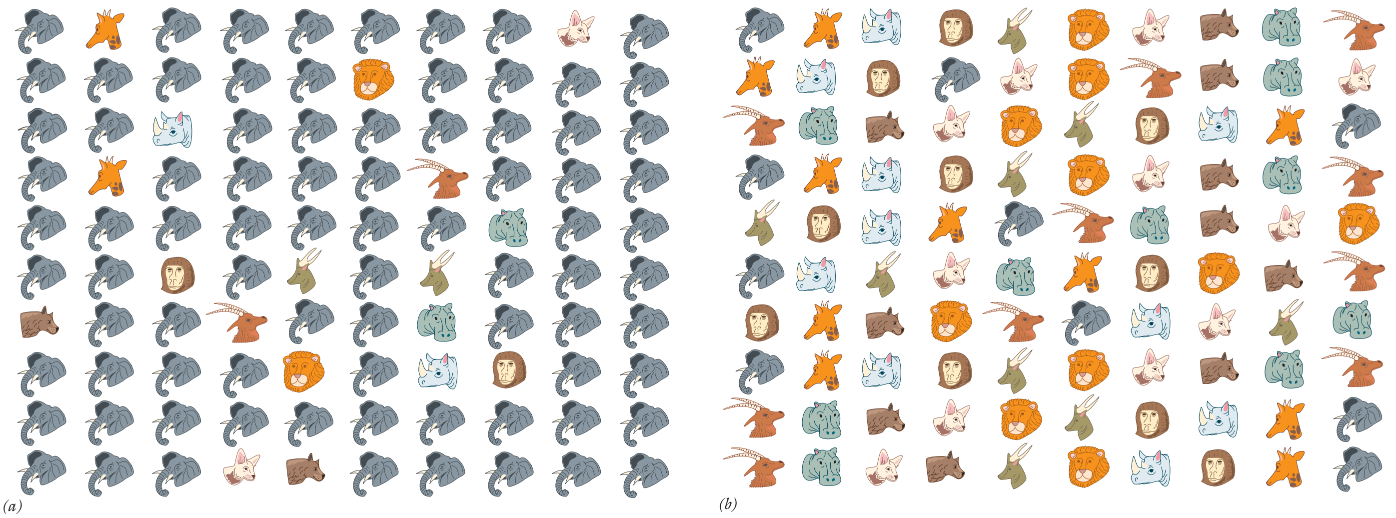


FIGURE 8.4 Diagram illustrating the difference between species evenness, which is the relative abundance of each species, and species richness, which is the total number of species. Figures **(a)** and **(b)** have the same number of species but different relative abundances. Lay a ruler across each diagram and count the number of species the edge crosses. Do this several times, and determine how many species are diagram **(a)** and diagram **(b)**. See text for explanation of results.

The first community would appear to have relatively little diversity until it was subjected to careful study, whereas in the second community even a casual visitor would see many of the species in a short time. You can test the probability of encountering a new species in either community by laying a ruler down in any direction on Figures 8.4a and 8.4b and counting the number of species that it touches.

As this example suggests, merely counting the number of species is not enough to describe biological diversity. Species diversity has to do with the relative chance of seeing species as much as it has to do with the actual number present. Ecologists refer to the total number of species in an area as **species richness**, the relative abundance of species as **species evenness**, and the most abundant species as **dominant**.

The Number of Species on Earth

Many species have come and gone on Earth. But how many exist today? Some 1.5 million species have been named, but available estimates suggest there may be almost 3 million (Table 8.1), and some biologists believe the number will turn out to be much, much larger. No one knows the exact number because new species are discovered all the time, especially in little-explored areas such as tropical savannas and rain forests.

For example, in the spring of 2008, an expedition sponsored by Conservation International and led by scientists from Brazilian universities discovered 14 new species in or near Serra Geral do Tocantins Ecological Station, a 716,000-hectare (1.77-million-acre) protected area in the Cerrado, a remote tropical savanna region of Brazil, said to be one of the world's most biodiverse areas. They found eight new fish, three new reptiles, one new amphibian, one new mammal, and one new bird.

In Laos, a new bird, the barefaced bulbul, was discovered in 2009 (Figure 8.5) and five new mammals have been discovered since 1992: (1) the spindle-horned oryx (which is not only a new species but also represents a previously unknown genus); (2) the small black muntjak; (3) the giant muntjak (the muntjak, also known as "barking deer," is a small deer; the giant muntjak is so called because it has large antlers); (4) the striped hare (whose nearest relative lives in Sumatra); and (5) a new species of civet cat. That such a small country with a long history of human occupancy would have so many mammal species previously unknown to science—and some of these were not all that small—suggests how little we still know about the total biological diversity on Earth. But as scientists we must act from what we know, so in this book we will focus on the 1.5 million species identified and named so far (see Table 8.1).

All living organisms are classified into groups called *taxa,* usually on the basis of their evolutionary relationships or similarity of characteristics. (Carl Linnaeus, a Swedish physician and biologist, who lived from 1707 to 1778, was the originator of the classification system and played a crucial role in working all this out. He explained this system in his book *Systema Naturae.*)

The hierarchy of these groups (from largest and most inclusive to smallest and least inclusive) begins with a domain or kingdom. In the recent past, scientists classified life into five kingdoms: animals, plants, fungi, protists, and bacteria. Recent evidence from the

Table 8.1 NUMBER OF SPECIES BY MAJOR FORMS OF LIFE AND BY NUMBER OF ANIMAL SPECIES (FOR A DETAILED LIST OF SPECIES BY TAXONOMIC GROUP, SEE APPENDIX.)

A. NUMBER OF SPECIES BY MAJOR FORMS OF LIFE

		ESTIMATED NUMBER	
LIFE-FORM	EXAMPLE	MINIMUM	MAXIMUM
Monera/Bacteria	Bacteria	4,800	10,000
Fungi	Yeast	71,760	116,260
Lichens	Old man's beard	13,500	13,500
Prostista/Protoctist	Ameba	80,710	194,760
Plantae	Maple tree	478,365	529,705
Animalia	Honeybee	873,084	1,870,019
Total		1,522,219	2,734,244

B. NUMBER OF ANIMAL SPECIES

ANIMALS			
Insecta	Honeybees	668,050	1,060,550
Chondrichthyes	Sharks, rays, etc.	750	850
Osteichthyes	Bony fish	20,000	30,000
Amphibia	Amphibians	200	4,800
Reptilia	Reptiles	5,000	7,000
Aves	Birds	8,600	9,000
Mammalia	Mammals	4,000	5,000
Animal total	Total	873,084	1,870,019

fossil record and studies in molecular biology suggest that it may be more appropriate to describe life as existing in three major domains, one called Eukaryota or

FIGURE 8.5 The barefaced bulbul, discovered in Laos in 2009, shows us once again that there are still species of animals and plants unknown to science.

Eukarya, which includes animals, plants, fungi, and protists (mostly single-celled organisms); Bacteria; and Archaea.[3] As you learned in Chapter 6, Eukarya cells include a nucleus and other small, organized features called organelles; Bacteria and Archaea do not. (Archaea used to be classified among Bacteria, but they have substantial molecular differences that suggest ancient divergence in heritage—see Chapter 6, Figure 6.7.)

The plant kingdom is made up of divisions, whereas the animal kingdom is made up of phyla (singular: phylum). A phylum or division is, in turn, made up of classes, which are made up of orders, which are made up of families, which are made up of genera (singular: genus), which are made up of species.

Some argue that the most important thing about biological diversity is the total number of species, and that the primary goal of biological conservation should be to maintain that number at its current known maximum. An interesting and important point to take away from Table 8.1 is that most of the species on Earth are insects (somewhere between 668,000 and more than 1 million) and plants (somewhere between 480,000 and 530,000), and also that there are many species of fungi (about 100,000) and protists (about 80,000 to almost 200,000). In contrast, our own kind, the kind of animals most celebrated on television and in movies, mammals, number a meager 4,000 to 5,000, about the same as reptiles. When it comes to numbers of species on Earth, our kind doesn't seem to matter much—we amount to about half a percent of all animals. If the total number in a species were the only gauge of a species' importance, we wouldn't matter.

8.3 Biological Evolution

The first big question about biological diversity is: How did it all come about? Before modern science, the diversity of life and the adaptations of living things to their environment seemed too amazing to have come about by chance. The great Roman philosopher and writer Cicero put it succinctly: "Who cannot wonder at this harmony of things, at this symphony of nature which seems to will the well-being of the world?" He concluded that "everything in the world is marvelously ordered by divine providence and wisdom for the safety and protection of us all."[4] The only possible explanation seemed to be that this diversity was created by God (or gods).

With the rise of modern science, however, other explanations became possible. In the 19th century, Charles Darwin found an explanation that became known as biological evolution. **Biological evolution** refers to the change in inherited characteristics of a population from generation to generation. It can result in new species—populations that can no longer reproduce with members of the original species but can (and at least occasionally do) reproduce with each other. Along with self-reproduction, biological evolution is one of the features that distinguish life from everything else in the universe. (The others are carbon-based, organic-compound-based, self-replicating systems.)

The word *evolution* in the term *biological evolution* has a special meaning. Outside biology, *evolution* is used broadly to mean the history and development of something. For example, book reviewers talk about the evolution of a novel's plot, meaning how the story unfolds. Geologists talk about the evolution of Earth, which simply means Earth's history and the geologic changes that have occurred over that history. Within biology, however, the term has a more specialized meaning. Biological evolution is a one-way process: Once a species is extinct, it is gone forever. You can run a machine, such as a mechanical grandfather clock, forward and backward, but when a new species evolves, it cannot evolve backward into its parents.

Our understanding of evolution today owes a lot to the modern science of molecular biology and the practice of genetic engineering, which are creating a revolution in how we think about and deal with species. At present, scientists have essentially the complete DNA code for a number of species, including the bacterium *Haemophilus influenzae*; the malaria parasite; its carrier the malaria mosquito;[5] the fruit fly (*Drosophila*); a nematode *C. elegans*, (a very small worm that lives in water); yeast; a small weed plant, thale cress (*Arabidopsis thaliana*); and ourselves—humans. Scientists focused on these species either because they are of great interest to us or because they are relatively easy to study, having either few base pairs (the nematode worm) or having already well-known genetic characteristics (the fruit fly).

According to the theory of biological evolution, new species arise as a result of competition for resources and the differences among individuals in their adaptations to environmental conditions. Since the environment continually changes, which individuals are best adapted changes too. As Darwin wrote, "Can it be doubted, from the struggle each individual has to obtain subsistence, that any minute variation in structure, habits, or instincts, adapting that individual better to the new [environmental] conditions, would tell upon its vigor and health? In the struggle it would have a better chance of surviving; and those of its offspring that inherited the variation, be it ever so slight, would also have a better chance."

Sounds plausible, but how does this evolution occur? Through four processes: mutation, natural selection, migration, and genetic drift.

The Four Key Processes of Biological Evolution

Mutation

Mutations are changes in genes. Contained in the chromosomes within cells, each **gene** carries a single piece of inherited information from one generation to the next, producing a **genotype**, the genetic makeup that is characteristic of an individual or a group.

Genes are made up of a complex chemical compound called deoxyribonucleic acid (DNA). DNA in turn is made up of chemical building blocks that form a code, a kind of alphabet of information. The DNA alphabet consists of four letters that stand for specific nitrogen-containing compounds, called bases, which are combined in pairs: (A) adenine, (C) cytosine, (G) guanine, and (T) thymine. Each gene has a set of the four base pairs, and how these letters are combined in long strands determines the genetic "message" interpreted by a cell to produce specific compounds.

The number of base pairs that make up a strand of DNA varies. To make matters more complex, some base pairs found in DNA are nonfunctional—they are not active and do not determine any chemicals produced by the cell. Furthermore, some genes affect the activity of others, turning those other genes on or off. And creatures such as ourselves have genes that limit the number of times a cell can divide, and thus determine the individual's maximum longevity.

When a cell divides, the DNA is reproduced and each new cell gets a copy. But sometimes an error in reproduction changes the DNA and thereby changes the inherited characteristics. Such errors can arise from various causes. Sometimes an external agent comes in contact with DNA and alters it. Radiation, such as X rays and gamma rays, can break the DNA apart or change its chemical structure. Certain chemicals, also, can change DNA. So can viruses. When DNA changes in any of these ways, it is said to have undergone **mutation**.

In some cases, a cell or an offspring with a mutation cannot survive (Figure 8.6a and b). In other cases, the mutation simply adds variability to the inherited characteristics (Figure 8.6c). But in still other cases, individuals with mutations are so different from their parents that they cannot reproduce with normal offspring of their species, so a new species has been created.

Natural Selection

When there is variation within a species, some individuals may be better suited to the environment than others. (Change is not always for the better. Mutation can result in a new species whether or not that species is better adapted than its parent species to the environment.) Organisms whose biological characteristics make them better able to survive and reproduce in their environment leave more offspring than others. Their descendants form a larger proportion of the next generation and are more "fit" for the environment. This process of increasing the proportion of offspring is called **natural selection**. Which inherited characteristics lead to more offspring depends on the specific characteristics of an environment, and as the environment changes over time, the characteristics' "fit" will also change. In summary, natural selection involves four primary factors:

- Inheritance of traits from one generation to the next and some variation in these traits—that is, genetic variability.
- Environmental variability.
- Differential reproduction (differences in numbers of offspring per individual), which varies with the environment.
- Influence of the environment on survival and reproduction.

Natural selection is illustrated in A Closer Look 8.1, which describes how the mosquitoes that carry malaria develop a resistance to DDT and how the microorganism that causes malaria develops a resistance to quinine, a treatment for the disease.

As explained before, when natural selection takes place over a long time, a number of characteristics can change. The accumulation of these changes may become so great that the present generation can no longer reproduce with individuals that have the original DNA structure, resulting in a new species.

Ironically, the *loss* of geographic isolation can also lead to a new species. This can happen when one population of a species migrates into a habitat already occupied by another population of that species, thereby changing gene frequency in that habitat. Such a change can result, for example, from the migration of seeds of flowering plants blown by wind or carried in the fur of mammals. If the seed lands in a new habitat, the environment may be different enough to favor genotypes not as favored by natural selection in the parents' habitat. Natural selection, in combination with geographic isolation and subsequent migration, can thus lead to new dominant genotypes and eventually to new species.

(a) (b) (c)

FIGURE 8.6 **(a) A normal fruit fly, (b) a fruit fly with an antennae mutation,** and **(c) *Tradescantia*, a small flowering plant used in the study of effects of mutagens**. The color of stamen hairs in the flower (pink versus clear) is the result of a single gene and changes when that gene is mutated by radiation or certain chemicals, such as ethylene chloride.

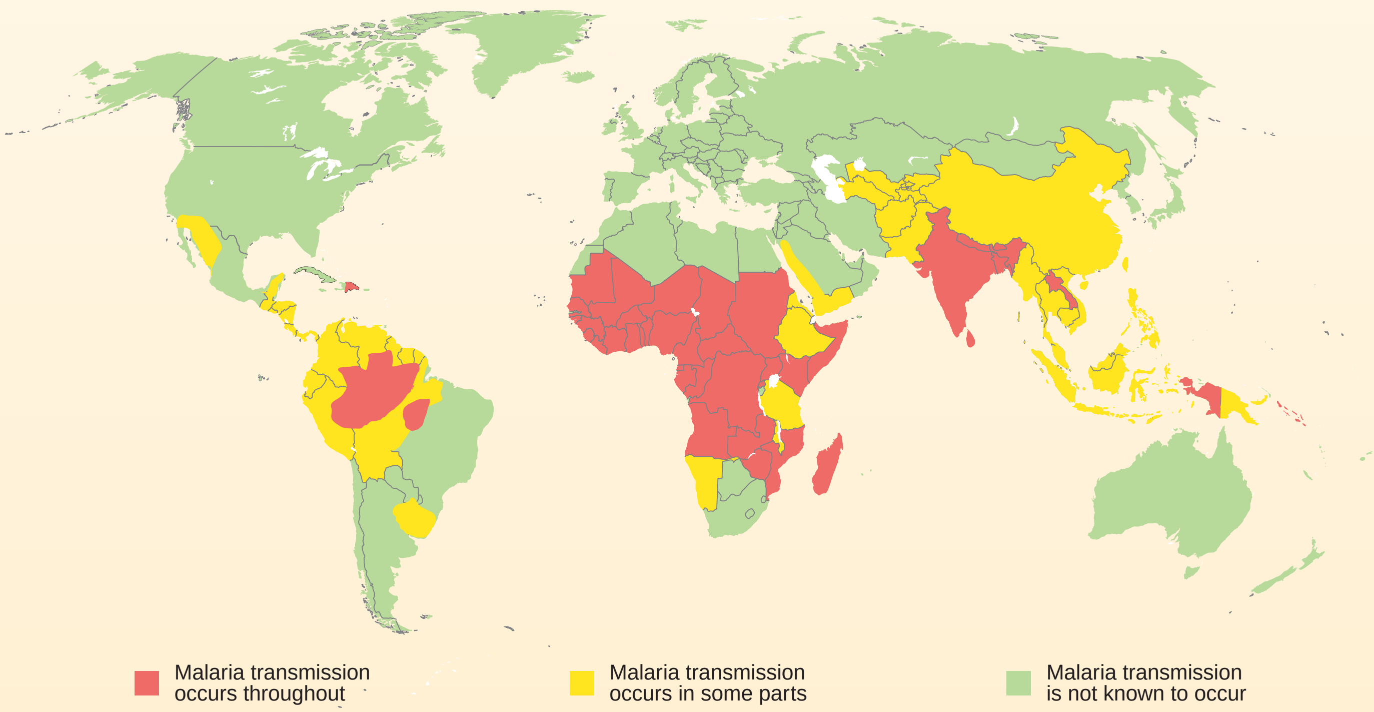
A CLOSER LOOK 8.1

Natural Selection: Mosquitoes and the Malaria Parasite

Malaria poses a great threat to 2.4 billion people—over one-third of the world's population—living in more than 90 countries, most of them in the tropics. In the United States, in 2003, Palm Beach County, Florida, experienced a small but serious malaria outbreak, and of particular concern is that the malaria was the result of bites from local mosquitoes, not brought in by travelers from nations where malaria is a continual problem. Worldwide, an estimated 300–400 million people are infected each year, and 1.1 million of them die (Figure 8.7).[6] It is the fourth largest cause of death of children in developing nations—in Africa alone, more than 3,000 children die daily from this disease.[7] Once thought to be caused by filth or bad air (hence the name *malaria*, from the Latin for "bad air"), malaria is actually caused by parasitic microbes (four species of the protozoon *Plasmodium*). These microbes affect and are carried by *Anopheles* mosquitoes, which then transfer the protozoa to people. One solution to the malaria problem, then, would be the eradication of *Anopheles* mosquitoes.

By the end of World War II, scientists had discovered that the pesticide DDT was extremely effective against *Anopheles* mosquitoes. They had also found chloroquine highly effective in killing *Plasmodium* parasites. (Chloroquine is an artificial derivative of quinine, a chemical from the bark of the quinine tree that was an early treatment for malaria.) In 1957 the World Health Organization (WHO) began a $6 billion campaign to rid the world of malaria using a combination of DDT and chloroquine.

(a)



(b)

FIGURE 8.7 **(a)** A child with malaria and **(b)** where malaria primarily occurs today. [*Source:* **(b)** U.S. Centers for Disease Control, http://www.cdc.gov/Malaria/distribution_epi/distribution.htm.]

At first, the strategy seemed successful. By the mid-1960s, malaria was nearly gone or had been eliminated from 80% of the target areas. However, success was short-lived. The mosquitoes began to develop a resistance to DDT, and the protozoa became resistant to chloroquine. In many tropical areas, the incidence of malaria worsened. For example, the WHO program had reduced the number of cases in Sri Lanka from 1 million to only 17 by 1963, but by 1975, 600,000 cases had been reported, and the actual number is believed to be four times higher. Worldwide, in 2006 (most recent data available) there were 247 million cases of malaria, resulting in 881,000 deaths. The mosquitoes' resistance to DDT became widespread, and resistance of the protozoa to chloroquine was found in 80% of the 92 countries where malaria was a major killer.[8]

The mosquitoes and the protozoa developed this resistance through natural selection. When they were exposed to DDT and chloroquine, the susceptible individuals died; they left few or no offspring, and any offspring they left were susceptible. The most resistant survived and passed their resistant genes on to their offspring. Thus, a change in the environment—the human introduction of DDT and chloroquine—caused a particular genotype to become dominant in the populations.

A practical lesson from this experience is that if we set out to eliminate a disease-causing species, we must attack it completely at the outset and destroy all the individuals before natural selection leads to resistance. But sometimes this is impossible, in part because of the natural genetic variation in the target species. Since the drug chloroquine is generally ineffective now, new drugs have been developed to treat malaria. However, these second- and third-line drugs will eventually become unsuccessful, too, as a result of the same process of biological evolution by natural selection. This process is speeded up by the ability of the *Plasmodium* to rapidly mutate. In South Africa, for example, the protozoa became resistant to mefloquine immediately after the drug became available as a treatment.

An alternative is to develop a vaccine against the *Plasmodium* protozoa. Biotechnology has made it possible to map the genetic structure of these malaria-causing organisms. Scientists are currently mapping the genetic structure of *P. falciparum*, the most deadly of the malaria protozoa, and expect to finish within several years. With this information, they expect to create a vaccine containing a variety of the species that is benign in human beings but produces an immune reaction.[9] In addition, scientists are mapping the genetic structure of *Anopheles gambiae*, the carrier mosquito. This project could provide insight into genes, which could prevent development of the malaria parasite within the mosquito. In addition, it could identify genes associated with insecticide resistance and provide clues to developing a new pesticide.

Migration and Geographic Isolation

Sometimes two populations of the same species become geographically isolated from each other for a long time. During that time, the two populations may change so much that they can no longer reproduce together even when they are brought back into contact. In this case, two new species have evolved from the original species. This can happen even if the genetic changes are not more fit but simply different enough to prevent reproduction. **Migration** has been an important evolutionary process over geologic time (a period long enough for geologic changes to take place).

Darwin's visit to the Galápagos Islands gave him his most powerful insight into biological evolution.[10] He found many species of finches that were related to a single species found elsewhere. On the Galápagos, each species was adapted to a different niche.[11] Darwin suggested that finches isolated from other species on the continents eventually separated into a number of groups, each adapted to a more specialized role. The process is called **adaptive radiation**. This evolution continues today, as illustrated by a recently discovered new species of finch on the Galápagos Islands (Figure 8.8).

More recently and more accessible to most visitors, we can find adapative radiation on the Hawaiian Islands, where a finchlike ancestor evolved into several

FIGURE 8.8 One of Darwin's finches. Charles Darwin's observations of the adaptive radiation of finches on the Galápagos Islands was a key to the development of the theory of biological evolution. This evolution continues today. In 1982 a finch new to the islands, a large ground finch, migrated there. Over the years since then, the beak of a smaller, native ground species of finch has been evolving to become larger, apparently in response to competition from the new arrival. Today, the offspring of the native ground finch have on average longer beaks than their ancestors'. This is said to be the first time such a response has been observed in progress on the islands.

species, including fruit and seed eaters, insect eaters, and nectar eaters, each with a beak adapted for its specific food (Figure 8.9).[12]

Genetic Drift

Genetic drift refers to changes in the frequency of a gene in a population due not to mutation, selection, or migration, but simply to chance. One way this happens is through the **founder effect**. The founder effect occurs when a small number of individuals are isolated from a larger population; they may have much less genetic variation than the original species (and usually do), and the characteristics that the isolated population has will be affected by chance. In the founder effect and genetic drift, individuals may not be better adapted to the environment—in fact, they may be more poorly adapted or neutrally adapted. Genetic drift can occur in any small population and may present conservation problems when it is by chance isolated from the main population.

For example, bighorn sheep live in the mountains of the southwestern deserts of the United States and Mexico. In the summer, these sheep feed high up in the mountains, where it is cooler, wetter, and greener. Before high-density European settlement of the region, the sheep could move freely and sometimes migrated from one mountain to another by descending into the valleys and crossing them in the winter. In this way, large numbers of sheep interbred. With the development of cattle ranches and other human activities, many populations of bighorn sheep could no longer migrate among the mountains by crossing the valleys. These sheep became isolated in very small groups—commonly, a dozen or so—and chance may play a large role in what inherited characteristics remain in the population.

This happened to a population of bighorn sheep on Tiburón Island in Mexico, which was reduced to 20 animals in 1975 but increased greatly to 650 by 1999. Because of the large recovery, this population has been used to repopulate other bighorn sheep habitats in northern Mexico. But a study of the DNA shows that the genetic variability is much less than in other populations in Arizona. Scientists who studied this population suggest that

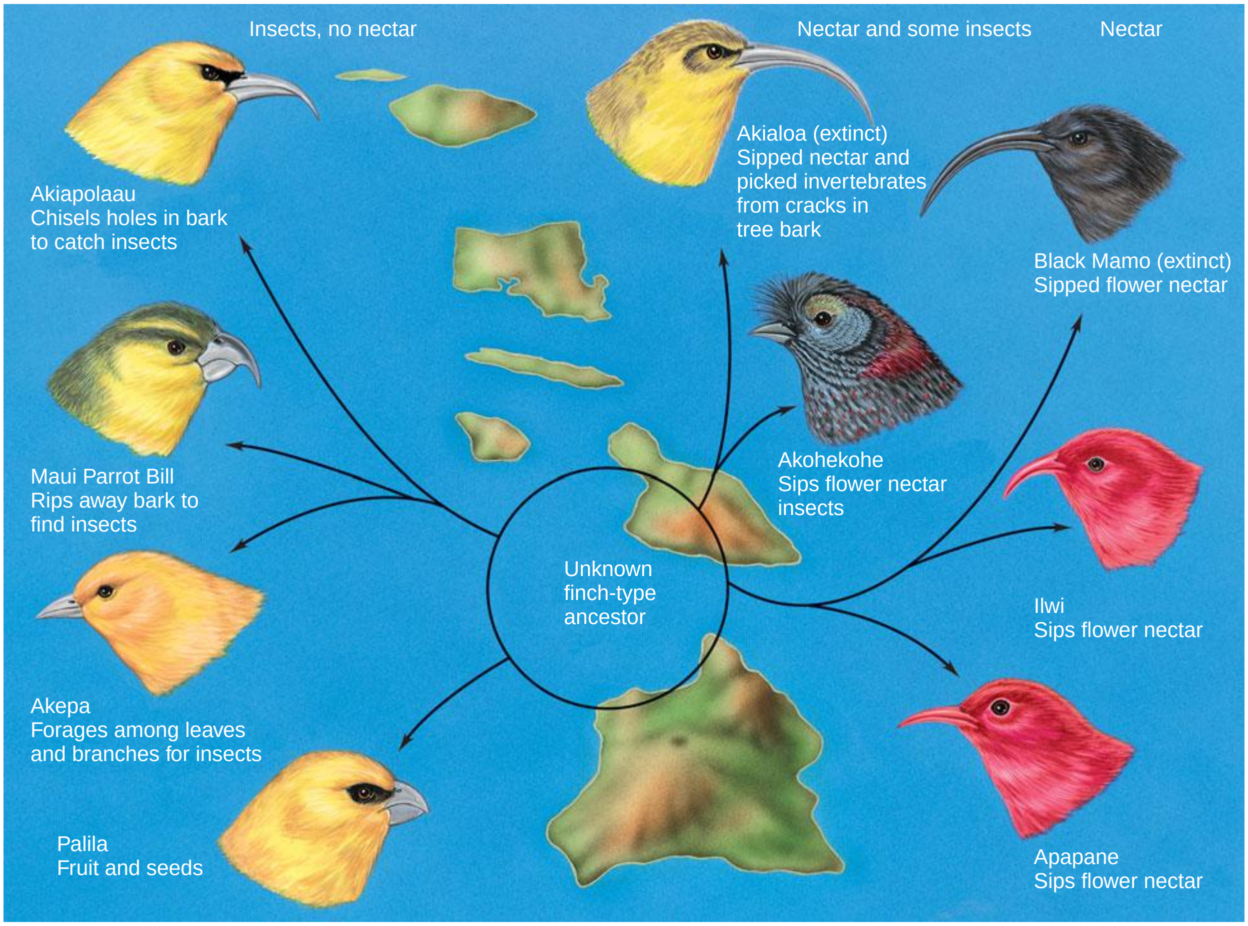


FIGURE 8.9 Evolutionary divergence among honeycreepers in Hawaii. Sixteen species of birds, each with a beak specialized for its food, evolved from a single ancestor. Nine of the species are shown here. The species evolved to fit ecological niches that, on the North American continent, had been filled by other species not closely related to the ancestor. (*Source:* From C.B. Cox, I.N. Healey, and P.D. Moore, *Biogeography* [New York: Halsted, 1973].)

individuals from other isolated bighorn sheep populations should be added to any new transplants to help restore some of the greater genetic variation of the past.[13]

Biological Evolution as a Strange Kind of Game

Biological evolution is so different from other processes that it is worthwhile to spend some extra time exploring the topic. There are no simple rules that species must follow to win or even just to stay in the game of life. Sometimes when we try to manage species, we assume that evolution will follow simple rules. But species play tricks on us; they adapt or fail to adapt over time in ways that we did not anticipate. Such unexpected outcomes result from our failure to fully understand how species have evolved in relation to their ecological situations. Nevertheless, we continue to hope and plan as if life and its environment will follow simple rules. This is true even for the most recent work in genetic engineering.

Complexity is a feature of evolution. Species have evolved many intricate and amazing adaptations that have allowed them to persist. It is essential to realize that these adaptations have evolved not in isolation but in the context of relationships to other organisms and to the environment. The environment sets up a situation within which evolution, by natural selection, takes place. The great ecologist G.E. Hutchinson referred to this interaction in the title of one of his books, *The Ecological Theater and the Evolutionary Play*. Here, the ecological situation—the condition of the environment and other species—is the theater and the scenery within which natural selection occurs, and natural selection results in a story of evolution played out in that theater—over the history of life on Earth.[14] These features of evolution are another reason that life and ecosystems are not simple, linear, steady-state systems (see Chapter 3).

In summary, the theory of biological evolution tells us the following about biodiversity:

- Since species have evolved and do evolve, and since some species are also always becoming extinct, biological diversity is always changing, and which species are present in any one location can change over time.
- Adaptation has no rigid rules; species adapt in response to environmental conditions, and complexity is a part of nature. We cannot expect threats to one species to necessarily be threats to another.
- Species and populations do become geographically isolated from time to time, and undergo the founder effect and genetic drift.
- Species are always evolving and adapting to environmental change. One way they get into trouble—become endangered—is when they do not evolve fast enough to keep up with the environment.

8.4 Competition and Ecological Niches

Why there are so many species on Earth has become a key question since the rise of modern ecological and evolutionary sciences. In the next sections we discuss the answers. They partly have to do with how species interact. Speaking most generally, they interact in three ways: competition, in which the outcome is negative for both; symbiosis, in which the interaction benefits both participants; and predation–parasitism, in which the outcome benefits one and is detrimental to the other.

The Competitive Exclusion Principle

The **competitive exclusion principle** supports those who argue that there should be only a few species. It states that *two species with exactly the same requirements cannot coexist in exactly the same habitat*. Garrett Hardin expressed the idea most succinctly: "Complete competitors cannot coexist."[15]

This is illustrated by the introduction of the American gray squirrel into Great Britain. It was introduced intentionally because some people thought it was attractive and would be a pleasant addition to the landscape. About a dozen attempts were made, the first perhaps as early as 1830 (Figure 8.10). By the 1920s, the American gray squirrel was well established in Great Britain, and in the 1940s and 1950s its numbers expanded greatly. It competes with the native red squirrel and is winning—there are now about 2.5 million gray squirrels in Great Britain, and only 140,000 red squirrels, most them in Scotland, where the gray squirrel is less abundant.[16] The two species have almost exactly the same habitat requirements.

One reason for the shift in the balance of these species may be that in the winter the main source of food for red squirrels is hazelnuts, while gray squirrels prefer acorns. Thus, red squirrels have a competitive advantage in areas with hazelnuts, and gray squirrels have the advantage in oak forests. When gray squirrels were introduced, oaks were the dominant mature trees in Great Britain; about 40% of the trees planted were oaks. But that is not the case today. This difference in food preference may allow the coexistence of the two, or perhaps not.

The competitive exclusion principle suggests that there should be very few species. We know from our discussions of ecosystems (Chapter 5) that food webs have at least four levels—producers, herbivores, carnivores, and decomposers. Suppose we allowed for several more levels of carnivores, so that the average food web had six levels. Since there are about 20 major kinds of ecosystems, one would guess that the total number of winners on Earth would be only 6×20, or 120 species.

(a) (b)

FIGURE 8.10 **(a) British red squirrel,** which is being outcompeted by the **(b) American gray squirrel** introduced into Great Britain.

Being a little more realistic, we could take into account adaptations to major differences in climate and other environmental aspects within kinds of ecosystems. Perhaps we could specify 100 environmental categories: cold and dry; cold and wet; warm and dry; warm and wet; and so forth. Even so, we would expect that within each environmental category, competitive exclusion would result in the survival of only a few species. Allowing six species per major environmental category would result in only 600 species.

That just isn't the case. How did so many different species survive, and how do so many coexist? Part of the answer lies in the different ways in which organisms interact, and part of the answer lies with the idea of the ecological niche.

Niches: How Species Coexist

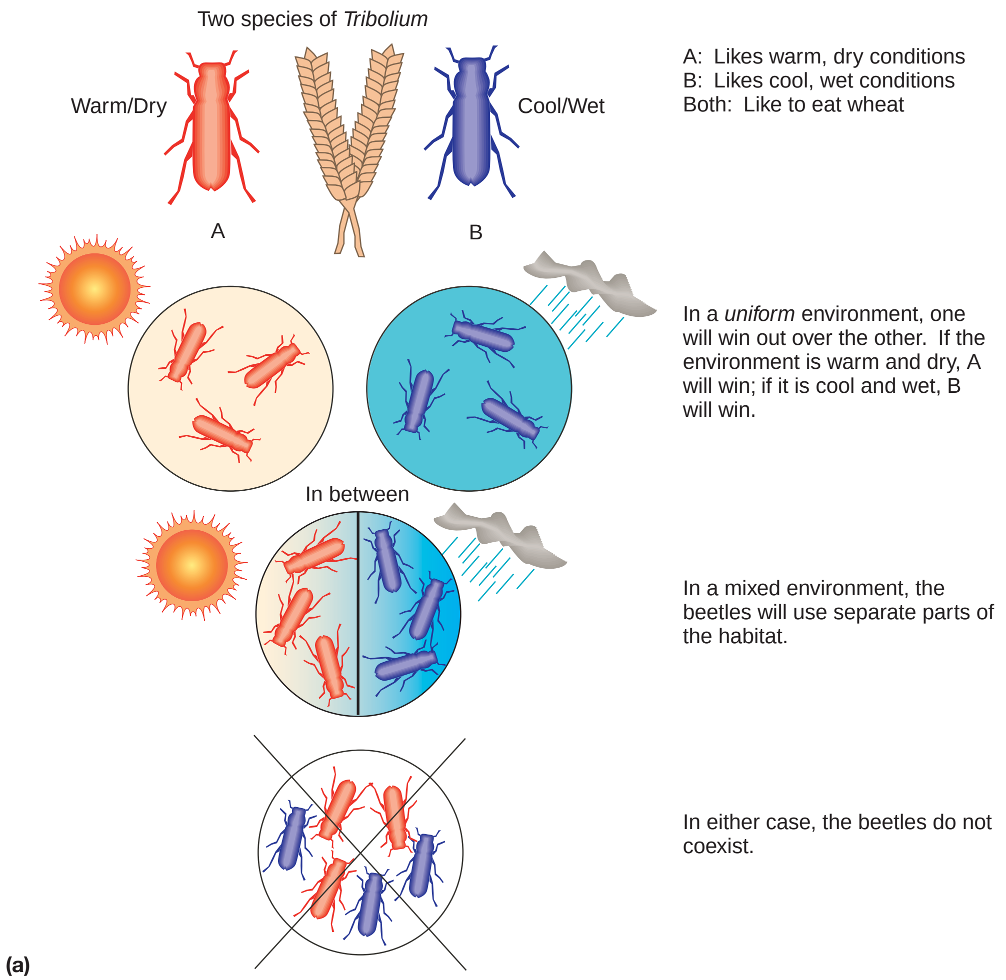
The **ecological niche** concept explains how so many species can coexist, and this concept is introduced most easily by experiments done with a small, common insect—the flour beetle (*Tribolium*), which, as its name suggests, lives on wheat flour. Flour beetles make good experimental subjects because they require only small containers of wheat flour to live and are easy to grow (in fact, too easy; if you don't store your flour at home properly, you will find these little beetles happily eating in it).

The flour beetle experiments work like this: A specified number of beetles of two species are placed in small containers of flour—each container with the same number of beetles of each species. The containers are then maintained at various temperature and moisture levels—some are cool and wet, others warm and dry. Periodically, the beetles in each container are counted. This is very easy. The experimenter just puts the flour through a sieve that lets the flour through but not the beetles. Then the experimenter counts the number of beetles of each species and puts the beetles back in their container to eat, grow, and reproduce for another interval. Eventually, one species always wins—some of its individuals continue to live in the container while the other species goes extinct. So far, it would seem that there should be only one species of *Tribolium*. But which species survives depends on temperature and moisture. One species does better when it is cold and wet, the other when it is warm and dry (Figure 8.11).

Curiously, when conditions are in between, sometimes one species wins and sometimes the other, seemingly randomly; but invariably one persists while the second becomes extinct. So the competitive exclusion principle holds for these beetles. Both species can survive in a complex environment—one that has cold and wet habitats as well as warm and dry habitats. In no location, however, do the species coexist.

The little beetles provide us with the key to the coexistence of many species. Species that require the same resources can coexist by using those resources under different environmental conditions. So it is habitat *complexity* that allows complete competitors—and not-so-complete competitors—to coexist because they avoid competing with each other.[17]

The flour beetles are said to have the same ecologically functional *niche,* which means they have the same *profession*—eating flour. But they have different *habitats*. Where a species lives is its habitat, but what it does for a living (its profession) is its ecological niche.[18] Suppose you have a neighbor who drives a school bus. Where your neighbor lives and works—your town—is his habitat. What your neighbor does—drive a bus—is his niche. Similarly, if someone says, "Here comes a wolf," you think not only of a creature that inhabits the northern forests (its habitat) but also of a predator that feeds on large mammals (its niche).



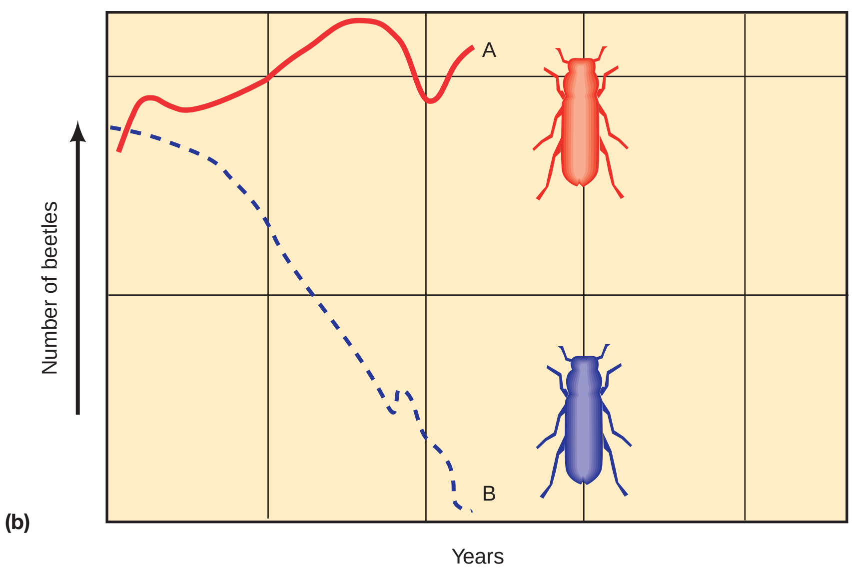


FIGURE 8.11 A classical experiment with flour beetles. Two species of flour beetles are placed in small containers of flour. Each container is kept at a specified temperature and humidity. Periodically, the flour is sifted, and the beetles are counted and then returned to their containers. Which species persists is observed and recorded. **(a)** The general process illustrating competitive exclusion in these species; **(b)** results of a specific, typical experiment under warm, dry conditions.

Understanding the niche of a species is useful in assessing the impact of land development or changes in land use. Will the change remove an essential requirement for some species' niche? A new highway that makes car travel easier might eliminate your neighbor's bus route (an essential part of his habitat) and thereby eliminate his profession (or niche). Other things could also eliminate this niche. Suppose a new school were built and all the children could now walk to school. A school bus driver would not be needed; this niche would no longer exist in your town. In the same way, cutting a forest may drive away prey and eliminate the wolf's niche.

Measuring Niches

An ecological niche is often described and measured as the set of all environmental conditions under which a species can persist and carry out its life functions.[19] It is illustrated by the distribution of two species of flatworm that live on the bottom of freshwater streams. A study of two species of these small worms in Great Britain found that some streams contained one species, some the other, and still others both.[17]

The stream waters are cold at their source in the mountains and become progressively warmer as they flow downstream. Each species of flatworm occurs within a specific range of water temperatures. In streams where species A occurs alone, it is found from 6° to 17°C (42.8°–62.6°F) (Figure 8.12a). Where species B occurs alone, it is found from 6° to 23°C (42.8°–73.4°F) (Figure 8.12b). When they occur in the same stream, their temperature ranges are much narrower. Species A lives in the upstream sections, where the temperature ranges from 6° to 14°C (42.8°–57.2°F), and species B lives in the warmer downstream areas, where temperatures range from 14° to 23°C (57.2°–73.4°F) (Figure 8.12c).

The temperature range in which species A occurs when it has no competition from B is called its *fundamental temperature niche*. The set of conditions under which it persists in the presence of B is called its *realized temperature niche*. The flatworms show that species divide up their habitat so that they use resources from different parts of it. Of course, temperature is only one aspect of the environment. Flatworms also have requirements relating to the acidity of the water and other factors. We could create graphs for each of these factors, showing the range within which A and B occurred. The collection of all those graphs would constitute the complete Hutchinsonian description of the niche of a species.

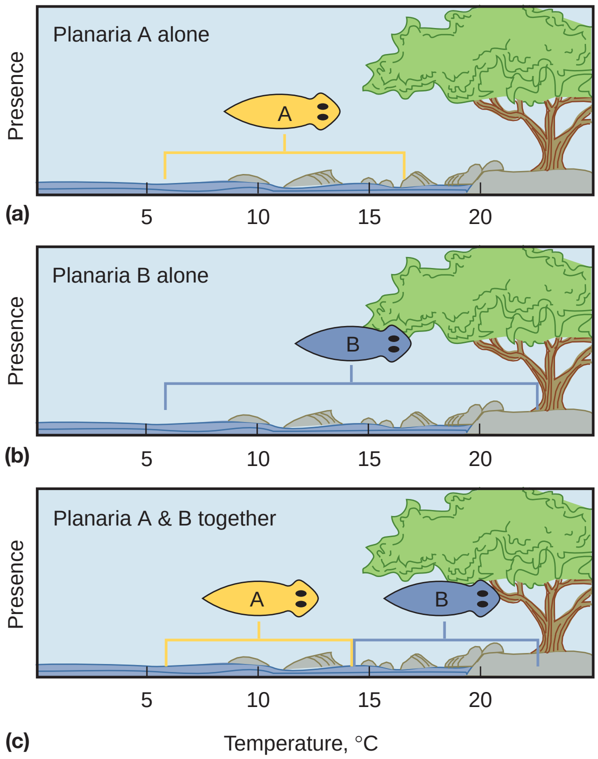


FIGURE 8.12 Fundamental and realized niches: The occurrence of freshwater flatworms in cold mountain streams in Great Britain. (a) The presence of species A in relation to temperature in streams where it occurs alone. **(b)** The presence of species B in relation to temperature in streams where it occurs alone. **(c)** The temperature range of both species in streams where they occur together. Inspect the three graphs: What is the effect of each species on the other?

A Practical Implication

From the discussion of the competitive exclusion principle and the ecological niche, we learn something important about the conservation of species: If we want to conserve a species in its native habitat, we must make sure that all the requirements of its niche are present. Conservation of endangered species is more than a matter of putting many individuals of that species into an area. All the life requirements for that species must also be present—we have to conserve not only a population but also its habitat and its niche.

8.5 Symbiosis

Our discussion up to this point might leave the impression that species interact mainly through competition—by interfering with one another. But symbiosis is also important. This term is derived from a Greek word meaning "living together." In ecology, **symbiosis** describes a relationship between two organisms that is beneficial to both and enhances each organism's chances of persisting. Each partner in symbiosis is called a **symbiont**.

Symbiosis is widespread and common; most animals and plants have symbiotic relationships with other species. We, too, have symbionts—microbiologists tell us that about 10% of our body weight is actually the weight of symbiotic microorganisms that live in our intestines. They help our digestion, and we provide a habitat that supplies all their needs; both we and they benefit. We become aware of this intestinal community when it changes—for example, when we take antibiotics that kill some of these organisms, changing the balance of that community, or when we travel to a foreign country and ingest new strains of bacteria. Then we suffer a well-known traveler's malady, gastrointestinal upset.

Another important kind of symbiotic interaction occurs between certain mammals and bacteria. A reindeer on the northern tundra may appear to be alone but carries with it many companions. Like domestic cattle, the reindeer is a ruminant, with a four-chambered stomach (Figure 8.13) teeming with microbes (a billion per cubic centimeter). In this partially closed environment, the respiration of microorganisms uses up the oxygen ingested by the reindeer while eating. Other microorganisms digest cellulose, take nitrogen from the air in the stomach, and make proteins. The bacterial species that digest the parts of the vegetation that the reindeer cannot digest itself (in particular, the cellulose and lignins of cell walls in woody tissue) require a peculiar environment: They can survive only in an environment without oxygen. One of the few places on Earth's surface where such an environment exists is the inside of a ruminant's stomach.[20] The bacteria and the reindeer are symbionts,

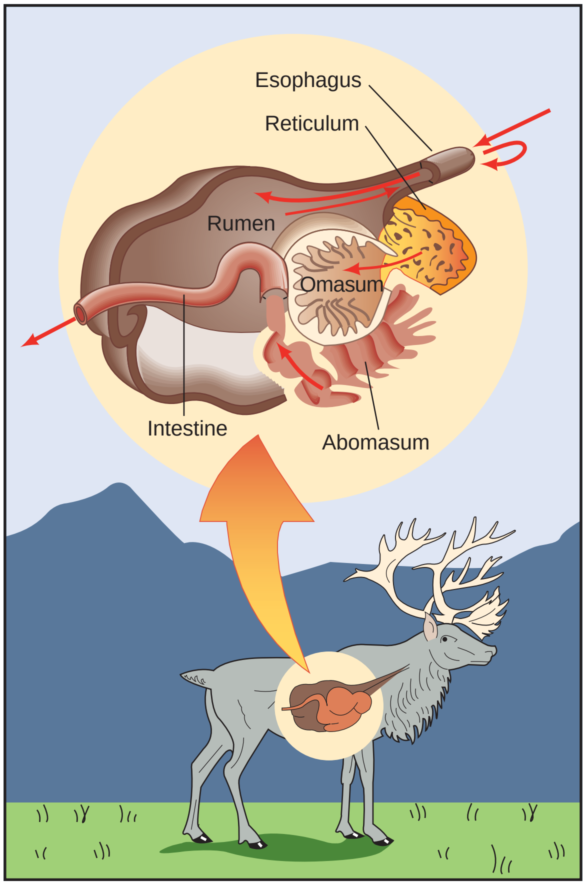


FIGURE 8.13 The stomach of a reindeer illustrates complex symbiotic relationships. For example, in the rumen, bacteria digest woody tissue the reindeer could not otherwise digest. The result is food for the reindeer and food and a home for the bacteria, which could not survive in the local environment outside.

each providing what the other needs, and neither could survive without the other. They are therefore called **obligate symbionts**.

Crop plants illustrate another kind of symbiosis. Plants depend on animals to spread their seeds and have evolved symbiotic relationships with them. That's why fruits are so eatable; it's a way for plants to get their seeds spread, as Henry David Thoreau discussed in his book *Faith in a Seed*.

A Broader View of Symbiosis

So far we have discussed symbiosis in terms of physiological relationships between organisms of different species. But symbiosis is much broader, and includes social and behavioral relationships that benefit both populations. Consider, for example, dogs and wolves. Wolves avoid human beings and have long been feared and disliked by many peoples, but dogs have done very well because of the behavioral connection with people. Being friendly, helpful, and companionable to people has made dogs very abundant. This is another kind of symbiosis.

A Practical Implication

We can see that symbiosis promotes biological diversity, and that if we want to save a species from extinction, we must save not only its habitat and niche but also its symbionts. This suggests another important point that will become more and more evident in later chapters: *The attempt to save a single species almost invariably leads us to conserve a group of species, not just a single species or a particular physical habitat.*

8.6 Predation and Parasitism

Predation–parasitism is the third way in which species interact. *In ecology, a predator–parasite relation is one that benefits one individual (the predator or parasite) and is negative for the other (the prey or host).* **Predation** is when an organism (a predator) feeds on other live organisms (prey), usually of another species. **Parasitism** is when one organism (the parasite) lives on or within another (the host) and depends on it for existence but makes no useful contribution to it and may in fact harm it.

Predation can increase the diversity of prey species. Think again about the competitive exclusion principle. Suppose two species are competing in the same habitat and have the same requirements. One will win out. But if a predator feeds on the more abundant species, it can keep that prey species from overwhelming the other. Both might persist, whereas without the predator only one would. For example, some studies have shown that a moderately grazed pasture has more species of plants than an ungrazed one. The same seems to be true for natural grasslands and savannas. Without grazers and browsers, then, African grasslands and savannas might have fewer species of plants.

A Practical Implication

Predators and parasites influence diversity and can increase it.

8.7 How Geography and Geology Affect Biological Diversity

Species are not uniformly distributed over the Earth's surface; diversity varies greatly from place to place. For instance, suppose you were to go outside and count all the species in a field or any open space near where you are reading this book (that would be a good way to begin to learn for yourself about biodiversity). The number of species you found would depend on where you are. If you live in northern Alaska or Canada, Scandinavia, or Siberia, you would probably find a significantly smaller number of species than if you live in the tropical areas of Brazil, Indonesia, or central Africa. Variation in diversity is partially a question of latitude—in general, greater diversity occurs at lower latitudes. Diversity also varies within local areas. If you count species in the relatively sparse environment of an abandoned city lot, for example, you will find quite a different number than if you count species in an old, long-undisturbed forest.

The species and ecosystems that occur on the land change with soil type and topography: slope, aspect (the direction the slope faces), elevation, and nearness to a drainage basin. These factors influence the number and kinds of plants, and the kinds of plants in turn influence the number and kinds of animals.

Such a change in species can be seen with changes in elevation in mountainous areas like the Grand Canyon and the nearby San Francisco Mountains of Arizona (Figure 8.14). Although such patterns are easiest to see in vegetation, they occur for all organisms.

Some habitats harbor few species because they are stressful to life, as a comparison of vegetation in two areas of Africa illustrates. In eastern and southern Africa, well-drained, sandy soils support diverse vegetation, including many species of *Acacia* and *Combretum* trees, as well as many grasses. In contrast, woodlands on the very heavy clay soils of wet areas near rivers, such as the Sengwa River in Zimbabwe, consist almost exclusively of a single species called *Mopane.* Very heavy clay soils store water and prevent most oxygen from reaching roots. As a result, only tree species with very shallow roots survive.

Moderate environmental disturbance can also increase diversity. For example, fire is a common disturbance in many forests and grasslands. Occasional light fires produce a mosaic of recently burned and unburned areas. These patches favor different kinds of species and increase overall diversity. Table 8.2 shows some of the major influences on biodiversity. Of course, people also affect diversity. In general, urbanization, industrialization, and agriculture decrease diversity, reducing the number of habitats and simplifying habitats. (See, for example, the effects of agriculture on habitats, discussed in Chapter 11.) In addition, we intentionally favor specific species and manipulate populations for our own purposes—for example, when a person plants a lawn or when a farmer plants a single crop over a large area.

Most people don't think of cities as having any beneficial effects on biological diversity. Indeed, the development of cities tends to reduce biological diversity. This is partly because cities have typically been located at good sites for travel, such as along rivers or near oceans, where biological diversity is often high. However, in recent years we have begun to realize that cities can contribute in important ways to the conservation of biological diversity.

Wallace's Realms: Biotic Provinces

As we noted, biological diversity differs among continents, in terms of both total species diversity and the particular species that occur. This large-scale difference has long fascinated naturalists and travelers, many of whom have discovered strange, new (for them) animals and plants as they have traveled between continents. In 1876 the great

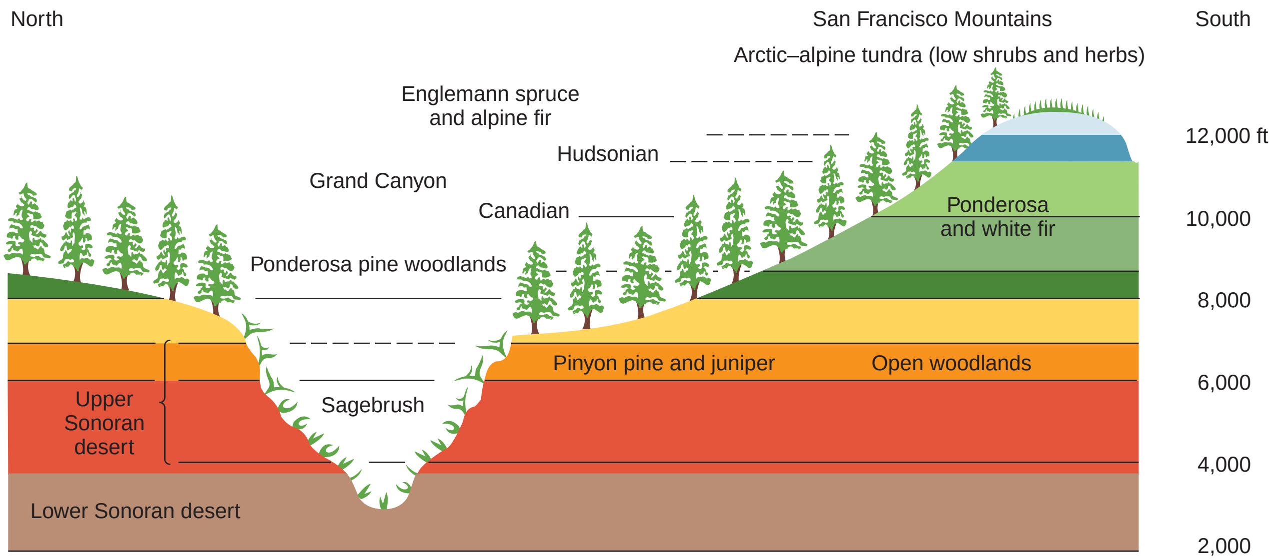


FIGURE 8.14 Change in the relative abundance of a species over an area or a distance is referred to as an *ecological gradient*. Such a change can be seen with changes in elevation in mountainous areas. The altitudinal zones of vegetation in the Grand Canyon of Arizona and the nearby San Francisco Mountains are shown. (*Source:* From C.B. Hunt, *Natural Regions of the United States and Canada* [San Francisco: W.H. Freeman, 1974].)

Table 8.2 SOME MAJOR FACTORS THAT INCREASE AND DECREASE BIOLOGICAL DIVERSITY

A. FACTORS THAT TEND TO INCREASE DIVERSITY
1. A physically diverse habitat
2. Moderate amounts of disturbance (such as fire or storm in a forest or a sudden flow of water from a storm into a pond).
3. A small variation in environmental conditions (temperature, precipitation, nutrient supply, etc.).
4. High diversity at one trophic level increases the diversity at another trophic level. (Many kinds of trees provide habitats for many kinds of birds and insects.)
5. An environment highly modified by life (e.g., a rich organic soil).
6. Middle stages of succession.
7. Evolution.
B. FACTORS THAT TEND TO DECREASE DIVERSITY
1. Environmental stress.
2. Extreme environments (conditions near the limit of what living things can withstand).
3. A severe limitation in the supply of an essential resource.
4. Extreme amounts of disturbance.
5. Recent introduction of exotic species (species from other areas).
6. Geographic isolation (being on a real or ecological island).

British biologist Alfred Russel Wallace (co-discoverer of the theory of biological evolution with Charles Darwin) suggested that the world could be divided into six biogeographic regions on the basis of fundamental features of the animals found in those areas.[21] He referred to these regions as realms and named them Nearctic (North America), Neotropical (Central and South America), Palaearctic (Europe, northern Asia, and northern Africa), Ethiopian (central and southern Africa), Oriental (the Indian subcontinent and Malaysia), and Australian. These have become known as Wallace's realms (Figure 8.15). Recognition of these worldwide patterns in animal species was the first step in understanding **biogeography**—the geographic distribution of species.

In each major biogeographic area (Wallace's realm), certain families of animals are dominant, and animals of these families fill the ecological niches. Animals filling a particular ecological niche in one realm are of different genetic stock from those filling the same niche in the other realms. For example, bison and pronghorn antelope are among the large mammalian herbivores in North America. Rodents such as the capybara fill the same niches in South America, and kangaroos fill them in Australia. In central and southern Africa, many species, including giraffes and antelopes, fill these niches.

This is the basic concept of Wallace's realms, and it is still considered valid and has been extended to all life-forms,[22] including plants (Figure 8.15b)[23] and invertebrates. These realms are now referred to as "biotic provinces."[24] A **biotic province** is a region inhabited by a characteristic set of taxa (species, families, orders), bounded by barriers that prevent the spread of those distinctive kinds of life to other regions and the immigration of foreign species.[10] So in a biotic province, organisms share a common genetic heritage but may live in a variety of environments as long as they are genetically isolated from other regions.

Biotic provinces came about because of continental drift, which is caused by plate tectonics and has periodically joined and separated the continents (see the discussion in Chapter 6).[25] The unification (joining) of continents enabled organisms to enter new habitats and allowed genetic mixing. Continental separation led to genetic isolation and the evolution of new species.

This at least partially explains why introducing species from one part of the Earth to another can cause problems. Within a realm, species are more likely to be related and to have evolved and adapted in the same place for a long time. But when people bring home a species from far away, they are likely to be introducing a species that is unrelated, or only distantly related, to native species. This new and unrelated "exotic" species has not evolved and adapted in the presence of the home species, so ecological and evolutionary adjustments are yet to take place. Sometimes an introduction brings in a superior competitor.

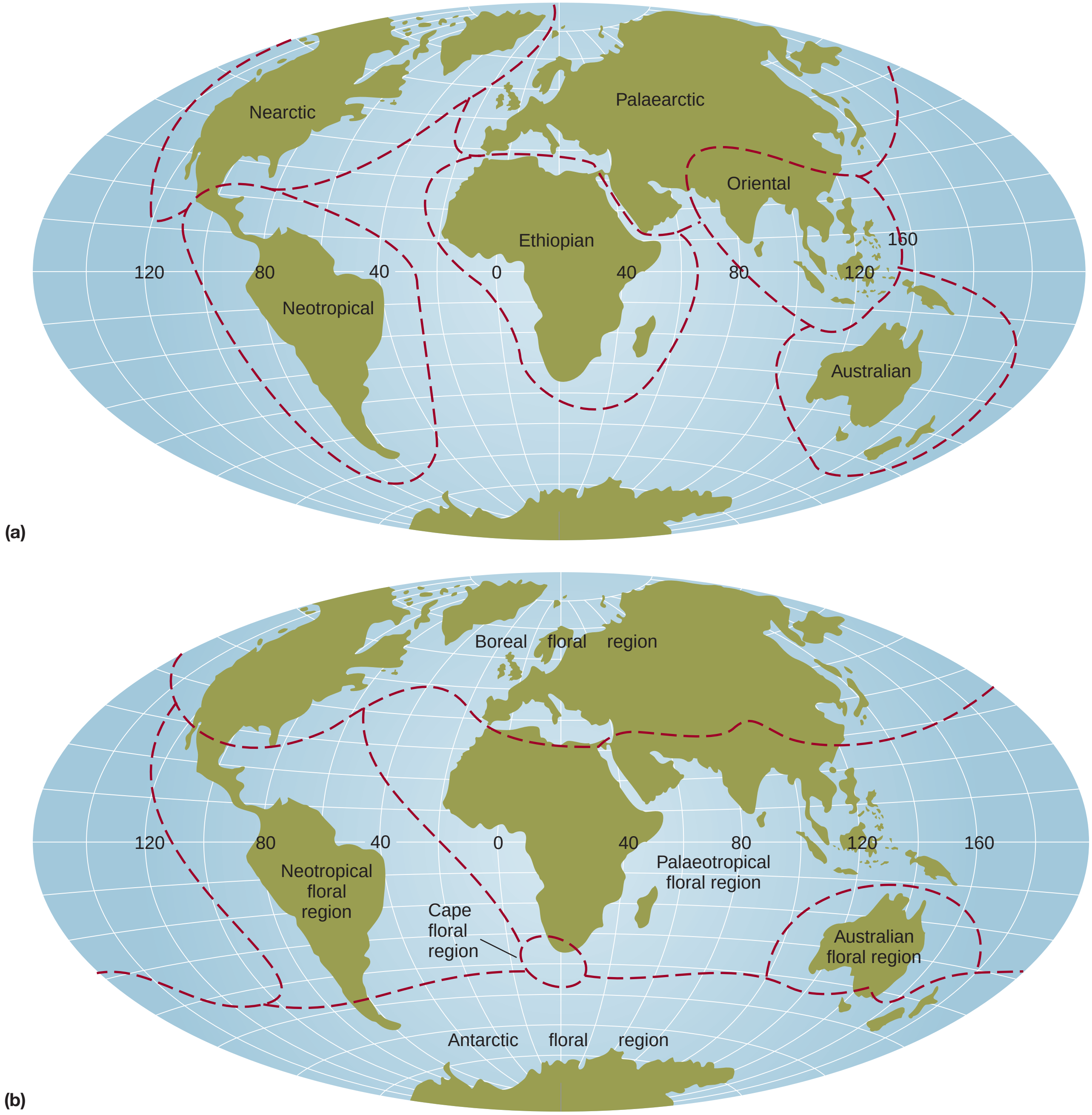


FIGURE 8.15 **Wallace's (Biogeographic) Realms (a)** for animals and **(b)** for plants are based on genetic factors. Within each realm, the vertebrates are in general more closely related to each other than to vertebrates filling similar niches in other realms; similarly, plants within a realm are more closely related to each other than to plants of other realms.

Biomes

A **biome** is a kind of ecosystem, such as a desert, a tropical rain forest, or a grassland. The same biome can occur on different continents because similar environments provide similar opportunities for life and similar constraints. As a result, similar environments lead to the evolution of organisms similar in form and function (but not necessarily in genetic heritage or internal makeup) and similar ecosystems. This is known as *the rule of climatic similarity*. The close relationship between environment and kinds of life-forms is shown in Figure 8.16.

In sum, the difference between a biome and a biotic province is that a biotic province is based on who is related to whom, while a biome is based on niches and habitats. In general, species within a biotic province are

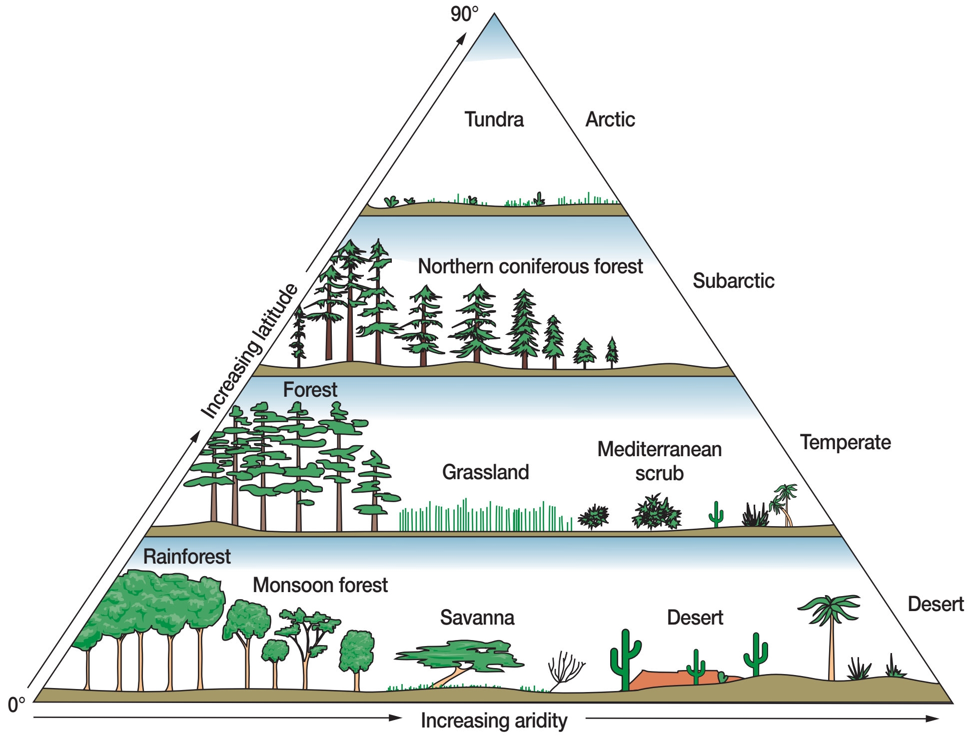


FIGURE 8.16 Simplified diagram of the relationship between precipitation and latitude and Earth's major land biomes. Here, latitude serves as an index of average temperature, so latitude can be replaced by average temperature in this diagram. (*Source:* Harm de Blij, Peter O. Muller, and Richard S. Williams, *Physical Geography of the Global Environment*, Figure 27-4, p. 293, edited by Harm de Blij, copyright 2004 by Oxford University Press. Used by permission of Oxford University Press.)

more closely related to each other than to species in other provinces. In two different biotic provinces, the same ecological niche will be filled with species that perform a specific function and may look very similar to each other but have quite different genetic ancestries. In this way, a biotic province is an evolutionary unit.

Convergent and Divergent Evolution

Plants that grow in deserts of North America and East Africa illustrate the idea of a biome (see Figure 8.17). The Joshua tree and saguaro cactus of North America and the giant Euphorbia of East and Southern Africa are tall, have succulent green stems that replace the leaves as the major sites of photosynthesis, and have spiny projections, but these plants are not closely related. The Joshua tree is a member of the agave family, the saguaro is a member of the cactus family, and the Euphorbia is a member of the spurge family. The ancestral differences between these look-alike plants can be found in their flowers, fruits, and seeds, which change the least over time and thus provide the best clues to the genetic history of a species. Geographically isolated for 180 million years, these plants have been subjected to similar climates, which imposed similar stresses and opened up similar ecological opportunities. On both continents, desert plants evolved to adapt to these stresses and potentials, and have come to look alike and prevail in like habitats. Their similar shapes result from evolution in similar desert climates, a process known as **convergent evolution**.

Another important process that influences life's geography is **divergent evolution**. In this process, a population is divided, usually by geographic barriers. Once separated into two populations, each evolves separately, but the two groups retain some characteristics in common. It is now believed that the ostrich (native to Africa), the rhea (native to South America), and the emu (native to Australia) have a common ancestor but evolved separately (Figure 8.18). In open savannas and grasslands, a large bird that can run quickly but feed efficiently on small seeds and insects has certain advantages over other organisms seeking the same food. Thus, these species maintained the same characteristics in widely separated areas. Both convergent and divergent evolution increase biological diversity.

People make use of convergent evolution when they move decorative and useful plants around the world. Cities that lie in similar climates in different parts of the world now share many of the same decorative plants. Bougainvillea, a spectacularly bright flowering shrub originally native to Southeast Asia, decorates cities as distant from each other as Los Angeles and the capital of Zimbabwe. In New York City and its outlying suburbs, Norway maple from Europe and the tree of heaven and gingko tree from China grow with native species such as sweet gum, sugar maple, and pin oak. People intentionally introduced the Asian and European trees.

(a)

(b)

(c)

FIGURE 8.17 Joshua Tree of North America and giant Euphorbia of Africa illustrate convergent evolution. Given sufficient time and similar climates in different areas, species similar in shape will tend to occur. The Joshua tree **(a)** and saguaro cactus **(b)** of North America look similar to the giant Euphorbia **(c)** of East Africa. But these plants are not closely related. Their similar shapes result from evolution under similar climates, a process known as *convergent evolution*.

(a) (b) (c)

FIGURE 8.18 Divergent evolution. Three large, flightless birds evolved from a common ancestor but are now found in widely separated regions: **(a)** the ostrich in Africa, **(b)** the rhea in South America, and **(c)** the emu in Australia.

8.8 Invasions, Invasive Species, and Island Biogeography

Ever since Darwin's voyage on *The Beagle,* which took him to the Galápagos Islands, biologists have been curious about how biological diversity can develop on islands: Do any rules govern this process? How do such invasions happen? And how is biological diversity affected by the size of and distance to a new habitat? E.O. Wilson and R. MacArthur established a theory of island biogeography that sets forth major principles about biological invasion of new habitats,[26] and as it turns out, the many jokes and stories about castaways on isolated islands have a basis in fact.

- Islands have fewer species than continents.
- The two sources of new species on an island are migration from the mainland and evolution of new species in place.
- The smaller the island, the fewer the species, as can be seen in the number of reptiles and amphibians in various West Indian islands (Figure 8.20).
- The farther the island is from a mainland (continent), the fewer the species (Figure 8.19).[27]

Clearly, the farther an island is from the mainland, the harder it will be for an organism to travel the distance, and the smaller the island, the less likely that it will be found by individuals of any species. In addition, the smaller the island, the fewer individuals it can support. Small islands tend to have fewer habitat types, and some habitats on a small island may be too small to support a population large enough to have a good chance of surviving for a long time. Generally, the smaller the population, the greater its risk of extinction. It might be easily extinguished by a storm, flood, or other catastrophe or disturbance, and every species is subject to the risk of extinction by predation, disease (parasitism), competition, climatic change, or habitat alteration.

A final generalization about island biogeography is that over a long time, an island tends to maintain a rather constant number of species, which is the result of the rate at which species are added minus the rate at which they become extinct. These numbers follow the curves shown in Figure 8.20. For any island, the number of species of a particular life-form can be predicted from the island's size and distance from the mainland.

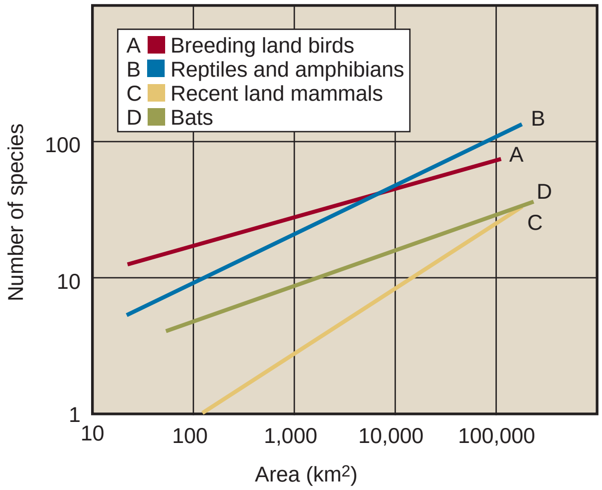


FIGURE 8.20 Islands have fewer species than do mainlands. The larger the island, the greater the number of species. This general rule is shown by a graph of the number of species of birds, reptiles and amphibians, recent land mammals, and bats for islands in the Caribbean. (Modified from B. Wilcox, ed., [Gland, Switzerland: IUCN, 1988].)

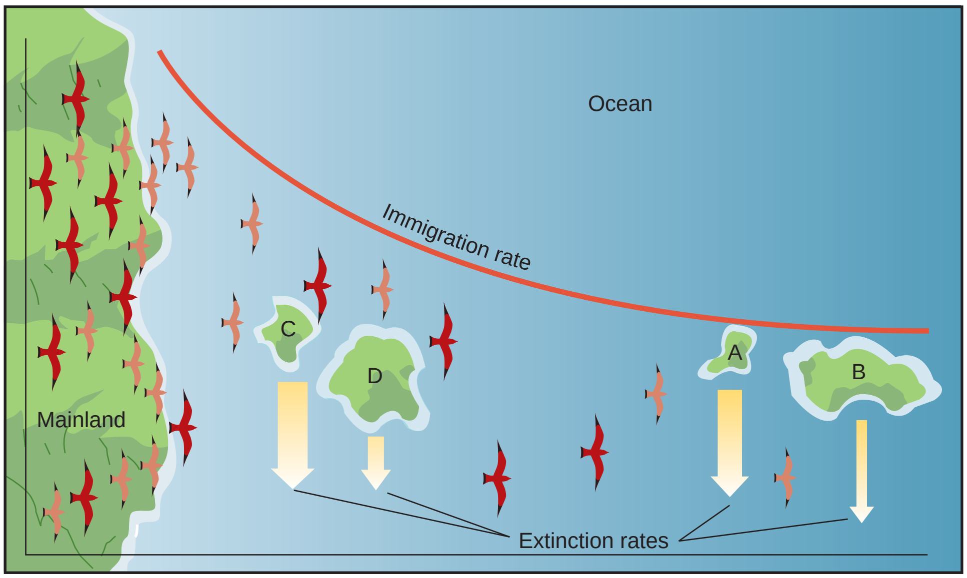


FIGURE 8.19 Idealized relation of an island's size, distance from the mainland, and number of species. The nearer an island is to the mainland, the more likely it is to be found by an individual, and thus the higher the rate of immigration. The larger the island, the larger the population it can support and the greater the chance of persistence of a species—small islands have a higher rate of extinction. The average number of species therefore depends on the rate of immigration and the rate of extinction. Thus, a small island near the mainland may have the same number of species as a large island far from the mainland. The thickness of the arrow represents the magnitude of the rate. (*Source:* Modified from R.H. MacArthur and E.O. Wilson, *The Theory of Island Biogeography* [Princeton, NJ: Princeton University Press, 1967].)

The concepts of island biogeography apply not just to real islands in an ocean but also to ecological islands. An **ecological island** is a comparatively small habitat separated from a major habitat of the same kind. For example, a pond in the Michigan woods is an ecological island relative to the Great Lakes that border Michigan. A small stand of trees within a prairie is a forest island. A city park is also an ecological island. Is a city park large enough to support a population of a particular species? To know whether it is, we can apply the concepts of island biogeography.

Biogeography and People

Benefits of Biological Invasions

We have seen that biogeography affects biological diversity. Changes in biological diversity in turn affect people and the living resources on which we depend. These effects extend from individuals to civilizations. For example, the last ice ages had dramatic effects on plants and animals and thus on human beings. Europe and Great Britain have fewer native species of trees than other temperate regions of the world. Only 30 tree species are native to Great Britain (that is, they were present prior to human settlement), although hundreds of species grow there today.

Why are there so few native species in Europe and Great Britain? Because of the combined effects of climate change and the geography of European mountain ranges. In Europe, major mountain ranges run east–west, whereas in North America and Asia the major ranges run north–south. During the past 2 million years, Earth has experienced several episodes of continental glaciation, when glaciers several kilometers thick expanded from the Arctic over the landscape. At the same time, glaciers formed in the mountains and expanded downward. Trees in Europe, caught between the ice from the north and the ice from the mountains, had few refuges, and many species became extinct. In contrast, in North America and Asia, as the ice advanced, tree seeds could spread southward, where they became established and produced new plants. Thus, the tree species "migrated" southward and survived each episode of glaciation.[16]

Since the rise of modern civilization, these ancient events have had many practical consequences. As we mentioned earlier, soon after Europeans discovered North America, they began to bring exotic North American species of trees and shrubs into Europe and Great Britain. These exotic imports were used to decorate gardens, homes, and parks and formed the basis of much of the commercial forestry in the region. For example, in the famous gardens of the Alhambra in Granada, Spain, Monterey cypress from North America are grown as hedges and cut in elaborate shapes. In Great Britain and Europe, Douglas fir and Monterey pine are important commercial timber trees today. These are only two examples of how knowledge of biogeography—enabling people to predict what will grow where based on climatic similarity—has been used for both aesthetic and economic benefits.

Why Invasive Species Are a Serious Problem Today

The ease and speed of long-distance travel have led to a huge rate of introductions, with invasive pests (including disease-causing microbes) arriving from all around the world both intentionally and unintentionally (Table 8.3 and Figure 8.21). Table 8.3 shows the number of plant pests intercepted by various means in 2007 by the U.S. government. The majority of interceptions—42,003—were at airports, ten times more than maritime interceptions, which before the jet age would have accounted for

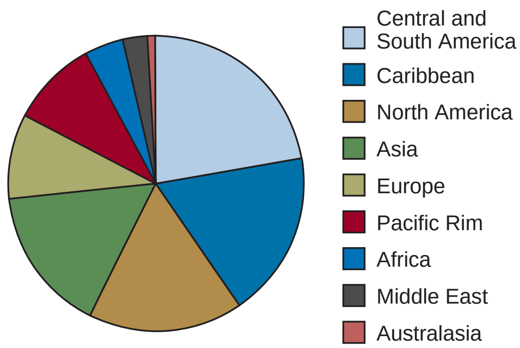


FIGURE 8.21 Where invasive pests are coming from. (*Source:* USDA.)

Table 8.3 REPORTABLE PLANT PEST INTERCEPTIONS, 2007

PLANT PEST INTERCEPTIONS	NUMBER	PERCENT
Airport	42,003	61%
Express carrier	6	0.01%
Inspection station	2,763	4.01%
Land border	14,394	20.91%
Maritime	4,518	6.56%
Other government programs	86	0.12%
Pre-departure	4,869	7.07%
Rail	16	0.02%
USPS Mail	184	0.27%
Total	**68,839**	**100%**

(*Source:* McCullough, D. G., T. T. Works, J. F. Cavey, A. M. Liebold, and D. Marshall. 2006. Interceptions of nonindigenous-plant pests at U.S. ports of entry and border crossings over a 17-year period. *Biological Invasions* 8: 611–630.)

CRITICAL THINKING ISSUE

Polar Bears and the Reasons People Value Biodiversity

In 2008, the U.S. Endangered Species Act listed polar bears as a threatened species. Worldwide, an estimated 20,000 to 25,000 polar bears roam the Arctic, hunting ringed and bearded seals, their primary food. About 5,000 of these polar bears live within the United States. Refer back to the reasons that people value biodiversity. Read up on polar bears (we've listed some sources below) and decide which of these reasons apply to this species. In particular, consider the following questions.

Critical Thinking Questions

1. As a top predator, is the polar bear a necessary part of its ecosystem? (*Hint:* Consider the polar bear's ecological niche.)
2. Do the Inuit who live among polar bears value them as part of the Arctic diversity of life? (This will take some additional study on your part.)
3. Of the nine reasons we discussed earlier for conserving biological diversity, which ones are the primary reasons for conservation of polar bears?

Some Additional Sources of Information about Polar Bears

U.S. Department of Interior Ruling on the Polar Bear: http://alaska.fws.gov/fisheries/mmm/polarbear/pdf/Polar_Bear_Final_Rule.pdf

About Polar Bears as a Species and Their Habitat and Requirements: Polar Bears: Proceedings of the 14th Working Meeting of the IUCN/SSC Polar Bear Specialist Group, June 20–24, 2005, Seattle, Washington. Available at the International Union for the Conservation of Nature (IUCN) website: http://www.iucnredlist.org/search/details.php/22823/summ

Global Warming and Polar Bears: A.E. Derocher, Nicholas J. Lunn, and Ian Stirling, 2004, Polar bears in a warming climate. *Integrative and Comparative Biology*, 44:13–176.

most of them. Passenger ships arrive at fewer locations and far less frequently than do commercial aircraft today. Bear in mind that the 42,003 were just those intercepted—no doubt many passed undetected—and that these are only for pests of plants, not for such things as zebra mussels dumped into American waters from cargo ships. According to the USDA, the present situation is not completely controllable.

Another major avenue of species invasions has been the international trade in exotic pets, like the Burmese python. Many of these are released outdoors when they get to be too big and too much trouble for their owners.

The upshot of this is that we can expect the invasion of species to continue in large numbers, and some will cause problems not yet known in the United States.

SUMMARY

- Biological evolution—the change in inherited characteristics of a population from generation to generation—is responsible for the development of the many species of life on Earth. Four processes that lead to evolution are mutation, natural selection, migration, and genetic drift.
- Biological diversity involves three concepts: genetic diversity (the total number of genetic characteristics), habitat diversity (the diversity of habitats in a given unit area), and species diversity. Species diversity, in turn, involves three ideas: species richness (the total number of species), species evenness (the relative abundance of species), and species dominance (the most abundant species).
- About 1.4 million species have been identified and named. Insects and plants make up most of these species. With further explorations, especially in tropical areas, the number of identified species, especially of invertebrates and plants, will increase.
- Species engage in three basic kinds of interactions: competition, symbiosis, and predation–parasitism. Each type of interaction affects evolution, the persistence of species, and the overall diversity of life. It is important to understand that organisms have evolved together, so predator, parasite, prey, competitor, and symbiont have adjusted to one another. Human interventions frequently upset these adjustments.

- The competitive exclusion principle states that two species that have exactly the same requirements cannot coexist in exactly the same habitat; one must win. The reason more species do not die out from competition is that they have developed a particular niche and thus avoid competition.
- The number of species in a given habitat is determined by many factors, including latitude, elevation, topography, severity of the environment, and diversity of the habitat. Predation and moderate disturbances, such as fire, can actually increase the diversity of species. The number of species also varies over time. Of course, people affect diversity as well.

REEXAMINING THEMES AND ISSUES

Human Population

The growth of human populations has decreased biological diversity. If the human population continues to grow, pressures will continue on endangered species, and maintaining existing biological diversity will be an ever-greater challenge.

Sustainability

Sustainability involves more than just having many individuals of a species. For a species to persist, its habitat must be in good condition and must provide that species' life requirements. A diversity of habitats enables more species to persist.

Global Perspective

For several billion years, life has affected the environment on a global scale. These global effects have in turn affected biological diversity. Life added oxygen to the atmosphere and removed carbon dioxide, thereby making animal life possible.

Urban World

People have rarely thought about cities as having any beneficial effects on biological diversity. However, in recent years there has been a growing realization that cities can contribute in important ways to the conservation of biological diversity. This topic will be discussed in Chapter 22.

People and Nature

People have always treasured the diversity of life, but we have been one of the main causes of the loss in diversity.

Science and Values

Perhaps no environmental issue causes more debate, is more central to arguments over values, or has greater emotional importance to people than biological diversity. Concern about specific endangered species has been at the heart of many political controversies. Resolving these conflicts and debates will require a clear understanding of the values at issue, as well as knowledge about species and their habitat requirements and the role of biological diversity in life's history on Earth.

KEY TERMS

adaptive radiation **152**
biogeography **160**
biological diversity **145**
biological evolution **149**
biome **161**
biotic province **160**
competitive exclusion principle **154**
convergent evolution **162**
divergent evolution **162**
dominant species **147**
ecological island **165**
ecological niche **155**
founder effect **153**
gene **149**
genetic drift **153**
genotype **149**
migration **152**
mutation **150**
natural selection **150**
obligate symbionts **158**
parasitism **158**
population **145**
predation **158**
species **145**
species evenness **147**
species richness **147**
symbiont **157**
symbiosis **157**

STUDY QUESTIONS

1. Why do introduced species often become pests?
2. On which of the following planets would you expect a greater diversity of species? (a) a planet with intense tectonic activity; (b) a tectonically dead planet. (Remember that *tectonics* refers to the geologic processes involving the movement of tectonic plates and continents, processes that lead to mountain building and so forth.)
3. You are going to conduct a survey of national parks. What relationship would you expect to find between the number of species of trees and the size of each park?
4. A city park manager has run out of money to buy new plants. How can the park's labor force alone be used to increase the diversity of (a) trees and (b) birds in the park?
5. A plague of locusts visits a farm field. Soon after, many kinds of birds arrive to feed on the locusts. What changes occur in animal dominance and diversity? Begin with the time before the locusts arrive and end after the birds have been present for several days.
6. What will happen to total biodiversity if (a) the emperor penguin becomes extinct? (b) the grizzly bear becomes extinct?
7. What is the difference between a habitat and a niche?
8. More than 600 species of trees grow in Costa Rica, most of them in the tropical rain forests. What might account for the coexistence of so many species with similar resource needs?
9. Which of the following can lead to populations that are less adapted to the environment than were their ancestors?
   (a) Natural selection
   (b) Migration
   (c) Mutation
   (d) Genetic drift

FURTHER READING

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CHAPTER 9

Ecological Restoration

The Florida Everglades from the air looks like a field of water islands and grasslike water plants. One of the largest ecological restoration projects is an attempt to help this national park.

LEARNING OBJECTIVES

Ecological restoration is the part of ecosystem management that deals with the recovery of ecosystems that have been damaged by human activities. It is a relatively new field. In this chapter, we explore the concepts of ecological restoration. After reading this chapter, you should understand . . .

- What it means to "restore" an ecosystem, since ecological systems are always changing;
- The main goals of restoration ecology;
- Basic approaches, methods, and limits of restoration;
- The general principles and processes of restoration ecology;
- The role of adaptive management in restoration;
- The criteria used to judge the success of restoration.

CASE STUDY

The Florida Everglades

The Florida Everglades is one of the nation's most valuable ecological treasures, listed by the United Nations as a World Heritage Site. The Everglades is also interconnected with a large area of the rest of Florida, beginning with a series of small lakes near Orlando, Florida (near the center of the state), and extending southward to the Florida Bay. The area south of Lake Okeechobee—about 175 km (110 mi) south of Orlando—is a long, wide system of shallow wetlands with slow-moving water. You can imagine the Everglades as a very wide, grass-filled, slow-moving, shallow river. Everglades National Park is at the very southern end of the system and extends out into Florida Bay to about the Florida Keys. Much of the flow of the Everglades is funneled through a location known as Shark Slough, and the velocity of flow of the lower Everglades, while still slow, is greater than that to the north.

Tourists from all over the world come to the Everglades to see its unusual landscape and wildlife. It is home to more than 11,000 species of plants, several hundred species of birds, and numerous species of fish and mammals. It is the last remaining habitat for approximately 70 threatened or endangered species or subspecies, including the Florida manatee (a subspecies of the West Indian manatee), the Florida panther (a subspecies of the American mountain lion), and the American crocodile. Unfortunately, in the past century, much of the Everglades has been drained for agriculture and urban development; today only 50% of the original wetlands remain (Figure 9.1a and b).

Restoration of the Everglades is complicated by agriculture and urbanization—several million people live in south Florida. All—agriculture, people, and the National Park—compete for the water resources. One of the major issues is to somehow arrive at a plan that will ensure long-term sustainability and quality of the water supply for the Everglades and also supply water for agriculture, towns, and cities.[1] This plan will involve the following:

- Reducing the area in agriculture and/or the water use per hectare in agriculture.
- Reducing the flow of agricultural fertilizers and pesticides from farmland into the Everglades.
- Managing land development that encroaches upon the Everglades.
- Managing access to the Everglades by people.
- Removing introduced exotic species that are dangerous to people, or threaten native species with extinction, or disrupt the presettlement ecosystems.

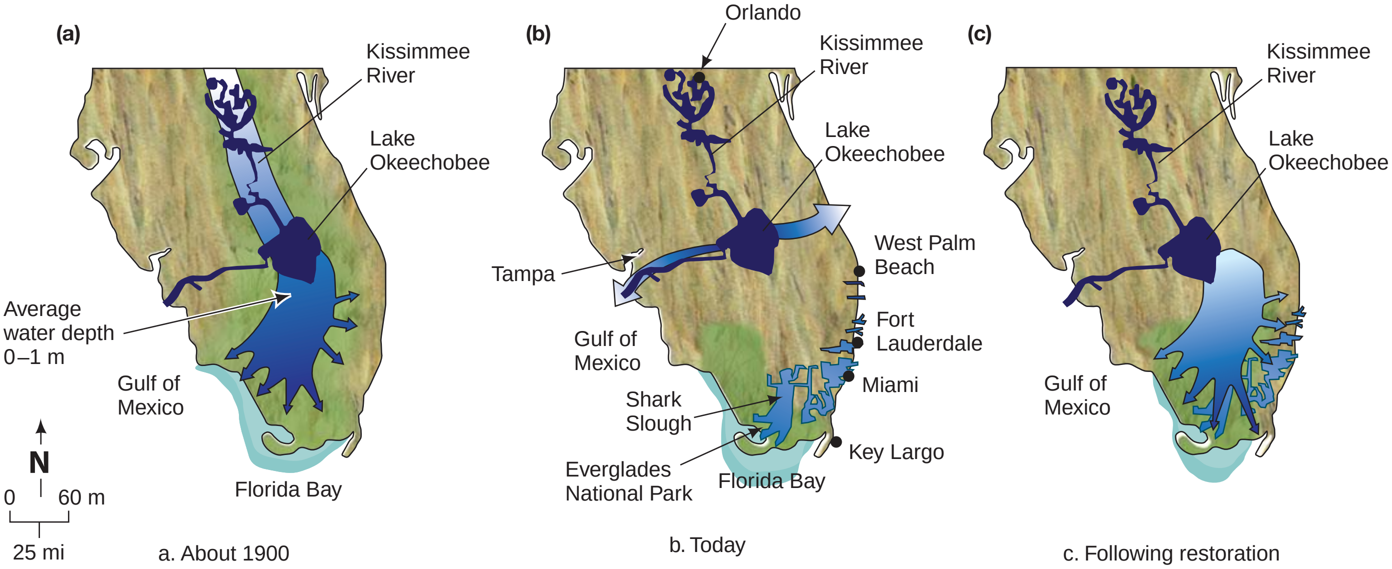

FIGURE 9.1 The Florida Everglades from about 1900 to the present (a and b) and projected into the future following restoration (c). Water flow (both surface and ground water) is shown in blue. Land development and water diversions changed the dominant flow from north-south to east-west. (*Sources*: Modified from the U.S. Geological Survey and Comprehensive Everglades Restoration Plan.)

- Developing scientific methods and theory to better predict the possible consequences of changes to the geologic, hydrologic, and biologic parts of the Everglades as restoration goes forward.
- Restoring the original large-scale water flow in south Florida—that grass-filled, slow-moving, shallow river. (Today the flow of water in the northern part of the Everglades is controlled by a complex system of canals, locks, and levees for a variety of purposes, including agriculture, flood control, and water supply.)

The Everglades restoration is the largest wetland-restoration project in the world. Known as the Comprehensive Everglades Restoration Plan, the project was developed by a number of government agencies, both local and federal, and is slated to continue over a 30-year period at a total cost of about $10 billion. To date, about $2.4 billion has been spent. Land acquired in 2008 that will be removed from agriculture and returned as part of the Everglades will enlarge the park's area by approximately 728 km^2 (281 mi^2). The acquired land will allow restoration of the hydrology of the Everglades in a much more significant way, as it is in the northern part of the system, where much of the water was used for agricultural purposes. Goals for the Florida Everglades include the following:

- Restoration of a more natural water flow (Figure 9.1c).
- Recovery of native and endangered species.
- Removal of invasive exotic species that are causing problems to the ecosystems and to people.
- Restoration of water quality, especially control of nutrients from agricultural and urban areas.
- Habitat restoration for wildlife that use the Everglades.

Progress to date has been significant. The amount of pollutants flowing into the Everglades from a variety of sources has been reduced by about 50%. Thousands of hectares have been treated to remove invasive, exotic species, including the Brazilian pepper tree and tilapia (a fish from Africa). In recent years, the Burmese python, which can grow to over 7 m (21 ft) and weigh over 100 kg (220 lbs), has become established in the Everglades (Figure 9.2). The snakes are an exotic, invasive species introduced by people who purchased small pythons as pets and released them into the wild when they became too large and difficult to keep. They have established a rapidly growing population in the Everglades (and elsewhere in Florida) and are becoming a top predator there, with increasing capacity to deplete populations of native birds and mammals. Recently, a large python killed and attempted to swallow a seven-foot alligator! A program is now under way to attempt to control the growing population of pythons (estimated to exceed 100,000), but it's unlikely that they can be completely eradicated.

FIGURE 9.2 Burmese python, an exotic, invasive species. Released by people who purchased them as pets, it has established a large population in the Everglades.

A purpose of this chapter is to provide an understanding of what is possible and what can be done to restore damaged ecosystems.

9.1 What Is Ecological Restoration?

Ecological restoration is defined as providing assistance to the recovery of an ecosystem that has been degraded, damaged, or destroyed.[2] As such, ecological restoration is applied science and derives from the science of restoration ecology. Some general principles for restoration are listed below.

- Ecosystems are dynamic, not static (change and natural disturbance are expected).
- No simple set of rules will be applicable to a specific restoration project.
- Adaptive management, using the best science, is necessary for restoration to succeed.
- Careful consideration of ecosystems (life), geology (rocks, soils), and hydrology (water) plays an important role in all restoration projects.

Of particular importance is the principle that ecosystems are dynamic, not static—that is, they are always changing and subject to natural disturbance. Any restoration plan must consider disturbance and how resilient the restored system will be. Also important is **adaptive management**, the application of science to the management process. Hypotheses may be tested, and, as restoration goes forward, flexible plans may be developed to accommodate change. Probably the most common projects involve river restoration and the restoration of freshwater and coastal wetlands.[3]

9.2 Goals of Restoration: What Is "Natural"?

If an ecosystem passes naturally through many different states and all of them are "natural," and if the change itself, caused by wildfire, flood, and windstorm, is natural, then what is its natural state? And how can restoration that involves such disturbance occur without damage to human life and property? Can we restore an ecological system to any one of its past states and claim that this is natural and successful restoration?

In Chapters 3 and 5, we discussed the ideas of steady-state and non-steady-state ecological systems. We argued that until the second half of the 20th century the predominant belief in Western civilization was that any natural area—a forest, a prairie, an intertidal zone—left undisturbed by people achieved a single condition that would persist indefinitely. This condition, as mentioned in Chapter 3, has been known as the balance of nature. The major tenets of a belief in the balance of nature are as follows:

- Left undisturbed, nature achieves a permanency of form and structure that persists indefinitely.
- If it is disturbed and the disturbance is removed, nature returns to exactly the same permanent state.
- In this permanent state of nature, there is a "great chain of being," with a place for each creature (a habitat and a niche) and each creature in its appropriate place.

These ideas have their roots in Greek and Roman philosophies about nature, but they have played an important role in modern environmentalism as well. In the early 20th century, ecologists formalized the belief in the balance of nature. At that time, people thought that wildfires were always detrimental to wildlife, vegetation, and natural ecosystems. *Bambi*, a 1942 Walt Disney movie, expressed this belief, depicting a fire that brought death to friendly animals. In the United States, Smokey Bear is a well-known symbol used for many decades by the U.S. Forest Service to warn visitors to be careful with fire and avoid setting wildfires. The message is that wildfires are always harmful to wildlife and ecosystems.

All of this suggests a belief that the balance of nature does in fact exist. But if that were true, the answer to the question "restore to what?" would be simple: restore to the original, natural, permanent condition. The way to do it would be simple, too: Get out of the way and let nature take its course. Since the second half of the 20th century, though, ecologists have learned that nature is not constant, and that forests, prairies—all ecosystems—undergo change. Moreover, since change has been a part of natural ecological systems for millions of years, many species have adapted to change. Indeed, many require specific kinds of change in order to survive. This means that we can restore ecosystem processes (flows of energy, cycling of chemical elements) and help populations of endangered and threatened species increase on average, but the abundances of species and conditions of ecosystems will change over time as they are subjected to internal and external changes, and following the process of succession discussed in Chapter 5.

Dealing with change—natural and human-induced— poses questions of human values as well as science. This is illustrated by wildfires in forests, grasslands, and shrublands, which can be extremely destructive to human life and property. From 1990 to 2009, three wildfires that started in chaparral shrubland in Santa Barbara, California, burned about 1,000 homes. The wildfire hazard can be minimized but not eliminated. Scientific understanding tells us that fires are natural, and that some species require them. But whether we choose to allow fires to burn, or even light fires ourselves, is a matter of values. **Restoration ecology** depends on science to discover what used to be, what is possible, what an ecosystem or species requires to persist, and how different goals can be achieved. But selecting goals for restoration is a matter of human values.

Some possible goals of restoration are listed in Table 9.1. Which state we attempt to restore a landscape to (pre-industrial to modern) depends on more-specific goals and possibilities that, again, are linked to values. For example, restoring the Florida Everglades to a pre-industrial state is not possible or desirable (a value) given the present land and water use that supports the people of Florida. The goal instead is to improve biodiversity, water flow through the Everglades, and water quality (see opening Case Study).

Table 9.1 SOME POSSIBLE RESTORATION GOALS

GOAL	APPROACH
1. Pre-industrial	Maintain ecosystems as they were in A.D. 1500
2. Presettlement (e.g., of North America)	Maintain ecosystems as they were about A.D. 1492
3. Preagriculture	Maintain ecosystems as they were about 5000 B.C.
4. Before any significant impact of human beings	Maintain ecosystems as they were about 10,000 B.C.
5. Maximum production	Independent of a specific time
6. Maximum diversity	Independent of a specific time
7. Maximum biomass	Independent of old growth
8. Preserve a specific endangered species	Whatever stage it is adapted to
9. Historical range of variation	Create the future like the known past

9.3 What Is Usually Restored?

Ecosystems of all types have undergone degradation and need restoration. However, certain kinds of ecosystems have undergone especially widespread loss and degradation and are therefore a focus of attention today. Table 9.2 gives examples of ecosystems that are commonly restored.

Attention has focused on forests, wetlands, and grasslands, especially the North American prairie; streams and rivers and the riparian zones alongside them; lakes; beaches; and habitats of threatened and endangered species. Also included are areas that people desire to restore for aesthetic and moral reasons, showing once again that restoration involves values. In this section, we briefly discuss the restoration of rivers and streams, wetlands, and prairies.

Rivers, Streams, and Wetlands Restoration: Some Examples

Rivers and streams and wetlands probably are restored more frequently than any other systems. Thousands of streams have been degraded by urbanization, agriculture, timber harvesting, and channelization (shortening, widening, and even paving over or confining the channel to culverts). In North America, large areas of both freshwater and coastal wetlands have been greatly altered during the past 200 years. It is estimated that California, for example, has lost more than 90% of its wetlands, both freshwater and coastal, and that the total wetland loss for the United States is about 50%. Not only the United States has suffered; wetlands around the world are affected.

Table 9.2 SELECTED EXAMPLES OF RESTORATION PROJECTS

SYSTEM	OBJECTIVE
Rivers/Streams	Improve biodiversity, water quality, bank stability. Very common practice across the U.S.
Coastal Wetlands	Improve biodiversity and water quality, store water, provide a buffer to erosion from storms to inland areas. Very common practice along all U.S. coastal areas.
Freshwater Wetlands	Improve biodiversity and water quality, store water, and, for river systems, reduce the flood hazard.
Beaches	Sustain beaches and their ecosystems. Most often involve sand supply.
Sand Dunes	Improve biodiversity in both inland and coastal areas.
Landscape	Increase biodiversity and conserve endangered species. Often a very complex process.
Land Disturbed by Mining	Reestablish desired ecosystems, reduce erosion, and improve water quality.

Rivers and Streams

One of the largest and most expensive restoration projects in the United States is the restoration of the Kissimmee River in Florida. This river was channelized, or straightened, by the U.S. Army Corps of Engineers to provide ship passage through Florida. However, although the river and its adjacent ecosystems were greatly altered, shipping never developed, and now several hundred million dollars must be spent to put the river back as it was before. The task includes restoring the meandering flow of the river and replacing the soil layers in the order in which they had lain on the bottom of the river prior to channelization.[4]

The Kissimmee at one time had an unusual hydrology because it inundated its floodplain for prolonged periods (Figure 9.3). The floodplain and river supported a biologically diverse ecosystem, including wetland plants, wading birds, waterfowl, fish, and other wildlife. Few people lived in the Kissimmee basin before about 1940, and the land use was mostly agricultural. Due to rapid development and growth in the past 50 years and a growing flood hazard as a result of inappropriate land use, people asked the federal government to design a flood-control plan for southern Florida. The channelization of the Kissimmee River occurred between 1962 and 1971 as part of the flood-control plan. About two-thirds of the floodplain was drained, and a straight canal was excavated. Turning the meandering river into a straight canal degraded the river ecosystem and greatly reduced the wetlands and populations of birds, mammals, and fish (Figure 9.4).

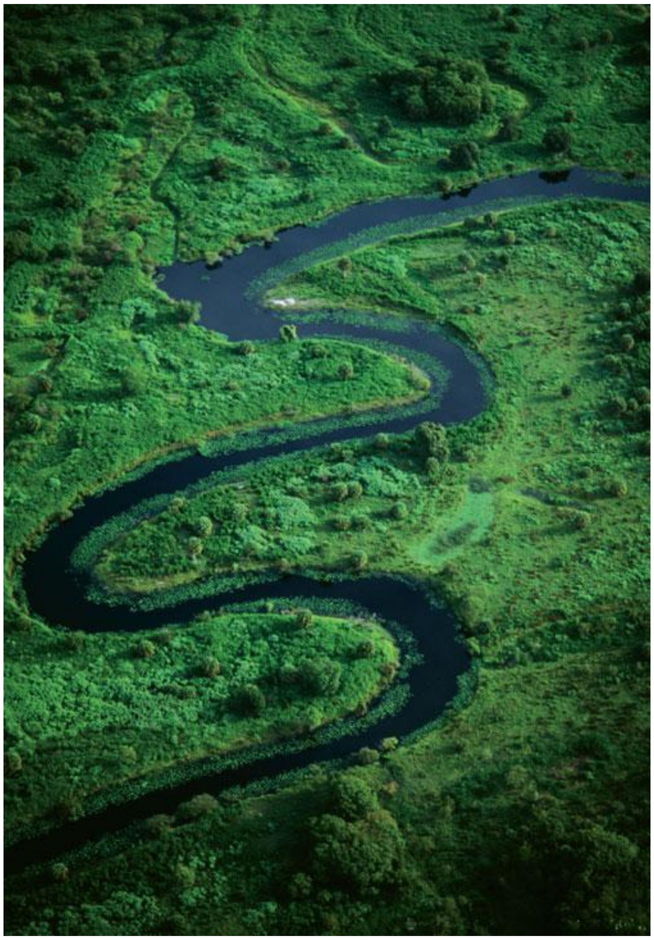

FIGURE 9.3 The Kissimmee River before channelization.

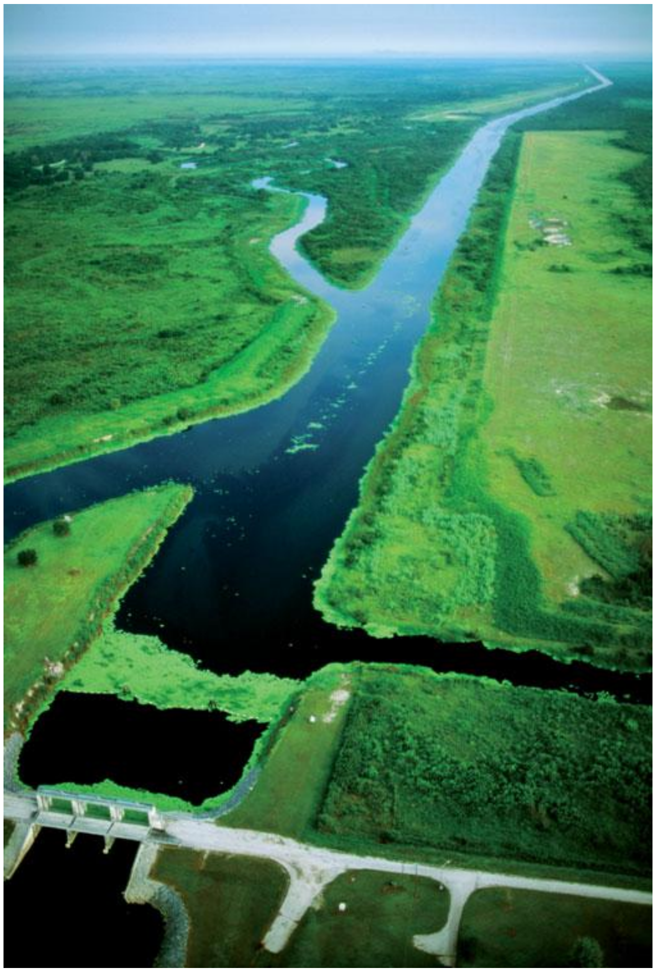

FIGURE 9.4 The Kissimmee River after channelization that produced a wide, straight ditch.

Criticism of the loss of the river ecosystem went on for years, finally leading to the current restoration efforts. The purpose of the restoration is to return part of the river to its historical meandering riverbed and wide floodplain. Before-and-after photos and specifics of the restoration plan are shown in Figure 9.5 and include restoring as much as possible of the historical biodiversity and ecosystem function; re-creating patterns of wetland plant communities as they existed before channelization; reestablishing prolonged flooding of the floodplain; and re-creating a river floodplain environment and connection to the main river similar to the way it used to be.[4]

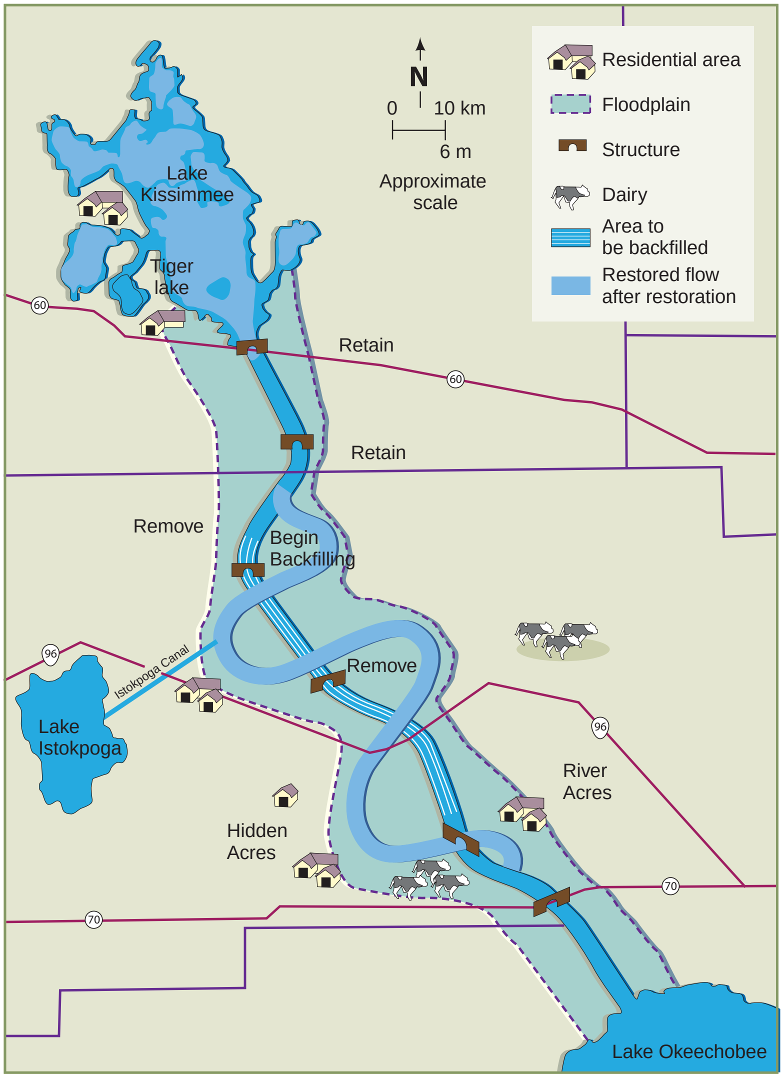

FIGURE 9.5 Map showing part of the Kissimmee River restoration plan. A major objective is to re-create the historical river floodplain environment that is wet much of the year, improving biodiversity and ecosystem function. (*Source*: Modified from South Florida Water Management District.)

The restoration project was authorized by the U.S. Congress in 1992, in partnership with the South Florida Water Management District and the U.S. Army Corps of Engineers. It is an ongoing project, and by 2001 approximately 12 km of the nearly straight channel had been restored to a meandering channel with floodplain wetlands about 24 km long. As a result, water again flowed through a meandering channel and onto the floodplain, wetland vegetation was reestablished, and birds and other wildlife returned. The potential flood hazard is being addressed. Some of the structures that control flooding will be removed, and others will be maintained. Flood protection is a main reason the entire river will not be returned to what it was before channelization.

The cost of the restoration of the Kissimmee River is several times greater than it was to channelize it. Thus, the decision to go forward with the restoration reflects the high value that people in south Florida place on conserving biological diversity and providing for recreational activities in a more natural environment.

Yellowstone National Park is another interesting case. It is the site of an unanticipated stream restoration resulting from the reintroduction of wolves. Wolves were eliminated from Yellowstone by the 1920s and were introduced back into the park in 1995–1996. Initially, 66 wolves were introduced, and by 2007 the wolf population had grown to about 1,500, with about 171 in Yellowstone itself (Figures 9.6 and 9.7), 700–800 in Idaho (outside the park), and the rest in other areas.

Mountain streams in Yellowstone generally consist of stream channels, beds, and banks composed of silt, sand, gravel, and bedrock. Cool, clean water is supplied via the hydrologic and geologic system from snowmelt and rain that infiltrate the rocks and soil to seep into streams. The water supports life in the stream, including fish and other organisms, as well as streamside vegetation adjacent to stream channels. The riparian vegetation is very different from vegetation on adjacent uplands. Stream bank vegetation helps retard erosion of the banks and thus the amount of sediment that enters the stream.

Riparian vegetation, such as cottonwood and willow trees, is also a popular food source for animals, such as elk. Extensive browsing

FIGURE 9.6 Wolves in Yellowstone National Park.

dramatically reduces the abundance of riparian plants, damaging the stream environment by reducing shade and by increasing bank erosion, which introduces fine sediment into the water. Fine sediment, such as fine sand and silt, not only degrades water quality but also may fill the spaces between gravel particles or seal the bed with mud, damaging fish and aquatic insect habitat.[5]

Before the wolves arrived in the mid-1990s, willows and other streamside plants were nearly denuded by browsing elk. It soon became apparent, however, that the wolves were most successful in hunting elk along streams, where the elk had to negotiate the complex, changing topography. The elk responded by avoiding the dangerous stream environment. Over a four-year period, from 1998 to 2002, the number of willows eaten by elk declined greatly, and the riparian vegetation recovered. As it did so, the stream channel and banks also recovered and became more productive for fish and other animals.

In sum, although the reintroduction of wolves to Yellowstone is controversial, the wolves are a *keystone species*—a species that, even if not overly abundant, plays an important role in maintaining an ecological community. By hunting elk and scaring them away from the streams, wolves improve the stream banks, the water quality, and the broader ecologic community (in this case, the stream ecosystem). The result is a higher-quality stream environment.[5]

Still, the debate about wolf introductions is complex. In Yellowstone, just over 90% of wolf prey is elk; there are far fewer bison, deer, and other animals. Land-use issues associated with grazing for cattle and sheep are more difficult to assess. How we choose to manage wolf populations will reflect both science and values.[5, 6]

FIGURE 9.7 **Wolf hunting elk in Yellowstone National Park.**

Wetlands

The famous cradle of civilization, the land between the Tigris and Euphrates rivers, is so called because the waters from these rivers and the wetlands they formed made possible one of the earliest sites of agriculture, and from this the beginnings of Western civilization. This well-watered land in the midst of a major desert was also one of the most biologically productive areas in the world, used by many species of wildlife, including millions of migratory birds. Ironically, the huge and famous wetlands between these two rivers, land that today is within Iraq, have been greatly diminished by the very civilization that they helped create. "We can see from the satellite images that by 2000, all of the marshes were pretty much drained, except for 7 percent on the Iranian border," said Dr. Curtis Richardson, director of the Duke University Wetland Center.[7]

A number of events of the modern age led to the marsh's destruction. Beginning in the 1960s, Turkey and Syria began to build dams upriver, in the Tigris and Euphrates, to provide irrigation and electricity, and now these number more than 30. Then in the 1980s Saddam Hussein had dikes and levees built to divert water from the marshes so that oil fields under the marshes could be drilled. For at least 5,000 years, the Ma'adan people—the Marsh Arabs—lived in these marshes. But the Iran–Iraq War (1980–1988) killed many of them and also added to the destruction of the wetlands (Figure 9.8a and b).[8]

Today efforts are under way to restore the wetlands. According to the United Nations Environment Program, since the early 1970s the area of the wetlands has increased by 58%.[9] But some scientists believe that there has been little improvement, and the question remains: Can ecosystems be restored once people have seriously changed them?

Prairie Restoration

Tallgrass prairie is also being restored. Prairies once occupied more land in the United States than any other kind of ecosystem. Today, only a few small remnants of prairie exist. Prairie restoration is of two kinds. In a few places, one can still find original prairie that has never been plowed. Here, the soil structure is intact, and restoration is simpler. One of the best known of these areas is the Konza Prairie near Manhattan, Kansas. In other places, where the land has been plowed, restoration is more complicated. Nevertheless, the restoration of prairies has gained considerable attention in recent decades, and restoration of prairie on previously plowed and farmed land is occurring in many midwestern states. The Allwine Prairie, within the city limits of Omaha,

(a)

(b)

FIGURE 9.8 **(a)** A Marsh Arab village in the famous wetlands of Iraq, said to be one of the places where Western civilization originated. The people in this picture are among an estimated 100,000 Ma'adan people who now live in their traditional marsh villages, many having returned recently. These marshes are among the most biologically productive areas on Earth. **(b)** Map of the Fertile Crescent, where the Marsh Arabs live, called the cradle of civilization. It is the land between the Tigris (the eastern river) and Euphrates (the western river) in what is now Iraq. Famous cities of history, such as Nineveh, developed here, made possible by the abundant water and good soil. The gray area shows the known original extent of the marshes, the bright green their present area.

Nebraska, has been undergoing restoration from farm to prairie for many years. Prairie restoration has also been taking place near Chicago.

About 10% of North American original tallgrass prairie remains in scattered patches from Nebraska east to Illinois and from southern Canada south to Texas (in the Great Plains physiographic province of the United States). A peculiarity of prairie history is that although most prairie land was converted to agriculture, this was not done along roads and railroads; thus, long, narrow strips of unplowed native prairie remain on these rights-of-way. In Iowa, for example, prairie once covered more than 80% of the state—11 million hectares (28 million acres). More than 99.9% of the prairie land has been converted to other uses, primarily agriculture, but along roadsides there are 242,000 hectares (600,000 acres) of prairie—more than in all of Iowa's county, state, and federal parks. These roadside and railway stretches of prairie provide some of the last habitats for native plants, and restoration of prairies elsewhere in Iowa is making use of these habitats as seed sources.[5]

Studies suggest that the species diversity of tallgrass prairie has declined as a result of land-use changes that have led to the loss or fragmentation of habitat.[9] For example, human-induced changes that nearly eliminated bison (another keystone species) from the prairie greatly changed the community structure and biodiversity of the ecosystem. Scientists evaluating the effects of grazing suggest that, managed properly, grazing by bison can restore or improve biodiversity of tallgrass prairie[9] (Figure 9.9). The effect of grazing by cattle is not as clear. Range managers have for years maintained that cattle grazing is good for ecosystems, but such grazing must be carefully managed. Cattle are not bison. Bison tend to range over a wider area and in a different pattern. Cattle tend to stay longer in a particular area and establish grazing trails with denuded vegetation. However, both cattle and bison, if too many of them are left too long in too small an area, will cause extensive damage to grasses.

Fire is another important factor in tallgrass prairies. Spring fires enhance the growth of the dominant tall grasses that bison prefer. Tallgrass prairie is a mixture of taller grasses, which prefer warm, dry environments, and other grasses, forbs, and woody plants, which prefer cooler, wetter conditions. The tall grasses often dominate and, if not controlled by fire and grazing, form a thick cover (canopy) that makes it more difficult for shorter plants to survive. Grazing opens the canopy and allows more light to reach closer to the ground and support more species. This increases biodiversity. Long ago, fires set by lightning and/or people helped keep the bison's grazing lands from turning into forests. Today, ecological restoration

FIGURE 9.9 American bison grazing in tallgrass prairie ecosystem, Custer State Park, South Dakota.

has attempted to use controlled burns to remove exotic species and woody growth (trees). However, fire alone is not sufficient in managing or restoring prairie ecosystem biodiversity. Moderate grazing is the hypothetical solution. Grazing of bison on degraded grassland will have negative impacts, but moderate grazing by bison or cattle on "healthy prairies" may work.

One of the newest threats to tallgrass prairie ecosystems is atmospheric nitrogen from automobile emissions. Nitrogen helps some species, but too much of it causes problems for tallgrass prairie ecosystems, whose diversity and productivity are significantly influenced by the availability of nitrogen. Fire and millions of grazing bison regulated nitrogen availability during prehistoric and pre-automobile times.

A CLOSER LOOK 9.1

Island Fox on Santa Cruz Island

The island fox is found on the Channel Islands, eight islands off the coast of Southern California (Figure 9. 10a). The fox evolved over the past 20,000 years into a separate species of its recent ancestors, the California gray fox. Due to isolation on the islands, as the island fox evolved, it became smaller, and today it is about the size of a house cat (Figure 9.10b).[10]

Island fox most likely reached the islands off the coast of Santa Barbara about 20,000 years ago, when sea levels were more than 120 meters lower than they are today and the distance to the mainland was much shorter, increasing the likelihood of animals' reaching the offshore environment. At that time, this consisted of one large island known as Santa Rosae. By the time Native Americans arrived, about 12,000 years ago, the island fox had become well established. Native Americans evidently kept the foxes as pets, and some burial sites suggest that foxes were, in fact, buried with their owners. The island

(a)

(b)

FIGURE 9.10 (a) The Santa Barbara Channel and Channel Islands; (b) Island fox.

(a) 

 (b)

FIGURE 9.11 **(a) Golden eagle eating an island fox on Santa Cruz Island and (b) a bald eagle hunting fish.**

fox in the Channel Islands lived to ages unheard of for mainland gray foxes. Many of them lived more than 10 years, and a few even about 12 years. A number of them became blind in their old age, from either cataracts or accident, and could be seen feeding on beaches and other areas despite their handicap.

A subspecies of the island fox evolved on the six islands on which they are found today, and until fairly recently they had no natural enemies. But in the 1990s, the populations of Island fox on several islands suddenly plummeted. On San Miguel Island, for example, a population of approximately 400 foxes in 1994 was reduced to about 15 in only five years. Similar declines occurred on Santa Rosa and Santa Cruz islands. At first it seemed that some disease must be spreading rapidly through the fox population. On Catalina Island, in fact, an occurrence of canine distemper did lead to a decline in the number of foxes on that island. On other islands, particularly in the Santa Barbara Channel, the cause was not so easily determined.

Ecologists eventually solved the mystery by discovering that foxes were being killed and eaten by golden eagles (Figure 9.11a), which had only recently arrived on the islands after the apparent demise of the islands' bald eagles (Figure 9.11b). The bald eagles primarily eat fish and hadn't bothered the foxes. Bald eagles are also territorial and kept golden eagles off the islands. It is believed that the bald eagles became endangered because the use of DDT in the 1970s and later led to increasing concentrations of the pesticide in fish that bald eagles ate, causing their eggshells to become too soft to protect the embryos. The golden eagles moved in and colonized the islands in the 1990s, apparently attracted by the amount of food they could easily obtain from their daylight hunting, as well as by the absence of bald eagles. The golden eagles found young feral pigs much to their liking and evidently also found island foxes to be easy targets.

Remains of island foxes have been found in eagle nests, and it is now generally agreed that the golden eagles are responsible for the decline in the fox populations. In fact, of 21 fox carcasses studied on Santa Cruz Island in the 1990s, 19 were apparently victims of golden eagle predation.[11,12]

To conserve the island fox on the three Channel Islands in Santa Barbara Channel, which are part of Channel Islands National Park, a management program was developed. The plan has five steps:[12]

1. Capture remaining island foxes and place them in protected areas.
2. Begin a captive breeding program to rebuild the fox populations.
3. Capture golden eagles and transfer them to the mainland. (The idea is to put them in suitable habitat far from the islands so they will not return.)
4. Reintroduce bald eagles into the island ecosystem. (It is hoped that the birds will establish territories and that this will prevent the return of golden eagles.)
5. Remove populations of feral pigs, which attract golden eagles to the islands.

This five-step program has been put into effect; foxes are now being bred in captivity at several sites, and new kits have been born. By 2009, golden eagles on Santa Cruz Island had been mostly removed, the pigs had also been removed, bald eagles had been reintroduced, and foxes raised in captivity had been released. The historical average population of fox on the islands is 1,400. By 2004 fewer than 100 were present, but by 2009 there were about 700—a remarkable recovery. If all the steps necessary to save the island fox are successful, then the island fox will again take its place as one of the keystone species on the Channel Islands.

9.4 Applying Ecological Knowledge to Restore Heavily Damaged Lands and Ecosystems

An example of how ecological succession can aid in the restoration (termed **reclamation** for land degraded by mining) of heavily damaged lands is the ongoing effort to undo mining damage in Great Britain, where some mines have been used since medieval times and approximately 55,000 hectares (136,000 acres) have been damaged. Recently, programs have been initiated to remove toxic pollutants from the mines and mine tailings, to restore these damaged lands to useful biological production, and to restore the attractiveness of the landscape.[13]

One area damaged by a long history of mining lies within the British Peak District National Park, where lead has been mined since the Middle Ages and waste tailings are as much as 5 m (16.4 ft) deep. The first attempts to restore this area used a modern agricultural approach: heavy application of fertilizers and planting of fast-growing agricultural grasses to revegetate the site rapidly. These grasses quickly green on the good soil of a level farm field, and it was hoped that, with fertilizer, they would do the same in this situation. But after a short period of growth, the grasses died. The soil, leached of its nutrients and lacking organic matter, continued to erode, and the fertilizers that had been added were soon leached away by water runoff. As a result, the areas were shortly barren again.

When the agricultural approach failed, an ecological approach was tried, using knowledge about ecological succession. Instead of planting fast-growing but vulnerable agricultural grasses, ecologists planted slow-growing native grasses, known to be adapted to mineral-deficient soils and the harsh conditions that exist in cleared areas. In choosing these plants, the ecologists relied on their observations of what vegetation first appeared in areas of Great Britain that had undergone succession naturally.[14] The result of the ecological approach has been the successful restoration of damaged lands (Figure 9.12).

FIGURE 9.12 Long-abandoned lead-mining area in Great Britain undergoing restoration (upper half of photograph). Restoration includes planting early-successional native grasses adapted to low-nutrient soil with little physical structure. The bottom hall of the photo shows the unrestored area.

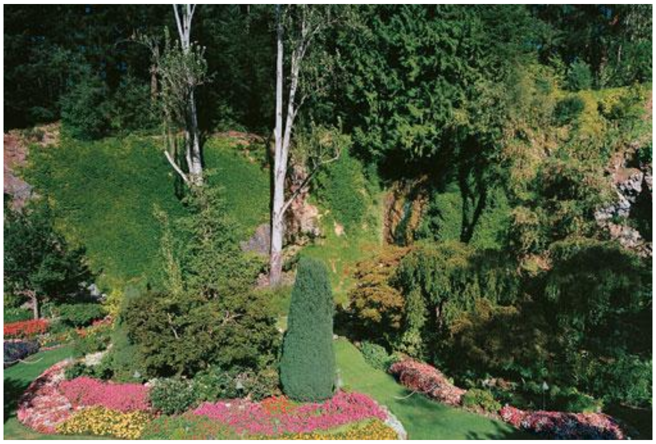

FIGURE 9.13 Restoration of a limestone quarry on Vancouver Island, Canada, in 1921 resulted in a tourist attraction known as Butchart Gardens that draws about 1 million visitors each year.

Heavily damaged landscapes can be found in many places. Restoration similar to that in Great Britain is done in the United States, Canada, and many other places to reclaim lands damaged by strip mining. Butchart Gardens, an open-pit limestone quarry on Vancouver Island, Canada, is an early-20th-century example of mine restoration. The quarry, a large, deep excavation where Portland cement was produced, was transformed into a garden that attracts a large number of visitors each year (Figure 9.13). The project was the vision of one person, the wife of the mine owner. One person can make all the difference!

9.5 Criteria Used to Judge the Success of Restoration

Criteria used to evaluate whether a specific restoration has been successful, and, if so, how successful, will vary, depending on details of the project and the target (reference) ecosystem to which the restoration is compared. Criteria used to judge the success of the Everglades restoration (with issues of endangered species) will be much different from criteria used to evaluate the success of **naturalization** of an urban stream to produce a greenbelt. However, some general criteria apply to both.[2]

- The restored ecosystem has the general structure and process of the target (reference) ecosystem.

- The physical environment (hydrology, soils, rocks) of the restored ecosystem is capable of sustainably supporting the stability of the system.
- The restored ecosystem is linked with and appropriately integrated into the larger landscape community of ecosystems.
- Potential threats to the stability of the restored ecosystem have been minimized to an acceptable level of risk.
- The restored ecosystem is sufficiently adapted to normally withstand expected disturbances that characterize the environment, such as windstorms or fire.
- The restored ecosystem is, as nearly as possible, as self-sustaining as the target (reference) ecosystem. It therefore undergoes the natural range of variation over time and space; otherwise it cannot be self-sustaining.

In the final analysis, restoration, broadly defined to include naturalization, is successful if it improves the environment and the well-being of the people who are linked to the environment. An example is development of city parks that allow people to better communicate with nature.

CRITICAL THINKING ISSUE

How Can We Evaluate Constructed Ecosystems?

What happens when restoring damaged ecosystems is not an option? In such cases, those responsible for the damage may be required to establish alternative ecosystems to replace the damaged ones. An example involved some saltwater wetlands on the coast of San Diego County, California.

In 1984, construction of a flood-control channel and two projects to improve interstate freeways damaged an area of saltwater marsh. The projects were of concern because California had lost 91% of its wetland area since 1943, and the few remaining coastal wetlands were badly fragmented. In addition, the damaged area provided habitat for three endangered species: the California least tern, the light-footed clapper rail, and a plant called the salt-marsh bird's beak. The California Department of Transportation, with funding from the Army Corps of Engineers and the Federal Highway Administration, was required to compensate for the damage by constructing new areas of marsh in the Sweetwater Marsh National Wildlife Refuge. To meet these requirements, eight islands, known as the Connector Marsh, with a total area of 4.9 hectares, were constructed in 1984. An additional 7-hectare area, known as Marisma de Nación, was established in 1990. Goals for the constructed marsh, which were established by the U.S. Fish and Wildlife Service, included the following:[14]

1. Establishment of tide channels with sufficient fish to provide food for the California least tern.
2. Establishment of a stable or increasing population of salt-marsh bird's beak for three years.
3. Selection of the Pacific Estuarine Research Laboratory (PERL) at San Diego State University to monitor progress on the goals and conduct research on the constructed marsh. In 1997, PERL reported that goals for the least tern and bird's beak had been met, but that attempts to establish a habitat suitable for the rail had been only partially successful (see Table 9.3).

During the past decade, PERL scientists have conducted extensive research on the constructed marsh to determine the reasons for its limited success. They found that rails live, forage, and nest in cordgrass more than 60 centimeters tall. Nests are built of dead cordgrass attached to stems of living cordgrass so that the nests can remain above the water as it rises and falls. If the cordgrass is too short, the nests are not high enough to avoid being washed out during high tides.[14]

Researchers suggested that the coarse soil used to construct the marsh did not retain the amount of nitrogen needed for cordgrass to grow tall. Adding nitrogen-rich fertilizer to the soil resulted in taller plants in the constructed marsh, but only if the fertilizer was added on a continuing basis.

Another problem is that the diversity and numbers of large invertebrates, which are the major food source of the rails, are lower in the constructed marsh than in natural marshes. PERL researchers suspect that this, too, is linked to low nitrogen levels. Because nitrogen stimulates the growth of algae and plants, which provide food for small invertebrates, and these in turn provide food for larger invertebrates, low nitrogen can affect the entire food chain.[15, 16, 17]

Table 9.3 GOALS, PROGRESS, AND STATUS AS OF 2006

SPECIES	MITIGATION GOALS	PROGRESS IN MEETING REQUIREMENTS	STATUS AS OF 2006
California	Tidal channels with 75% of the fish species and 75% of the number of fish found in natural channels	Met standards	FWS recommended change from endangered to threatened
Salt-marsh bird's beak	Through reintroduction, at least 5 patches (20 plants each) that remain stable or increase for 3 years	Did not succeed on constructed islands but an introduced population on natural Sweetwater Marsh thrived for 3 years (reached 140,000 plants); continue to monitor because plant is prone to dramatic fluctuations in population	Still listed as endangered
Light-footed clappeer rail	Seven home ranges (82 ha), each having tidal channels with:	Constructed	Still listed as endangered; in 2005, eight captive-raised birds were released
	a. Forage Species equal to 75% of the invertebrate species and 75% of the number of invertebrates in natural areas	Met standards	
	b. High marsh areas for rails to find refuge during high tides	Sufficient in 1996 but two home ranges fell short in 1997	
	c. Low marsh for nesting with 50% coverage by tall cordgrass **d.** Population of tall cordgrass that is self-sustaining for 3 years	All home ranges met low marsh acreage requirement and all but one met cordgrass requirement and six lacked suffcient tall cordgrass Plant height can be increased with continual use of fertilizer but tall cordgrass is not self-sustaining	

Note: FWS stands for U.S. Fish and Wildlife Service

Critical Thinking Questions

1. Make a diagram of the food web in the marsh showing how the clapper rail, cordgrass, invertebrates, and nitrogen are related.
2. The headline of an article about the Sweetwater Marsh project in the April 17, 1998, issue of *Science* declared, "Restored Wetlands Flunk Real-World Test." Based on the information you have about the project, would you agree or disagree with this judgment? Explain your answer.
3. How do you think one can decide whether a constructed ecosystem is an adequate replacement for a natural ecosystem?
4. The term *adaptive management* refers to the use of scientific research in ecosystem management. In what ways has adaptive management been used in the Sweetwater Marsh project? What lessons from the project could be used to improve similar projects in the future?

SUMMARY

- Ecological restoration is the process of helping degraded ecosystems to recover and become more self-sustaining, and therefore able to pass through their natural range of conditions.
- Overarching goals of ecological restoration are to help transform degraded ecosystems into sustainable ecosystems and to develop new relationships between the natural and human-modified environments.
- Adaptive management, which applies science to the restoration process, is necessary if restoration is to be successful.
- Restoration of damaged ecosystems is a relatively new emphasis in environmental sciences that is developing into a new field. Restoration involves a combination of human activities and natural processes. It is also a social activity.
- Disturbance, change, and variation in the environment are natural, and ecological systems and species have evolved in response to these changes. These natural variations must be part of the goals of restoration.

REEXAMINING THEMES AND ISSUES

Human Population

If we degrade ecosystems to the point where their recovery from disturbance is slowed or they cannot recover at all, then we have reduced the local carrying capacity of those areas for human beings. For this reason, an understanding of the factors that determine ecosystem restoration is important to developing a sustainable human population.

Sustainability

Heavily degraded land, such as land damaged by pollution or overgrazing, loses the capacity to recover. By helping degraded ecosystems to recover, we promote sustainability. Ecological principles are useful in restoring ecosystems and thereby achieving sustainability.

Global Perspective

Each degradation of the land takes place locally, but such degradation has been happening around the world since the beginnings of civilization. Ecosystem degradation is therefore a global issue.

Urban World

In cities, we generally eliminate or damage the processes of succession and the ability of ecosystems to recover. As our world becomes more and more urban, we must learn to maintain these processes within cities, as well as in the countryside. Ecological restoration is an important way to improve city life.

People and Nature

Restoration is one of the most important ways that people can compensate for their undesirable effects on nature.

Science and Values

Because ecological systems naturally undergo changes and exist in a variety of conditions, there is no single "natural" state for an ecosystem. Rather, there is the process of succession, with all of its stages. In addition, there are major changes in the species composition of ecosystems over time. While science can tell us what conditions are possible and have existed in the past, which ones we choose to promote in any location is a question of values. Values and science are intimately integrated in ecological restoration.

KEY TERMS

adaptive management **172**
naturalization **180**
reclamation **180**
restoration ecology **172**

STUDY QUESTIONS

1. Develop a plan to restore an abandoned field in your town to natural vegetation for use as a park. The following materials are available: bales of hay; artificial fertilizer; and seeds of annual flowers, grasses, shrubs, and trees.
2. Oil has leaked for many years from the gasoline tanks of a gas station. Some of the oil has oozed to the surface. As a result, the gas station has been abandoned and revegetation has begun to occur. What effects would you expect this oil to have on the process of succession?
3. Refer to the Everglades in the opening case study. Assume there is no hope of changing water diversion from the upstream area that feeds water to the Everglades. Develop a plan to restore the Everglades, assuming the area of wetlands will decrease by another 30% as more water is diverted for people and agriculture in the next 20 years.
4. How can adaptive management best be applied to restoration projects?

FURTHER READING

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CHAPTER 10

Environmental Health, Pollution, and Toxicology

Houston, Texas, Ship Channel, where many oil refineries are located.

LEARNING OBJECTIVES

Serious health problems may arise from toxic substances in water, air, soil, and even the rocks on which we build our homes. After reading this chapter, you should understand . . .

- How the terms *toxin, pollution, contamination, carcinogen, synergism*, and *biomagnification* are used in environmental health;
- What the classifications and characteristics are of major groups of pollutants in environmental toxicology;
- Why there is controversy and concern about synthetic organic compounds, such as dioxin;
- Whether we should be concerned about exposure to human-produced electromagnetic fields;
- What the dose-response concept is, and how it relates to LD-50, TD-50, ED-50, ecological gradients, and tolerance;
- How the process of biomagnification works, and why it is important in toxicology;
- Why the threshold effects of environmental toxins are important;
- What the process of risk assessment in toxicology is, and why such processes are often difficult and controversial.

CASE STUDY

Toxic Air Pollution and Human Health: Story of a Southeast Houston Neighborhood

Manchester is a neighborhood in southeast Houston, Texas, that is nearly surrounded by oil refineries and petrochemical plants. Residents and others have long noted the peculiar and not so pleasant smells of the area, but only recently have health concerns been raised. The neighborhood is close to downtown Houston, and the houses are relatively inexpensive, the streets safe. It was a generally positive neighborhood except for the occasional complaints about nosebleeds, coughing, and acidic smoke smells. Over a period of years, the number of oil refineries, petrochemical plants, and waste-disposal sites grew along what is known as the Houston Ship Channel (see opening photograph).[1]

Cancer is the second leading cause of death of U.S. children who are not linked to a known health risk before being stricken by the disease. Investigations into childhood cancer from air pollution are few in number but now include exposure to benzene and 1,3-butadiene, commonly referred to simply as butadiene.[1]

Benzene is a colorless toxic liquid that evaporates into the air. Exposure to benzene has a whole spectrum of possible consequences for people, such as drowsiness, dizziness, and headaches; irritation to eyes, skin, and respiratory tract; and loss of consciousness at high levels of exposure. Long-term (chronic) exposure through inhalation can cause blood disorders, including reduced numbers of red blood cells (anemia), in industrial settings. Inhalation has reportedly resulted in reproductive problems for women and, in tests on animals, adverse effects on the developing fetus. In humans, occupational exposure to benzene is linked to increased incidence of leukemia (a cancer of the tissues that form white blood cells). The many potential sources of exposure to benzene include tobacco smoke and evaporating gasoline at service stations. Of particular concern are industrial sources; for example, the chemical is released when gasoline is refined from oil.

The chemical 1,3-butadiene is a colorless gas with a mild gasoline-like odor. One way it is produced is as a by-product of refining oil. Health effects from this toxin are fairly well known and include both acute and chronic problems. Some of the acute problems are irritation of the eyes, throat, nose, and lungs. Possible chronic health effects of exposure to 1,3-butadiene include cancer, disorders of the central nervous system, damage to kidneys and liver, birth defects, fatigue, lowered blood pressure, headache, nausea, and cancer.[1,2] While there is controversy as to whether exposure to 1,3-butadiene causes cancer in people, more definitive studies of animals (rats and mice) exposed to the toxin have prompted the Environmental Protection Agency to classify 1,3-butadiene as a known human carcinogen.[1,2]

Solving problems related to air toxins in the Houston area has not been easy. First of all, the petrochemical facilities along the Houston Ship Channel were first established decades ago, during World War II, when the area was nearly unpopulated; since then, communities such as Manchester have grown up near the facilities. Second, the chemical plants at present are not breaking state or federal pollution laws. Texas is one of the states that have not established air standards for toxins emitted by the petrochemical industry. Advocates of clean air argue that the chemical industry doesn't own the air and doesn't have the right to contaminate it. People in the petrochemical industry say they are voluntarily reducing emissions of some of the chemicals known to cause cancer. Butadiene emissions have in fact decreased significantly in the last several years, but this is not much comfort to parents who believe their child contracted leukemia as a result of exposure to air toxins. Some people examining the air toxins released along Houston's Ship Channel have concluded that although further reducing emissions would be expensive, we have the technology to do it. Petrochemical companies are taking steps to reduce the emissions and the potential health risks associated with them, but more may be necessary.

A recent study set out to study neighborhoods (census tracts near the Ship Channel) with the highest levels of benzene and 1,3-butadiene in the air and evaluate whether these neighborhoods had a higher incidence of childhood lymphohematopoietic cancer. After adjusting for sex, ethnicity, and socioeconomic status, the study found that census tracts with the highest exposure to benzene had higher rates of leukemia.[1] The study concluded that elevated exposure to benzene and 1,3-butadiene may contribute to increased rates of childhood leukemia, but the possible link between the air pollution and disease needs further exploration.

The case history of the Houston Ship Channel, oil refineries, and disease is a complex problem for several reasons:

1. Disease seldom has a one-cause/one-effect relationship.
2. Data on air-pollution exposure are difficult to collect and link to a population of people who are moving around and have different responses to exposure to chemicals.
3. It is difficult to definitively link health problems to toxic air pollutants.
4. There have been few other studies with which the Houston study can be compared.

In this chapter we will explore selected aspects of exposure to toxins in the environment and real and potential health consequences to people and ecosystems.

10.1 Some Basics

As members of Earth's biological community, humans have a place in the biosphere—dependent on complex interrelations among the biosphere, atmosphere, hydrosphere, and lithosphere. We are only beginning to inquire into and gain a basic understanding of the total range of environmental factors that affect our health and well-being. As we continue our exploration of minute quantities of elements in soil, rocks, water, and air in relation to regional and global patterns of climate and earth science, we are making important discoveries about how these factors influence death rates and the incidence of disease. Incidence of a particular disease varies significantly from one area to another,[3,4] and some of the variability is the result of geologic, hydrologic, biologic, and chemical factors linked to Earth's climate system.

Disease—impairment of an individual's well-being and ability to function—is often due to poor adjustment between the individual and the environment. Disease occurs on a continuum—between a state of health and a state of disease is a *gray zone* of suboptimal health, a state of imbalance. In the gray zone, a person may not be diagnosed with a specific disease but may not be healthy.[5] There are many gray zones in environmental health, such as the many possible states of suboptimal health resulting from exposure to man-made chemicals, including pesticides; food additives, such as coloring, preservatives, and artificial saturated fat, some of which alter the chemical structure of food; exposure to tobacco smoke; exposure to air pollutants, such as ozone; exposure to chemicals in gasoline and in many household cleaners; and exposure to heavy metals, such as mercury or lead. As a result of exposure to chemicals in the environment from human activity, we may be in the midst of an epidemic of chronic disease that is unprecedented in human history.[5]

As noted in the opening case study, disease seldom has a one-cause/one-effect relationship with the environment. Rather, the incidence of a disease depends on several factors, including the physical environment, biological environment, and lifestyle. Linkages between these factors are often related to other factors, such as local customs and the level of industrialization. More primitive societies that live directly off the local environment are usually plagued by different environmental health problems than those in an urban society. For example, industrial societies have nearly eliminated such diseases as cholera, dysentery, and typhoid.

People are often surprised to learn that the water we drink, the air we breathe, the soil in which we grow crops, and the rocks on which we build our homes and workplaces may affect our chances of experiencing serious health problems and diseases (although, as suggested, direct relationships between the environment and disease are difficult to establish). At the same time, the environmental factors that contribute to disease—soil, rocks, water, and air—can also influence our chances of living longer, more productive lives.

Many people believe that soil, water, and air in a so-called natural state must be good, and that if human activities have changed or modified them, they have become contaminated, polluted, and therefore bad.[6] This is by no means the entire story; many natural processes—including dust storms, floods, and volcanic processes—can introduce materials harmful to people and other living things into the soil, water, and air.

A tragic example occurred on the night of August 21, 1986, when there was a massive natural release of carbon dioxide (CO_2) gas from Lake Nyos in Cameroon, Africa. The carbon dioxide was probably initially released from volcanic vents at the bottom of the lake and accumulated there over time. Pressure of the overlying lake water normally kept the dissolved gas down at the bottom, but the water was evidently agitated by a slide or small earthquake, and the bottom water moved upward. When the CO_2 gas reached the surface of the lake, it was released quickly into the air. But because CO_2 gas is heavier than air, it flowed downhill from the lake and settled in nearby villages, killing many animals and more than 1,800 people by asphyxiation (Figure 10.1).

It was estimated that a similar event could recur within about 20 years, assuming that carbon dioxide continued to be released at the bottom of the lake.[7] Fortunately, a hazard-reduction project funded by the U.S. Office of Foreign Disaster Assistance (scheduled to be completed early in the 21st century) includes inserting pipes into the

(a)

(b)

FIGURE 10.1 **(a)** In 1986, Lake Nyos in Cameroon, Africa, released carbon dioxide that moved down the slopes of the hills to settle in low places, asphyxiating animals and people. **(b).** Animals asphyxiated by carbon dioxide.

bottom of Lake Nyos, then pumping the gas-rich water to the surface, where the CO_2 gas is safely discharged into the atmosphere. In 2001, a warning system was installed, and one degassing pipe released a little more CO_2 than was seeping naturally into the lake. Recent data suggest that the single pipe now there barely keeps ahead of the CO_2 that continues to enter the bottom, so the lake's 500,000 tons of built-up gas have dropped only 6%. At this rate, it could take 30 to 50 years to make Lake Nyos safe. In the meantime, there could be another eruption.[8]

Terminology

What do we mean when we use the terms *pollution, contamination, toxin,* and *carcinogen?* A polluted environment is one that is impure, dirty, or otherwise unclean. The term **pollution** refers to an unwanted change in the environment caused by the introduction of harmful materials or the production of harmful conditions (heat, cold, sound). **Contamination** has a meaning similar to that of *pollution* and implies making something unfit for a particular use through the introduction of undesirable materials—for example, the contamination of water by hazardous waste. The term **toxin** refers to substances (pollutants) that are poisonous to living things. **Toxicology** is the science that studies toxins or suspected toxins, and toxicologists are scientists in this field. A **carcinogen** is a toxin that increases the risk of cancer. Carcinogens are among the most feared and regulated toxins in our society.

An important concept in considering pollution problems is **synergism**, the interaction of different substances, resulting in a total effect that is greater than the sum of the effects of the separate substances. For example, both sulfur dioxide (SO_2) and coal dust particulates are air pollutants. Either one taken separately may cause adverse health effects, but when they combine, as when SO_2 adheres to the coal dust, the dust with SO_2 is inhaled deeper than SO_2 alone and causes greater damage to lungs. Another aspect of synergistic effects is that the body may be more sensitive to a toxin if it is simultaneously subjected to other toxins.

Pollutants are commonly introduced into the environment by way of **point sources**, such as smokestacks (see A Closer Look 10.1), pipes discharging into waterways, a small stream entering the ocean (Figure 10.2), or accidental spills. **Area sources**, also called *nonpoint sources*, are more diffused over the land and include urban runoff and **mobile sources**, such as automobile exhaust. Area sources are difficult to isolate and correct because the problem is often widely dispersed over a region, as in agricultural runoff that contains pesticides.

FIGURE 10.2 This southern California urban stream flows into the Pacific Ocean at a coastal park. The stream water often carries high counts of fecal coliform bacteria. As a result, the stream is a point source of pollution for the beach, which is sometimes closed to swimming following runoff events.

Measuring the Amount of Pollution

How the amount or concentration of a particular pollutant or toxin present in the environment is reported varies widely. The amount of treated wastewater entering Santa Monica Bay in the Los Angeles area is a big number, reported in millions of gallons per day. Emission of nitrogen and sulfur oxides into the air is also a big number, reported in millions of tons per year. Small amounts of pollutants or toxins in the environment, such as pesticides, are reported in units as parts per million (ppm) or parts per billion (ppb). It is important to keep in mind that the concentration in ppm or ppb may be by volume, mass, or weight. In some toxicology studies, the units used are milligrams of toxin per kilogram of body mass (1 mg/kg is equal to 1 ppm). Concentration may also be recorded as a percentage. For example, 100 ppm (100 mg/kg) is equal to 0.01%. (How many ppm are equal to 1%?)

When dealing with water pollution, units of concentration for a pollutant may be milligrams per liter (mg/L) or micrograms per liter (μg/L). A milligram is one-thousandth of a gram, and a microgram is one-millionth of a gram. For water pollutants that do not cause significant change in the density of water (1 g/cm^3), a pollutant concentration of 1 mg/L is approximately equivalent to 1 ppm. Air pollutants are commonly measured in units such as micrograms of pollutant per cubic meter of air (μg/m^3).

Units such as ppm, ppb, or μg/m^3 reflect very small concentrations. For example, if you were to use 3 g (one-tenth of an ounce) of salt to season popcorn in order to have salt at a concentration of 1 ppm by weight of the popcorn, you would have to pop approximately 3 metric tons of kernels!

10.2 Categories of Pollutants

A partial classification of pollutants by arbitrary categories is presented below. We discuss examples of other pollutants in other parts of the book.

Infectious Agents

Infectious diseases—spread by the interactions between individuals and by the food, water, air, soil, and animals we come in contact with—constitute some of the oldest health problems that people face. Today, infectious diseases have the potential to pose rapid threats, both local and global, by spreading in hours via airplane travelers. Terrorist activity may also spread diseases. Inhalation anthrax caused by a bacterium sent in powdered form in envelopes through the mail killed several people in 2001. New diseases are emerging, and previous ones may emerge again. Although we have cured many diseases, we have no known reliable vaccines for others, such as HIV, hantavirus, and dengue fever.

The H1N1 flu pandemic (widespread outbreak of a disease) that became apparent in 2009 started in Mexico and has spread around the world. The complete origin of H1N1 remains unknown, but it has genetic markers of two swine flues, a human flu, and an avian (bird) flu. As we live closer together, nearer large numbers of animals such as chickens and pigs in large industrial farms and tightly confined animals in smaller farms, the probability of a disease crossing from animals to humans increases. People working closely with pigs have an increased risk of contracting swine flu.

A CLOSER LOOK 10.1

Sudbury Smelters: A Point Source

A famous example of a point source of pollution is provided by the smelters that refine nickel and copper ores at Sudbury, Ontario. Sudbury contains one of the world's major nickel and copper ore deposits. A number of mines, smelters, and refineries lie within a small area. The smelter stacks used to release large amounts of particulates containing toxic metals—including arsenic, chromium, copper, nickel, and lead—into the atmosphere, much of which was then deposited locally in the soil. In addition, because the areas contained a high percentage of sulfur, the emissions included large amounts of sulfur dioxide (SO_2). During its peak output in the 1960s, this complex was the largest single source of SO_2 emissions in North America, emitting 2 million metric tons per year.

As a result of the pollution, nickel contaminated soils up to 50 km (about 31 mi) from the stacks. The forests that once surrounded Sudbury were devastated by decades of acid rain (produced from SO_2 emissions) and the deposition of particulates containing heavy metals. An area of approximately 250 km^2 (96 mi^2) was nearly devoid of vegetation, and damage to forests in the region has been visible over an area

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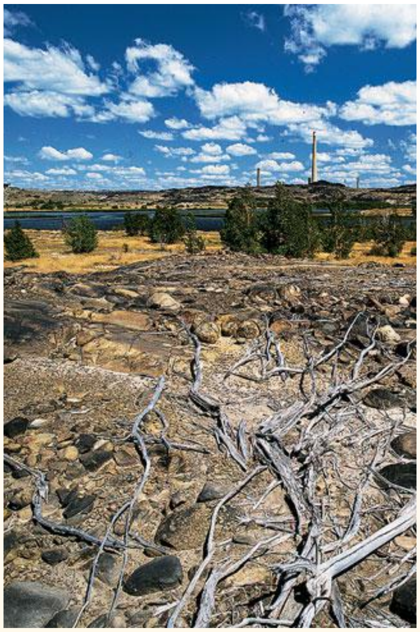


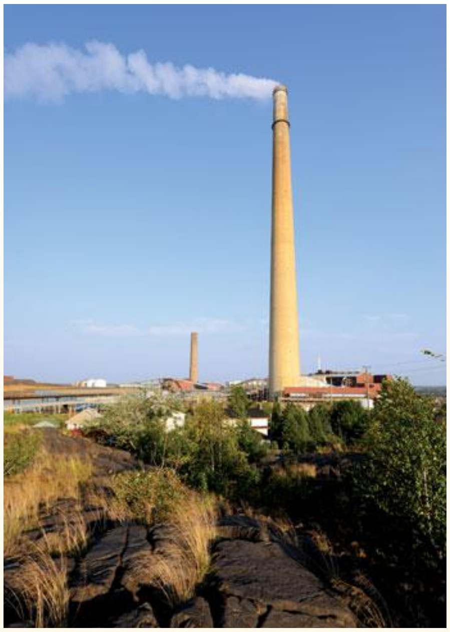

(b)

FIGURE 10.3 **(a) Lake St. Charles, Sudbury, Ontario, prior to restoration**. Note high stacks (smelters) in the background and lack of vegetation in the foreground, resulting from air pollution (acid and heavy-metal deposition). **(b) Recent photo showing regrowth and restoration**.

of approximately 3,500 km^2 (1,350 mi^2); see Figure 10.3a. To control emissions from Sudbury, the Ontario government set standards to reduce emissions to less than 365,000 tons per year by 1994. The goal was achieved by reducing production from the smelters and by treating the emissions to reduce pollution.[9]

Reducing emissions from Sudbury has allowed surrounding areas to recover from the pollution (Figure 10.3b). Species of trees once eradicated from some areas have begun to grow again. Recent restoration efforts have included planting over 7 million trees and 75 species of herbs, moss, and lichens—all of which have contributed to the increase of biodiversity. Lakes damaged by acid precipitation in the area are rebounding and now support populations of plankton and fish.[9]

The case of the Sudbury smelters provides a positive example of emphasizing the key theme of thinking globally but acting locally to reduce air pollution. It also illustrates the theme of science and values: Scientists and engineers can design pollution-abatement equipment, but spending the money to purchase the equipment reflects what value we place on clean air.

Environmentally Transmitted Infectious Disease

Diseases that can be controlled by manipulating the environment, such as by improving sanitation or treating water, are classified as environmental health concerns. Although there is great concern about the toxins and carcinogens produced in industrial society today, the greatest mortality in developing countries is caused by environmentally transmitted infectious disease. In the United States, thousands of cases of waterborne illness and food poisoning occur each year. These diseases can be spread by people; by mosquitoes and fleas; or by contact with contaminated food, water, or soil. They can also be transmitted through ventilation systems in buildings. The following are some examples of environmentally transmitted infectious diseases:

- Legionellosis, or Legionnaires' disease, which often occurs where air-conditioning systems have been contaminated by disease-causing organisms.
- Giardiasis, a protozoan infection of the small intestine, spread via food, water, or person-to-person contact.
- Salmonella, a food-poisoning bacterial infection that is spread via water or food.
- Malaria, a protozoan infection transmitted by mosquitoes.
- Lyme borreliosis (Lyme disease), transmitted by ticks.
- Cryptosporidiosis, a protozoan infection transmitted via water or person-to-person contact (see Chapter 19).[10]
- Anthrax, spread by terrorist activity.

We sometimes hear about epidemics in developing nations. An example is the highly contagious Ebola virus in Africa, which causes external and internal bleeding and kills 80% of those infected. We may tend to think of such epidemics as problems only for developing nations, but this may give us a false sense of security. True, monkeys and bats spread Ebola, but the origin of the virus in the tropical forest remains unknown. Developed countries, where outbreaks may occur in the future, must learn from the developing countries' experiences. To accomplish this and avoid potential global tragedies, more funds must be provided for the study of infectious diseases in developing countries.

Toxic Heavy Metals

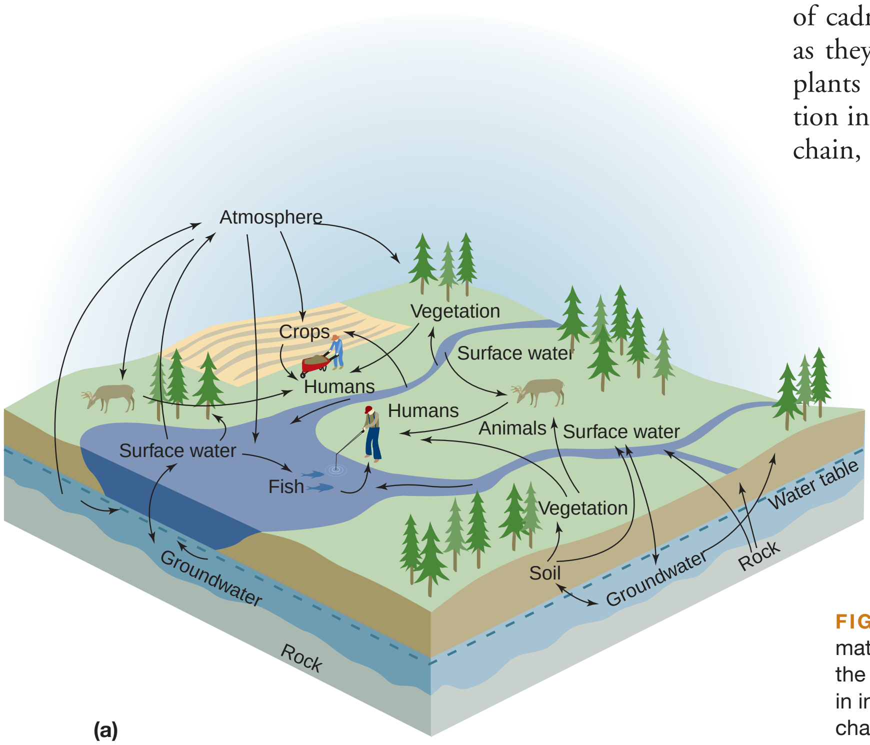
The major **heavy metals** (metals with relatively high atomic weight; see Chapter 6) that pose health hazards to people and ecosystems include mercury, lead, cadmium, nickel, gold, platinum, silver, bismuth, arsenic, selenium, vanadium, chromium, and thallium. Each of these elements may be found in soil or water not contaminated by people, each has uses in our modern industrial society, and each is also a by-product of the mining, refining, and use of other elements. Heavy metals often have direct physiological toxic effects. Some are stored or incorporated in living tissue, sometimes permanently. Heavy metals tend to be stored (accumulating with time) in fatty body tissue. A little arsenic each day may eventually result in a fatal dose—the subject of more than one murder mystery.

The quantity of heavy metals in our bodies is referred to as the *body burden*. The body burden of toxic heavy elements for an average human body (70 kg) is about 8 mg of antimony, 13 mg of mercury, 18 mg of arsenic, 30 mg of cadmium, and 150 mg of lead. The average body burden of lead (for which we apparently have no biological need) is about twice that of the others combined, reflecting our heavy use of this potentially toxic metal.

Mercury, thallium, and lead are very toxic to people. They have long been mined and used, and their toxic properties are well known. Mercury, for example, is the "Mad Hatter" element. At one time, mercury was used to stiffen felt hats, and because mercury damages the brain, hatters in Victorian England were known to act peculiarly. Thus, the Mad Hatter in Lewis Carroll's *Alice in Wonderland* had real antecedents in history.

Toxic Pathways

Chemical elements released from rocks or human processes can become concentrated in people (see Chapter 6) through many pathways (Figure 10.4). These pathways may involve what is known as **biomagnification**—the accumulation or increasing concentration of a substance in living tissue as it moves through a food web (also known as *bioaccumulation*). For example, cadmium, which increases the risk of heart disease, may enter the environment via ash from burning coal. The cadmium in coal is in very low concentrations (less than 0.05 ppm). However, after coal is burned in a power plant, the ash is collected in a solid form and disposed of in a landfill. The landfill is covered with soil and revegetated. The low concentration of cadmium in the ash and soil is taken into the plants as they grow, but the concentration of cadmium in the plants is three to five times greater than the concentration in the ash. As the cadmium moves through the food chain, it becomes more and more concentrated. By the



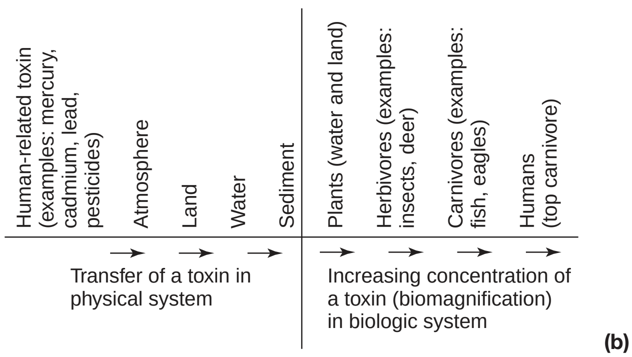


FIGURE 10.4 **(a)** Potential complex pathways for toxic materials through the living and nonliving environment. Note the many arrows into humans and other animals, sometimes in increasing concentrations as they move through the food chain **(b)**.

time it is incorporated into the tissue of people and other carnivores, the concentration is approximately 50 to 60 times the original concentration in the coal.

Mercury in aquatic ecosystems offers another example of biomagnification. Mercury is a potentially serious pollutant of aquatic ecosystems such as ponds, lakes, rivers, and the ocean. Natural sources of mercury in the environment include volcanic eruptions and erosion of natural mercury deposits, but we are most concerned with human input of mercury into the environment by, for example, burning coal in power plants, incinerating waste, and processing metals such as gold. Rates of input of mercury into the environment through human processes are poorly understood. However, it is believed that human activities have doubled or tripled the amount of mercury in the atmosphere, and it is increasing at about 1.5% per year.[11]

A major source of mercury in many aquatic ecosystems is deposition from the atmosphere through precipitation. Most of the deposition is of inorganic mercury (Hg^{++}, ionic mercury). Once this mercury is in surface water, it enters into complex biogeochemical cycles and a process known as *methylation* may occur. Methylation changes inorganic mercury to methyl mercury $[CH_3Hg]^+$ through bacterial activity. Methyl mercury is much more toxic than inorganic mercury, and it is eliminated more slowly from animals' systems. As the methyl mercury works its way through food chains, biomagnification occurs, resulting in higher concentrations of methyl mercury farther up the food chain. In short, big fish that eat little fish contain higher concentrations of mercury than do smaller fish and the aquatic insects that the fish feed on.

Selected aspects of the mercury cycle in aquatic ecosystems are shown in Figure 10.5. The figure emphasizes the input side of the cycle, from deposition of inorganic mercury through formation of methyl mercury, biomagnification, and sedimentation of mercury at the bottom of a pond. On the output side of the cycle, the mercury that enters fish may be taken up by animals that eat the fish; and sediment may release mercury by a variety of processes, including resuspension in the water, where eventually the mercury enters the food chain or is released into the atmosphere through volatilization (conversion of liquid mercury to a vapor form).

Biomagnification also occurs in the ocean. Because large fish, such as tuna and swordfish, have elevated mercury levels, we are advised to limit our consumption of these fish, and pregnant women are advised not to eat them at all.

The threat of mercury poisoning is widespread. Millions of young children in Europe, the United States, and other industrial countries have mercury levels that exceed health standards.[12] Even children in remote areas of the far north are exposed to mercury through their food chain.

During the 20th century, several significant incidents of methyl mercury poisoning were recorded. One, in Minamata Bay, Japan, involved the industrial release of methyl mercury (see A Closer Look 10.2). Another, in Iran, involved a methyl mercury fungicide used to treat wheat seeds. In each of these cases, hundreds of people were killed and thousands were permanently damaged.[11]

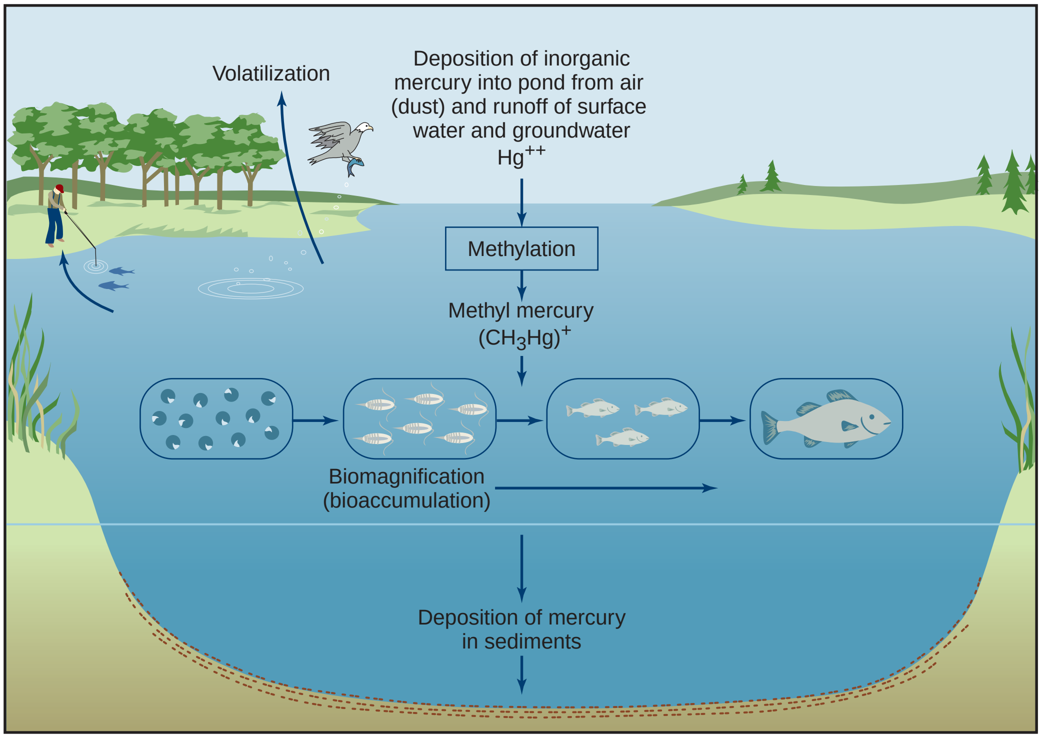


FIGURE 10.5 Idealized diagram showing selected pathways for movement of mercury into and through an aquatic ecosystem. (*Source*: Modified from G.L. Waldbott, *Health Effects of Environmental Pollutants*, 2nd ed. [Saint Louis, MO: C.V. Mosby, 1978].)

The cases in Minamata Bay and Iran involved local-exposure mercury. What is being reported in the Arctic, however, emphasizes mercury at the global level, in a region far from emission sources of the toxic metal. The Inuit people in Quanea, Greenland, live above the Arctic Circle, far from any roads and 45 minutes by helicopter from the nearest outpost of modern society. Nevertheless, they are some of the most chemically contaminated people on Earth, with as much as 12 times more mercury in their blood than is recommended in U.S. guidelines. The mercury gets to the Inuit from the industrialized world by way of what they eat. The whale, seal, and fish they eat contain mercury that is further concentrated in the tissue and blood of the people. The process of increasing concentrations of mercury farther up the food chain is an example of biomagnification.[12]

What needs to be done to stop mercury toxicity at the local to global level is straightforward. The answer is to reduce emissions of mercury by capturing it before emission or by using alternatives to mercury in industry. Success will require international cooperation and technology transfer to countries such as China and India, which, with their tremendous increases in manufacturing, are the world's largest users of mercury today.[12]

Organic Compounds

Organic compounds are carbon compounds produced naturally by living organisms or synthetically by industrial processes. It is difficult to generalize about the environmental and health effects of artificially produced organic compounds because there are so many of them, they have so many uses, and they can produce so many different kinds of effects.

Synthetic organic compounds are used in industrial processes, pest control, pharmaceuticals, and food additives. We have produced over 20 million synthetic chemicals, and new ones are appearing at a rate of about 1 million per year! Most are not produced commercially, but up to 100,000 chemicals are now being used, or have been used in the past. Once used and dispersed in the environment, they may become a hazard for decades or even hundreds of years.

A CLOSER LOOK 10.2

Mercury and Minamata, Japan

In the Japanese coastal town of Minamata, on the island of Kyushu, a strange illness began to occur in the middle of the 20th century. It was first recognized in birds that lost their coordination and fell to the ground or flew into buildings, and in cats that went mad, running in circles and foaming at the mouth.[13] The affliction, known by local fishermen as the "disease of the dancing cats," subsequently affected people, particularly families of fishermen. The first symptoms were subtle: fatigue, irritability, headaches, numbness in arms and legs, and difficulty in swallowing. More severe symptoms involved the sensory organs; vision was blurred and the visual field was restricted. Afflicted people became hard of hearing and lost muscular coordination. Some complained of a metallic taste in their mouths; their gums became inflamed, and they suffered from diarrhea. Lawsuits were brought, and approximately 20,000 people claimed to be affected. In the end, according to the Japanese government, almost 3,000 people were affected and almost 1,800 died. Those affected lived in a small area, and much of the protein in their diet came from fish from Minamata Bay.

A vinyl chloride factory on the bay used mercury in an inorganic form in its production processes. The mercury was released in waste that was discharged into the bay. Mercury forms few organic compounds, and it was believed that the mercury, though poisonous, would not get into food chains. But the inorganic mercury released by the factory was converted by bacterial activity in the bay into methyl mercury, an organic compound that turned out to be much more harmful. Unlike inorganic mercury, methyl mercury readily passes through cell membranes. It is transported by the red blood cells throughout the body, and it enters and damages brain cells.[14] Fish absorb methyl mercury from water 100 times faster than they absorb inorganic mercury. (This was not known before the epidemic in Japan.) And once absorbed, methyl mercury is retained two to five times longer than is inorganic mercury.

In 1982, lawsuits were filed by plaintiffs affected by the mercury. Twenty-two years later, in 2004—almost 50 years after the initial poisonings—the government of Japan agreed to a settlement of $700,000.

Harmful effects of methyl mercury depend on a variety of factors, including the amount and route of intake, the duration of exposure, and the species affected. The effects of the mercury are delayed from three weeks to two months from the time of ingestion. If mercury intake ceases, some symptoms may gradually disappear, but others are difficult to reverse.[14]

The mercury episode at Minamata illustrates four major factors that must be considered in evaluating and treating toxic environmental pollutants.

Individuals vary in their response to exposure to the same dose, or amount, of a pollutant. Not everyone in Minamata responded in the same way; there were variations even among those most heavily exposed. Because we cannot predict exactly how any single individual will respond, we need to find a way to state an expected response of a particular percentage of individuals in a population.

Pollutants may have a threshold—that is, a level below which the effects are not observable and above which the effects become apparent. Symptoms appeared in individuals with concentrations of 500 ppb of mercury in their bodies; no measurable symptoms appeared in individuals with significantly lower concentrations.

Some effects are reversible. Some people recovered when the mercury-filled seafood was eliminated from their diet.

The chemical form of a pollutant, its activity, and its potential to cause health problems may be changed markedly by ecological and biological processes. In the case of mercury, its chemical form and concentration changed as the mercury moved through the food webs.

Sources: Mary Kugler, R.N. Thousands poisoned, disabled, and killed. About.com. Created October 23, 2004. About.com Health's Disease and Condition content is reviewed by our Medical Review Board. Also, BBC News, "Japan remembers mercury victims." http://news.bbc.co.uk/go/pr/fr/-/2/hi/asia-pacific/4959562.stm Published 2006/05/01 15:03:11 GMT ©BBC MM VIII.

Persistent Organic Pollutants

Some synthetic compounds are called **persistent organic pollutants**, or **POPs**. Many were first produced decades ago, when their harm to the environment was not known, and they are now banned or restricted (see Table 10.1 and A Closer Look 10.3). POPs have several properties that define them:[15]

- They have a carbon-based molecular structure, often containing highly reactive chlorine.
- Most are manufactured by people—that is, they are synthetic chemicals.
- They are persistent in the environment—they do not easily break down in the environment.
- They are polluting and toxic.
- They are soluble in fat and likely to accumulate in living tissue.
- They occur in forms that allow them to be transported by wind, water, and sediments for long distances.

For example, consider polychlorinated biphenyls (PCBs), which are heat-stable oils originally used as an insulator in electric transformers.[15] A factory in Alabama manufactured PCBs in the 1940s, shipping them to a General Electric factory in Massachusetts. They were put in insulators and mounted on poles in thousands of locations. The transformers deteriorated over time. Some were damaged by lightning, and others were damaged or destroyed during demolition. The PCBs leaked into the soil or were carried by surface runoff into streams and rivers. Others combined with dust, were transported by wind around the world, and were deposited in ponds, lakes, or rivers, where they entered the food chain. First the PCBs entered algae. Insects ate the algae and were in turn eaten by shrimp and fish. In each stage up the food web, the concentration of PCBs increased. Fish are caught and eaten, passing the PCBs on to people, where they are concentrated in fatty tissue and mother's milk.

Table 10.1 SELECTED COMMON PERSISTENT ORGANIC POLLUTANTS (POPs)

CHEMICAL	EXAMPLE OF USE
Aldrin[a]	Insecticide
Atrazine[b]	Herbicide
DDT[a]	Insecticide
Dieldrin[a]	Insecticide
Endrin[c]	Insecticide
PCBs[a]	Liquid insulators in electric transformers
Dioxins	By-product of herbicide production

[a] Banned in the United States and many other countries.

[b] Degrades in the environment. It is persistent when reapplied often.

[c] Restricted or banned in many countries.

Source: Data in part from Anne Platt McGinn, "Phasing Out Persistent Organic Pollutants," in Lester R. Brown et al., *State of the World 2000* (New York: Norton, 2000).

A CLOSER LOOK 10.3

Dioxin: How Dangerous Is It?

Dioxin, a persistent organic pollutant, or POP, may be one of the most toxic man-made chemicals in the environment. The history of the scientific study of dioxin and its regulation illustrates the interplay of science and values.

Dioxin is a colorless crystal made up of oxygen, hydrogen, carbon, and chlorine. It is classified as an organic compound because it contains carbon. About 75 types of dioxin and dioxinlike compounds are known; they are distinguished from one another by the arrangement and number of chlorine atoms in the molecule.

Dioxin is not normally manufactured intentionally but is a by-product of chemical reactions, including the combustion of compounds containing chlorine in the production of herbicides.[16] In the United States, there are a variety of sources for dioxinlike compounds (specifically, chlorinated dibenzo-*p*-dioxin, or CDD, and chlorinated dibenzofurans, or CDF). These compounds are emitted into the air through such processes as incineration of municipal waste (the major source), incineration of medical waste, burning of gasoline and diesel fuels in vehicles, burning of wood as a fuel, and refining of metals such as copper.

The good news is that releases of CDDs and CDFs decreased about 75% from 1987 to 1995. However, we are only beginning to understand the many sources of dioxin emissions into the air, water, and land and the linkages and rates of transfer from dominant airborne transport to deposition in water, soil, and the biosphere. In too many cases, the amounts of dioxins emitted are based more on expert opinion than on high-quality data, or even on limited data.[17]

Studies of animals exposed to dioxin suggest that some fish, birds, and other animals are sensitive to even small amounts. As a result, it can cause widespread damage to wildlife, including birth defects and death. However, the concentration at which it poses a hazard to human health is still controversial. Studies suggest that workers exposed to high concentrations of dioxin for longer than a year have an increased risk of dying of cancer.[18]

The Environmental Protection Agency (EPA) has classified dioxin as a known human carcinogen, but the decision is controversial. For most of the exposed people, such as those eating a diet high in animal fat, the EPA puts the risk of developing cancer between 1 in 1,000 and 1 in 100. This estimate represents the highest possible risk for individuals who have had the greatest exposure. For most people, the risk will likely be much lower.[19] The EPA has set an acceptable intake of dioxin at 0.006 pg per kilogram of body weight per day (1 pg = 10^{-12} g; see Appendix for prefixes and multiplication factors). This level is deemed too low by some scientists, who argue that the acceptable intake ought to be 100 to 1,000 times higher, or approximately 1 to 10 pg per day.[18] The EPA believes that setting the level this much higher could result in health effects.

The dioxin problem became well known in 1983 when Times Beach, Missouri, a river town just west of Saint Louis with a population of 2,400, was evacuated and purchased for $36 million by the government. The evacuation and purchase occurred after the discovery that oil sprayed on the town's roads to control dust contained dioxin, and that the entire area had been contaminated. Times Beach was labeled a dioxin ghost town (Figure 10.6). The buildings were bulldozed, and all that was left was a grassy and woody area enclosed by a barbed-wire-topped chain-link fence. The evacuation has since been viewed by some scientists (including the person who ordered the evacuation) as a government overreaction to a perceived dioxin hazard. Following clean up, trees were planted and today Times Beach is part of Route 66 State Park and a bird refuge.

The controversy about the toxicity of dioxin is not over.[20-23] Some environmental scientists argue that the regulation of dioxin must be tougher, whereas the industries producing the chemical argue that the dangers of exposure are exaggerated.

FIGURE 10.6 Soil samples from Times Beach, Missouri, thought to be contaminated by dioxin.

Hormonally Active Agents (HAAs)

HAAs are also POPs. An increasing body of scientific evidence indicates that certain chemicals in the environment, known as **hormonally active agents (HAAs)**, may cause developmental and reproductive abnormalities in animals, including humans (see A Closer Look 10.4). HAAs include a wide variety of chemicals, such as some herbicides, pesticides, phthalates (compounds found in many chlorine-based plastics), and PCBs. Evidence in support of the hypothesis that HAAs are interfering with the growth and development of organisms comes from studies of wildlife in the field and laboratory studies of human diseases, such as breast, prostate, and ovarian cancer, as well as abnormal testicular development and thyroid-related abnormalities.[24]

Studies of wildlife include evidence that alligator populations in Florida that were exposed to pesticides, such as DDT, have genital abnormalities and low egg production. Pesticides have also been linked to reproductive problems in several species of birds, including gulls, cormorants, brown pelicans, falcons, and eagles. Studies are ongoing on Florida panthers; they apparently have abnormal ratios of sex hormones, and this may be affecting their reproductive capability. In sum, the studies of major disorders in wildlife have centered on abnormalities, including thinning of birds' eggshells, decline in populations of various animals and birds, reduced viability of offspring, and changes in sexual behavior.[25]

With respect to human diseases, much research has been done on linkages between HAAs and breast cancer by exploring relationships between environmental estrogens and cancer. Other studies are ongoing to understand relationships between PCBs and neurological behavior that results in poor performance on standard intelligence tests. Finally, there is concern that exposure of people to phthalates that are found in plastics containing chlorine is also causing problems. Consumption of phthalates in the United States is considerable, with the highest exposure in women of childbearing age. The products being tested as the source of contamination include perfumes and other cosmetics, such as nail polish and hairspray.[25]

In sum, there is good scientific evidence that some chemical agents, in sufficient concentrations, will affect human reproduction through endocrine and hormonal disruption. The human endocrine system is of primary importance because it is one of the two main systems (the other is the nervous system) that regulate and control growth, development, and reproduction. The human endocrine system consists of a group of hormone-secreting glands, including the thyroid, pancreas, pituitary, ovaries (in women), and testes (in men). The bloodstream transports the hormones to virtually all parts of the body, where they act as chemical messengers to control growth and development of the body.[24]

The National Academy of Sciences completed a review of the available scientific evidence concerning HAAs and recommends continued monitoring of wildlife and human populations for abnormal development and reproduction. Furthermore, where wildlife species are known to be experiencing declines in population associated with abnormalities, experiments should be designed to study the phenomena with respect to chemical contamination. For people, the recommendation is for additional studies to document the presence or absence of associations between HAAs and human cancers. When associations are discovered, the causality is investigated in the relationship between exposure and disease, and indicators of susceptibility to disease of certain groups of people by age and sex.[25]

A CLOSER LOOK 10.4

Demasculinization and Feminization of Frogs

The story of wild leopard frogs (Figure 10.7) from a variety of areas in the midwestern United States sounds something like a science-fiction horror story. In affected areas, between 10 and 92% of male frogs exhibit gonadal abnormalities, including retarded development and hermaphroditism, meaning they have both male and female reproductive organs. Other frogs have vocal sacs with retarded growth. Since their vocal sacs are used to attract female frogs, these frogs are less likely to mate.

What is apparently causing some of the changes in male frogs is exposure to atrazine, the most widely used herbicide in the United States today. The chemical is a weed killer, used primarily in agricultural areas. The region of the United States with the highest frequency (92%) of sex reversal of male frogs is in Wyoming, along the North Platte River. Although the region is not near any large agricultural activity, and the use of atrazine there is not particularly significant, hermaphrodite frogs are common there because the North Platte River flows from areas in Colorado where atrazine is commonly used.

The amount of atrazine released into the environment of the United States is estimated at approximately 7.3 million kg (16 million lbs) per year. The chemical degrades in the environment, but the degradation process is longer than the application cycle. Because of its continual application every year, the waters of the Mississippi River basin, which drains about 40% of the lower

FIGURE 10.7 Wild leopard frogs in America have been affected by man-made chemicals (the herbicide atrazine) in the environment.

United States, discharge approximately 0.5 million kg (1.2 million lbs) of atrazine per year to the Gulf of Mexico. Atrazine easily attaches to dust particles and has been found in rain, fog, and snow. As a result, it has contaminated groundwater and surface water in regions where it isn't used. The EPA states that up to 3 parts per billion (ppb) of atrazine in drinking water is acceptable, but at this concentration it definitely affects frogs that swim in the water. Other studies around the world have confirmed this. For example, in Switzerland, where atrazine is banned, it commonly occurs with a concentration of about 1 ppb, and that is sufficient to change some male frogs into females. In fact, atrazine can apparently cause sex change in frogs at concentrations as low as one-thirteenth of the level set by the EPA for drinking water.

Of particular interest and importance is the process that causes the changes in leopard frogs. We begin the discussion with the endocrine system, composed of glands that secrete hormones such as testosterone and estrogen directly into the bloodstream, which carries them to parts of the body where they regulate and control growth and sexual development. Testosterone in male frogs is partly responsible for development of male characteristics. The atrazine is believed to switch on a gene that turns testosterone into estrogen, a female sex hormone. It's the hormones, not the genes, that actually regulate the development and structure of reproductive organs.

Frogs are particularly vulnerable during their early development, before and as they metamorphose from tadpoles into adult frogs. This change occurs in the spring, when atrazine levels are often at a maximum in surface water. Apparently, a single exposure to the chemical may affect the frog's development. Thus, the herbicide is known as a hormone disrupter.

In a more general sense, substances that interact with the hormone systems of an organism, whether or not they are linked to disease or abnormalities, are known as hormonally active agents (HAAs). These HAAs are able to trick the organism's body (in this case, the frog's) into believing that the chemicals have a role to play in its functional development. An analogy you might be more familiar with is a computer virus that fools the computer into accepting it as part of the system by which the computer works. Similar to computer viruses, the HAAs interact with an organism and the mechanisms for regulating growth and development, thus disrupting normal growth functions.

What happens when HAAs—in particular, hormone disrupters (such as pesticides and herbicides)—are introduced into the system is shown in Figure 10.8. Natural hormones produced by the body send chemical messages to cells, where receptors for the hormone molecules are found on the outside and inside of cells. These natural hormones then transmit instructions to the cells' DNA, eventually directing development and growth. We now know that chemicals, such as some pesticides and herbicides, can also bind to the receptor molecules and either mimic or obstruct the role of the natural hormones. Thus, hormonal disrupters may also be known as HAAs.[24–28]

The story of wild leopard frogs in America dramatizes the importance of carefully evaluating the role of man-made chemicals in the environment. Populations of frogs and other amphibians are declining globally, and much research has been directed toward understanding why. Studies to evaluate past or impending extinctions of organisms often center on global processes such as climate change, but the story of leopard frogs leads us down another path, one associated with our use of the natural environment. It also raises a number of more disturbing questions: Are we participating in an unplanned experiment on how man-made chemicals, such as herbicides and pesticides, might transform the bodies of living beings, perhaps even people? Are these changes in organisms limited to only certain plants and animals, or are they a forerunner of what we might expect in the future on a much broader scale? Perhaps we will look back on this moment of understanding as a new beginning in meaningful studies that will answer some of these important questions.

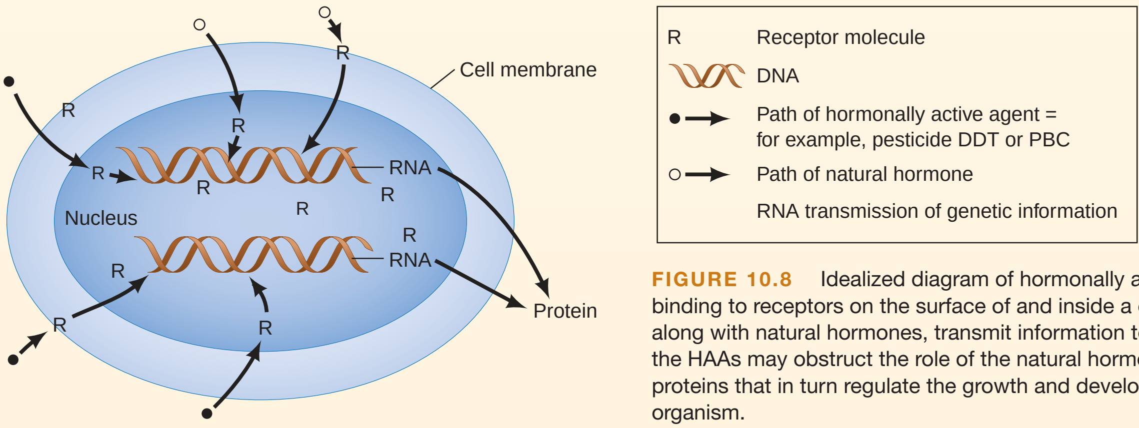


FIGURE 10.8 Idealized diagram of hormonally active agents (HAAs) binding to receptors on the surface of and inside a cell. When HAAs, along with natural hormones, transmit information to the cells' DNA, the HAAs may obstruct the role of the natural hormones that produce proteins that in turn regulate the growth and development of an organism.

Nuclear Radiation

Nuclear radiation is introduced here as a category of pollution. We discuss it in detail in Chapter 17, in conjunction with nuclear energy. We are concerned about nuclear radiation because excessive exposure is linked to serious health problems, including cancer. (See Chapter 21 for a discussion of radon gas as an indoor air pollutant.)

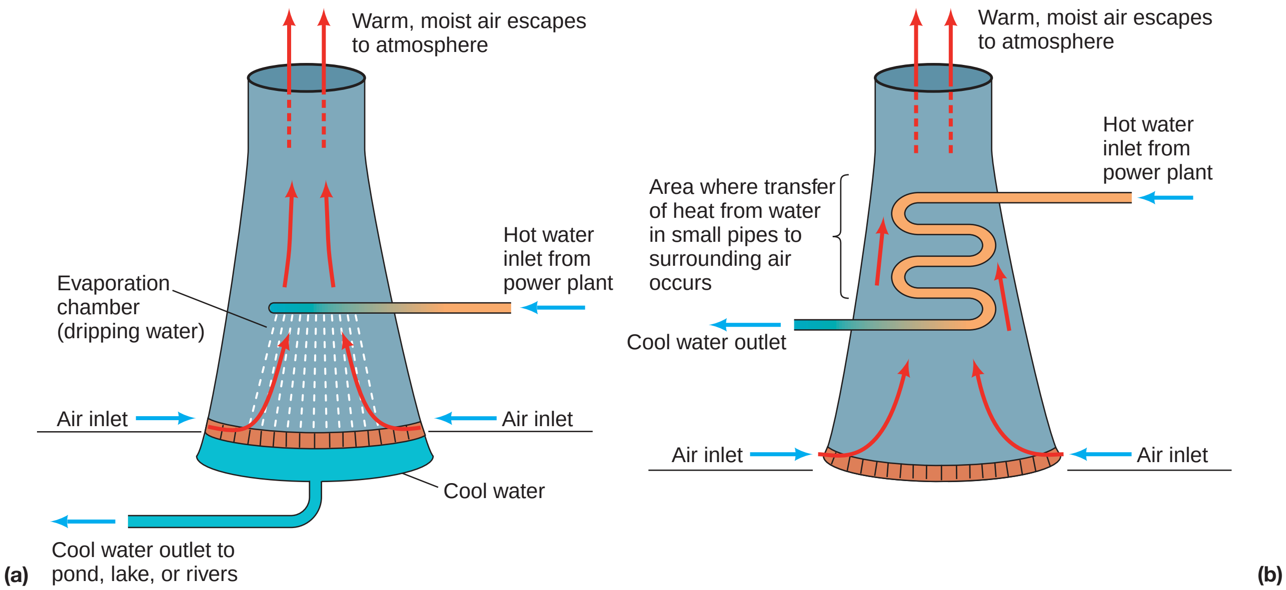
Thermal Pollution

Thermal pollution, also called *heat pollution*, occurs when heat released into water or air produces undesirable effects. Heat pollution can occur as a sudden, acute event or as a long-term, chronic release. Sudden heat releases may result from natural events, such as brush or forest fires and volcanic eruptions, or from human activities, such as agricultural burning.

The major sources of chronic heat pollution are electric power plants that produce electricity in steam generators and release large amounts of heated water into rivers. This changes the average water temperature and the concentration of dissolved oxygen (warm water holds less oxygen than cooler water), thereby changing a river's species composition (see the discussion of eutrophication in Chapter 19). Every species has a temperature range within which it can survive and an optimal temperature for living. For some species of fish, the range is small, and even a small change in water temperature is a problem. Lake fish move away when the water temperature rises more than about 1.5°C above normal; river fish can withstand a rise of about 3°C.

Heating river water can change its natural conditions and disturb the ecosystem in several ways. Fish spawning cycles may be disrupted, and the fish may have a heightened susceptibility to disease. Warmer water also causes physical stress in some fish, making them easier for predators to catch, and warmer water may change the type and abundance of food available for fish at various times of the year.

There are several solutions to chronic thermal discharge into bodies of water. The heat can be released into the air by cooling towers (Figure 10.9), or the heated water can be temporarily stored in artificial lagoons until it



(c)

FIGURE 10.9 Two types of cooling towers. (a) Wet cooling tower. Air circulates through the tower; hot water drips down and evaporates, cooling the water. **(b) Dry cooling tower.** Heat from the water is transferred directly to the air, which rises and escapes the tower. **(c) Cooling towers emitting steam at Didcot power plant**, Oxfordshire, England. Red and white lines are vehicle lights resulting from long exposure time (photograph taken at dusk).

cools down to normal temperatures. Some attempts have been made to use the heated water to grow organisms of commercial value that require warmer water. Waste heat from a power plant can also be captured and used for a variety of purposes, such as warming buildings (see Chapter 14 for a discussion of cogeneration).

Particulates

Particulates here refer to small particles of dust (including soot and asbestos fibers) released into the atmosphere by many natural processes and human activities. Modern farming and the burning of oil and coal add considerable amounts of particulates to the atmosphere, as do dust storms, fires (Figure 10.10), and volcanic eruptions. The 1991 eruptions of Mount Pinatubo in the Philippines were the largest volcanic eruptions of the 20th century, explosively hurling huge amounts of volcanic ash, sulfur dioxide, and other volcanic material and gases as high as 30 km (18.6 mi) into the atmosphere. Eruptions can have a significant impact on the global environment and are linked to global climate change and stratospheric ozone depletion (see Chapters 21 and 22). In addition, many chemical toxins, such as heavy metals, enter the biosphere as particulates. Sometimes, nontoxic particulates link with toxic substances, creating a synergetic threat. (See discussion of particulates in Chapter 21.)

Asbestos

Asbestos is a term for several minerals that take the form of small, elongated particles, or fibers. Industrial use of asbestos has contributed to fire prevention and has provided protection from the overheating of materials. Asbestos is also used as insulation for a variety of other purposes. Unfortunately, however, excessive contact with asbestos has led to asbestosis (a lung disease caused by inhaling asbestos) and to cancer in some industrial workers. Experiments with animals have demonstrated that asbestos can cause tumors if the fibers are embedded in lung tissue.[29] The hazard related to certain types of asbestos under certain conditions is considered so serious that extraordinary steps have been taken to reduce the use of asbestos or ban it outright. The expensive process of asbestos removal from old buildings (particularly schools) in the United States is one of those steps.

FIGURE 10.10 Fires in Indonesia in 1997 caused serious air pollution. The person here is wearing a surgical mask in an attempt to breathe cleaner air.

There are several types of asbestos, and they are not equally hazardous. Most commonly used in the United States is white asbestos, which comes from the mineral chrysolite. It has been used to insulate pipes, floor and ceiling tiles, and brake linings of automobiles and other vehicles. Approximately 95% of the asbestos that is now in place in the United States is of the chrysolite type. Most of this asbestos was mined in Canada, and environmental health studies of Canadian miners show that exposure to chrysolite asbestos is not particularly harmful. However, studies involving another type of asbestos, known as crocidolite asbestos (blue asbestos), suggest that exposure to this mineral can be very hazardous and evidently does cause lung disease. Several other types of asbestos have also been shown to be harmful.[29]

A great deal of fear has been associated with nonoccupational exposure to chrysolite asbestos in the United States. Tremendous amounts of money have been spent to remove it from homes, schools, public buildings, and other sites, even though no asbestos-related disease has been recorded among those exposed to chrysolite in nonoccupational circumstances. It is now thought that much of the removal was unnecessary and that chrysolite asbestos doesn't pose a significant health hazard. Additional research into health risks from other varieties of asbestos is necessary to better understand the potential problem and to outline strategies to eliminate potential health problems.

For example, from 1979 to 1998 a strip mine near Libby, Montana, produced vermiculite (a natural mineral) that was contaminated (commingled) with a fibrous form of the mineral tremolite, classified as an asbestos. People in Libby were exposed to asbestos by workers in the mines (occupational exposure) who brought it home on clothes. Libby is in a valley with very poor ventilation, allowing the asbestos particles to settle out over everything. The EPA has documented hundreds of asbestos-related cases of disease, including many deaths. Asbestos mortality in Libby was much higher than expected, compared to the United States as a whole and to other parts of Montana. In 2009 the EPA declared Libby a public-health emergency. Medical care is being provided, and plans for cleanup of the now closed mine and Libby are under way.[30]

Electromagnetic Fields

Electromagnetic fields (EMFs) are part of everyday urban life. Cell phones, electric motors, electric transmission lines for utilities, and our electrical appliances—toasters, electric blankets, computers, and so forth—all produce magnetic fields. There is currently a controversy over whether these fields produce a health risk.

Early on, investigators did not believe that magnetic fields were harmful, because fields drop off quickly with distance from the source, and the strengths of the fields that most people come into contact with are relatively weak. For example, the magnetic fields generated by power transmission lines or by a computer terminal are normally only about 1% of Earth's magnetic field; directly below power lines, the electric field induced in the body is about what the body naturally produces within cells.[31]

Several early studies, however, concluded that children exposed to EMFs from power lines have an increased risk of contracting leukemia, lymphomas, and nervous-system cancers.[32] Investigators concluded that children so exposed are about one and a half to three times more likely to develop cancer than children with very low exposure to EMFs, but the results were questioned because of perceived problems with the research design (problems of sampling, tracking children, and estimating exposure to EMFs).

A later study analyzed more than 1,200 children, approximately half of them suffering from acute leukemia. It was necessary to estimate residential exposure to magnetic fields generated by power lines near the children's present and former homes. That study, the largest such investigation to date, found no association between childhood leukemia and measured exposure to magnetic fields.[31, 32]

In other studies, electric utility workers' exposure to magnetic fields has been compared with the incidence of brain cancer and leukemia. One study concluded that the association between exposure to magnetic fields and both brain cancer and leukemia is not strong and not statistically significant.[33]

Saying that data are not statistically significant is another way of stating that the relationship between exposure and disease cannot be reasonably established given the database that was analyzed. It does not mean that additional data in a future study will not find a statistically significant relationship. Statistics can predict the strength of the relationship between variables, such as exposure to a toxin and the incidence of a disease, but statistics cannot prove a cause-and-effect relationship between them.

In sum, despite the many studies that have evaluated relationships between cancer (brain, leukemia, and breast) and exposure to magnetic fields in our modern urban environment, the jury is still out. [34, 35] There seems to be some indication that magnetic fields cause health problems for children,[36, 37] but the risks to adults (with the exception of utility workers) appear relatively small and difficult to quantify.[38-41]

Noise Pollution

Noise pollution is unwanted sound. Sound is a form of energy that travels as waves. We hear sound because our ears respond to sound waves through vibrations of the eardrum. The sensation of loudness is related to the intensity of the energy carried by the sound waves and is measured in decibels (dB). The threshold for human hearing is 0 dB; the average sound level in the interior of a home is

Table 10.2 EXAMPLES OF SOUND LEVELS

SOUND SOURCE	INTENSITY OF SOUND (dB)	HUMAN PERCEPTION
Threshold of hearing	0	
Rustling of leaf	10	Very quiet
Faint whisper	20	Very quiet
Average home	45	Quiet
Light traffic (30 m away)	55	Quiet
Normal conversation	65	Quiet
Chain saw (15 m away)	80	Moderately loud
Jet aircraft flyover at 300 m	100	Very loud
Rock music concert	110	Very loud
Thunderclap (close)	120	Uncomfortably loud
Jet aircraft takeoff at 100 m	125	Uncomfortably loud
	140	Threshold of pain
Rocket engine (close)	180	Traumatic injury

Source:

about 45 dB; the sound of an automobile, about 70 dB; and the sound of a jet aircraft taking off, about 120 dB (see Table 10.2). A tenfold increase in the strength of a particular sound adds 10 dB units on the scale. An increase of 100 times adds 20 units.[13] The decibel scale is logarithmic—it increases exponentially as a power of 10. For example, 50 dB is 10 times louder than 40 dB and 100 times louder than 30 dB.

Environmental effects of noise depend not only on the total energy but also on the sound's pitch, frequency, and time pattern and length of exposure to the sound. Very loud noises (more than 140 dB) cause pain, and high levels can cause permanent hearing loss. Human ears can take sound up to about 60 dB without damage or hearing loss. Any sound above 80 dB is potentially dangerous. The noise of a lawn mower or motorcycle will begin to damage hearing after about eight hours of exposure. In recent years, there has been concern about teenagers (and older people, for that matter) who have suffered some permanent loss of hearing following extended exposure to amplified rock music (110 dB). At a noise level of 110 dB, damage to hearing can occur after only half an hour. Loud sounds at the workplace are another hazard. Even noise levels below the hearing-loss level may still interfere with human communication and may cause irritability. Noise in the range of 50–60 dB is sufficient to interfere with sleep, producing a feeling of fatigue upon awakening.

Voluntary Exposure

Voluntary exposure to toxins and potentially harmful chemicals is sometimes referred to as exposure to personal pollutants. The most common of these are tobacco, alcohol, and other drugs. Use and abuse of these substances have led to a variety of human ills, including death and chronic disease; criminal activity, such as reckless driving and manslaughter; loss of careers; street crime; and the straining of human relations at all levels.

10.3 General Effects of Pollutants

Almost every part of the human body is affected by one pollutant or another, as shown in Figure 10.11a. For example, lead and mercury (remember the Mad Hatter) affect the brain; arsenic, the skin; carbon monoxide, the heart; and fluoride, the bones. Wildlife is affected as well. Locations in the body where pollutants may affect humans and wildlife are shown in Figure 10.11b; effects of pollutants on wildlife populations are listed in Table 10.3.

The lists of potential toxins and affected body sites for humans and other animals in Figure 10.11 may be somewhat misleading. For example, chlorinated hydrocarbons, such as dioxin, are stored in the fat cells of animals, but they cause damage not only to fat cells but to the entire organism through disease, damaged skin, and birth defects. Similarly, a toxin that affects the brain, such as mercury, causes a wide variety of problems and symptoms, as illustrated in the Minamata, Japan, example (discussed in A Closer Look 10.2). The value of Figure 10.11 is in helping us to understand in general the adverse effects of excess exposure to chemicals.

Concept of Dose and Response

Five centuries ago, the physician and alchemist Paracelsus wrote that "everything is poisonous, yet nothing is poisonous." By this he meant, essentially, that too much of any substance can be dangerous, yet in an extremely

Table 10.3 EFFECTS OF POLLUTANTS ON WILDLIFE

EFFECT ON POPULATION	EXAMPLES OF POLLUTANTS
Changes in abundance	Arsenic, asbestos, cadmium, fluoride, hydrogen sulfide, nitrogen oxides, particulates, sulfur oxides, vanadium, POPs[a]
Changes in distribution	Fluoride, particulates, sulfur oxides, POPs
Changes in birth rates	Arsenic, lead, POPs
Changes in death rates	Arsenic, asbestos, beryllium, boron, cadmium, fluoride, hydrogen sulfide, lead, particulates, selenium, sulfur oxides, POPs
Changes in growth rates	Boron, fluoride, hydrochloric acid, lead, nitrogen oxides, sulfur oxides, POPs

[a] Pesticides, PCBs, hormonally active agents, dioxin, and DDT are examples (see Table 10.1).

Source: J.R. Newman, *Effects of Air Emissions on Wildlife*, U.S. Fish and Wildlife Service, 1980. Biological Services Program, National Power Plant Team, FWS/OBS-80/40, U.S. Fish and Wildlife Service, Washington, DC.

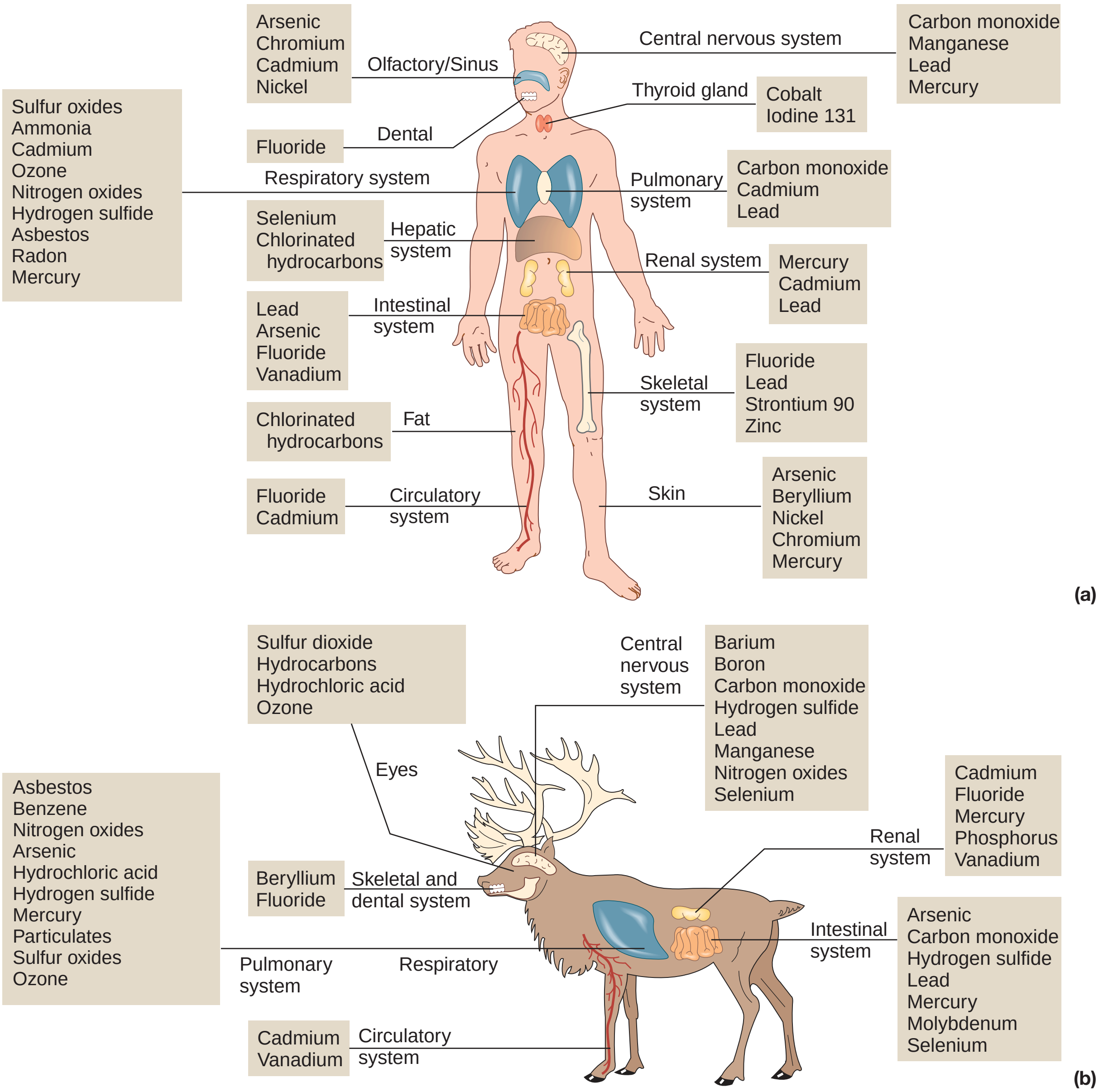


FIGURE 10.11 **(a)** Effects of some major pollutants in human beings. **(b)** Known sites of effects of some major pollutants in wildlife.

small amount can be relatively harmless. Every chemical element has a spectrum of possible effects on a particular organism. For example, selenium is required in small amounts by living things but may be toxic or increase the probability of cancer in cattle and wildlife when it is present in high concentrations in the soil. Copper, chromium, and manganese are other chemical elements required in small amounts by animals but toxic in higher amounts.

It was recognized many years ago that the effect of a certain chemical on an individual depends on the dose. This concept, termed **dose response**, can be represented by a generalized dose-response curve, such as that shown in Figure 10.12. When various concentrations of a chemical present in a biological system are plotted against the effects on the organism, two things are apparent: Relatively large concentrations are toxic and even lethal (points *D*, *E*, and *F* in Figure 10.12), but trace concentrations may actually be beneficial for life (between points *A* and *D*). The dose-response curve forms a plateau of optimal concentration and maximum benefit between two points (*B* and *C*). Points *A*, *B*, *C*, *D*, *E*, and *F* in Figure 10.12 are important thresholds in the dose-response curve. Unfortunately, the amounts at which points *E* and *F* occur are known only for a few substances for a few organisms, including people, and the very important point *D* is all but unknown. Doses that are beneficial, harmful, or lethal may differ widely for different organisms and are difficult to characterize.

Fluorine provides a good example of the general dose-response concept. Fluorine forms fluoride compounds that prevent tooth decay and promote development of a healthy bone structure. Relationships between the concentration of fluoride (in a compound of fluorine, such

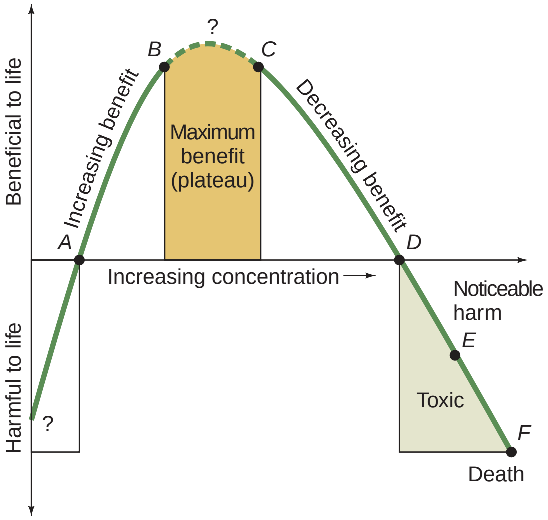


FIGURE 10.12 Generalized dose-response curve. Low concentrations of a chemical may be harmful to life (below point *A*). As the concentration of the chemical increases from *A* to *B*, the benefit to life increases. The maximum concentration that is beneficial to life lies within the benefit plateau (*B*–*C*). Concentrations greater than this plateau provide less and less benefit (*C*–*D*) and will harm life (*D*–*F*) as toxic concentrations are reached. Increased concentrations above the toxic level may result.

as sodium fluoride, NaF) and health show a specific dose-response curve (Figure 10.13). The plateau for an optimal concentration of fluoride (point *B* to point *C*) to reduce dental caries (cavities) is from about 1 ppm to just less than 5 ppm. Levels greater than 1.5 ppm do not significantly decrease tooth decay but do increase the occurrence of tooth discoloration. Concentrations of 4–6 ppm reduce the prevalence of osteoporosis, a disease characterized by loss of bone mass; and toxic effects are noticed between 6 and 7 ppm (point *D* in Figure 10.13).

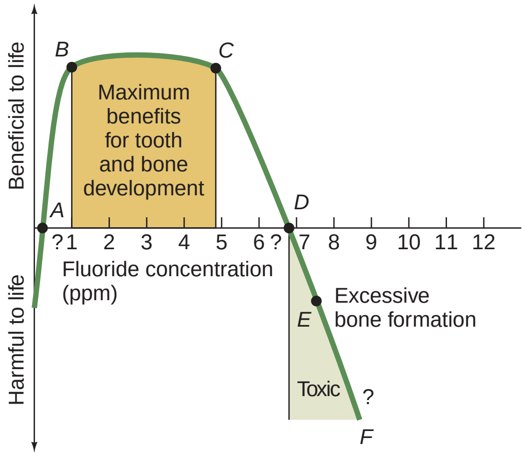


FIGURE 10.13 General dose-response curve for fluoride, showing the relationship between fluoride concentration and physiological benefit.

Dose-Response Curve (LD-50, ED-50, and TD-50)

Individuals differ in their response to chemicals, so it is difficult to predict the dose that will cause a response in a particular individual. It is more practical to predict instead what percentage of a population will respond to a specific dose of a chemical.

For example, the dose at which 50% of the population dies is called the lethal dose 50, or LD-50. The **LD-50** is a crude approximation of a chemical's toxicity. It is a gruesome index that does not adequately convey the sophistication of modern toxicology and is of little use in setting a standard for toxicity. However, the LD-50 determination is required for new synthetic chemicals as a way of estimating their toxic potential. Table 10.4 lists, as examples, LD-50 values in rodents for selected chemicals.

Table 10.4 APPROXIMATE LD–50 VALUES (FOR RODENTS) FOR SELECTED AGENTS

AGENT	LD-50(mg/kg)[a]
Sodium chloride (table salt)	4,000
Ferrous sulfate (to treat anemia)	1,520
2,4-D (a weed killer)	368
DDT (an insecticide)	135
Caffeine (in coffee)	127
Nicotine (in tobacco)	24
Strychnine sulfate (used to kill certain pests)	3
Botulinum toxin (in spoiled food)	0.00001

[a] Milligrams per kilogram of body mass (termed mass weight, although it really isn't a weight) administered by mouth to rodents. Rodents are commonly used in such evaluations, in part because they are mammals (as we are), are small, have a short life expectancy, and their biology is well known.

Source: H.B. Schiefer, D.C. Irvine, and S.C. Buzik, *Understanding Toxicology* (New York: CRC Press, 1997).

The **ED-50** (effective dose 50%) is the dose that causes an effect in 50% of the observed subjects. For example, the ED-50 of aspirin would be the dose that relieves headaches in 50% of the people observed.[42]

The **TD-50** (toxic dose 50%) is defined as the dose that is toxic to 50% of the observed subjects. TD-50 is often used to indicate responses such as reduced enzyme activity, decreased reproductive success, or the onset of specific symptoms, such as hearing loss, nausea, or slurred speech.

For a particular chemical, there may be a whole family of dose-response curves, as illustrated in Figure 10.14. Which dose is of interest depends on what is being evaluated. For example, for insecticides we may wish to know the dose that will kill 100% of the insects exposed; therefore, LD-95 (the dose that kills 95% of the insects) may be the minimum acceptable level. However, when considering human health and exposure to a particular toxin, we often want to know the LD-0—the maximum dose that does not cause any deaths.[42] For potentially toxic compounds, such as insecticides that may form a residue on food or food additives, we want to ensure that the expected levels of human exposure will have no known toxic effects. From an environmental perspective, this is important because of concerns about increased risk of cancer associated with exposure to toxic agents.[42]

For drugs used to treat a particular disease, the efficiency of the drug as a treatment is of paramount importance. In addition to knowing what the effective dose (ED-50) is, it is important to know the drug's relative safety. For example, there may be an overlap between the effective dose (ED) and the toxic dose (TD). That is, the dose that causes a positive therapeutic response in some individuals might be toxic to others. A quantitative measure of the relative safety of a particular drug is the *therapeutic index*, defined as the ratio of the LD-50 to the ED-50. The greater the therapeutic index, the safer the drug is believed to be.[43] In other words, a drug with a large difference between the lethal and therapeutic dose is safer than one with a smaller difference.

Threshold Effects

Recall from A Closer Look 10.2 that a **threshold** is a level below which no effect occurs and above which effects begin to occur. If a threshold dose of a chemical exists, then a concentration of that chemical in the environment below the threshold is safe. If there is no threshold dose, then even the smallest amount of the chemical has some negative effect (Figure 10.15).

Whether or not there is a threshold for environmental toxins is an important environmental issue. For example, the U.S. Federal Clean Water Act originally stated a goal to reduce to zero the discharge of pollutants into water. The goal implies there is no such thing as a threshold—that no level of toxin will be legally permitted. However, it is unrealistic to believe that zero discharge of a water pollutant can be achieved or that we can reduce to zero the concentration of chemicals shown to be carcinogenic.

A problem in evaluating thresholds for toxic pollutants is that it is difficult to account for synergistic effects. Little

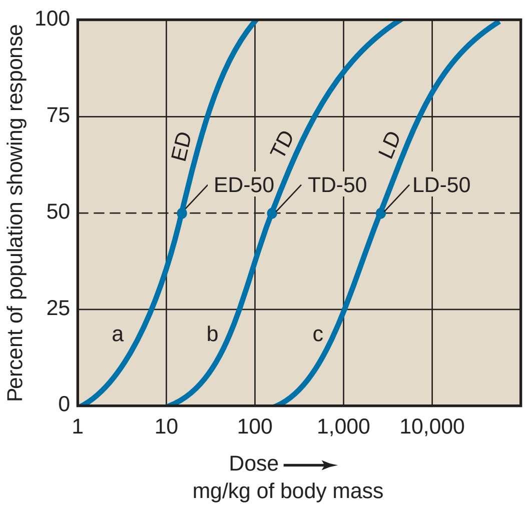


FIGURE 10.14 Idealized diagram illustrating a family of dose-response curves for a specific drug: ED (effective dose), TD (toxic dose), and LD (lethal dose). Notice the overlap for some parts of the curves. For example, at ED-50, a small percentage of the people exposed to that dose will suffer a toxic response, but none will die. At TD-50, about 1% of the people exposed to that dose will die.

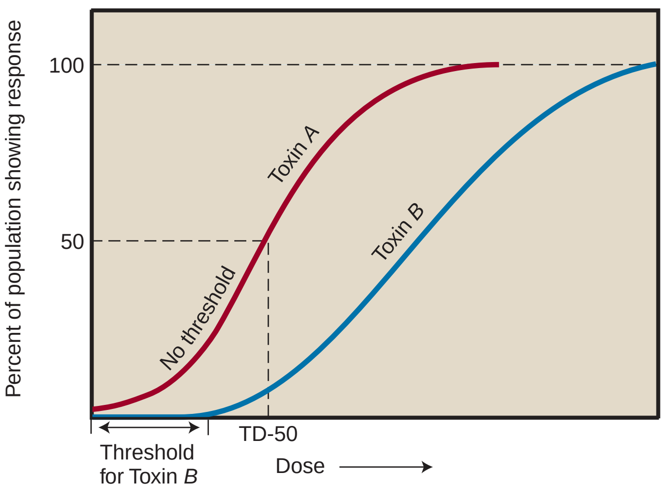


FIGURE 10.15 In this hypothetical toxic dose-response curve, toxin *A* has no threshold; even the smallest amount has some measurable effect on the population. The TD-50 for toxin *A* is the dose required to produce a response in 50% of the population. Toxin *B* has a threshold (flat part of curve) where the response is constant as the dose increases. After the threshold dose is exceeded, the response increases.

is known about whether or how thresholds might change if an organism is exposed to more than one toxin at the same time or to a combination of toxins and other chemicals, some of which are beneficial. Exposures of people to chemicals in the environment are complex, and we are only beginning to understand and conduct research on the possible interactions and consequences of multiple exposures.

Ecological Gradients

Dose response differs among species. For example, the kinds of vegetation that can live nearest to a toxic source are often small plants with relatively short lifetimes (grasses, sedges, and weedy species usually regarded as pests) that are adapted to harsh and highly variable environments. Farther from the toxic source, trees may be able to survive. Changes in vegetation with distance from a toxic source define the **ecological gradient**.

Ecological gradients may be found around smelters and other industrial plants that discharge pollutants into the atmosphere from smokestacks. For example, ecological gradient patterns can be observed in the area around the smelters of Sudbury, Ontario, discussed earlier in this chapter (see A Closer Look 10.1). Near the smelters, an area that was once forest was a patchwork of bare rock and soil occupied by small plants.

Tolerance

The ability to resist or withstand stress from exposure to a pollutant or harmful condition is referred to as **tolerance**. Tolerance can develop for some pollutants in some populations, but not for all pollutants in all populations. Tolerance may result from behavioral, physiological, or genetic adaptation.

Behavioral tolerance results from changes in behavior. For example, mice learn to avoid traps.

Physiological tolerance results when the body of an individual adjusts to tolerate a higher level of pollutant. For example, in studies at the University of California Environmental Stress Laboratory, students were exposed to ozone (O_3), an air pollutant often present in large cities (Chapter 21). The students at first experienced symptoms that included irritation of eyes and throat and shortness of breath. However, after a few days, their bodies adapted to the ozone, and they reported that they believed they were no longer breathing ozone-contaminated air, even though the concentration of O_3 stayed the same. This phenomenon explains why some people who regularly breathe polluted air say they do not notice the pollution. Of course, it does not mean that the ozone is doing no damage; it is, especially to people with existing respiratory problems. There are many mechanisms for physiological tolerance, including *detoxification*, in which the toxic chemical is converted to a nontoxic form, and internal transport of the toxin to a part of the body where it is not harmful, such as fat cells.

Genetic tolerance, or adaptation, results when some individuals in a population are naturally more resistant to a toxin than others. They are less damaged by exposure and more successful in breeding. Resistant individuals pass on the resistance to future generations, who are also more successful at breeding. Adaptation has been observed among some insect pests following exposure to some chemical pesticides. For example, certain strains of malaria-causing mosquitoes are now resistant to DDT, and some organisms that cause deadly infectious diseases have become resistant to common antibiotic drugs, such as penicillin.

Acute and Chronic Effects

Pollutants can have acute and chronic effects. *An acute effect* is one that occurs soon after exposure, usually to large amounts of a pollutant. A *chronic effect* occurs over a long period, often from exposure to low levels of a pollutant. For example, a person exposed all at once to a high dose of radiation may be killed by radiation sickness soon after exposure (an acute effect). However, that same total dose received slowly in small amounts over an entire lifetime may instead cause mutations and lead to disease or affect the person's DNA and offspring (a chronic effect).

10.4 Risk Assessment

Risk assessment in this context can be defined as the process of determining potential adverse health effects of exposure to pollutants and potentially toxic materials (recall the discussion of measurements and methods of science in Chapter 2). Such an assessment generally includes four steps:[44]

1. *Identification of the hazard.* This consists of testing materials to determine whether exposure is likely to cause health problems. One method used is to investigate populations of people who have been previously exposed. For example, to understand the toxicity of radiation produced from radon gas, researchers studied workers in uranium mines. Another method is to perform experiments to test effects on animals, such as mice, rats, or monkeys. This method has drawn increasing criticism from groups who believe such experiments are unethical. Another approach is to try to understand how a particular chemical works at the molecular level on cells. For example, research has been

done to determine how dioxin interacts with living cells to produce an adverse response. After quantifying the response, scientists can develop mathematical models to assess dioxin's risk.[18, 19] This relatively new approach might also be applicable to other potential toxins that work at the cellular level.

2. *Dose-response assessment*. This next step involves identifying relationships between the dose of a chemical (therapeutic drug, pollutant, or toxin) and the health effects on people. Some studies involve administering fairly high doses of a chemical to animals. The effects, such as illness, or symptoms, such as rashes or tumor development, are recorded for varying doses, and the results are used to predict the response in people. This is difficult, and the results are controversial for several reasons:
   - The dose that produces a particular response may be very small and subject to measurement errors.
   - There may be arguments over whether thresholds are present or absent.
   - Experiments on animals such as rats, mice, or monkeys may not be directly applicable to humans.
   - The assessment may rely on probability and statistical analysis. Although statistically significant results from experiments or observations are accepted as evidence to support an argument, statistics cannot establish that the substance tested *caused* the observed response.
3. *Exposure assessment.* This step evaluates the intensity, duration, and frequency of human exposure to a particular chemical pollutant or toxin. The hazard to society is directly proportional to the total population exposed. The hazard to an individual is generally greater closer to the source of exposure. Like dose-response assessment, exposure assessment is difficult, and the results are often controversial, in part because of difficulties in measuring the concentration of a toxin in doses as small as parts per million, billion, or even trillion. Some questions that exposure assessment attempts to answer follow:
   - How many people were exposed to concentrations of a toxin thought to be dangerous?
   - How large an area was contaminated by the toxin?
   - What are the ecological gradients for exposure to the toxin?
   - How long were people exposed to a particular toxin?
4. *Risk characterization:* The goal of this final step is to delineate health risk in terms of the magnitude of the health problem that might result from exposure to a particular pollutant or toxin. To do this, it is necessary to identify the hazard, complete the dose-response assessment, and evaluate the exposure assessment, as has been outlined. This step involves all the uncertainties of the prior steps, and results are again likely to be controversial.

In sum, *risk assessment* is difficult, costly, and controversial. Each chemical is different, and there is no one method of determining responses of humans to specific EDs or TDs. Toxicologists use the scientific method of hypothesis-testing with experiments (see Chapter 2) to predict how specific doses of a chemical may affect humans. Warning labels listing potential side effects of a specific medication are required by law, and these warnings result from toxicology studies to determine a drug's safety. Finally, risk assessment requires making scientific judgments and formulating actions to help minimize health problems related to human exposure to environmental pollutants and toxins.

The process of *risk management* integrates the assessment of risk with technical, legal, political, social, and economic issues.[18, 19] The toxicity of a particular material is often open to debate. For example, there is debate as to whether the risk from dioxin is linear. That is, do effects start at minimum levels of exposure and gradually increase, or is there a threshold exposure beyond which health problems occur? (See A Closer Look 10.3.)[18, 19, 29] It is the task of people in appropriate government agencies assigned to manage risk to make judgments and decisions based on the risk assessment and then to take appropriate actions to minimize the hazard resulting from exposure to toxins. This might involve invoking the precautionary principle discussed in Chapter 1.

CRITICAL THINKING ISSUE

Is Lead in the Urban Environment Contributing to Antisocial Behavior?

Lead is one of the most common toxic metals in our inner-city environments, and it may be linked to delinquent behavior in children. Lead is found in all parts of the urban environment (air, soil, older pipes, and some paint, for example) and in biological systems, including people (Figure 10.16). There is no apparent biological need for lead, but it is sufficiently concentrated in the blood and bones of children living in inner cities to cause health and behavior problems. In some populations, over 20% of the children have blood concentrations of lead that are higher than those believed safe.[45]

Lead affects nearly every system of the body. Thus, acute lead toxicity may cause a variety of symptoms, including anemia, mental retardation, palsy, coma, seizures, apathy, uncoordination, subtle loss of recently acquired skills, and bizarre behavior.[46,47] Lead toxicity is particularly a problem for young children, who are more apt than adults to put things in their mouths and apparently are also more susceptible to lead poisoning. In some children the response to lead poisoning is aggressive, difficult-to-manage behavior.[45-48]

The occurrence of lead toxicity or lead poisoning has cultural, political, and sociological implications. Over 2,000 years ago, the Roman Empire produced and used tremendous amounts of lead for a period of several hundred years. Production rates were as high as 55,000 metric tons per year. Romans had a wide variety of uses for lead. Lead was used in pots in which grapes were crushed and processed into a syrup for making wine, in cups and goblets from which wine was drunk, and as a base for cosmetics and medicines. In the homes of Romans wealthy enough to have running water, lead was used to make the pipes that carried the water. It has been argued that lead poisoning among the upper class in Rome was partly responsible for Rome's decline. Lead poisoning probably resulted in widespread stillbirths, deformities, and brain damage. Studies analyzing the lead content of bones of ancient Romans tend to support this hypothesis.[49]

FIGURE 10.16 The lead in urban soils (a legacy of our past use of lead in gasoline) is still concentrated where children are likely to play. Lead-based paint in older buildings, such as these in New York, also remains a hazard to young children, who sometimes ingest flakes of paint.

The occurrence of lead in glacial ice cores from Greenland has also been studied. Glaciers have an annual growth layer of ice. Older layers are buried by younger layers, allowing us to identify the age of each layer. Researchers drill glaciers, taking continuous samples of the layers. The samples look like long, solid rods of glacial ice and are called *cores*. Measurements of lead in these cores show that lead concentrations during the Roman period, from approximately 500 B.C. to A.D. 300, are about four times higher than before and after this period. This suggests that the mining and smelting of lead in the Roman Empire added small particles of lead to the atmosphere that eventually settled out in the glaciers of Greenland.[49]

Lead toxicity, then, seems to have been a problem for a long time. Now, an emerging, interesting, and potentially significant hypothesis is that, in children, even lead concentrations below the levels known to cause physical damage may be associated with an increased potential for antisocial, delinquent behavior. This is a testable hypothesis. (See Chapter 2 for a discussion of hypotheses.) If the hypothesis is correct, then some of our urban crime may be traced to environmental pollution!

A recent study in children aged 7 to 11 measured the amount of lead in bones and compared it with data concerning behavior over a four-year period. Even taking into account such factors as maternal intelligence, socioeconomic status, and quality of child rearing, the study concluded that an above-average concentration of lead in children's bones was associated with an increased risk of attention-deficit disorder, aggressive behavior, and delinquency.[45]

Critical Thinking Questions

1. What is the main point of the discussion about lead in the bones of children and children's behavior?
2. What are the main assumptions of the argument? Are they reasonable?
3. What other hypotheses might be proposed to explain the behavior?

SUMMARY

- Disease is an imbalance between an organism and the environment. Disease seldom has a one-cause/one-effect relationship, and there is often a gray zone between the state of health and the state of disease.
- Pollution produces an impure, dirty, or otherwise unclean state. Contamination means making something unfit for a particular use through the introduction of undesirable materials.
- Toxic materials are poisonous to people and other living things; toxicology is the study of toxic materials.
- A concept important in studying pollution problems is synergism, whereby actions of different substances produce a combined effect greater than the sum of the effects of the individual substances.
- How we measure the amount of a particular pollutant introduced into the environment or the concentration of that pollutant varies widely, depending on the substance. Common units for expressing the concentration of pollutants are parts per million (ppm) and parts per billion (ppb). Air pollutants are commonly measured in units such as micrograms of pollutant per cubic meter of air ($\mu g/m^3$).
- Categories of environmental pollutants include toxic chemical elements (particularly heavy metals), organic compounds, nuclear radiation, heat, particulates, electromagnetic fields, and noise.
- Organic compounds of carbon are produced by living organisms or synthetically by people. Artificially produced organic compounds may have physiological, genetic, or ecological effects when introduced into the environment. The potential hazards of organic compounds vary: Some are more readily degraded in the environment than others; some are more likely to undergo biomagnification; and some are extremely toxic, even at very low concentrations. Organic compounds of serious concern include persistent organic pollutants, such as pesticides, dioxin, PCBs, and hormonally active agents.
- The effect of a chemical or toxic material on an individual depends on the dose. It is also important to determine tolerances of individuals, as well as acute and chronic effects of pollutants and toxins.
- Risk assessment involves identifying the hazard, assessing the exposure and the dose response, and characterizing the possible results.

REEXAMINING THEMES AND ISSUES

Human Population

As the total population and population density increase, the probability that more people will be exposed to hazardous materials increases as well. Finding acceptable ways to dispose of hazardous substances also becomes more difficult as populations increase and people live closer to industrial areas and waste-disposal sites.

Sustainability

Ensuring that future generations inherit a relatively unpolluted, healthy environment remains a challenging problem. Sustainable development requires that our use of chemicals and other materials not damage the environment.

Global Perspective

Releasing toxins into the environment can cause global patterns of contamination or pollution, particularly when a toxin or contaminant enters the atmosphere, surface water, or oceans and becomes widely dispersed. For example, pesticides, herbicides, and heavy metals emitted into the atmosphere in the midwestern United States may be transported by winds and deposited on glaciers in polar regions.

Urban World

Industrial processes in urban areas concentrate potentially toxic materials that may be inadvertently, accidentally, or deliberately released into the environment. Human exposure to a variety of pollutants—including lead, asbestos, particulates, organic chemicals, radiation, and noise—is often greater in urban areas.

People and Nature

Feminization of frogs and other animals from exposure to human-produced, hormonally active agents (HAAs) is an early warning or red flag that we are disrupting some basic aspects of nature. We are performing unplanned experiments on nature, and the consequences to us and other living organisms with which we share the environment are poorly understood. Control of HAAs seems an obvious candidate for application of the precautionary principle, discussed in Chapter 1.

Science and Values

Because we value both human and nonhuman life, we are interested in learning all we can about the risks of exposing living things to chemicals, pollutants, and toxins. Unfortunately, our knowledge of risk assessment is often incomplete, and the dose response for many chemicals is poorly understood. What we decide to do about exposure to toxic chemicals reflects our values. Increased control of toxic materials in homes and the work environment is expensive. To reduce environmental hazards at worksites in other countries, are we willing to pay more for the goods those workers manufacture?

KEY TERMS

area sources **188**
asbestos **199**
biomagnification **191**
carcinogen **188**
contamination **188**
disease **187**
dose response **202**
ecological gradient **205**
ED-50 **204**
electromagnetic fields (EMFs) **199**
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threshold **204**
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toxicology **188**
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STUDY QUESTIONS

1. Do you think the hypothesis that some crime is caused in part by environmental pollution is valid? Why? Why not? How might the hypothesis be further tested? What are the social ramifications of the tests?
2. What kinds of life-forms would most likely survive in a highly polluted world? What would be their general ecological characteristics?
3. Some environmentalists argue that there is no such thing as a threshold for pollution effects. What do they mean? How would you determine whether it was true for a specific chemical and a specific species?
4. What is biomagnification, and why is it important in toxicology?

5. You are lost in Transylvania while trying to locate Dracula's castle. Your only clue is that the soil around the castle is known to have an unusually high concentration of the heavy metal arsenic. You wander in a dense fog, able to see only the ground a few meters in front of you. What changes in vegetation warn you that you are nearing the castle?
6. Distinguish between acute effects and chronic effects of pollutants.
7. Design an experiment to test whether tomatoes or cucumbers are more sensitive to lead pollution.
8. Why is it difficult to establish standards for acceptable levels of pollution? In giving your answer, consider physical, climatological, biological, social, and ethical reasons.
9. A new highway is built through a pine forest. Driving along the highway, you notice that the pines nearest the road have turned brown and are dying. You stop at a rest area and walk into the woods. One hundred meters away from the highway, the trees seem undamaged. How could you make a crude dose–response curve from direct observations of the pine forest? What else would be necessary to devise a dose–response curve from direct observation of the forest? What else would be necessary to devise a dose–response curve that could be used in planning the route of another highway?
10. Do you think your personal behavior is placing you in the gray zone of suboptimal health? If so, what can you do to avoid chronic disease in the future?

FURTHER READING

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Carson, R., *Silent Spring* (Boston: Houghton Mifflin, 1962). A classic book on problems associated with toxins in the environment.

Schiefer, H.B., D.G. Irvine, and S.C. Buzik, *Understanding Toxicology: Chemicals, Their Benefits and Risks* (Boca Raton, FL: CRC Press, 1997). A concise introduction to toxicology as it pertains to everyday life, including information about pesticides, industrial chemicals, hazardous waste, and air pollution.

Travis, C.C., and H.A. Hattemer-Frey. "Human Exposure to Dioxin," *The Science of the Total Environment* 104: 97–127, 1991. An extensive technical review of dioxin accumulation and exposure.

CHAPTER 11

Agriculture, Aquaculture, and the Environment

Modern agriculture uses modern technology (here a computer controls more than 100 center-pivot sprinklers) but continues to depend on the environment in major ways (here the need for water to grow wheat, alfalfa, potatoes, and melons along the Columbia River near Hermiston, Oregon).

LEARNING OBJECTIVES

The big question about farming and the environment is: Can we produce enough food to feed Earth's growing human population, and do this sustainably? The major agricultural challenges facing us today are to increase the productivity of the land, acre by acre, hectare by hectare; to distribute food adequately around the world; to decrease the negative environmental effects of agriculture; and to avoid creating new kinds of environmental problems as agriculture advances. After reading this chapter, you should understand . . .

- How agroecosystems differ from natural ecosystems;
- What role limiting factors play in determining crop yield;
- How the growing human population, the loss of fertile soils, and the lack of water for irrigation can lead to future food shortages worldwide;
- The relative importance of food *distribution* and food *production*;
- Why some lands are best used for grazing, but how overgrazing can damage land;
- How alternative agricultural methods—including integrated pest management, no-till agriculture, mixed cropping, and other methods of soil conservation—can provide major environmental benefits;
- That genetic modification of crops could improve food production and benefit the environment, but perhaps also could create new environmental problems.

CASE STUDY

Biofuels and Banana Chips: Food Crops vs. Fuel Crops

In 2007 Alfred Smith, a farmer in Garland, North Carolina, was feeding his pigs trail mix, banana chips, yogurt-covered raisins, dried papaya, and cashews, according to an article in the *Wall Street Journal*.[1] The pigs were on this diet, Mr. Smith says, because the demand for the biofuel ethanol, produced from corn and other crops, had driven up prices of feed (the largest cost of raising livestock) to the point where it became cheaper to feed his animals our snack food. In 2007 he bought enough trail mix to feed 5,000 hogs, saving $40,000. Other farmers in the U.S. Midwest were feeding their pigs and cattle cookies, licorice, cheese curls, candy bars, french fries, frosted Mini-Wheats, and Reese's Peanut Butter Cups. Near Hershey, Pennsylvania, farmers were getting waste cocoa and candy trimmings from the Hershey Company and feeding it to their cattle. Their problem has been caused by competition with crops grown directly to be turned into fuels (Figure 11.1).

This raises the fundamental question about agriculture and the environment: For many decades world food production has exceeded demand. But the demand for food crops is growing rapidly due to a rapid rise in the standards of living of many people and continued human population growth, both of which have also increased the demand for fuels and thus competition with crops grown for biofuels. Can we find ways to feed all the people of the world without undue damage to the environment?

World food prices rose almost 40% in 2007. According to the United Nations Food and Agriculture Organization (UNFAO), in February 2008 corn prices had risen 25% and the price of wheat was 80% higher than a year before.[4] Wheat prices have reached record levels, doubling the average cost of just a few years ago, and stocks of wheat (the amount stored for future sale and use) are reaching a 30-year low, in part because of Australian droughts.[5] The FAO predicts a world food crisis, with 36 countries currently facing food crises and

FIGURE 11.1 Harvest of experimental oilseed crops at Piedmont Biofuels farm in Moncure, North Carolina.[2,3] Interest in and enthusiasm about biofuels are growing among some operating small farms, like the members of the Piedmont Biofuels Cooperative in North Carolina. Will biofuel agriculture be the wave of the future and prove environmentally sound and sustainable?

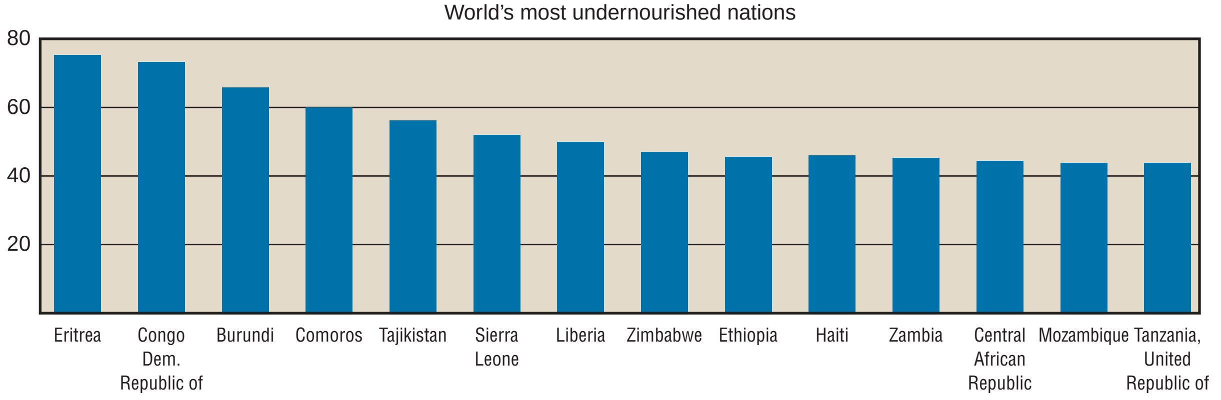


FIGURE 11.2 The world's most undernourished peoples, according to the United Nations Food and Agriculture Organization. This graph shows the 14 nations with the greatest percentage of undernourished people. Of these, 10 are in Africa. In the New World, only Haiti makes this group.[7]

Africa leading the list with 21 nations. In the Republic of the Congo, three-quarters of the population is undernourished, and in 25 nations at least one-third of the population is undernourished, according to the UNFAO (Figure 11.2).[6]

Suddenly, people of the world need a great increase in food production, in part because of the expanding human population, in part because of competition between crops for food and crops for fuel, and in part because of droughts, floods, and other environmental impacts that have decreased agricultural production. What can be done to meet the world's growing need for food and, second to that, its need for fuel? Can agricultural production increase? By how much? And at what costs, environmental and economic?

11.1 An Ecological Perspective on Agriculture

Farming creates novel ecological conditions, referred to as **agroecosystems.** Agroecosystems differ from natural ecosystems in six ways (Figure 11.3).

Ecological succession is halted to keep the agroecosystem in an early-successional state (see Chapter 5). Most crops are early-successional species, which means that they grow fast, spread their seeds widely and rapidly, and do best when sunlight, water, and chemical nutrients in the soil are abundant. Under natural conditions, crop species would eventually be replaced by later-successional

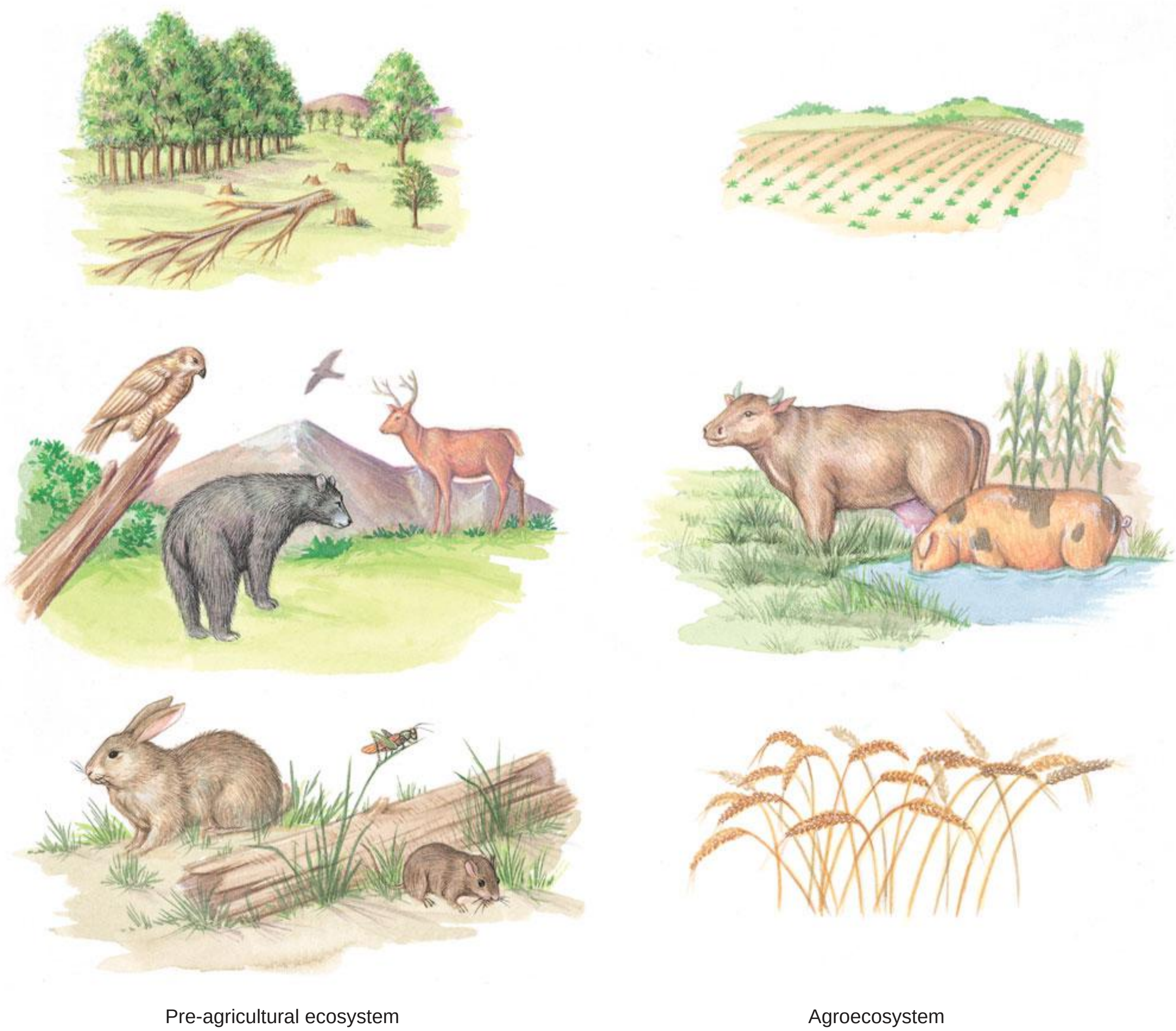


FIGURE 11.3 **How farming changes an ecosystem.** It converts complex ecosystems of high structural and species diversity to a monoculture of uniform structure, and greatly modifies the soil. See text for additional information about the agricultural effects on ecosystems.

plants. Slowing or stopping natural ecological succession requires time and effort on our part.

Biological diversity and food chains are simplified.

The focus is on monoculture, one plant species rather than many. Large areas are planted with a single species or even a single strain or subspecies, such as a single hybrid of corn. The downside of monoculture is that it makes the entire crop vulnerable to attack by a single disease or a single change in environmental conditions. Repeated planting of a single species can reduce the soil content of certain essential elements, reducing overall soil fertility.

Crops are planted in neat rows and fields. These simple geometric layouts make life easy for pests because the crop plants have no place to hide. In natural ecosystems, many different species of plants grow mixed together in complex patterns, so it is harder for pests to find their favorite victims.

Agroecosystems require plowing, which is unlike any natural soil disturbance—nothing in nature repeatedly and regularly turns over the soil to a specific depth. Plowing exposes the soil to erosion and damages its physical structure, leading to a decline in organic matter and a loss of chemical elements.

They may include genetically modified crops.

FIGURE 11.4 **Plowing rich prairie soil in South Dakota, around 1916**, a historical photograph from the Library of Congress. The prairie had never been turned over like this.

The Plow Puzzle

There is nothing in nature like a plow, and thus there are big differences between the soils of a forest or grassland and the soils of land that has been plowed and used for crops for several thousand years. These differences were observed and written about by one of the originators of the modern study of the environment, George Perkins Marsh. Born in Vermont in the 19th century, Marsh became the U.S. ambassador to Italy and Egypt. While in Italy, he was so struck by the differences in the soils of the forests of his native Vermont and the soils that had been farmed for thousands of years on the Italian peninsula that he made this a major theme in his landmark book, *Man and Nature*, published in 1864. The farmland he observed in Italy had once been forests. While the soil in Vermont was rich in organic matter and had definite layers, the soil of Italian farmland had little organic matter and lacked definite layers.

Here's the plow puzzle: One would expect that farming that caused such major modification (see Figure 11.4) would eventually make the soils unsustainable, at least in terms of crop production, but much of the farmland in Italy and France, in China, and elsewhere, has been in continuous use since pre-Roman times and is still highly productive. How can this be? And what has been the long-term effect of such agriculture on the environment? The American Dust Bowl seemed to demonstrate how destructive plowing could be (see A Closer Look 11.1).

Deepening the plow puzzle, since the end of World War II, mechanized farming has seriously damaged more than 1 billion hectares (2.47 billion acres) of land. That's about 10.5% of the world's best soil, equal to the combined area of China and India. In addition, overgrazing and deforestation have damaged approximately 9 million hectares (22 million acres) to the point where recovery will be difficult; restoration of the rest will require serious actions.[8]

In the United States, since European settlement, about one-third of the topsoil has been lost, making 80 million hectares (198 million acres) unproductive or only marginally productive.[8] For now, think about this puzzle. We will discuss solutions to it later.

11.2 Can We Feed the World?

Can we produce enough food to feed Earth's growing human population? The answer has a lot to do with the environment and our treatment of it: Can we grow crops sustainably, so that both crop production and agricultural ecosystems remain viable? Can we produce this food without seriously damaging other ecosystems that receive the wastes of agriculture? And to these concerns we must now add: Can we produce all this

Table 11.1 LAND, PEOPLE AND AGRICULTURE, 2006

LOCATION	TOTAL LAND AREA (sq km)	HUMAN POPULATION (MILLIONS)	PEOPLE PER AREA	CROP AREA (sq km)	CROP AREA PER PERSON (sq km)	CROP LAND AS % OF TOTAL LAND
Asia	30,988,970	3,823	123.37	16,813,750	0.044	54%
Africa	29,626,570	850	28.69	11,460,700	0.135	39%
N. and C. America	21,311,580	507	23.79	6,189,030	0.122	29%
S. America	17,532,370	936	53.39	5,842,850	0.062	33%
Europe	22,093,160	362	16.39	4,836,410	0.134	22%
Australia	7,682,300	19	2.47	4,395,000	2.313	57%
World	130,043,970	6,301	48.45	49,734,060	0.079	38%

Source: FAO Statistics 2006 http://faostat.fao.org/faostat/

Note: Data are available for crops until 2003; hence, some population values in this table will differ from those elsewhere in the chapter, which are for 2005.

food and also grow crops used only to produce fuels? To answer these questions, let us begin by considering how crops grow and how productive they can be.

A surprisingly large percentage of the world's land area is in agriculture: approximately 38% (excluding Antarctica), an area about the size of South and North America combined and enough to make agriculture a human-induced biome (Table 11.1 and Figure 11.5).[9]

The history of agriculture is a series of human attempts to overcome environmental limitations and problems. Each new solution has created new environmental problems, which in turn have required their own solutions. Thus, in seeking to improve agricultural systems, we should expect some undesirable side effects and be ready to cope with them.

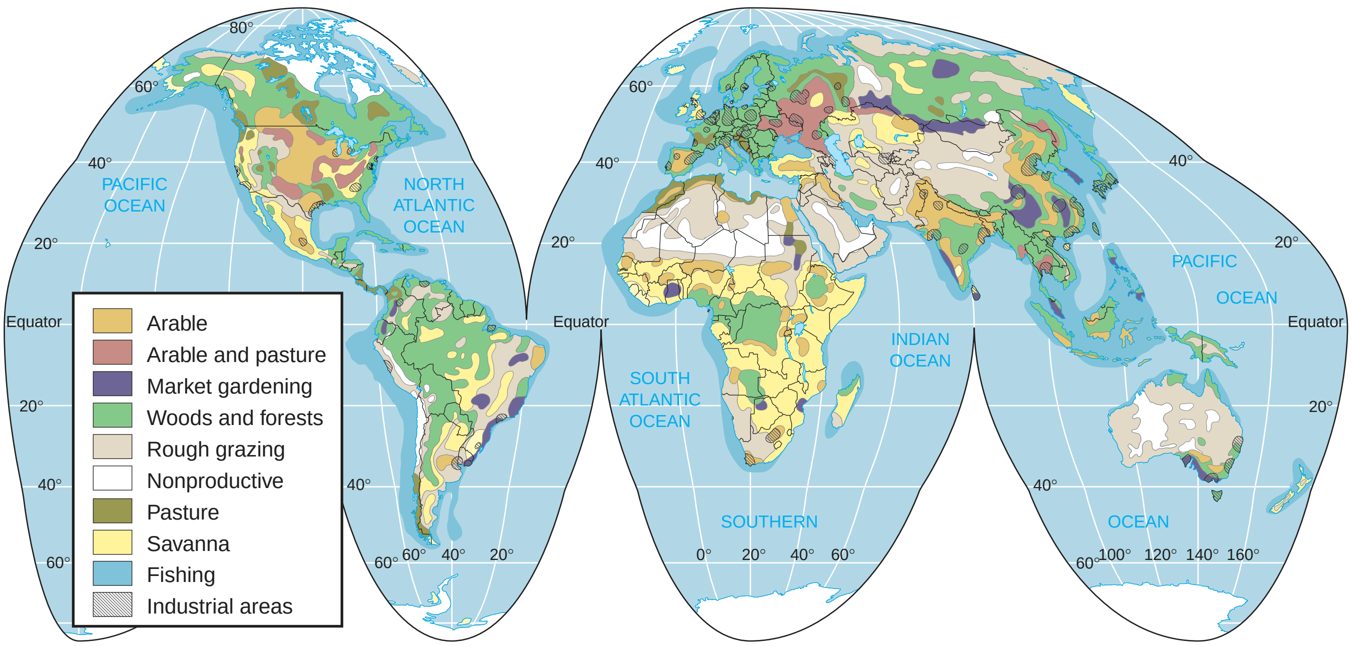


FIGURE 11.5 World land use showing arable (farmable) land. The percentage of land in agriculture varies considerably among continents, from 22% of the land in Europe to 57% in Australia. In the United States, cropland occupies 18% of the land and an additional 26% is used for pasture and rangeland, so agriculture uses 44% of the land. (*Source*: Phillips Atlas.)

The world's food supply is also greatly influenced by social disruptions and social attitudes, which affect the environment and in turn affect agriculture. In Africa, social disruptions since 1960 have included more than 20 major wars and more than 100 coups.[10] Such social instability makes sustained agricultural yields difficult—indeed, it makes any agriculture difficult if not impossible.[11] So does variation in weather, the traditional bane of farmers.[12]

How We Starve

People "starve" in two ways: undernourishment and malnourishment. World food production must provide adequate nutritional quality, not just total quantity. **Undernourishment** results from insufficient calories in available food, so that one has little or no ability to work or even move and eventually dies from the lack of energy. **Malnourishment** results from a lack of specific chemical components of food, such as proteins, vitamins, or other essential chemical elements. Widespread undernourishment manifests itself as famines that are obvious, dramatic, and fast-acting. Malnourishment is long term and insidious. Although people may not die outright, they are less productive than normal and can suffer permanent impairment and even brain damage.

Among the major problems of undernourishment are marasmus, which is progressive emaciation caused by a lack of protein and calories; kwashiorkor, which results from a lack of sufficient protein in the diet and in infants leads to a failure of neural development and thus to learning disabilities (Figure 11.6); and chronic hunger, when people have enough food to stay alive but not enough to lead satisfactory and productive lives (see Figure 11.7).

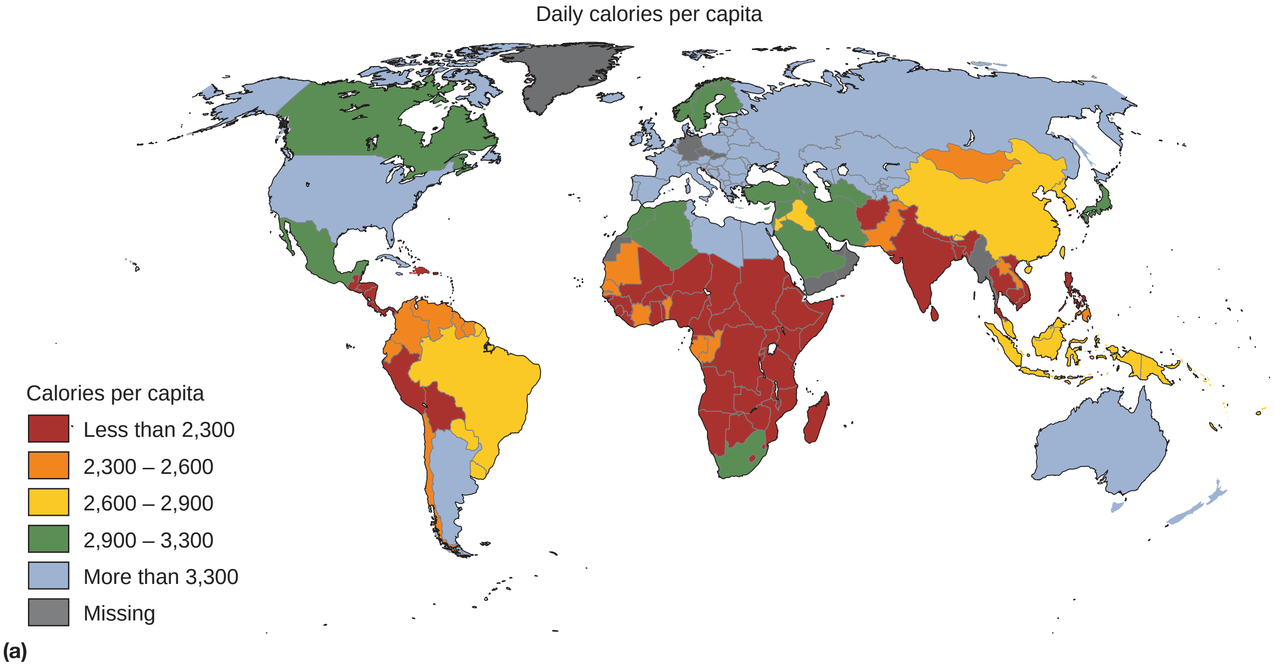
FIGURE 11.6 **Photograph of a child suffering from kwashiorkor.**

The supply of protein has been the major nutritional-quality problem. Animals are the easiest protein food source for people, but depending on animals for protein raises several questions of values. These include ecological ones (Is it better to eat lower on the food chain?), environmental ones (Do domestic animals erode soil faster than crops do?), and ethical ones (Is it morally right to eat animals?). How people answer these questions affects approaches to agriculture and thereby influences the environmental effects of agriculture. Once again, the theme of science and values arises.

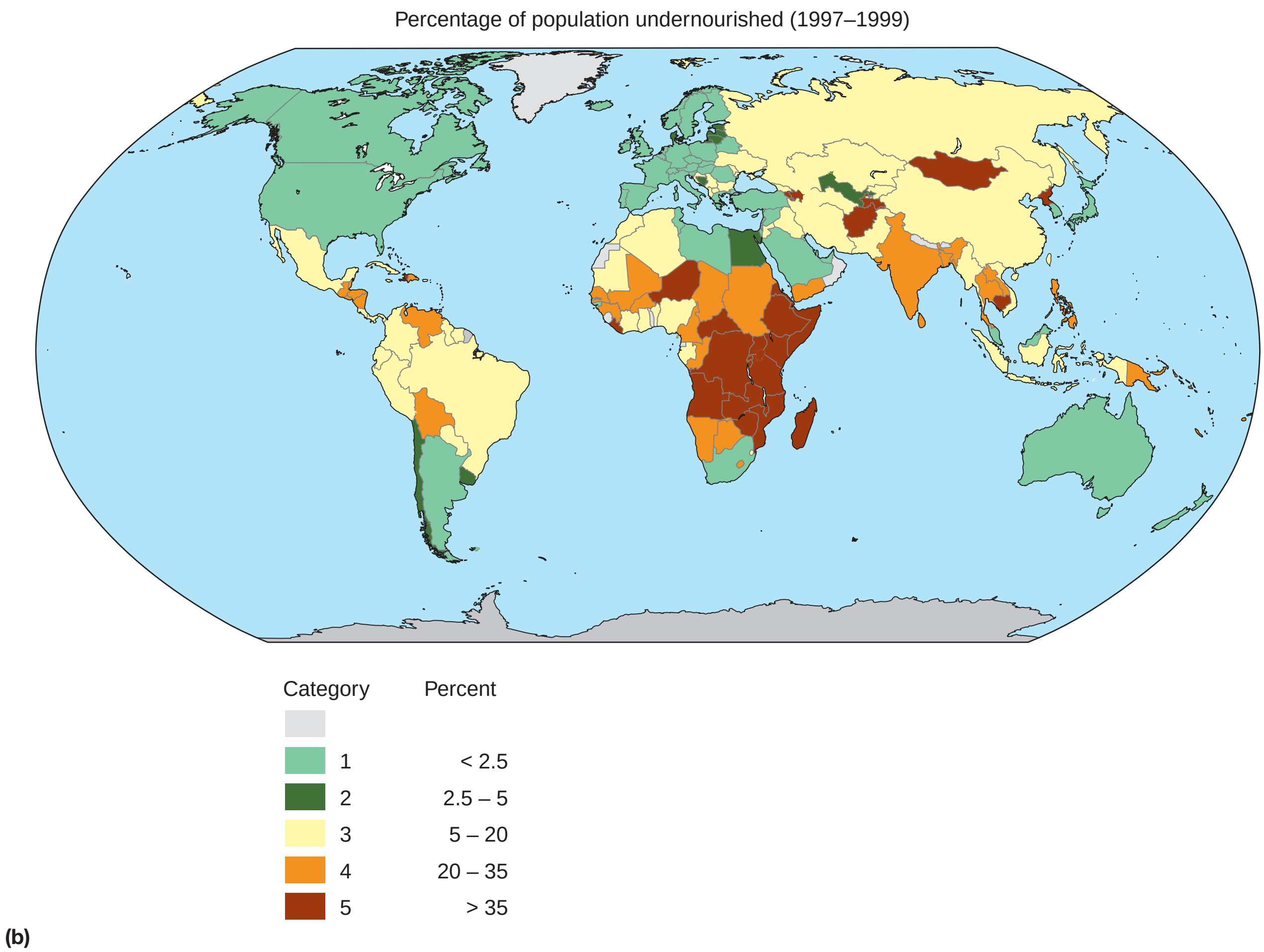
Since the end of World War II, rarely has a year passed without a famine somewhere in the world.[11] Food emergencies affected 34 countries worldwide at the end of the 20th century. Varying weather patterns in Africa, Latin America, and Asia, as well as an inadequate international trade in food, contributed to these emergencies. Examples include famines in Ethiopia (1984–1985), Somalia (1991–1993), and the 1998 crisis in Sudan. As we noted earlier, Africa remains the continent with the most acute food shortages, due to adverse weather and civil strife.[11]

A common remedy is food aid among nations, where one nation provides food to another or gives or lends money to purchase food. In the 1950s and 1960s, only a few industrialized countries provided food aid, using stocks of surplus food. A peak in international food aid occurred in the 1960s, when a total of 13.2 million tons per year of food were given. A world food crisis in the early 1970s raised awareness of the need for greater attention to food supply and stability. But during the 1980s, donor commitments totaled only 7.5 million tons. A record level of 15 million tons of food aid in 1992–1993 met less than 50% of the minimum caloric needs of the people fed. If food aid alone is to bring the world's malnourished people to a desired nutritional status, an estimated 55 million tons will be required by the year 2010—more than six times the amount available in 1995.[13]

Availability of food grown locally avoids disruptions in distribution and the need to transport food over long distances. But ironically, food aid can work against increased availability of locally grown food in regions receiving aid. Free food undercuts local farmers—they cannot compete with it. The only complete solution to famine is to develop long-term, sustainable, local agriculture. The old saying "Give a man a fish and feed him for a day; teach him to fish and feed him for life" is true.



(a)



(b)

FIGURE 11.7 **(a) Daily intake of calories worldwide. (b) Where people are undernorished.** The percentage is the portion of the country's total population that is undernourished. (*Source*: World Resources Institute Web site: http://www.wri.org/.)

11.3 What We Grow on the Land

Crops

Of Earth's half-million plant species, only about 3,000 have been used as agricultural crops and only 150 species have been cultivated on a large scale. In the United States, 200 species are grown as crops. Most of the world's food is provided by only 14 species. In approximate order of importance, these are wheat, rice, maize, potatoes, sweet potatoes, manioc, sugarcane, sugar beet, common beans, soybeans, barley, sorghum, coconuts, and bananas (Figure 11.8). Of these, six provide more than 80% of the total calories that people consume either directly or indirectly.[12]

There is a large world trade in small grains. Only the United States, Canada, Australia, and New Zealand are major exporters (see Figure 11.9); the rest of the world's nations are net importers. World small-grain production increased greatly in the second half of the 20th century, from 0.8 billion metric tons in 1961 to 1 billion in 1966, and doubled to 2 billion in 1996, a remarkable increase in 30 years. In 2005, world small-grain production was 2.2 billion tons, a record crop.[2] But production has remained relatively flat since then. The question we must ask, and cannot answer at this time, is whether this means that the world's carrying capacity for small grains has been reached or simply that the demand is not growing (Figure 11.10).

Some crops, called *forage*, are grown as food for domestic animals. These include alfalfa, sorghum, and various species of grasses grown as hay. Alfalfa is the most important forage crop in the United States, where 14 million hectares (about 30 million acres) are planted in alfalfa—one-half the world's total.

Livestock: The Agriculture of Animals

Worldwide, people keep 14 billion chickens, 1.3 billion cattle, more than 1 billion sheep, more than a billion ducks, almost a billion pigs, 700 million goats, more than 160 million water buffalo, and about 18 million camels.[18] Interestingly, the number of cattle in the world has risen slightly, by about 0.2% in the past ten years; the number of sheep has remained about the same; and the number of goats increased from 660 million in 1995 to 807 million in 2005. The production of beef, however, rose from 57 million metric tons (MT) in 1995 to 63 million MT in 2005 (the most recent date for which information is available). During the same period, the production of meat from chickens increased greatly, from 46 million MT to 70 million MT, and meat from pigs increased from 80 million MT to more than 100 million MT.[2] These are important food sources and have a major impact on the land.

Grazing on Rangelands: An Environment Benefit or Problem?

Traditional herding practices and industrialized production of domestic animals have different effects on the environment. Most cattle live on rangeland or pasture. **Rangeland** provides food for grazing and browsing animals without plowing and planting. **Pasture** is plowed, planted, and harvested to provide forage for animals. More than 34 million square kilometers (km^2) are in permanent

(a)

(b)

(c)


FIGURE 11.8 **Among the world's major crops are (a) wheat, (b) rice, and (c) soybeans.** See text for a discussion of the relative importance of these three.

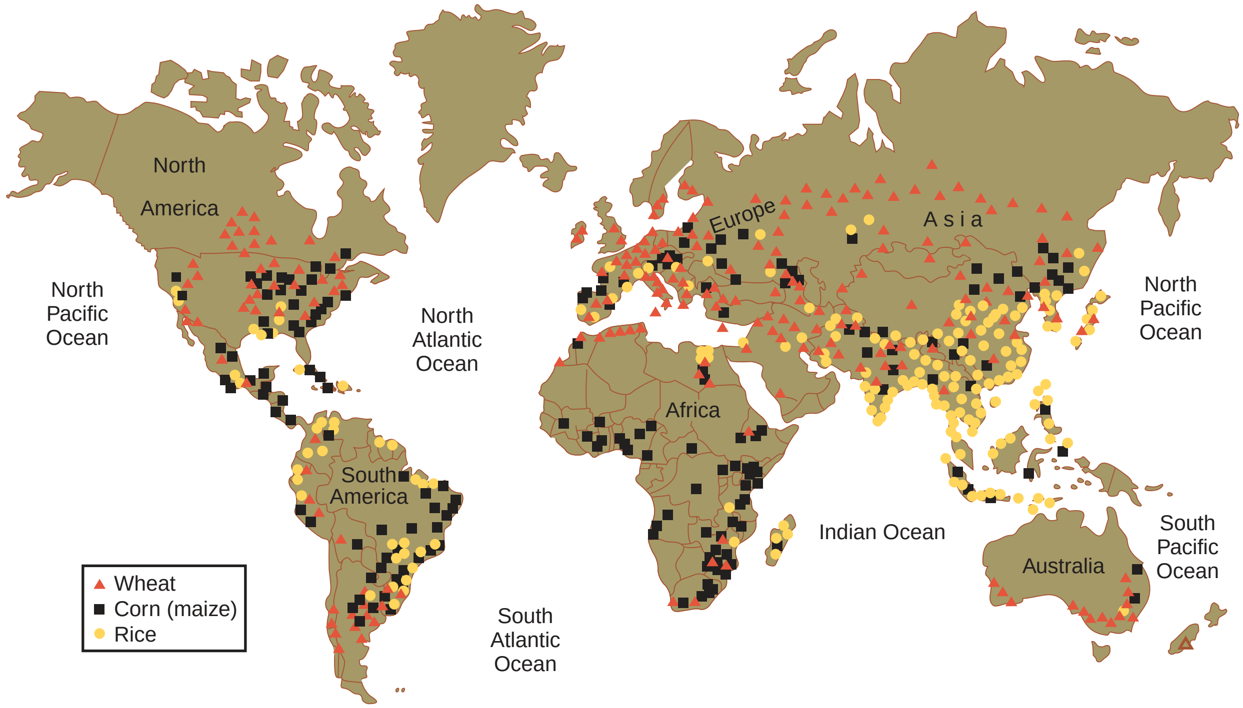


FIGURE 11.9 **Geographic distribution of world production of a few major small-grain crops.**

FIGURE 11.10 **World small-grain production since 1983**. (*Source*: FAO statistics FAOSTATS Web site.)

pasture worldwide—an area larger than the combined sizes of Canada, the United States, Mexico, Brazil, Argentina, and Chile.[2]

Almost half of Earth's land area is used as rangeland, and about 30% of Earth's land is arid rangeland, land easily damaged by grazing, especially during drought. Much of the world's rangeland is in poor condition from overgrazing. In the United States, where more than 99% of rangeland is west of the Mississippi River, rangeland conditions have improved since the 1930s, especially in upland areas. However, land near streams and the streams themselves continue to be heavily affected by grazing.

Grazing cattle trample stream banks and release their waste into stream water. Therefore, maintaining a high-quality stream environment requires that cattle be fenced behind a buffer zone. The upper Missouri River is famous for its beautiful "white cliffs," but private lands along the river that are used to graze cattle take away from the scenic splendor. The large numbers of cattle that come down to the Missouri River to drink damage

FIGURE 11.11 Cattle graze along the upper Missouri River, polluting it with their manure and increasing erosion of trampled ground near the river.

the land along the river, and the river itself runs heavy with manure (Figure 11.11). These effects extend to an area near a federally designated wild and scenic portion of the upper Missouri River, and tourists traveling on the Missouri have complained. In recent years, fencing along the upper Missouri River has increased, with small openings to allow cattle to drink, but otherwise restricting what they can do to the shoreline.

In modern industrialized agriculture, cattle are initially raised on open range and then transported to feedlots, where they are fattened for market. Feedlots have become widely known in recent years as sources of local pollution. The penned cattle are often crowded and are fed grain or forage that is transported to the feedlot. Manure builds up in large mounds and pollutes local streams when it rains. Feedlots are popular with meat producers because they are economical for rapid production of good-quality meat. However, large feedlots require intense use of resources and have negative environmental effects.

Traditional herding practices, by comparison, chiefly affect the environment through overgrazing. Goats are especially damaging to vegetation, but all domestic herbivores can destroy rangeland. The effect of domestic herbivores on the land varies greatly with their density relative to rainfall and soil fertility. At low to moderate densities, the animals may actually aid growth of aboveground vegetation by fertilizing soil with their manure and stimulating plant growth by clipping off plant ends in grazing, just as pruning stimulates plant growth. But at high densities, the vegetation is eaten faster than it can grow; some species are lost, and the growth of others is greatly reduced.

One benefit of farming animals rather than crops is that land too poor for crops that people can eat can be excellent rangeland, with grasses and woody plants that domestic livestock can eat (Figures 11.12 and 11.13). These lands occur on steeper slopes, with thinner soils or with less rainfall. Thus, from the point of view of sustainable agriculture, there is value in rangeland or pasture. The wisest approach to sustainable agriculture involves a

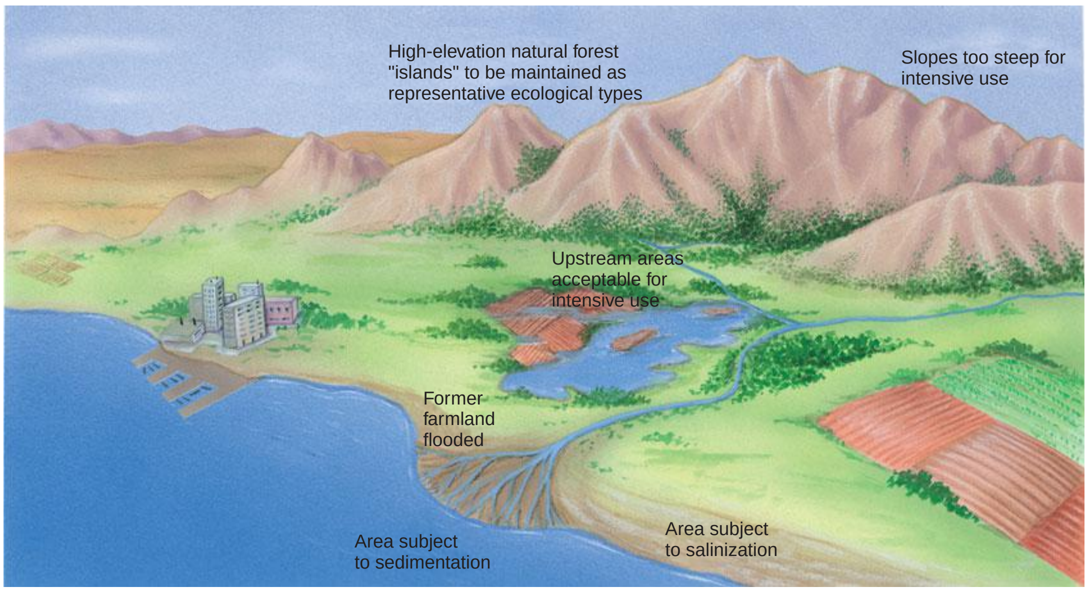


FIGURE 11.12 Physical and ecological considerations in watershed development—such as slope, elevation, floodplain, and river delta location—limit land available for agriculture.

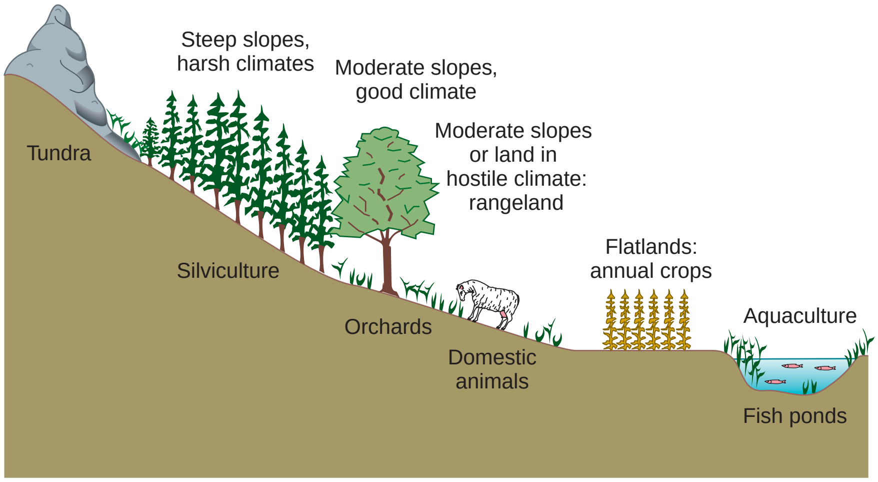


FIGURE 11.13 Land unsuitable for crop production on a sustainable basis can be used for grazing and for other purposes.

combination of different kinds of land use: using the best agricultural lands for crops, using poorer lands for pasture and rangeland.

11.4 Soils

To most of us, soils are just "dirt." But in fact soils are a key to life on the land, affecting life and affected by it. Soils develop for a very long time, perhaps thousands of years, and if you look at them closely, they are quite remarkable. You won't find anything like Earth soil on Mars or Venus or the moon. The reason is that water and life have greatly altered the land surface.

Geologically, soils are earth materials modified over time by physical, chemical, and biological processes into a series of layers. Each kind of soil has its own chemical composition. If you dig carefully into a soil so that you leave a nice, clean vertical cut, you will see the soil's layers. In a northern forest, a soil is dark at the top, then has a white powdery layer, pale as ash, then a brightly colored layer, usually much deeper than the white one and typically orangish. Below that is a soil whose color is close to that of the bedrock (which geologists call "the parent material," for obvious reasons). We call the layers *soil horizons*. The soil horizons shown in Figure 11.14 are not necessarily all present in any one soil. Very young soils may have only an upper *A* horizon over a *C* horizon, whereas mature soils may have nearly all the horizons shown.

Rainwater is slightly acid (it has a pH of about 5.5) because it has some carbon dioxide from the air dissolved in it, and this forms carbonic acid, a mild acid. As a result, when rainwater moves down into the soil, iron, calcium, magnesium, and other nutritionally important elements are leached from the upper horizons (*A* and *E*) and may be deposited in a lower horizon (*B*). The upper horizons are usually full of life and are viewed by ecologists as complex ecosystems, or ecosystem units (horizons *O* and *A*).

Within soil, decomposition is the name of the game as fungi, bacteria, and small animals live on what plants and animals on the surface produce and deposit. Bacteria and fungi, the great chemical factories of the biosphere, decompose organic compounds from the surface. Soil animals, such as earthworms, eat leaves, twigs, and other remains, breaking them into smaller pieces that are easier for the fungi and bacteria to process. In this way, the earthworms and other soil animals affect the rate of chemical reactions in the soil. There are also predators on soil animals, so there is a soil ecological food chain.

Soil *fertility* is the capacity of a soil to supply nutrients necessary for plant growth. Soils that have formed on geologically young materials are often nutrient-rich. Soils in humid areas and tropics may be heavily leached and relatively nutrient-poor due to the high rainfall. In such soils, nutrients may be cycled through the organic-rich upper horizons; and if forest cover is removed, reforestation may be very difficult. Soils that accumulate certain clay minerals in semiarid regions may swell when they get wet and shrink as they dry out, cracking roads, walls, buildings, and other structures. Expansion and contraction of soils in the United States cause billions of dollars' worth of property damage each year.

Coarse-grained soils, especially those composed primarily of sand, are particularly susceptible to erosion by water and wind. Sand and gravel have relatively large spaces between grains, so water moves through them quickly. Soils with small clay particles retain water well and retard the movement of water. Soils with a mixture of clay and sand can retain water well enough for plant growth but also drain well. Soils with a high percentage of organic

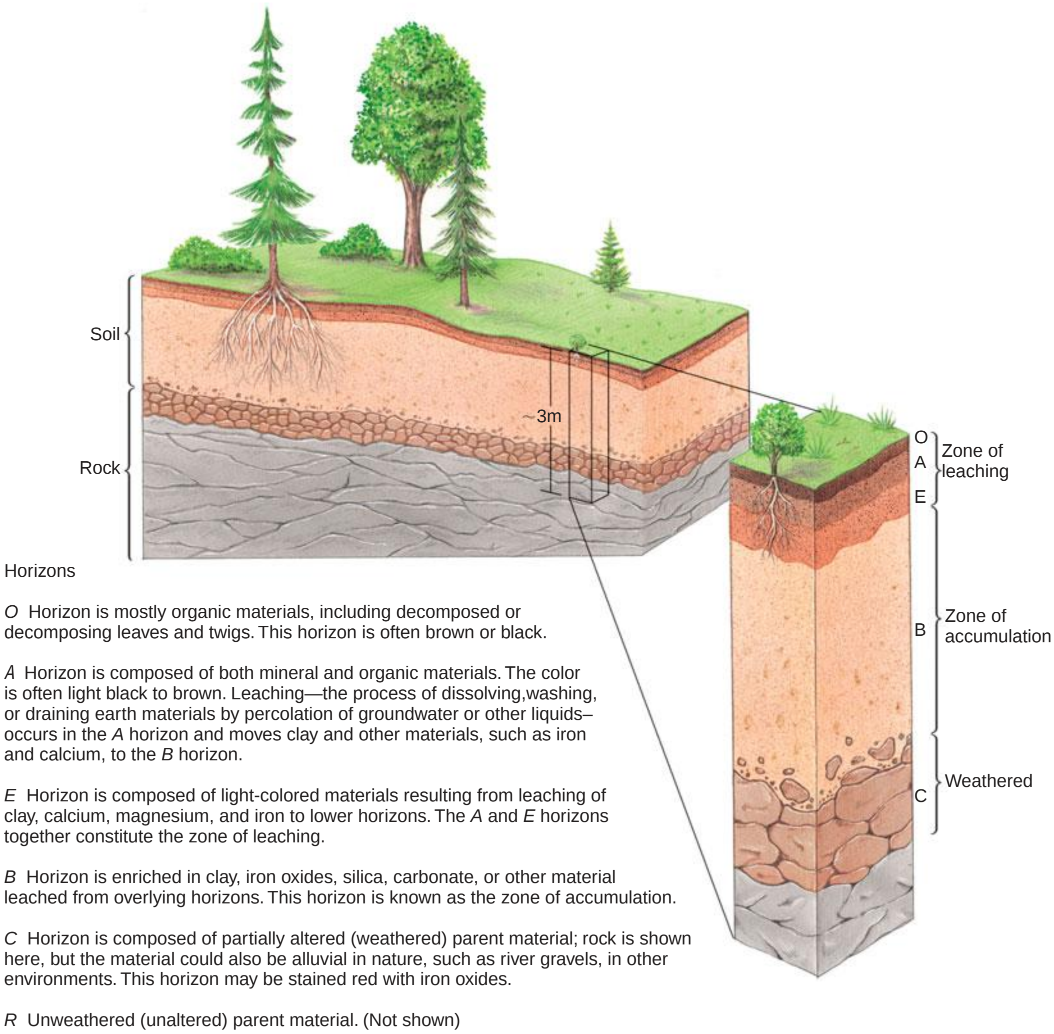


FIGURE 11.14 **Idealized diagram of a soil, showing soil horizons.**

matter also retain water and chemical nutrients for plant growth. It is an advantage to have good drainage, so a coarse-grained soil is a good place to build your house. If you are going to farm, you'll do best in a loam soil, which has a mixture of particle sizes.

Restoring Our Soils

Part of the answer to the plow puzzle that we discussed earlier in this chapter is the application of organic and inorganic fertilizer. Another part of the answer is general improvements in how plowing is done and where.

Because of improved farming practices, soil erosion has slowed 40% in the United States. According to the U.S. Department of Agriculture, "water (sheet & rill) erosion on cropland dropped from 4.0 tons per acre per year in 1982 to 2.6 tons per acre per year in 2003; wind erosion rates dropped from 3.3 to 2.1 tons per acre per year."[14]

One outstanding example is the drainage area of Coon Creek, Wisconsin, an area of 360 km^2 that has been heavily farmed for more than a century. This stream's watershed was the subject of a detailed study in the 1930s by the U.S. Soil Conservation Service, and was then restudied in the 1970s and 1990s. Measurements at these three times showed that soil erosion was only 6% of what it had been in the 1930s.[15] The bad news is that, even so, the soil is eroding faster than new soil is being generated.[16]

Fertilizers

Traditionally, farmers combated the decline in soil fertility by using organic fertilizers, such as animal manure, which improve both chemical and physical characteristics of soil. But organic fertilizers have drawbacks, especially under intense agriculture on poor soils. In such situations, they do not provide enough of the chemical elements needed to replace what is lost.

A CLOSER LOOK 11.1

The Great American Dust Bowl

Soil erosion became a national issue in the United States in the 1930s, when intense plowing, combined with a major drought, loosened the soil over large areas. The soil blew away, creating dust storms that buried automobiles and houses, destroyed many farms, impoverished many people, and led to a large migration of farmers from Oklahoma and other western and midwestern states to California. The human tragedies of the Dust Bowl were made famous by John Steinbeck's novel *The Grapes of Wrath,* later a popular movie starring Henry Fonda (Figure 11.15).

The land that became the Dust Bowl had been part of America's great prairie, where grasses rooted deep, creating a heavily organic soil a meter or more down. The dense cover provided by grass stems and the anchoring power of roots protected the soil from the erosive forces of water and wind. When the plow turned over those roots, the soil was exposed directly to sun, rain, and wind, which further loosened the soil.

FIGURE 11.15 The Dust Bowl. Poor agricultural practices and a major drought created the Dust Bowl, which lasted about ten years during the 1930s. Heavily plowed lands lacking vegetative cover blew away easily in the dry winds, creating dust storms and burying houses.

The development of industrially produced fertilizers, commonly called "chemical" or "artificial" fertilizers, was a major factor in greatly increasing crop production in the 20th century. One of the most important advances was the invention of industrial processes to convert molecular nitrogen gas in the atmosphere to nitrate that can be used directly by plants. Phosphorus, another biologically important element, is mined, usually from a fossil source that was biological in origin, such as deposits of bird guano on islands used for nesting (Figure 11.16). The scientific-industrial age brought with it mechanized mining of phosphates and their long-distance transport, which, at a cost, led to short-term increases in soil fertility. Nitrogen, phosphorus, and other elements are combined in proportions appropriate for specific crops in specific locations.

Limiting Factors

Crops require about 20 chemical elements. These must be available in the right amounts, at the right times, and in the right proportions to each other. It is customary to divide these life-important chemical elements into two groups, macronutrients and micronutrients. A **macronutrient** is a chemical element required by all living things in relatively large amounts. Macronutrients are sulfur, phosphorus, magnesium, calcium, potassium, nitrogen, oxygen, carbon, and hydrogen. A **micronutrient** is a chemical element required in small amounts—either in extremely small amounts by all forms of life or in moderate to small amounts for some forms of life. Micronutrients are often rarer metals, such as molybdenum, copper, zinc, manganese, and iron.

High-quality agricultural soil has all the chemical elements required for plant growth and also has a physical structure that lets both air and water move freely through the soil and yet retain water well. The best agricultural soils have a high organic content and a mixture of sediment particle sizes. Lowland rice grows in flooded ponds and requires a heavy, water-saturated soil, while watermelons grow best in very sandy soil. Soils rarely have everything a crop needs. The question for a farmer is: What needs to be added or done to make a soil more productive for a crop? The traditional answer is that, at any time, just one factor is limiting. If that **limiting factor** can be improved, the soil will be more productive; if that single factor is not improved, nothing else will make a difference.

The idea that some single factor determines the growth and therefore the presence of a species is known as **Liebig's law of the minimum**, after Justus von Liebig, a 19th-century agriculturalist credited with first stating this idea. A general statement of Liebig's law is: The growth of a plant is affected by one limiting factor at a time—the one whose availability is the least in comparison to the needs of a plant.

FIGURE 11.16 Boobies on a guano island stand on centuries of bird droppings. The birds feed on ocean fish and nest on islands. In dry climates, their droppings accumulate, becoming a major source of phosphorus for agriculture for centuries.

Striking cases of soil-nutrient limitations have been found in Australia—which has some of the oldest soils in the world—on land that has been above sea level for many millions of years, during which time severe leaching has taken place. Sometimes trace elements are required in extremely small amounts. For example, it is estimated that in certain Australian soils adding an ounce of molybdenum to a field increases the yield of grass by 1 ton/year. The idea of a limiting growth factor, originally used in reference to crop plants, has been extended by ecologists to include all life requirements for all species in all habitats.

If Liebig were always right, then environmental factors would always act one by one to limit the distribution of living things. But there are exceptions. For example, nitrogen is a necessary part of every protein, and proteins are essential building blocks of cells. Enzymes, which make many cell reactions possible, contain nitrogen. A plant given little nitrogen and phosphorus might not make enough of the enzymes involved in taking up and using phosphorus. Increasing nitrogen to the plant might therefore increase the plant's uptake and use of phosphorus. If this were so, the two elements would have a **synergistic effect**, in which a change in the availability of one resource affects the response of an organism to some other resource.

So far we have discussed the effects of chemical elements when they are in short supply. But it is also possible to have too much of a good thing—most chemical elements become toxic in concentrations that are too high. As a simple example, plants die when they have too little water but also when they are flooded, unless they have specific adaptations to living in water. So it is with chemical elements required for life.

11.5 Controlling Pests

From an ecological point of view, pests are undesirable competitors, parasites, or predators. The major agricultural pests are insects that feed mainly on the live parts of plants, especially leaves and stems; nematodes (small worms), which live mainly in the soil and feed on roots and other plant tissues; bacterial and viral diseases; weeds (plants that compete with the crops); and vertebrates (mainly rodents and birds) that feed on grain or fruit. Even today, with modern technology, the total losses from all pests are huge; in the United States, pests account for an estimated loss of one-third of the potential harvest and about one-tenth of the harvested crop. Preharvest losses are due to competition from weeds, diseases, and herbivores; postharvest losses are largely due to herbivores.[17]

Because a farm is maintained in a very early stage of ecological succession and is enriched by fertilizers and water, it is a good place not only for crops but also for other early-successional plants. These noncrop and therefore undesirable plants are what we call weeds. A weed is just a plant in a place we do not want it to be. There are about 30,000 species of weeds, and in any year a typical farm field is infested with between 10 and 50 of them. Some weeds can have a devastating effect on crops. For example, the production of soybeans is reduced by 60% if a weed called cocklebur grows three individuals per meter (one individual per foot).[18]

Pesticides

Before the Industrial Revolution, farmers could do little to prevent pests except remove them or use farming methods that tended to decrease their density. Pre-industrial farmers planted aromatic herbs and other vegetation that repels insects.

The scientific industrial revolution brought major changes in agriculture pest control, which we can divide into four stages:

Stage 1: Broad-Spectrum Inorganic Toxins

With the beginning of modern science-based agriculture, people began to search for chemicals that would reduce the abundance of pests. Their goal was a "magic bullet"—a chemical (referred to as a narrow-spectrum pesticide) that would have a single target, just one pest, and not affect anything else. But this proved elusive. The earliest pesticides were simple inorganic compounds that were widely toxic. One of the earliest was arsenic, a chemical element toxic to all life, including people. It was certainly effective in killing pests, but it killed beneficial organisms as well and was very dangerous to use.

Stage 2: Petroleum-Based Sprays and Natural Plant Chemicals (1930s on)
Many plants produce chemicals as a defense against disease and herbivores, and these chemicals are effective pesticides. Nicotine, from the tobacco plant, is the primary agent in some insecticides still widely used today. However, although natural plant pesticides are comparatively safe, they were not as effective as desired.

Stage 3: Artificial Organic Compounds
Artificial organic compounds have created a revolution in agriculture, but they have some major drawbacks (see Risk–Benefit Analysis in Chapter 7). One problem is secondary pest outbreaks, which occur after extended use (and possibly because of extended use) of a pesticide. Secondary pest outbreaks can come about in two ways: (1) Reducing one target species reduces competition with a second species, which then flourishes and becomes a pest, or (2) the pest develops resistance to the pesticides through evolution and natural selection, which favor those who have a greater immunity to the chemical. Resistance has developed to many pesticides. For example, Dasanit (fensulfothion), an organophosphate first introduced in 1970 to control maggots that attack onions in Michigan, was originally successful but is now so ineffective that it is no longer used for that crop.

Some artificial organic compounds, such as DDT, are broad-spectrum, but more effective than natural plant chemicals. However, they also have had unexpected environmental effects. For example, aldrin and dieldrin have been widely used to control termites as well as pests on corn, potatoes, and fruits. Dieldrin is about 50 times as toxic to people as DDT. These chemicals are designed to remain in the soil and typically do so for years. Therefore, they have spread widely.

World use of pesticides exceeds 2.5 billion kg (5 billion pounds), and in the United States it exceeds 680 million kg (1,200 million pounds) (Figure 11.17). The total amount paid for these pesticides is \$32 billion worldwide and \$11 billion in the United States.[12] But the magic bullet has remained elusive. Once applied, these chemicals may decompose in place or may be blown by the wind or transported by surface and subsurface waters, meanwhile continuing to decompose. Sometimes the initial breakdown products (the first, still complex chemicals produced from the original pesticides) are toxic, as is the case with DDT. Eventually, the toxic compounds are decomposed to their original inorganic or simple, nontoxic organic compounds, but for some chemicals this can take a very long time.

Public-health standards and environmental-effects standards have been established for some of these compounds. The United States Geological Survey has established a network for monitoring 60 sample watersheds throughout the nation. These are medium-size watersheds, not the entire flow from the nation's major rivers. One such watershed is that of the Platte River, a major tributary of the Missouri River.

The most common herbicides used for growing corn, sorghum, and soybeans along the Platte River were alachlor, atrazine, cyanazine, and metolachlor, all organonitrogen herbicides. Monitoring of the Platte near Lincoln, Nebraska, suggested that during heavy spring runoff, concentrations of some herbicides might be reaching or exceeding established public-health standards. But this research is just beginning, and it is difficult to reach definitive conclusions as to whether present concentrations are causing harm in public water supplies or to wildlife, fish, algae in freshwater, or vegetation. Advances in knowledge give us much more information, on a more regular basis, about how much of many artificial compounds are in our waters, but we are still unclear about their environmental effects. A wider and better program to monitor pesticides in water and soil is important to provide a sound scientific basis for dealing with pesticides.

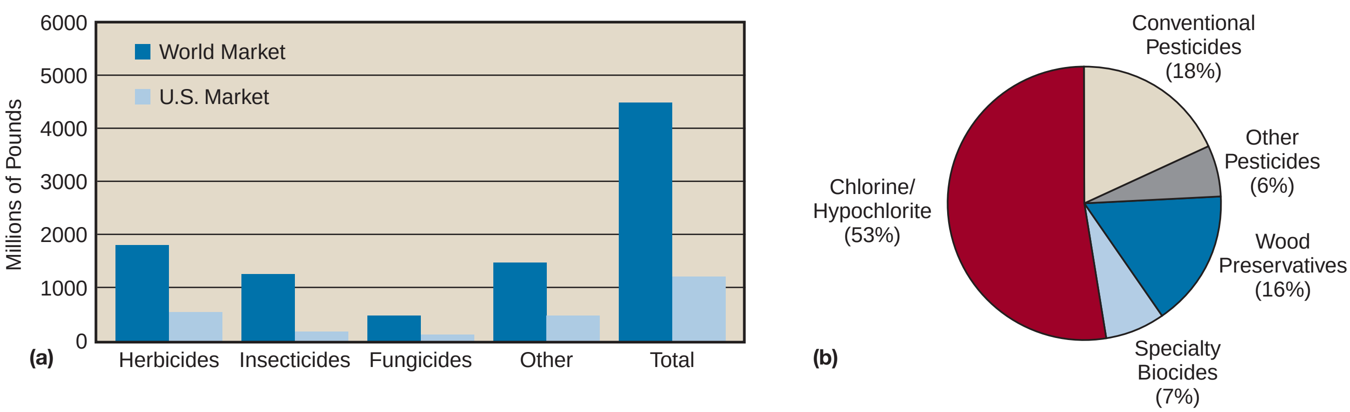


FIGURE 11.17 **World use of pesticides.** **(a)** Total amounts, **(b)** percentage by main type. (*Sources*: EPA [2006]."2000–2001Pesticide Market Esimates: Usage.")

Stage 4: Integrated Pest Management and Biological Control

Integrated pest management (IPM) uses a combination of methods, including biological control, certain chemical pesticides, and some methods of planting crops (Figure 11.18). A key idea underlying IPM is that the goal can be control rather than complete elimination of a pest. This is justified for several reasons. Economically, it becomes more and more expensive to eliminate a greater and greater percentage of a pest, while the value of ever-greater elimination, in terms of crops to sell, becomes less and less. This suggests that it makes economic sense to eliminate only enough to provide benefit and leave the rest. In addition, allowing a small but controlled portion of a pest population to remain does less damage to ecosystems, soils, water, and air.

Integrated pest management also moves away from monoculture growing in perfectly regular rows. Studies have shown that just the physical complexity of a habitat can slow the spread of parasites. In effect, a pest, such as a caterpillar or mite, is trying to find its way through a maze. If the maze consists of regular rows of nothing but what the pest likes to eat, the maze problem is easily solved by the dumbest of animals. But if several species, even two or three, are arranged in a more complex pattern, pests have a hard time finding their prey.

No-till or low-till agriculture is another feature of IPM because this helps natural enemies of some pests to build up in the soil, whereas plowing destroys the habitats of these enemies.

Biological control includes using one species that is a natural enemy of another. One of the most effective is the bacterium ***Bacillus thuringiensis***, known as BT, which causes a disease that affects caterpillars and the larvae of other insect pests. Spores of BT are sold commercially—you can buy them at your local garden store and use them in your home garden. BT has been one of the most important ways to control epidemics of gypsy moths, an introduced moth whose larvae periodically strip most of the leaves from large areas of forests in the eastern United States. BT has proved safe and effective—safe because it causes disease only in specific insects and is harmless to people and other mammals, and because, as a natural biological "product," its presence and its decay are nonpolluting.

Another group of effective biological-control agents are small wasps that are parasites of caterpillars. Control of the oriental fruit moth, which attacks a number of fruit crops, is an example of IPM biological control. The moth was found to be a prey of a species of wasp, *Macrocentrus ancylivorus*, and introducing the wasp into fields helped control the moth. Interestingly, in peach fields the wasp was more effective when strawberry fields were nearby. The strawberry fields provided an alternative habitat for the wasp, especially important for overwintering.[9] As this example shows, spatial complexity and biological diversity also become parts of the IPM strategy.

In the list of biological-control species we must not forget ladybugs, which are predators of many pests. You can buy these, too, at many garden stores and release them in your garden.

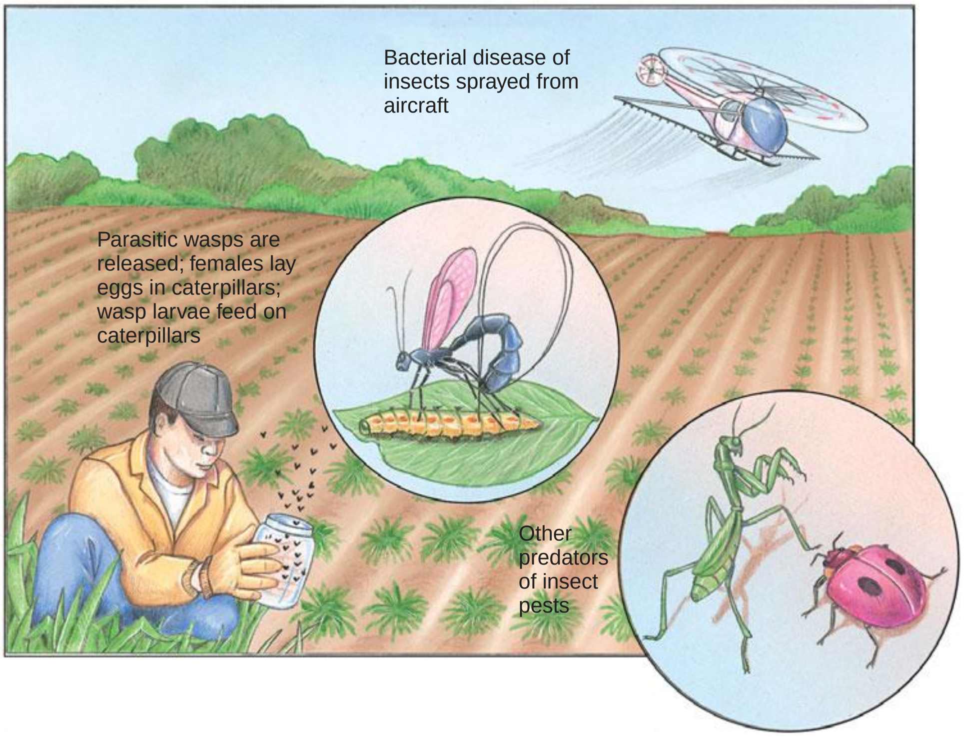


FIGURE 11.18 Integrated pest management. The goal is to reduce the use of artificial pesticides, reduce costs, and efficiently control pests.

Another biological control uses sex pheromones, chemicals released by most species of adult insects (usually the female) to attract members of the opposite sex. In some species, pheromones have been shown to be effective up to 4.3 km (2.7 mi) away. These chemicals have been identified, synthesized, and used as bait in insect traps, in insect surveys, or simply to confuse the mating patterns of the insects involved.

While biological control works well, it has not solved all problems with agricultural pests. As for artificial pesticides, although they are used in integrated pest management, they are used along with the other techniques, so the application of these pesticides can be sparing and specific. This would also greatly reduce the costs to farmers for pest control.

11.6 The Future of Agriculture

Today, there are three major technological approaches to agriculture. One is modern mechanized agriculture, where production is based on highly mechanized technology that has a high demand for resources—including land, water, and fuel—and makes little use of biologically-based technologies. Another approach is resource-based—that is, agriculture based on biological technology and conservation of land, water, and energy. An offshoot of this second approach is organic food production—growing crops without artificial chemicals (including pesticides) or genetic engineering but instead using ecological control methods. The third approach is genetic engineering.

In mechanized agriculture, production is determined by economic demand and limited by that demand, not by resources. In resource-based agriculture, production is limited by environmental sustainability and the availability of resources, and economic demand usually exceeds production.

With these methods in mind, we can consider what can be done to help crop production keep pace with human population growth. Here are some possibilities.

Increased Production per Acre

Some agricultural scientists and agricultural corporations believe that production per unit area will continue to increase, partially through advances in genetically modified crops. This new methodology, however, raises some important potential environmental problems, which we will discuss later. Furthermore, increased production in the past has depended on increased use of water and fertilizers. Water is a limiting factor in many parts of the world and will become a limiting factor in more areas in the future.

Increased Farmland Area

A United Nations Food and Agriculture Organization conference held in early 2008 considered the coming world food crisis. It was reported that 23 million hectares (more than 46 million acres) of farmland had been withdrawn from production in Eastern Europe and the Commonwealth of Independent States (CIS) region, especially in countries such as Kazakhstan, Russia, and Ukraine, and that at least half—13 million hectares (15 million acres)—could be readily put back into production with little environmental effect.[19] This would be like adding all the farmland in Iowa, Illinois, and Indiana.[20]

The need for additional farmland brings up, once again, the problem that agrifuels bring to agriculture: taking land away from food production to produce fuels instead.

New Crops and Hybrids

Since there are so many plant species, perhaps some yet unused ones could provide new sources of food and grow in environments little used for agriculture. Those interested in conserving biological diversity urge a search for such new crops on the grounds that this is one utilitarian justification for the conservation of species. It is also suggested that some of these new crops may be easier on the environment and therefore more likely to allow sustainable agriculture. But it may be that over the long history of human existence those species that are edible have already been found, and the number is small. Research is under way to seek new crops or plants that have been eaten locally but whose potential for widespread, intense cultivation has not been tested.

Among the likely candidates for new crops are amaranth for seeds and leaves; *Leucaena*, a legume useful for animal feed; and triticale, a synthetic hybrid of wheat and rye.[21] A promising source of new crops is the desert; none of the 14 major crops are plants of arid or semiarid regions, yet there are vast areas of desert and semidesert. The United States has 200,000 million hectares (about 500,000 million acres) of arid and semiarid rangeland. In Africa, Australia, and South America, the areas are even greater. Several species of plants can be grown commercially under arid conditions, allowing us to use a biome for agriculture that has been little used in this way in the past. Examples of these species are guayule (a source of rubber), jojoba (for oil), bladderpod (for oil from seeds), and gumweed (for resin). Jojoba, a native shrub of the American Sonoran Desert, produces an extremely fine oil, remarkably resistant to bacterial degradation, which is useful in cosmetics and as a fine lubricant. Jojoba is now grown commercially in Australia, Egypt, Ghana, Iran, Israel, Jordan, Mexico, Saudi Arabia, and the United States.[22] Although these examples are not food crops, they release other lands, now used to produce similar products, to grow food.

FIGURE 11.19 Experimental rice plots at the International Rice Research Institute, Philippines, showing visual crop variation based on the use of fertilizers.

Among the most successful developments of new hybrids have been those developed by the **green revolution**, the name attached to post–World War II programs that have led to the development of new strains of crops with higher yields, better resistance to disease, or better ability to grow under poor conditions. These crops include superstrains of rice (at the International Rice Research Institute in the Philippines) (see Figure 11.19) and strains of maize with improved disease resistance (at the International Maize and Wheat Improvement Center in Mexico).

Better Irrigation

Drip irrigation—from tubes that drip water slowly—greatly reduces the loss of water from evaporation and increases yield. However, it is expensive and thus most likely to be used in developed nations or nations with a large surplus of hard currency—in other words, in few of the countries where hunger is most severe.

Organic Farming

Organic farming is typically considered to have three qualities: It is more like natural ecosystems than monoculture; it minimizes negative environmental impacts; and the food that results from it does not contain artificial compounds. According to the U.S. Department of Agriculture (USDA), organic farming has been one of the fastest-growing sectors in U.S. agriculture, although it still occupies a small fraction of U.S. farmland and contributes only a small amount of agriculture income. By the end of the 20th century it amounted to about $6 billion—much less than the agricultural production of California.

In the 1990s, the number of organic milk cows rose from 2,300 to 12,900, and organic layer hens increased from 44,000 to more than 500,000. In the United States only 0.01% of the land planted in corn and soybeans used certified organic farming systems in the mid-1990s; about 1% of dry peas and tomatoes were grown organically, and about 2% of apples, grapes, lettuce, and carrots. On the high end, nearly one-third of U.S. buckwheat, herb, and mixed vegetable crops were grown under organic farming conditions.[23] USDA certification of organic farming became mandatory in 2002. After that, organic cropland that was listed as certified more than doubled, and the number of farmers certifying their products rose 40%. In the United States today, more than 1.3 million acres are certified as organic. There are about 12,000 organic farmers in the United States, and the number is growing 12% per year.[24]

Eating Lower on the Food Chain

Some people believe it is ecologically unsound to use domestic animals as food, on the grounds that eating each step farther up a food chain leaves much less food to eat per acre. This argument is as follows: No organism is 100% efficient; only a fraction of the energy in food taken in is converted to new organic matter. Crop plants may convert 1–10% of sunlight to edible food, and cows may convert only 1–10% of hay and grain to meat. Thus, the same area could produce 10 to 100 times more vegetation than meat per year. This holds true for the best agricultural lands, which have deep, fertile soils on level ground.

11.7 Genetically Modified Food: Biotechnology, Farming, and Environment

The discovery that DNA is the universal carrier of genetic information has led to development and use of genetically modified crops, which has given rise to new environmental controversies as well as a promise of increased agricultural production.

Genetic engineering in agriculture involves several different practices, which we can group as follows: (1) faster and more efficient ways to develop new hybrids; (2) introduction of the "terminator gene"; and (3) transfer of genetic properties from widely divergent kinds of life. These three practices have quite different potentials and problems. We need to keep in mind a general rule of environmental actions, the rule of natural change: If actions we take are similar in kind and frequency to natural changes, then the effects on the environment are likely to be benign. This is because species have had a long time to evolve and adapt to these changes. In contrast, changes that are novel—that do not occur in nature—are more likely to have negative or undesirable environmental effects, both direct and indirect. We can apply this rule to the three categories of genetically engineered crops.

The jury is out as to whether the benefits of genetically modified crops will outweigh undesirable effects. As with many new technologies of the industrial age, application has preceded environmental investigation and understanding, and the widespread use of **genetically modified crops** (GMCs) is under way before the environmental effects are well understood. The challenge for environmental science is to gain an understanding of environmental effects of GMCs quickly.

New Hybrids

The development of hybrids within a species is a natural phenomenon, and the development of hybrids of major crops, especially of small grains, has been a major factor in the great increase in productivity of 20th-century agriculture. So, strictly from an environmental perspective, genetic engineering to develop hybrids within a species is likely to be as benign as the development of agricultural hybrids has been with conventional methods.

There is an important caveat, however. Some people are concerned that the great efficiency of genetic modification methods may produce "superhybrids" that are so productive they can grow where they are not wanted and become pests. There is also concern that some of the new hybrid characteristics could be transferred by interbreeding with closely related weeds. This could inadvertently create a "superweed" whose growth, persistence, and resistance to pesticides would make it difficult to control. Another environmental concern is that new hybrids might be developed that could grow on more and more marginal lands. Raising crops on such marginal lands might increase erosion and sedimentation and lead to decreased biological diversity in specific biomes. Still another potential problem is that "superhybrids" might require much more fertilizer, pesticide, and water. This could lead to greater pollution and the need for more irrigation.

On the positive side, genetic engineering could lead to hybrids that require less fertilizer, pesticide, and water. For example, right now only legumes (peas and their relatives) have symbiotic relationships with bacteria and fungi that allow them to fix nitrogen. Attempts are under way to transfer this capability to other crops, so that more kinds of crops would enrich the soil with nitrogen and require much less external application of nitrogen fertilizer.

The Terminator Gene

The **terminator gene** makes seeds from a crop sterile. This is done for environmental and economic reasons. In theory, it prevents a genetically modified crop from spreading. It also protects the market for the corporation that developed it: Farmers cannot avoid purchasing seeds by using some of their crops' hybrid seeds the next year. But this poses social and political problems. Farmers in less-developed nations, and governments of nations that lack genetic-engineering capabilities, are concerned that the terminator gene will allow the United States and a few of its major corporations to control the world food supply. Concerned observers believe that farmers in poor nations must be able to grow next year's crops from their own seeds because they cannot afford to buy new seeds every year. This is not directly an environmental problem, but it can become an environmental problem indirectly by affecting total world food production, which then affects the human population and how land is used in areas that have been in agriculture.

Transfer of Genes from One Major Form of Life to Another

Most environmental concerns have to do with the third kind of genetic modification of crops: the transfer of genes from one major kind of life to another. This is a novel effect and, as we have explained, therefore more likely to have undesirable results. In several cases, in fact, this type of genetic modification has affected the environment in unforeseen and undesirable ways. Perhaps the best-known involves potatoes and corn, caterpillars that eat these crops, a disease of caterpillars that controls these pests, and an endangered species, monarch butterflies. Here is what happened.

As discussed earlier, the bacterium *Bacillus thuringiensis* is a successful pesticide that causes a disease in many caterpillars. With the development of biotechnology, agricultural scientists studied the bacteria and discovered the toxic chemical and the gene that caused its production within the bacteria. This gene was then transferred to potatoes and corn so that the biologically engineered plants produced their own pesticide. At first, this was believed to be a constructive step in pest control because it was no longer necessary to spray a pesticide. However, the genetically engineered potatoes and corn produced the toxic BT substance in every cell—not just in the leaves that the caterpillars ate, but also in the potatoes and corn sold as food, in the flowers, and in the pollen. This has a potential, not yet demonstrated, to create problems for species that are not intended targets of the BT (Figure 11.20).

A strain of rice has been developed that produces beta-carotene, important in human nutrition. The rice thus has added nutritional benefits that are particularly valuable for the poor of the world who depend on rice as a primary food. The gene that enables rice to make beta-carotene comes from daffodils, but the modification actually required the introduction of four specific genes and would likely be impossible without genetic-engineering techniques. That is, genes were transferred between plants that would not exchange genes in nature. Once again, the rule of natural change suggests that we should monitor such actions carefully. Indeed, although the genetically modified rice appears to have beneficial effects, the government of India has refused to allow it to be grown in that country.[15]

There is much concern worldwide about the political, social, and environmental effects of genetic modification of crops. This is a story in process, one that will change rapidly in the next few years. You can check on these fast-moving events on the textbook's Web site.

(a)


Bacillus thuringiensis bacteria (a natural pecticide). The gene that caused the pecticide (BT) was placed in corn through genetic engineering.

(b)


BT corn contains its own pesticide in every cell of the plant.

(c)


Pollen from the BT corn is also toxic and when it lands on milkweed, monarch butterflies that eat the milkweed may die.

FIGURE 11.20 The flow of the BT toxin from bacteria **(a)** to corn through genetic engineering **(b)** and the possible ecological transfer of toxic substances to monarch butterflies **(c)**.

11.8 Aquaculture

In contrast to food obtained on land, we still get most of our marine and freshwater food by hunting. Hunting wild fish has not been sustainable (see Chapter 13), and thus **aquaculture**, the farming of this important source of protein in both marine and freshwater habitats, is growing rapidly and could become one of the major ways to provide food of high nutritional quality. Popular aquacultural animals include carp, tilapia, oysters, and shrimp, but in many nations other species are farm-raised and culturally important, such as yellowtail (important in Japan and perhaps just one of several species); crayfish (United States); eels and minnows (China); catfish (southern and midwestern United States); salmon (Canada, Chile, Norway, and the United States); trout (United States); plaice, sole, and the Southeast Asian milkfish (Great Britain); mussels (Canada, France, Spain, and Southeast Asian countries); and sturgeon (Ukraine). A few species—trout and carp—have been subject to genetic breeding programs.[25]

Although relatively new in the United States, aquaculture has a long history elsewhere, especially in China, where at least 50 species are grown, including finfish, shrimp, crab, other shellfish, sea turtles, and sea cucumbers (not a vegetable but a marine animal).[14] In the Szechuan area of China, fish are farmed on more than 100,000 hectares (about 250,000 acres) of flooded rice fields. This is an ancient practice that can be traced back to a treatise on fish culture written by Fan Li in 475 B.C.[14] In China and other Asian countries, farmers often grow several species of fish in the same pond, exploiting their different ecological niches. Ponds developed mainly for carp, a bottom-feeding fish, also contain minnows, which feed at the surface on leaves added to the pond.

Aquaculture can be extremely productive on a per-area basis, in part because flowing water brings food from outside into the pond or enclosure. Although the area of Earth that can support freshwater aquaculture is small, we can expect this kind of aquaculture to increase and become a more important source of protein.

Sometimes fishponds use otherwise wasted resources, such as fertilized water from treated sewage. Other fishponds exist in natural hot springs (Idaho) or use water warmed by being used to cool electric power plants (Long Island, New York; Great Britain).[14]

Mariculture, the farming of ocean fish, though producing a small part of the total marine fish catch, has grown rapidly in the last decades and will likely continue to do so. Oysters and mussels are grown on rafts lowered into the ocean, a common practice in the Atlantic Ocean in Portugal and in the Mediterranean in such nations as France. These animals are filter feeders—they obtain food from water that moves past them. Because a small raft is exposed to a large volume of water, and thus a large volume of food, rafts can be extremely productive. Mussels grown on rafts in bays of Galicia, Spain, produce 300 metric tons per hectare, whereas public harvesting grounds of wild shellfish in the United States yield only about 10 kg/ha (that's just a hundredth of a metric ton).[14] Oysters and mussels are grown on artificial pilings in the intertidal zone in the state of Washington (Figure 11.21).

FIGURE 11.21 **An oyster farm in Poulsbo, Washington.** Oysters are grown on artificial pilings in the intertidal zone.

Some Negatives

Although aquaculture has many benefits and holds great promise for our food supply, it also causes environmental problems. Fishponds and marine fish kept in shallow enclosures connected to the ocean release wastes from the fish and chemicals such as pesticides, polluting local environments. In some situations, aquaculture can damage biological diversity. This is a concern with salmon aquaculture in the Pacific Northwest, where genetic strains not native to a stream are grown and some are able to mix with wild populations and breed. Problems with salmon aquaculture demonstrate the need for improved methods and greater care about environmental effects.

CRITICAL THINKING ISSUE

Will There Be Enough Water to Produce Food for a Growing Population?

Between 2000 and 2025, scientists estimate, the world population will increase from 6.6 billion to 7.8 billion, approximately double what it was in 1974. To keep pace with the growing population, the United Nations Food and Agriculture Organization predicts, that food production will have to double by 2025, and so will the amount of water consumed by food crops. Will the supply of freshwater be able to meet this increased demand, or will the water supply limit global food production?

Growing crops consume water through transpiration (loss of water from leaves as part of the photosynthetic process) and evaporation from plant and soil surfaces. The volume of water consumed by crops worldwide—including rainwater and irrigated water—is estimated at 3,200 billion m^3 per year. An almost equal amount of water is used by other plants in and near agricultural fields. Thus, it takes 7,500 billion m^3 per year of water to supply crop ecosystems around the world (see Table 11.2). Grazing and pastureland account for another 5,800 billion m^3, and evaporation from irrigated water another 500 billion m^3, for a total of 13,800 billion m^3 of water per year for food production, or 20% of the water evaporated and transpired worldwide. By 2025, therefore, humans will be appropriating almost half of all the water available to life on land for growing food for their own use. Where will the additional water come from?

Table 11.2 ESTIMATED WATER REQUIREMENTS OF FOOD AND FORAGE CROPS

CROP	LITERS/KG
Potatoes	500
Wheat	900
Alfalfa	900
Sorghum	1,110
Corn	1,400
Rice	1,912
Soybeans	2,000
Broiler chicken	3,500*
Beef	100,000*

* Includes water used to raise feed and forage.

Source: D. Pimentel et al., "Water Resources: Agriculture, the Environment, and Society," *Bioscience* 4, no. 2 [February 1997]: 100.

Although the amount of rainwater cannot be increased, it can be used more efficiently through farming methods such as terracing, mulching, and contouring. Forty percent of the global food harvest now comes from irrigated land, and some scientists estimate that the volume of irrigation water available to crops will have to triple by 2025—to a volume equaling 24 Nile rivers or 110 Colorado rivers.[26] A significant saving of water can therefore come from more efficient irrigation methods, such as improved sprinkler systems, drip irrigation, night irrigation, and surge flow.

Surge flow is the intermittent application of water along furrows—on and off periods of water flow at constant or variable intervals. Often, this can completely irrigate a crop in much less time and therefore wastes much less water than does constant irrigation, which allows much more time for water to evaporate. Surge flow is also useful for young plants, which need only a small amount of water.

Additional water could be diverted from other uses to irrigation, but this might not be as easy as it sounds because of competing needs for water. For example, if water were provided to the 1 billion people in the world who currently lack drinking and household water, less would be available for growing crops. And the new billions of people to be added to the world population in the next decades will also need water. People already use 54% of the world's runoff. Increasing this to more than 70%, as will be required to feed the growing population, may result in a loss of freshwater ecosystems, decline in world fisheries, and extinction of aquatic species.

In many places, groundwater and aquifers are being used faster than they are being replaced—a process that is unsustainable in the long run. Many rivers are already so heavily used that they release little or no water to the ocean. These include the Ganges and most other rivers in India, the Huang He (Yellow River) in China, the Chao Phraya in Thailand, the Amu Darya and Syr Darya in the Aral Sea basin, and the Nile and Colorado rivers.

Two hundred years ago, Thomas Malthus put forth the proposition that population grows more rapidly than the ability of the soil to grow food and that at some time the human population will outstrip the food supply. Malthus might be surprised to know that by applying science and technology to agriculture, food production has so far kept pace with population growth. For example, between 1950 and 1995, the world population increased 122% while grain productivity increased 141%. Since 1995, however, grain production has slowed down (see Figure 11.22), and the question remains whether Malthus will be proved right in the 21st century. Will science and technology be able to solve the problem of water supply for growing food for people, or will water prove a limiting factor in agricultural production?

Critical Thinking Questions

1. How might dietary changes in developed countries affect water availability?
2. How might global warming affect estimates of the amount of water needed to grow crops in the 21st century?
3. Withdrawing water from aquifers faster than the replacement rate is sometimes referred to as "mining water." Why do you think this term is used?
4. Many countries in warm areas of the world are unable to raise enough food, such as wheat, to supply their populations. Consequently, they import wheat and other grains. How is this equivalent to importing water?
5. Malthusians are those who believe that sooner or later, unless population growth is checked, there will not be enough food for the world's people. Anti-Malthusians believe that technology will save the human race from a Malthusian fate. Analyze the issue of water supply for agriculture from both points of view.

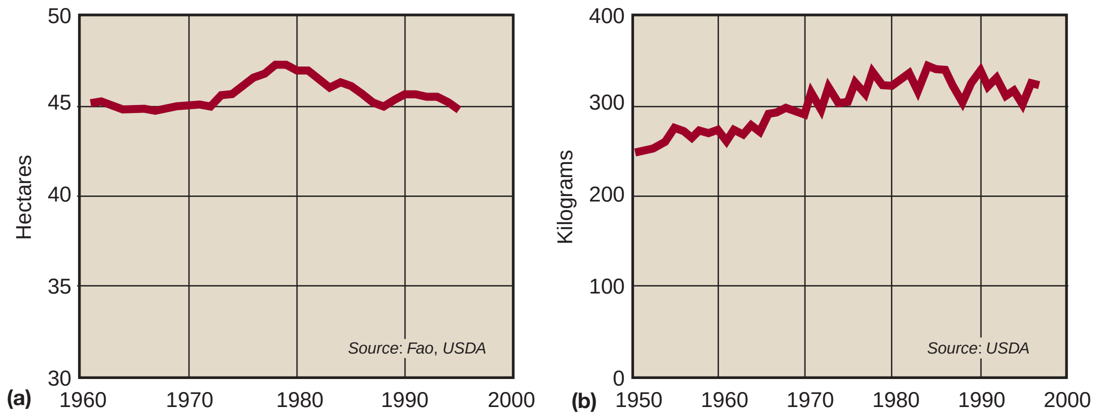


FIGURE 11.22 **(a) World irrigated area per thousand people, 1961–95.** (*Source*: L.R. Brown, M. Renner, and C. Flavin, *Vital Signs: 1998* [New York: Norton, 1998], p. 47.) **(b)** World grain production per person, 1950–1977. (*Source*: Brown, Renner, and Flavin, *Vital Signs*, p. 29.)

SUMMARY

- Agriculture changes the environment; the more intense the agriculture, the greater the changes.
- From an ecological perspective, agriculture is an attempt to keep an ecosystem in an early-successional stage.
- Farming greatly simplifies ecosystems, creating short and simple food chains, growing a single species or genetic strain in regular rows in large areas, reducing species diversity and reducing the organic content and overall fertility of soils.
- These simplifications open farmed land to predators and parasites, increased soil loss, erosion, and, thus, downstream sedimentation, and increased pollution of soil and water with pesticides, fertilizers, and heavy metals concentrated by irrigation.
- The history of agriculture can be viewed as a series of attempts to overcome environmental limitations and problems. Each new solution has created new environmental problems, which have in turn required their own solutions.
- The Industrial Revolution and the rise of agricultural sciences have revolutionized agriculture in two areas—one ecological and the other genetic—with many benefits and some serious drawbacks.
- Modern fertilizers, irrigation methods, and hybridization have greatly increased the yield per unit area. Modern chemistry has led to the development of a wide variety of pesticides that have reduced, though not eliminated, the loss of crops to weeds, diseases, and herbivores, but these have also had undesirable environmental effects. In the future, pest control will be dominated by integrated pest management.

- Most 20th-century agriculture has relied on machinery and the use of abundant energy, with relatively little attention paid to the loss of soils, the limits of groundwater, and the negative effects of chemical pesticides.
- Overgrazing has severely damaged lands. It is important to properly manage livestock, including using appropriate lands for grazing and keeping livestock at a sustainable density.

REEXAMINING THEMES AND ISSUES

Human Population

Agriculture is the world's oldest and largest industry; more than one-half of all the people in the world still live on farms. Because the production, processing, and distribution of food alter the environment, and because of the size of the industry, large effects on the environment are unavoidable.

Sustainability

Alternative agricultural methods appear to offer the greatest hope of sustaining agricultural ecosystems and habitats over the long term, but more tests and better methods are needed. As the experience with European agriculture shows, crops can be produced on the same lands for thousands of years as long as sufficient fertilizers and water are available; however, the soils and other aspects of the original ecosystem are greatly changed—these are not sustained. In agriculture, production can be sustained, but the ecosystem may not be.

Global Perspective

Agriculture has numerous global effects. It changes land cover, affecting climate at regional and global levels, increasing carbon dioxide in the atmosphere, and adding to the buildup of greenhouse gases, which in turn affects climate. Fires to clear land for agriculture may significantly affect the climate by adding small particulates to the atmosphere. Genetic modification is a new global issue that has not only environmental but also political and social effects.

Urban World

The agricultural revolution makes it possible for fewer and fewer people to produce more and more food and leads to greater productivity per acre. Freed from dependence on farming, people flock to cities, which leads to increased urban effects on the land. Thus, agricultural effects on the environment indirectly extend to the cities.

People and Nature

Farming is one of the most direct and large-scale ways that people affect nature. Our own sustainability, as well as the quality of our lives, depends heavily on how we farm.

Science and Values

Human activities have seriously damaged one-fourth of the world's total land area, impacting one-sixth of the world's population (about 1 billion people). Overgrazing, deforestation, and destructive farming practices have caused so much damage that recovery in some areas will be difficult, and restoration of the rest will require serious actions. A major value judgment we must make in the future is whether our societies will allocate funds to restore these damaged lands. Restoration requires scientific knowledge, both about present conditions and about actions required for restoration. Will we seek this knowledge and pay for it?

KEY TERMS

agroecosystem **213**
aquaculture **230**
biological control **226**
genetically modified crops **229**
green revolution **228**
integrated pest management **226**
Liebig's law of the minimum **223**
limiting factor **223**
macronutrient **223**
malnourishment **216**
mariculture **230**
micronutrient **223**
monoculture **214**
organic farming **228**
pasture **218**
rangeland **218**
synergistic effect **224**
terminator gene **229**
undernourishment **216**

STUDY QUESTIONS

1. Design an integrated pest management scheme for a small vegetable garden in a city lot behind a house. How would this scheme differ from integrated pest management used on a large farm? What aspects of IPM could not be used? How might the artificial structures of a city be put to use to benefit IPM?

2. Under what conditions might grazing cattle be sustainable when growing wheat is not? Under what conditions might a herd of bison provide a sustainable supply of meat when cows might not?

4. Pick one of the nations in Africa that has a major food shortage. Design a program to increase its food production. Discuss how reliable that program might be given the uncertainties that nation faces.

5. Should genetically modified crops be considered acceptable for "organic" farming?

6. You are about to buy your mother a bouquet of 12 roses for Mother's Day, but you discover that the roses were genetically modified to give them a more brilliant color and to produce a natural pesticide through genetic energy. Do you buy the flowers? Explain and justify your answer based on the material presented in this chapter.

7. A city garbage dump is filled, and it is suggested that the area be turned into a farm. What factors in the dump might make it a good area to farm, and what might make it a poor area to farm?

8. You are sent into the Amazon rain forest to look for new crop species. In what kinds of habitats would you look? What kinds of plants would you look for?

FURTHER READING

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CHAPTER 12

Landscapes: Forests, Parks, and Wilderness

A long line of trucks in Malaysia carrying logs from tropical rain forests. As land ownership changes in the United States, American corporations have purchased more and more forestland in less-developed parts of the world.

LEARNING OBJECTIVES

Forests and parks are among our most valued resources. Their conservation and management require that we understand landscapes—a larger view that includes populations, species, and groups of ecosystems connected together. After reading this chapter, you should understand . . .

- What ecological services are provided by landscapes of various kinds;
- The basic principles of forest management, including its historical context;
- The basic conflicts over forest ownership.
- The basic principles of park management;
- The roles that parks and nature preserves play in the conservation of wilderness.

CASE STUDY

Jamaica Bay National Wildlife Refuge: Nature and the Big City

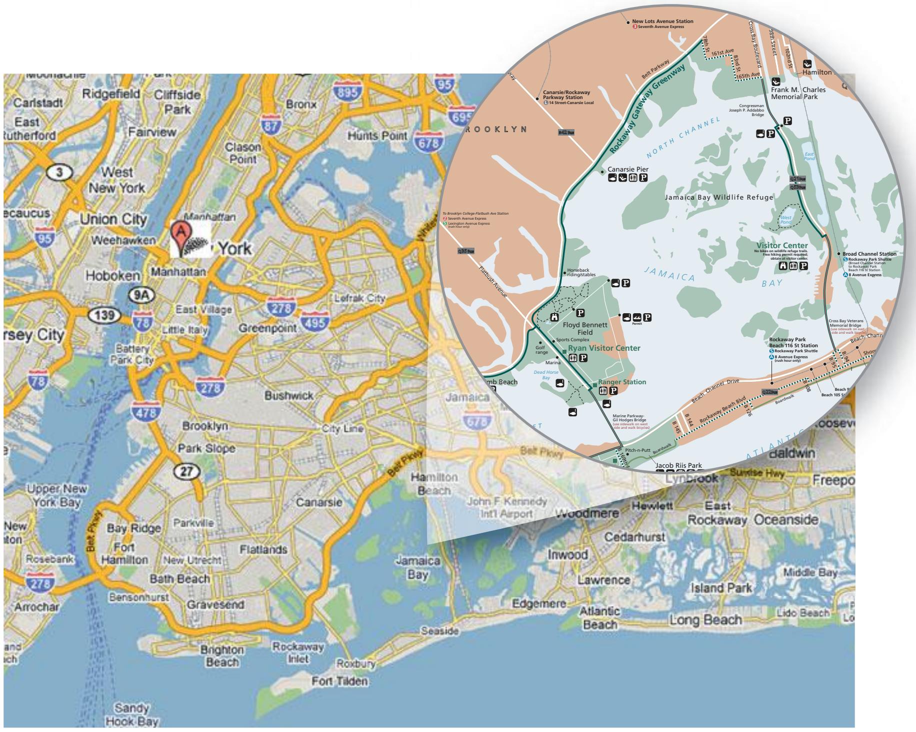
The largest bird sanctuary in the northeastern United States is—surprise!—in New York City. It is the Jamaica Bay Wildlife Refuge, covering more than 9,000 acres—14 square miles of land, 20,000 acres in total, within view of Manhattan's Empire State Building (see Figure 12.1). Jamaica Bay is run by the National Park Service, and you can get there by city bus or subway.[1] More than 300 bird species have been seen there, including the glossy ibis, common farther south, and the curlew sandpiper, which breeds in northern Siberia. Clearly, this wildlife refuge, like the city itself, is a major transportation crossroads. In fact, it is one of the major stopovers on the Atlantic bird migration flyway.

We are not as likely to think of viewing nature near a big city as we are to think of taking a trip far away to wilderness, but as more and more of us become urban dwellers, parks and preserves within easy reach of cities are going to become more important. Also, cities like New York usually lie at important crossroads, not just for people but for wildlife, as illustrated by Jamaica Bay's many avian visitors.

In the 19th century, this bay was a rich source of shellfish, but these were fished out and their habitats destroyed by urban development of many kinds. And like so many other natural areas, parks, and preserves, Jamaica Bay Wildlife Refuge has troubles. The estuary that it is part of is today only half the size it was in colonial times, and the refuge's salt marshes are disappearing at a rate that alarms conservationists. Some of the wetlands have been filled, some shorelines bulkheaded to protect developments, and channels dredged. A lot of marshland disappeared with the building of Kennedy International Airport, just a few miles away. The salt marshes and brackish waters of the bay are also damaged by a large

(a)


FIGURE 12.1 Jamaica Bay Wildlife Refuge, New York City. **(a)** The largest wildlife refuge in the northeastern United States is within view of New York City's Empire State Building. It's a surprisingly good place for birdwatching, since it is used by 325 species of birds. **(b) This map of the Jamaica Bay Wildlife Refuge shows how near the refuge is to Manhattan Island.**



(b)

flow of freshwater from treated sewage. Contrary to what you may think, the only difficulty with this water is that it is fresh, which is a problem to the bay's ecosystems.

Help may be on the way. A watershed protection plan has been written, and there is growing interest in this amazing refuge. The good news is that plentiful wildlife viewing is within a commuter's trip for more than 10 million people. Still, natural areas like the wetlands and bay near New York City and the forests and prairies throughout North America present a conflict. On the one hand, they have been valued for the profits to be made from developing the land for other uses. On the other hand, people value and want to preserve the wildlife and vegetation, the natural ecosystems, for all the reasons discussed in Chapter 7 on biological diversity.

In the 17th century, when the first Europeans arrived in what is now New York City and Long Island, they found a landscape already occupied by the Lenape Indians, who farmed, hunted, fished, and made trails that ran from Manhattan to Jamaica Bay.[2] Much of the land, especially land extending north along the Hudson River, was forested, and the forests, too, were occupied and used for their resources by the Lenape and other Indians. The dual uses of landscapes were already established: They were both harvested for many resources and appreciated for their beauty and variety.

Although since then the entire landscape has been heavily altered, those dual uses of the land are still with us and give rise to conflicts about which should dominate.

In this chapter we look at various kinds of landscapes: parks, nature preserves, and especially forests, a major kind of landscape that is harvested for commercial products but is also considered important for biological conservation. Which use to emphasize—harvest, or preservation and aesthetic appreciation—underlies all the environmental issues about landscapes. We will talk about these kinds of natural resources and how to conserve and manage them while benefiting from them in many ways.

12.1 Forests and Forestry

How People Have Viewed Forests

Forests have always been important to people; indeed, forests and civilization have always been closely linked. Since the earliest civilizations—in fact, since some of the earliest human cultures—wood has been one of the major building materials and the most readily available and widely used fuel. Forests provided materials for the first boats and the first wagons. Even today, nearly half the people in the world depend on wood for cooking, and in many developing nations wood remains the primary heating fuel.[3]

At the same time, people have appreciated forests for spiritual and aesthetic reasons. There is a long history of sacred forest groves. When Julius Caesar was trying to conquer the Gauls in what is now southern France, he found the enemy difficult to defeat on the battlefield, so he burned the society's sacred groves to demoralize them—an early example of psychological warfare. In the Pacific Northwest, the great forests of Douglas fir provided the Indians with many practical necessities of life, from housing to boats, but they were also important to them spiritually.

Today, forests continue to benefit people and the environment indirectly through what we call *public-service functions*. Forests retard erosion and moderate the availability of water, improving the water supply from major watersheds to cities. Forests are habitats for endangered species and other wildlife. They are important for recreation, including hiking, hunting, and bird and wildlife viewing. At regional and global levels, forests may also be significant factors affecting the climate.

Forestry

Forestry has a long history as a profession. The professional growing of trees is called **silviculture** (from *silvus*, Latin for "forest," and *cultura*, for "cultivate"). People have long practiced silviculture, much as they have grown crops, but forestry developed into a science-based activity and into what we today consider a profession in the late 19th and early 20th centuries. The first modern U.S. professional forestry school was established at Yale University around the turn of the 20th century, spurred by growing concerns about the depletion of America's living resources. In the early days of the 20th century, the goal of silviculture was generally to maximize the yield in the harvest of a single resource. The ecosystem was a minor concern, as were nontarget, noncommercial species and associated wildlife.

In this chapter, we approach forestry as professionals who make careful use of science and whose goals are the conservation and preservation of forests and the sustainability of timber harvest and of forest ecosystems. Unfortunately, these goals sometimes conflict with the goals of others.

Modern Conflicts over Forestland and Forest Resources

What is the primary purpose of national forests? A national source of timber? The conservation of living resources? Recreation?

Who should own and manage our forests and their resources? The people? Corporations? Government agencies?

In the past decade a revolution has taken place as to who owns America's forests, and this has major implications for how, and how well, our forests will be managed, conserved, sustained, and used in the future. The state of Maine illustrates the change. About 80% of forestland owned by industrial forest companies was sold in that state between 1994 and 2000. Most of it (60%) was purchased by timber investment management organizations (TIMOs). The rest was sold to nongovernment entities, primarily conservation and environmental organizations.

Industrial forest companies, such as International Paper and Weyerhaeuser, owned the forestland, harvested the timber and planned how to do it, and made products from it. They employed professional foresters, and the assumption within the forest industry was that the profession of forestry and the science on which it was based played an important role in improving harvests and maintaining the land. Although timber companies' practices were often heavily criticized by environmental groups, both sides shared a belief in sound management of forests, and in the 1980s and 1990s the two sides made many attempts to work together to improve forest ecosystem sustainability.

In contrast, TIMOs are primarily financial investors who view forestland as an opportunity to profit by buying and selling timber. It is unclear how much sound forestry will be practiced on TIMO-owned land, but there is less emphasis on professional forestry and forest science,[4] and far fewer professional foresters have been employed. The danger is that forestland viewed only as a commercial commodity will be harvested and abandoned once the resource is used. If this happens, it will be the exact opposite of what most people involved in forestry, both in the industry and in conservation groups, hoped for and thought was possible throughout the 20th century.

Meanwhile, funding for forest research by the U.S. Forest Service has also been reduced. Our national forests, part of our national heritage, may also be less well managed and therefore less well conserved in the future.

How could this have come about? It is an ironic result of political and ideological activities. Ultimately, the conflict between industrial forestry and environmental conservation seems to have led timberland owners to decide it was less bothersome and less costly to just sell off forestland, buy wood from whomever owned it, and let them deal with the consequences of land use. Consistent with this rationale, much forest ownership by organizations in the United States has moved offshore, to places with fewer environmental constraints and fewer and less powerful environmental groups. This change should be all the more worrisome to those interested in environmental conservation because it has happened without much publicity and

FIGURE 12.2 **The dual human uses of forests.** This temperate rain forest on Vancouver Island illustrates the beauty of forests. Its tree species are also among those most desired for commercial timber production.

is relatively little known by the general public except where forestry is a major livelihood, as it is in the state of Maine.

In sum, then, modern conflicts about forests center on the following questions:

- Should a forest be used only as a resource to provide materials for people and civilization, or should a forest be used only to conserve natural ecosystems and biological diversity (see Figure 12.2), including specific endangered species?
- Can a forest serve some of both of these functions at the same time and in the same place?
- Can a forest be managed sustainably for either use? If so, how?
- What role do forests play in our global environment, such as climate?
- When are forests habitats for specific endangered species?
- When and where do we need to conserve forests for our water supply?

World Forest Area and Global Production and Consumption of Forest Resources

At the beginning of the 21st century, approximately 26% of Earth's surface was forested—about 3.8 billion hectares (15 million square miles) (Figure 12.3).[5] This works out to about 0.6 hectares (about 1 acre) per person. The forest area is up from 3.45 billion hectares (13.1 million square

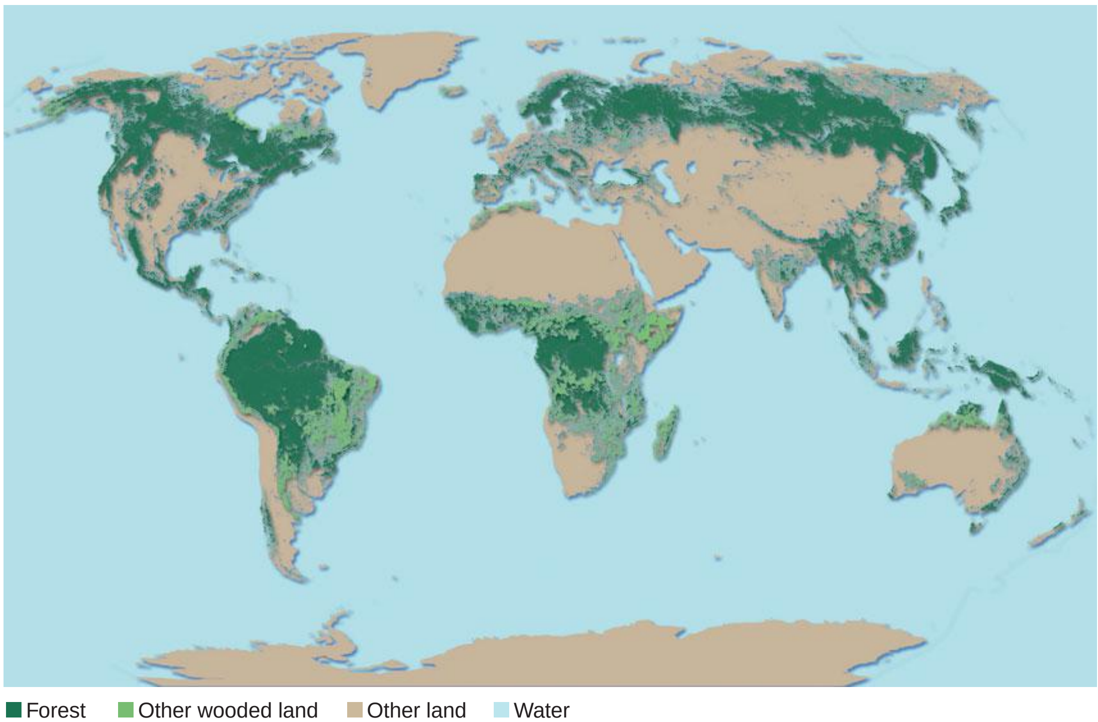


FIGURE 12.3 **Forests of the world.** (*Source:* Food and Agriculture Organization of the United Nations, Viale delle Terme di Caracalla, 00153 Rome, Italy.)

miles, or 23% of the land area) estimated in 1990, but down from 4 billion hectares (15.2 million square miles, or 27%) in 1980.

Countries differ greatly in their forest resources, depending on the suitability of their land and climate for tree growth and on their history of land use and deforestation. Ten nations have two-thirds of the world's forests. In descending order, these are the Russian Federation, Brazil, Canada, the United States, China, Australia, the Democratic Republic of the Congo, Indonesia, Angola, and Peru (Figure 12.4).

Developed countries account for 70% of the world's total production and consumption of industrial wood products; developing countries produce and consume about 90% of wood used as firewood. Timber for construction, pulp, and paper makes up approximately 90% of the world timber trade; the rest consists of hardwoods used for furniture, such as teak, mahogany, oak, and maple. North America is the world's dominant supplier. Total global production/consumption is about 1.5 billion m^3 annually. To think of this in terms easier to relate to, a cubic meter of timber is a block of wood 1 meter thick on each side. A billion cubic meters would be a block of wood 1 meter (39 inches) thick in a square 1,000 km (621 miles) long on each side. This is a distance greater than that between Washington, DC, and Atlanta, Georgia, and longer than the distance between San Diego and Sacramento, California. The great pyramid of Giza, Egypt, has a volume of more than 2.5 million cubic meters, so the amount of timber consumed in a year would fill 600 great pyramids of Egypt.

The United States has approximately 304 million hectares (751 million acres) of forests, of which 86 million hectares (212 million acres) are considered commercial-grade forest, defined as forest capable of producing at least 1.4 m^3/ha (20 ft^3/acre) of wood per year.[6] Commercial timberland occurs in many parts of the United States. Nearly 75% is in the eastern half of the country (about equally divided between the North and South); the rest is in the West (Oregon, Washington, California, Montana, Idaho, Colorado, and other Rocky Mountain states) and in Alaska.

In the United States, 56% of forestland is privately owned, 33% is federal land, 9% is state land, and 3% is on county and town land.[7] Publicly owned forests are primarily in the Rocky Mountain and Pacific Coast states on sites of poor quality and high elevation (Figure 12.5).[8] In contrast, worldwide most forestland (84%) is said to be publicly owned, although information is spotty.[9]

In the last several decades, world trade in timber does not appear to have grown much, if at all, based on the information reported by nations to the United Nations Food and Agriculture Organization. Thus, the amount traded annually (about 1.5 billion m^3, as mentioned earlier) is a reasonable estimate of the total present world demand for the 6.6 billion people on Earth, at their present standards of living. The fundamental questions are whether and how Earth's forests can continue to produce at least this amount of timber for an indefinite period, and whether and how they can produce even more as the world's human population continues to grow and as standards of living rise worldwide. Keep in mind, all of this has to happen while forests continue to perform their other functions, which include public-service functions, biological conservation functions, and functions involving the aesthetic and spiritual needs of people.

In terms of the themes of this book, the question is: How can forest production be sustainable while meeting the needs of people *and* nature? The answer involves science and values.

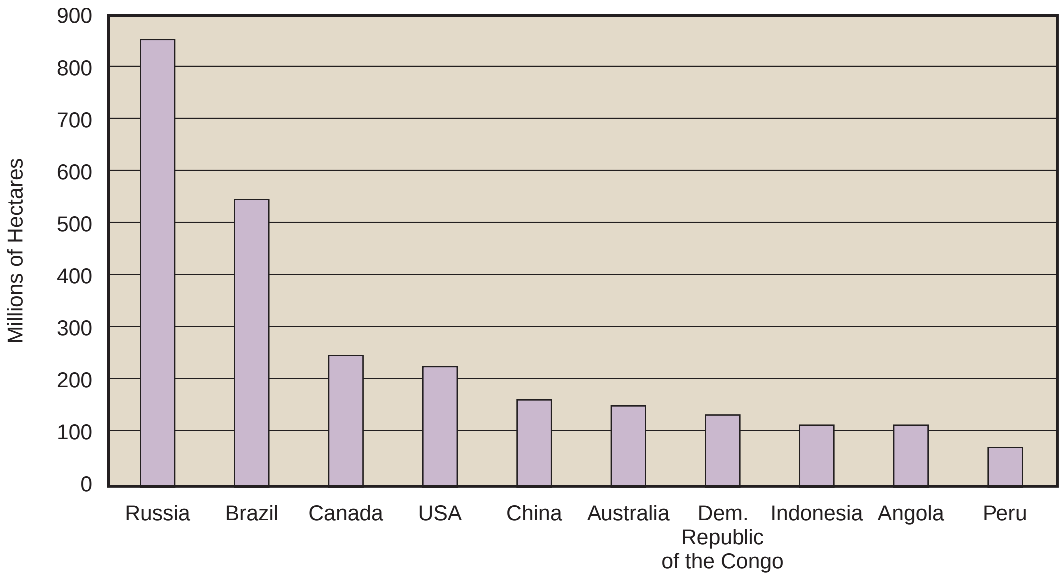


FIGURE 12.4 Countries with the largest forest areas. (*Source*: Data from www.mapsofworld.com)

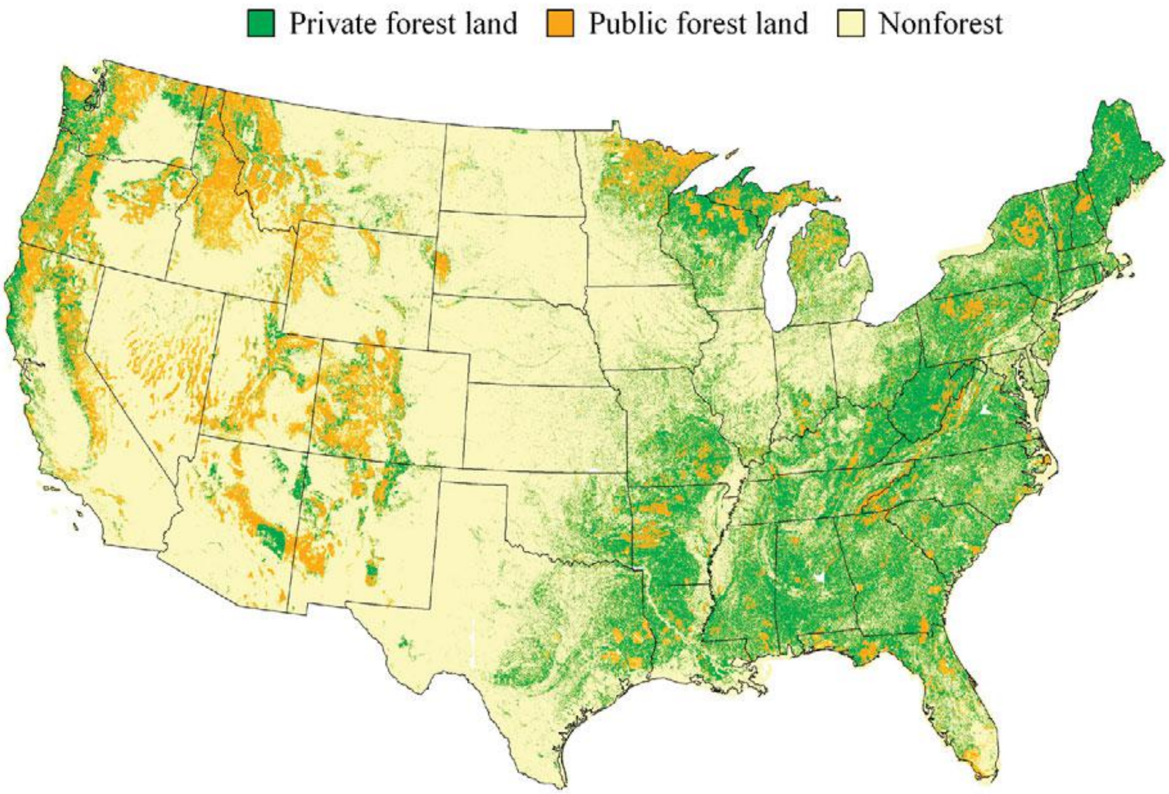


FIGURE 12.5 **Forest ownership in the lower 48 states of the United States in 2008.** (*Source:* U.S. Forest Service, Northern Research Station.)

As we mentioned, wood is a major energy source in many parts of the world. Some 63% of all wood produced in the world, or 2.1 million m^3, is used for firewood. Firewood provides 5% of the world's total energy use,[10] 2% of total commercial energy in developed countries, but 15% of the energy in developing countries, and is the major source of energy for most countries of sub-Saharan Africa, Central America, and continental Southeast Asia.[11]

As the human population grows, the use of firewood increases. In this situation, management is essential, including management of woodland stands (an informal term that foresters use to refer to groups of trees) to improve growth. However, well-planned management of firewood stands has been the exception rather than the rule.

How Forests Affect the Whole Earth

Trees affect the earth by evaporating water, slowing erosion, and providing habitat for wildlife (see Figure 12.6). Trees can also affect climate. Indeed, vegetation of any kind can affect the atmosphere in four ways, and since forests cover so much of the land, they can play an especially important role in the biosphere (Figure 12.7):

1. By changing the color of the surface and thus the amount of sunlight reflected and absorbed.
2. By increasing the amount of water transpired and evaporated from the surface to the atmosphere.
3. By changing the rate at which greenhouse gases are released from Earth's surface into the atmosphere.
4. By changing "surface roughness," which affects wind speed at the surface.

In general, vegetation warms the Earth by making the surface darker, so it absorbs more sunlight and reflects less. The contrast is especially strong between the dark needles of conifers and winter snow in northern forests and between the dark green of shrublands and the yellowish soils of many semiarid climates. Vegetation in general and forests in particular tend to evaporate more water than bare surfaces. This is because the total surface area of the many leaves is many times larger than the area of the soil surface.

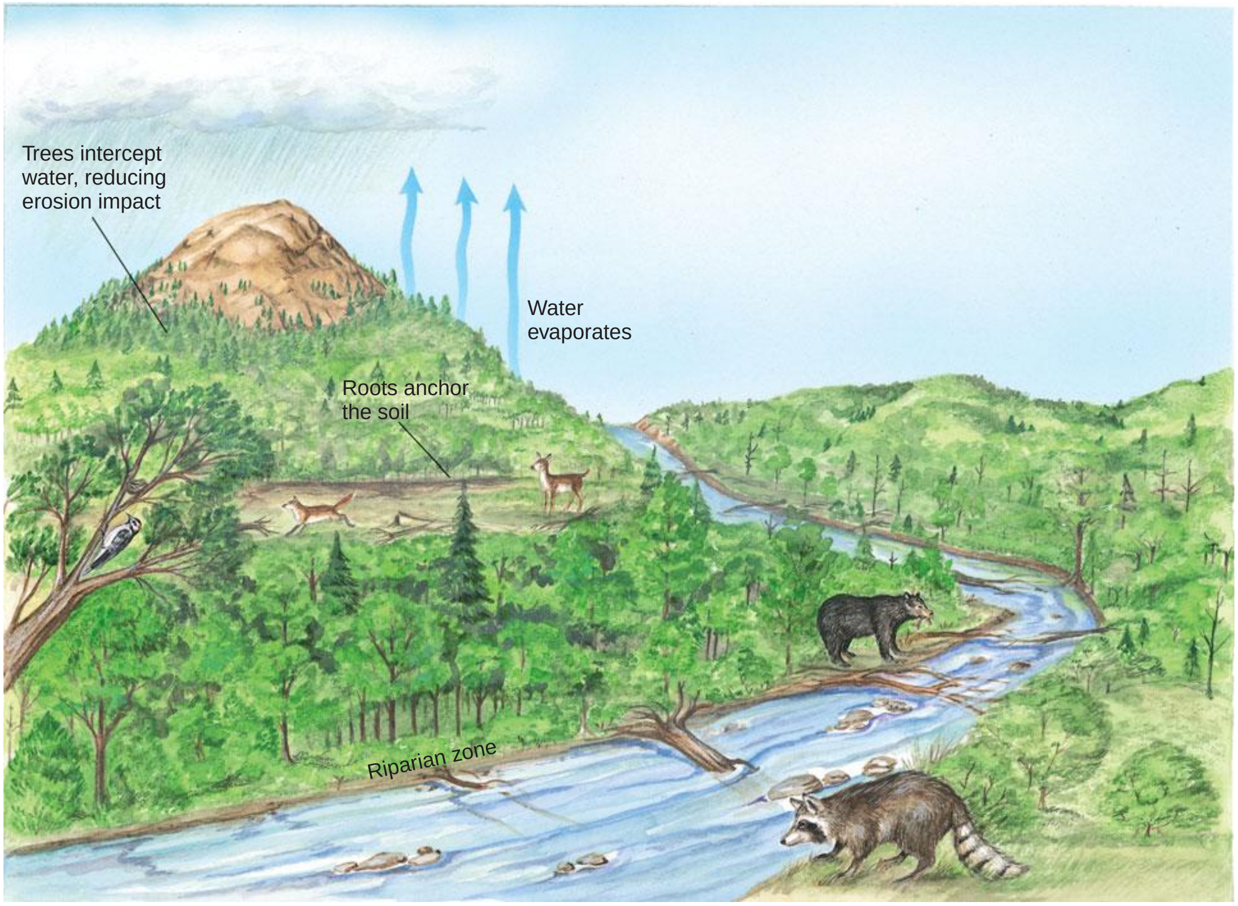


FIGURE 12.6 A forested watershed, showing the effects of trees in evaporating water, retarding erosion, and providing wildlife habitat.

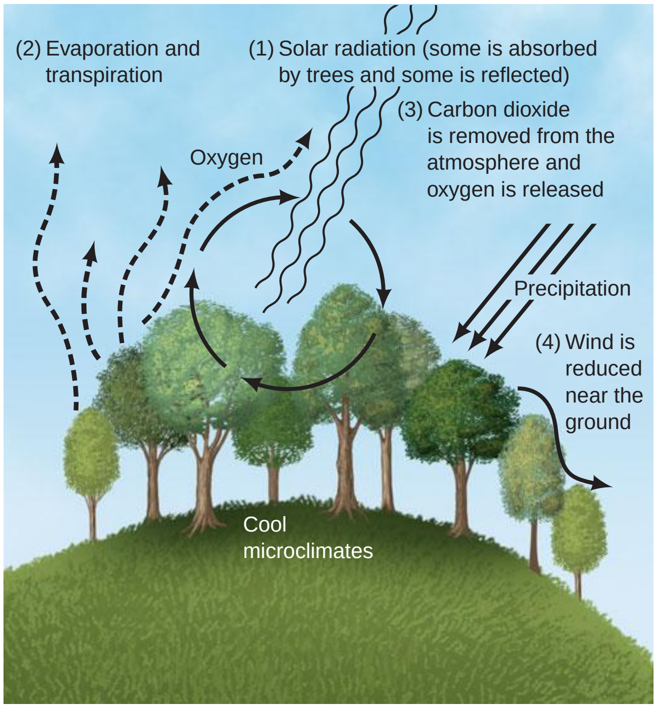


FIGURE 12.7 Four ways that a forest (or a vegetated area) can affect the atmosphere: (1) Some solar radiation is absorbed by vegetation and some is reflected, changing the local energy budget, compared to a nonforest environment; (2) evaporation and transpiration from plants, together called *evapotranspiration*, transfers water to the atmosphere; (3) photosynthesis by trees releases oxygen into the atmosphere and removes carbon dioxide, a greenhouse gas, cooling the temperature of the atmosphere; and (4) near-surface wind is reduced because the vegetation—especially trees—produces roughness near the ground that slows the wind.

Is this increased evaporation good or bad? That depends on one's goals. Increasing evaporation means that less water runs off the surface. This reduces erosion. Although increased evaporation also means that less water is available for our own water supply and for streams, in most situations the ecological and environmental benefits of increased evaporation outweigh the disadvantages.

The Ecology of Forests

Each species of tree has its own niche (see Chapter 5) and is thus adapted to specific environmental conditions. For example, in boreal forests, one of the determinants of a tree niche is the water content of the soil. White birch grows well in dry soils; balsam fir in well-watered sites; and northern white cedar in bogs (Figure 12.8).

Another determinant of a tree's niche is its tolerance of shade. Some trees, such as birch and cherry, can grow only in the bright sun of open areas and are therefore found in clearings and called "shade-intolerant." Other species, such as sugar maple and beech, can grow in deep shade and are called "shade-tolerant."

Most of the big trees of the western United States require open, bright conditions and certain kinds of disturbances in order to germinate and survive the early stages of their lives. These trees include coastal redwood, which wins in competition with other species only if both fires and floods occasionally occur; Douglas fir, which begins its growth in openings; and the giant sequoia, whose seeds will germinate only on bare, mineral soil—where there is a thick layer of organic mulch, the sequoia's seeds cannot reach the surface and will die before they can germinate. Some trees are adapted to early stages of succession, where sites are open and there is bright sunlight. Others are adapted to later stages of succession, where there is a high density of trees (see the discussion of ecological succession in Chapter 5).

Understanding the niches of individual tree species helps us to determine where we might best plant them as a commercial crop, and where they might best contribute to biological conservation or to landscape beauty.

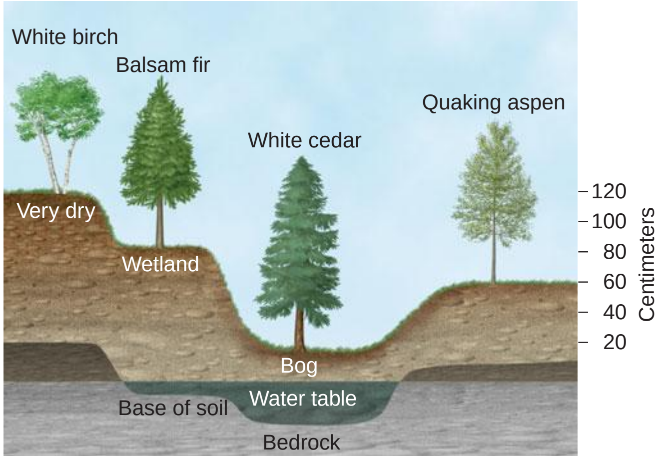


FIGURE 12.8 Some characteristics of tree niches. Tree species have evolved to be adapted to different kinds of environments. In northern boreal forests, white birch grows on dry sites (and early-successional sites); balsam fir grows in wetter soils, up to wetlands; and white cedar grows in even the wetter sites of northern bogs.

A CLOSER LOOK 12.1

The Life of a Tree

To solve the big issues about forestry, we need to understand how a tree grows, how an ecosystem works, and how foresters have managed forestland (Figure 12.9). Leaves of a tree take up carbon dioxide from the air and absorb sunlight. These, in combination with water transported up from the roots, provide the energy and chemical elements for leaves to carry out *photosynthesis*. Through photosynthesis, the leaves convert carbon dioxide and water into a simple sugar and molecular oxygen. This simple sugar is then combined with other chemical elements to provide all the compounds that the tree uses.

Tree roots take up water, along with chemical elements dissolved in the water and small inorganic compounds, such as the nitrate or ammonia necessary to make proteins. Often the process of extracting minerals and compounds from the soil is aided by symbiotic relationships between the tree

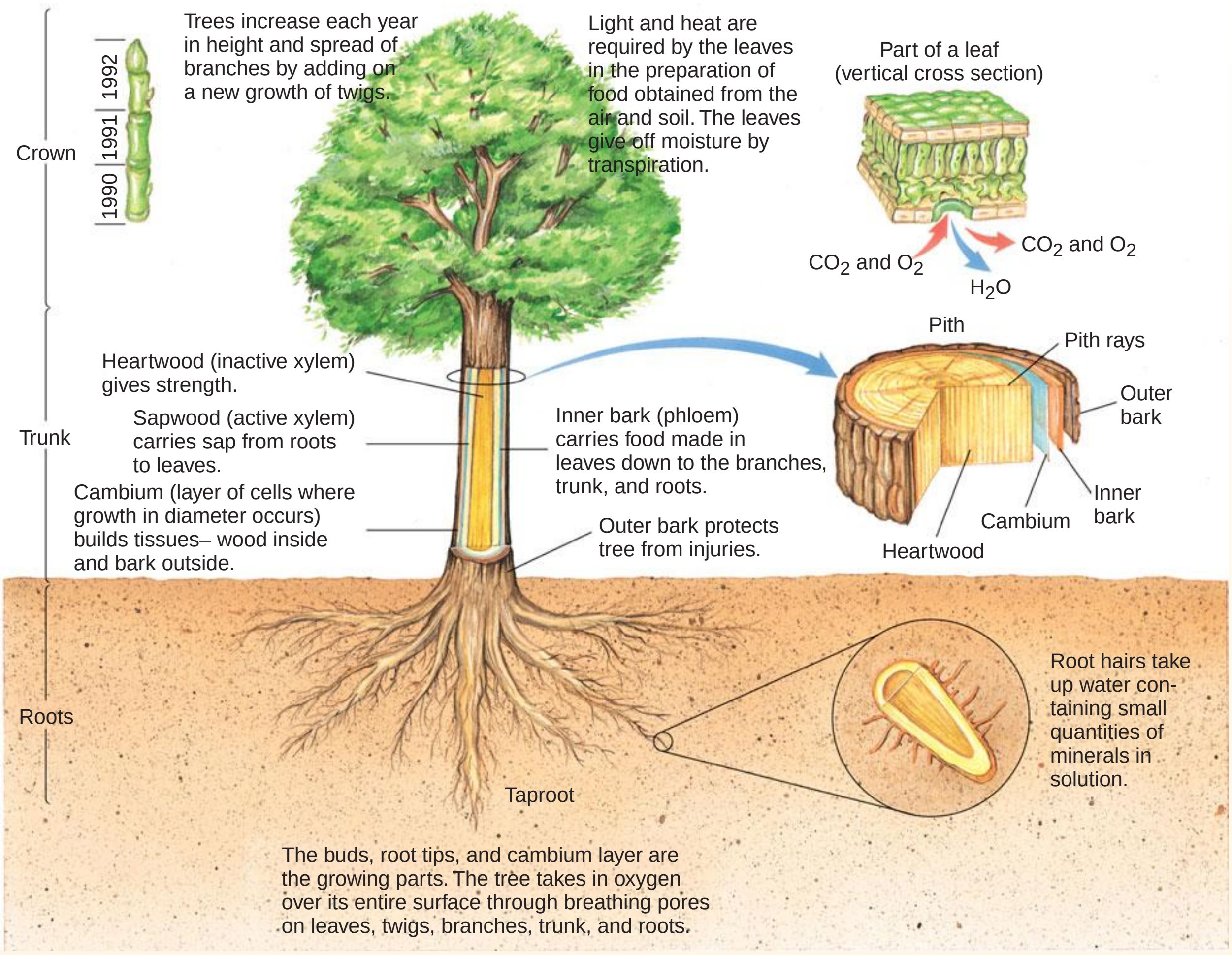


FIGURE 12.9 How a tree grows. (*Source*: C.H. Stoddard, *Essentials of Forestry Practice*, 3rd ed. [New York: Wiley, 1978].)

roots and fungi. Tree roots release sugars and other compounds that are food for the fungi, and the fungi benefit the tree as well.

Leaves and roots are connected by two transportation systems. Phloem, on the inside of the living part of the bark, transports sugars and other organic compounds down to stems and roots. Xylem, farther inside (Figure 12.9), transports water and inorganic molecules upward to the leaves. Water is transported upward by a sun-powered pump—that is, sunlight provides energy to pump the water up the tree by heating leaves so they evaporate water. Water from below is then pulled upward to replace water that evaporated.

Forest Management

A Forester's View of a Forest

Traditionally, foresters have managed trees locally in stands. Trees in a **stand** are usually of the same species or group of species and often at the same successional stage. Stands can be small (half a hectare) to medium size (several hundred hectares) and are classified by foresters on the basis of tree composition. The two major kinds of commercial stands are *even-aged stands*, where all live trees began growth from seeds and roots germinating the same year, and *uneven-aged stands*, which have at least three distinct age classes. In even-aged stands, trees are approximately the same height but differ in girth and vigor.

A forest that has never been cut is called a *virgin forest* or sometimes an **old-growth forest**. A forest that has been cut and has regrown is called a **second-growth forest**. Although the term old-growth forest has gained popularity in several well-publicized disputes about forests, it is not a scientific term and does not yet have an agreed-on, precise meaning. Another important management term is **rotation time**, the time between cuts of a stand.

Foresters and forest ecologists group the trees in a forest into the **dominants** (the tallest, most common, and most vigorous), **codominants** (fairly common, sharing the canopy or top part of the forest), **intermediate** (forming a layer of growth below dominants), and **suppressed** (growing in the understory). The productivity of a forest varies according to soil fertility, water supply, and local climate. Foresters classify sites by **site quality**, which is the maximum timber crop the site can produce in a given time. Site quality can decline with poor management.

Although forests are complex and difficult to manage, one advantage they have over many other ecosystems is that trees provide easily obtained information that can be a great help to us. For example, the age and growth rate of trees can be measured from tree rings. In temperate and boreal forests, trees produce one growth ring per year.

Harvesting Trees

Managing forests that will be harvested can involve removing poorly formed and unproductive trees (or selected other trees) to permit larger trees to grow faster, planting genetically controlled seedlings, controlling pests and diseases, and fertilizing the soil. Forest geneticists breed new strains of trees just as agricultural geneticists breed new strains of crops. There has been relatively little success in controlling forest diseases, which are primarily fungal.

Harvesting can be done in several ways. **Clear-cutting** (Figure 12.10) is the cutting of all trees in a stand at the same time. Alternatives to clear-cutting are selective cutting, strip-cutting, shelterwood cutting, and seed-tree cutting.

In **selective cutting**, individual trees are marked and cut. Sometimes smaller, poorly formed trees are selectively removed, a practice called **thinning**. At other times, trees of specific species and sizes are removed. For example, some forestry companies in Costa Rica cut only some of the largest mahogany trees, leaving less valuable trees to help maintain the ecosystem and permitting some of the large mahogany trees to continue to provide seeds for future generations.

FIGURE 12.10 **A clear-cut forest in western Washington.**

In **strip-cutting**, narrow rows of forest are cut, leaving wooded corridors whose trees provide seeds. Strip-cutting offers several advantages, such as protection against erosion.

Shelterwood cutting is the practice of cutting dead and less desirable trees first, and later cutting mature trees. As a result, there are always young trees left in the forest.

Seed-tree cutting removes all but a few seed trees (mature trees with good genetic characteristics and high seed production) to promote regeneration of the forest.

Scientists have tested the effects of clear-cutting, which is one of the most controversial forest practices.[12, 13, 14] For example, in the U.S. Forest Service Hubbard Brook experimental forest in New Hampshire, an entire watershed was clear-cut, and herbicides were applied to prevent regrowth for two years.[14] The results were dramatic. Erosion increased, and the pattern of water runoff changed substantially. The exposed soil decayed more rapidly, and the concentrations of nitrates in the stream water exceeded public-health standards. In another experiment, at the U.S. Forest Service H.J. Andrews experimental forest in Oregon, a forest where rainfall is high (about 240 cm, or 94 in., annually), clear-cutting greatly increased the frequency of landslides, as did the construction of logging roads.[15]

Clear-cutting also changes chemical cycling in forests and can open the way for the soil to lose chemical elements necessary for life. Exposed to sun and rain, the ground becomes warmer. This accelerates the process of decay, with chemical elements, such as nitrogen, converted more rapidly to forms that are water-soluble and thus readily lost in runoff during rains (Figure 12.11).[16]

The Forest Service experiments show that clear-cutting can be a poor practice on steep slopes in areas of moderate to heavy rainfall. The worst effects of clear-cutting resulted from the logging of vast areas of North America during the 19th and early 20th centuries. Clear-cutting on such a large scale is neither necessary nor desirable for the best timber production. However, where the ground is level or slightly sloped, where rainfall is moderate, and where the desirable species require open areas for growth, clear-cutting on an appropriate spatial scale may be a useful way to regenerate desirable species. The key here is that clear-cutting is neither all good nor all bad for timber production or forest ecosystems. Its use must be evaluated on a case-by-case basis, taking into account the size of cuts, the environment, and the available species of trees.

Plantations

Sometimes foresters grow trees in a **plantation**, which is a stand of a single species, typically planted in straight rows (Figure 12.12). Usually plantations are fertilized, sometimes by helicopter, and modern machines harvest rapidly—some remove the entire tree, root and all.

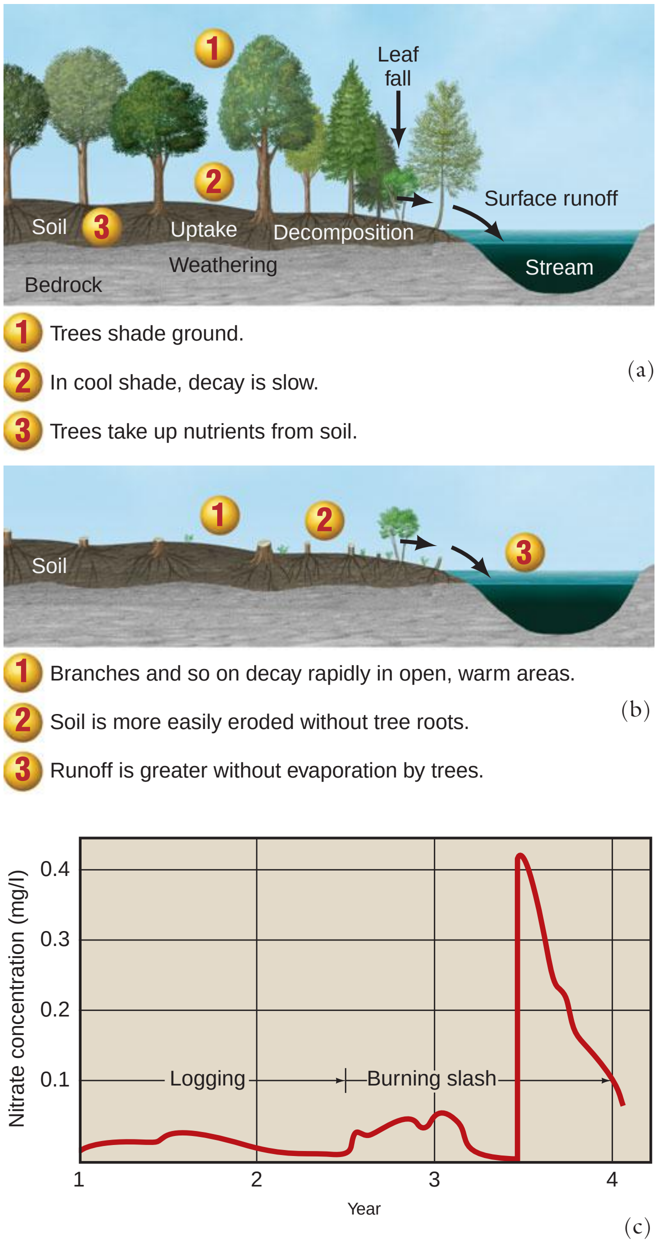


FIGURE 12.11 Effects of clear-cutting on forest chemical cycling. Chemical cycling **(a)** in an old-growth forest and **(b)** after clear-cutting. **(c)** Increased nitrate concentration in streams after logging and the burning of slash (leaves, branches, and other tree debris). (*Source*: adapted from R.L. Fredriksen, "Comparative Chemical Water Quality—Natural and Disturbed Streams Following Logging and Slash Burning," in *Forest Land Use and Stream Environment* [Corvallis: Oregon State University, 1971], pp. 125–137.)

FIGURE 12.12 A modern forest plantation in Queensland, Australia. Note that the trees are evenly spaced and similar, if not identical, in size.

In short, plantation forestry is a lot like modern agriculture. Intensive management like this is common in Europe and parts of the northwestern United States and offers an important alternative solution to the pressure on natural forests. If plantations were used where forest production was high, then a comparatively small percentage of the world's forestland could provide all the world's timber. For example, high-yield forests produce 15–20 m^3/ha/yr. According to one estimate, if plantations were put on timberland that could produce at least 10 m^3/ha/yr, then 10% of the world's forestland could provide enough timber for the world's timber trade.[17] This could reduce pressure on old-growth forests, on forests important for biological conservation, and on forestlands important for recreation.

Can We Achieve Sustainable Forestry?

There are two basic kinds of ecological sustainability: (1) sustainability of the harvest of a specific resource that grows within an ecosystem; and (2) sustainability of the entire ecosystem—and therefore of many species, habitats, and environmental conditions. For forests, this translates into sustainability of the harvest of timber and sustainability of the forest as an ecosystem. Although sustainability has long been discussed in forestry, we don't have enough scientific data to show that sustainability of either kind has been achieved in forests in more than a few unusual cases.

Certification of Forest Practices

If the data do not indicate whether a particular set of practices has led to sustainable forestry, what can be done? The general approach today is to compare the actual practices of specific corporations or government agencies with practices that are believed to be consistent with sustainability. This has become a formal process called **certification of forestry**, and there are organizations whose main function is to certify forest practices. The catch here is that nobody actually knows whether the beliefs are correct and therefore whether the practices will turn out to be sustainable. Since trees take a long time to grow, and a series of harvests is necessary to prove sustainability, the proof lies in the future. Despite this limitation, certification of forestry is becoming common. As practiced today, it is as much an art or a craft as it is a science.

Worldwide concern about the need for forest sustainability has led to international programs for certifying forest practices, as well as to attempts to ban imports of wood produced from purportedly unsustainable forest practices. Some European nations have banned the import of certain tropical woods, and some environmental organizations have led demonstrations in support of such bans. However, there is a gradual movement away from calling certified forest practices "sustainable," instead referring to "well-managed forests" or "improved management."[19, 20] And some scientists have begun to call for a new forestry that includes a variety of practices that they believe increase the likelihood of sustainability.

Most basic is accepting the dynamic characteristics of forests—that to remain sustainable over the long term, a forest may have to change in the short term. Some of the broader, science-based concerns are spoken of as a group—the need for ecosystem management and a landscape context. Scientists point out that any application of a certification program creates an experiment and should be treated accordingly. Therefore, any new programs that claim to provide sustainable practices must include, for comparison, control areas where no cutting is done and must also include adequate scientific monitoring of the status of the forest ecosystem.

Deforestation

Deforestation is believed to have increased erosion and caused the loss of an estimated 562 million hectares (1.4 billion acres) of soil worldwide, with an estimated annual loss of 5–6 million hectares.[21] Cutting forests in one country affects other countries. For example, Nepal, one of the most mountainous countries in the world, lost more than half its forest cover between 1950 and 1980. This destabilized soil, increasing the frequency of landslides, amount of runoff, and sediment load in streams. Many Nepalese streams feed rivers that flow into India (Figure 12.13). Heavy flooding in India's Ganges Valley has caused about a billion dollars' worth of property damage a year and is blamed on the loss of large forested watersheds in Nepal and other countries.[20] Nepal continues to lose forest cover at a rate of about 100,000 hectares (247,000 acres) per year. Reforestation efforts replace less than 15,000 hectares (37,050 acres) per year. If present trends continue, little forestland will remain in Nepal, thus permanently exacerbating India's flood problems.[19, 20]

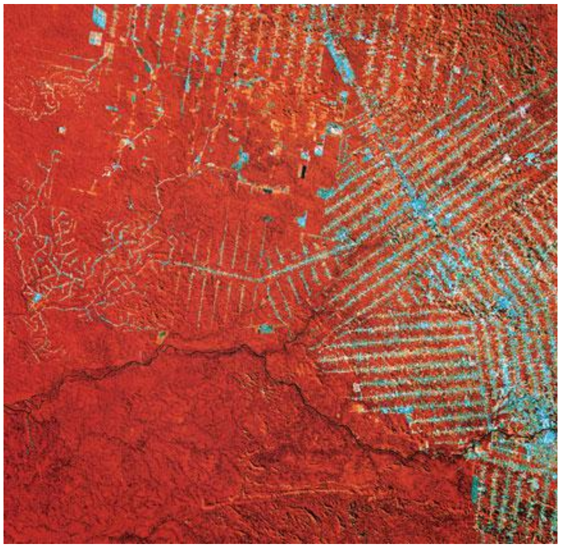
Because forests cover large, often remote areas that are little visited or studied, information is lacking on which to determine whether the world's forestlands are expanding or shrinking, and precisely how fast and how much. Some experts argue that there is a worldwide net increase in forests because large areas in the temperate zone, such as the eastern and midwestern United States, were cleared in the 19th and early 20th centuries and are now regenerating. Only recently have programs begun to obtain accurate estimates of the distribution and abundance of forests, and these suggest that past assessments overestimated forest biomass by 100 to 400%.[22]

On balance, we believe that the best estimates are those suggesting that the rate of deforestation in the 21st century is 7.3 million hectares a year—an annual loss equal to the size of Panama. The good news is that this is 18% less than the average annual loss of 8.9 million hectares in the 1990s.[23]

(a)

(b)

FIGURE 12.13 **(a) Planting pine trees on the steep slopes in Nepal to replace entire forests that were cut.** The dark green in the background is yet-uncut forest, and the contrast between foreground and background suggests the intensity of clearing that is taking place. **(b) The Indus River in northern India carries a heavy load of sediment**, as shown by the sediments deposited within and along the flowing water and by the color of the water itself. This scene, near the headwaters, shows that erosion takes place at the higher reaches of the river.



(a)

(b)

FIGURE 12.14 **(a)** A satellite image showing clearings in the tropical rain forests in the Amazon in Brazil. The image is in false infrared. Rivers appear black, and the bright red is the leaves of the living rain forest. The straight lines of other colors, mostly light blue to gray, are of deforestation by people extending from roads. Much of the clearing is for agriculture. The distance across the image is about 100 km (63 mi). **(b)** An intact South American rain forest with its lush vegetation of many species and a complex vertical structure. This one is in Peru.

History of Deforestation

Forests were cut in the Near East, Greece, and the Roman Empire before the modern era. Removal of forests continued northward in Europe as civilization advanced. Fossil records suggest that prehistoric farmers in Denmark cleared forests so extensively that early-successional weeds occupied large areas. In medieval times, Great Britain's forests were cut, and many forested areas were eliminated. With colonization of the New World, much of North America was cleared.[24]

The greatest losses in the present century have taken place in South America, where 4.3 million acres have been lost on average per year since 2000 (Figure 12.14). Many of these forests are in the tropics, mountain regions, or high latitudes, places difficult to exploit before the advent of modern transportation and machines. The problem is especially severe in the tropics because of rapid human population growth. Satellite images provide a new way to detect deforestation (Figure 12.14a).

Causes of Deforestation

Historically, the two most common reasons people cut forests are to clear land for agriculture and settlement and to use or sell timber for lumber, paper products, or fuel. Logging by large timber companies and local cutting by villagers are both major causes of deforestation. Agriculture is a principal cause of deforestation in Nepal and Brazil and was one of the major reasons for clearing forests in New England during the first settlement by Europeans. A more subtle cause of the loss of forests is indirect deforestation—the death of trees from pollution or disease.

If global warming occurs as projected by global climate models, indirect forest damage might occur over large regions, with major die-offs in many areas and major shifts in the areas of potential growth for each species of tree due to altered combinations of temperature and rainfall.[25] The extent of this effect is controversial. Some suggest that global warming would merely change the location of forests, not their total area or production. However, even if a climate conducive to forest growth were to move to new locations, trees would have to reach these areas. This would take time because changes in the geographic distribution of trees depend primarily on seeds blown by the wind or carried by animals. In addition, for production to remain as high as it is now, climates that meet the needs of forest trees would have to occur where the soils also meet these needs. This combination of climate and soils occurs widely now but might become scarcer with large-scale climate change.

12.2 Parks, Nature Preserves, and Wilderness

As suggested by this chapter's opening case study about Jamaica Bay Wildlife Refuge, governments often protect landscapes from harvest and other potentially destructive uses by establishing parks, nature preserves, and legally designated wilderness areas. So do private organizations, such as the Nature Conservancy, the Southwest Florida Nature Conservancy, and the Land

Trust of California, which purchase lands and maintain them as nature preserves. Whether government or private conservation areas succeed better in reaching the goals listed in Table 12.1 is a matter of considerable controversy.

Parks, natural areas, and wilderness provide benefits within their boundaries and can also serve as migratory corridors between other natural areas. Originally, parks were established for specific purposes related to the land within the park boundaries (discussed later in this chapter). In the future, the design of large landscapes to serve a combination of land uses—including parks, preserves, and wilderness—needs to become more important and a greater focus of discussion.

What's the Difference between a Park and a Nature Preserve?

A park is an area set aside for use by people. A nature preserve, although it may be used by people, has as its primary purpose the conservation of some resource, typically a biological one. Every park or preserve is an ecological island of one kind of landscape surrounded by a different kind of landscape, or several different kinds. Ecological and physical islands have special ecological qualities, and concepts of island biogeography are used in the design and management of parks. Specifically, the size of the park and the diversity of habitats determine the number of species that can be maintained there. Also, the farther the park is from other parks or sources of species, the fewer species are found. Even the shape of a park can determine what species can survive within it.

One of the important differences between a park and a truly natural wilderness area is that a park has definite boundaries. These boundaries are usually arbitrary from an ecological viewpoint and have been established for political, economic, or historical reasons unrelated to the natural ecosystem. In fact, many parks have been developed on areas that would have been considered wastelands, useless for any other purpose. Even where parks or preserves have been set aside for the conservation of some species, the boundaries are usually arbitrary, and this has caused problems.

For example, Lake Manyara National Park in Tanzania, famous for its elephants, was originally established with boundaries that conflicted with elephant habits. Before this park was established, elephants spent part of the year feeding along a steep incline above the lake. At other times of the year, they would migrate down to the valley floor, depending on the availability of food and water. These annual migrations were necessary for the elephants to obtain food of sufficient nutritional quality throughout the year. However, when the park was established, farms that were laid out along its northern border crossed the traditional pathways of the elephants. This had two negative effects. First, elephants came into direct conflict with farmers. Elephants crashed through farm fences, eating corn and other crops and causing general disruption. Second, whenever the farmers succeeded in keeping elephants out, the animals were cut off from reaching their feeding ground near the lake.

When it became clear that the park boundaries were arbitrary and inappropriate, the boundaries were adjusted to include the traditional migratory routes. This eased the conflicts between elephants and farmers.

Table 12.1 GOALS OF PARKS, NATURE PRESERVES, AND WILDERNESS AREAS

Parks are as old as civilization. The goals of park and nature-preserve management can be summarized as follows:

1. Preservation of unique geological and scenic wonders of nature, such as Niagara Falls and the Grand Canyon
2. Preservation of nature without human interference (preserving wilderness for its own sake)
3. Preservation of nature in a condition thought to be representative of some prior time (e.g., the United States prior to European settlement)
4. Wildlife conservation, including conservation of the required habitat and ecosystem of the wildlife
5. Conservation of specific endangered species and habitats
6. Conservation of the total biological diversity of a region
7. Maintenance of wildlife for hunting
8. Maintenance of uniquely or unusually beautiful landscapes for aesthetic reasons
9. Maintenance of representative natural areas for an entire country
10. Maintenance for outdoor recreation, including a range of activities from viewing scenery to wilderness recreation (hiking, cross-country skiing, rock climbing) and tourism (car and bus tours, swimming, downhill skiing, camping)
11. Maintenance of areas set aside for scientific research, both as a basis for park management and for the pursuit of answers to fundamental scientific questions
12. Provision of corridors and connections between separated natural areas

A CLOSER LOOK 12.2

A Brief History of Parks Explains Why Parks Have Been Established

The French word *parc* once referred to an enclosed area for keeping wildlife to be hunted. Such areas were set aside for the nobility and excluded the public. An example is Coto Doñana National Park on the southern coast of Spain. Originally a country home of nobles, today it is one of Europe's most important natural areas, used by 80% of birds migrating between Europe and Africa (Figure 12.16).

The first major *public* park of the modern era was Victoria Park in Great Britain, authorized in 1842. The concept of a *national* park, whose purposes would include protection of nature as well as public access, originated in North America in the 19th century.[26] The world's first national park was Yosemite National Park in California (Figure 12.15), made a park by an act signed by President Lincoln in 1864. The term *national park*, however, was not used until the establishment of Yellowstone in 1872.

The purpose of the earliest national parks in the United States was to preserve the nation's unique, awesome landscapes—a purpose that Alfred Runte, a historian of national parks, refers to as "monumentalism." In the 19th century, Americans considered their national parks a contribution to civilization equivalent to the architectural treasures of the Old World and sought to preserve them as a matter of national pride.[27]

In the second half of the 20th century, the emphasis of park management became more ecological, with parks established both to conduct scientific research and to maintain examples of representative natural areas. For instance, Zimbabwe established Sengwa National Park (now called Matusadona National Park) solely for scientific research. It has no tourist areas, and tourists are not generally allowed; its purpose is the study of natural ecosystems with as little human interference as possible so that the principles of wildlife and wilderness management can be better formulated and understood. Other national parks in the countries of eastern and southern Africa—including those of Kenya, Uganda, Tanzania, Zimbabwe, and South Africa—have been established primarily for viewing wildlife and for biological conservation.

In recent years, the number of national parks throughout the world has increased rapidly. The law establishing national parks in France was first enacted in 1960. Taiwan had no national parks prior to 1980 but now has six. In the United States, the area in national and state parks has expanded from less than 12 million hectares (30 million acres) in 1950 to nearly 83.6 million acres today, with much of the increase due to the establishment of parks in Alaska.[28]

FIGURE 12.15 **The famous main valley of Yosemite National Park.**

(a)

(b)

FIGURE 12.16 **(a) Flamingos are among the many birds that use Coto Doñana National Park,** a major stopover on the Europe-to-Africa flyway. **(b)** Map of Coto Doñana National Park, Spain (*Source*: Colours of Spain. World Heritage Sites http://www.coloursofspain.com/travelguidedetail/17/andalucia_andalusia/world_heritage_sites_donana_national_park/)

Conserving representative natural areas of a country is an increasingly common goal of national parks. For example, the goal of New Zealand's national park planning is to include at least one area representative of each major ecosystem of the nation, from seacoast to mountain peak. In some cases, such as Spain's Coto Doñana National Park, national parks are among the primary resting grounds of major bird flyways (Figure 12.16) or play other crucial roles in conservation of biodiversity.

Conflicts Relating to Parks

Size, Access, and Types of Activities

Major conflicts over parks generally have to do with their size and what kinds and levels of access and activities will be available. The idea of a national, state, county, or city park is well accepted in North America, but conflicts arise over what kinds of activities and what intensity of activities should be allowed in parks. Often, biological conservation and the needs of individual species require limited human access, but, especially in beautiful areas desirable for recreation, people want to go there. As a recent example, travel into Yellowstone National Park by snowmobile in the winter has become popular, but this has led to noise and air pollution and has marred the experience of the park's beauty for many visitors. In 2003 a federal court determined that snowmobile use should be phased out in this park.

Alfred Runte explained the heart of the conflict. "This struggle was not against Americans who like their snowmobiles, but rather against the notion that anything goes in the national parks," he said. "The courts have reminded us that we have a different, higher standard for our national parks. Our history proves that no one loses when beauty wins. We will find room for snowmobiles, but just as important, room without them, which is the enduring greatness of the national parks."[29]

Many of the recent conflicts relating to national parks have concerned the use of motor vehicles. Voyageurs National Park in northern Minnesota, established in 1974—fairly recently compared with many other national parks—occupies land that was once used by a variety of recreational vehicles and provided livelihoods for hunting and fishing guides and other tourism businesses. These people felt that restricting motor-vehicle use would destroy their livelihoods. Voyageurs National Park has 100 miles of snowmobile trails and is open to a greater variety of motor-vehicle recreation than Yellowstone.[30]

Interactions Between People and Wildlife

While many people like to visit parks to see wildlife, some wildlife, such as grizzly bears in Yellowstone National Park, can be dangerous. There has been conflict in the past between conserving the grizzly and making the park as open as possible for recreation.

How Much Land Should Be in Parks?

Another important controversy in managing parks is what percentage of a landscape should be in parks or nature preserves, especially with regard to the goals of biological diversity. Because parks isolate populations genetically, they may provide too small a habitat for maintaining a minimum safe population size. If parks are to function as biological preserves, they must be adequate in size and habitat diversity to maintain a population large enough to avoid the serious genetic difficulties that can develop in small populations. An alternative, if necessary, is for a park manager to move individuals of one species—say, lions in African preserves—from one park to another to maintain genetic diversity. But park size is a source of conflicts, with conservationists typically wanting to make parks bigger and commercial interests typically wanting to keep them smaller. Proponents of the Wildlands Projects, for example, argue that large areas are necessary to conserve ecosystems, so even America's large parks, such as Yellowstone, need to be connected by conservation corridors.

Nations differ widely in the percentage of their total area set aside as national parks. Costa Rica, a small country with high biological diversity, has more than 12% of its land in national parks.[31] Kenya, a larger nation that also has numerous biological resources, has 7.6% of its land in national parks.[32] In France, an industrialized nation in which civilization has altered the landscape for several thousand years, only 0.7% of the land is in the nation's six national parks. However, France has 38 regional parks that encompass 11% (5.9 million hectares) of the nation's area.

The total amount of protected natural area in the United States is more than 104 million hectares (about 240 million acres), approximately 11.2% of the total U.S. land area.[33] However, the states differ greatly in the percentage of land set aside for parks, preserves, and other conservation areas. The western states have vast parks, whereas the six Great Lakes states (Michigan, Minnesota, Illinois, Indiana, Ohio, and Wisconsin), covering an area approaching that of France and Germany combined, allocate less than 0.5% of their land to parks and less than 1% to designated wilderness.[34]

12.3 Conserving Wilderness

What It Is, and Why It Is of Growing Importance

As a modern legal concept, **wilderness** is an area undisturbed by people. The only people in a wilderness are visitors, who do not remain. The conservation of wilderness is a new idea introduced in the second half of the 20th century. It is one that is likely to become more important as the human population increases and the effects of civilization become more pervasive throughout the world.

The U.S. Wilderness Act of 1964 was landmark legislation, marking the first time anywhere that wilderness was recognized by national law as a national treasure to be preserved. Under this law, wilderness includes "an area of undeveloped Federal land retaining its primeval character and influence, without permanent improvements or human habitation, which is protected and managed so as to preserve its natural conditions." Such lands are those in which (1) the imprint of human work is unnoticeable, (2) there are opportunities for solitude and for primitive and unconfined recreation, and (3) there are at least 5,000 acres. The law also recognizes that these areas are valuable for ecological processes, geology, education, scenery, and history. The Wilderness Act required certain maps and descriptions of wilderness areas, resulting in the U.S. Forest Service's Roadless Area Review and Evaluation (RARE I and RARE II), which evaluated lands for inclusion as legally designated wilderness.

Where You'll Find It and Where You Won't

Countries with a significant amount of wilderness include New Zealand, Canada, Sweden, Norway, Finland, Russia, and Australia; some countries of eastern and southern Africa; many countries of South America, including parts of the Brazilian and Peruvian Amazon basin; the mountainous high-altitude areas of Chile and Argentina; some of the remaining interior tropical forests of Southeast Asia; and the Pacific Rim countries (parts of Borneo, the Philippines, Papua New Guinea, and Indonesia). In addition, wilderness can be found in the polar regions, including Antarctica, Greenland, and Iceland.

Many countries have no wilderness left to preserve. In the Danish language, the word for wilderness has even disappeared, although that word was important in the ancestral languages of the Danes.[32] Switzerland is a country in which wilderness is not a part of preservation. For example, a national park in Switzerland lies in view of the Alps—scenery that inspired the English romantic poets of the early 19th century to praise what they saw as wilderness and to attach the adjective *awesome* to what they saw. But the park is in an area that has been heavily exploited for such activities as mining and foundries since the Middle Ages. All the forests are planted.[32]

The Wilderness Experience: Natural vs. Naturalistic

In a perhaps deeper sense, wilderness is an idea and an ideal that can be experienced in many places, such as Japanese gardens, which might occupy no more than a few hundred square meters. Henry David Thoreau distinguished between "wilderness" and "wildness." He thought of wilderness as a physical place and wildness as a state of mind. During his travels through the Maine woods in the 1840s, he concluded that wilderness was an interesting place to visit but not to live in. He preferred long walks through the woods and near swamps around his home in Concord, Massachusetts, where he was able to experience a *feeling* of wildness. Thus, Thoreau raised a fundamental question: Can one experience true wildness only in a huge area set aside as a wilderness and untouched by human actions, or can wildness be experienced in small, heavily modified and, though not entirely natural, *naturalistic* landscapes, such as those around Concord in the 19th century?[31]

As Thoreau suggests, small, local, naturalistic parks may have more value than some of the more traditional wilderness areas as places of solitude and beauty. In Japan, for instance, there are roadless recreation areas, but they are filled with people. One two-day hiking circuit leads to a high-altitude marsh where people can stay in small cabins. Trash is removed from the area by helicopter. People taking this hike experience a sense of wildness.

In some ways, the answer to the question raised by Thoreau is highly personal. We must discover for ourselves what kind of natural or naturalistic place meets our spiritual, aesthetic, and emotional needs. This is yet another area in which one of our key themes, science and values, is evident.

Conflicts in Managing Wilderness

The legal definition of *wilderness* has given rise to several controversies. The wilderness system in the United States began in 1964 with 3.7 million hectares (9.2 million acres) under U.S. Forest Service control. Today, the United States has 633 legally designated wilderness areas, covering 44 million hectares (106 million acres)—more than 4% of the nation. Another 200 million acres meet the legal requirements and could be protected by the Wilderness Act. Half of this area is in Alaska, including the largest single area, Wrangell–St. Elias (Figure 12.17), covering 3.7 million hectares (9 million acres).[33, 35]

Those interested in developing the natural resources of an area, including mineral ores and timber, have argued that the rules are unnecessarily stringent, protecting too much land from exploitation when there is plenty of wilderness elsewhere. Those who wish to conserve additional wild areas have argued that the interpretation of the U.S. Wilderness Act is too lenient and that mining and logging are inconsistent with the wording of the Act. These disagreements are illustrated by the argument over drilling in the Arctic National Wildlife Refuge, a dispute that reemerged with the rising price of petroleum.

FIGURE 12.17 **Wrangell–St. Elias Wilderness Area, Alaska**, designated in 1980 and now covering 9,078,675 acres. As the photograph suggests, this vast area gives a visitor a sense of wilderness as a place where a person is only a visitor and human beings seem to have no impact.

The notion of managing wilderness may seem paradoxical—is it still wilderness if we meddle with it? In fact, though, with the great numbers of people in the world today, even wilderness must be defined, legally set aside, and controlled. We can view the goal of managing wilderness in two ways: in terms of the wilderness itself and in terms of people. In the first instance, the goal is to preserve nature undisturbed by people. In the second, the purpose is to provide people with a wilderness experience.

Legally designated wilderness can be seen as one extreme in a spectrum of environments to manage. The spectrum ranges from wilderness rarely disturbed by anyone to preserves in which some human activities are allowed to be visible—parks designed for outdoor recreation, forests for timber production and various kinds of recreation, hunting preserves, and urban parks—and finally, at the other extreme, open-pit mines. You can think of many stages in between on this spectrum.

Wilderness management should involve as little direct action as possible, so as to minimize human influence. This also means, ironically, that one of the necessities is to control human access so that a visitor has little, if any, sense that other people are present.

Consider, for example, the Desolation Wilderness Area in California, consisting of more than 24,200 hectares (60,000 acres), which in one year had more than 250,000 visitors. Could each visitor really have a wilderness experience there, or was the human carrying capacity of the wilderness exceeded? This is a subjective judgment. If, on one hand, all visitors saw only their own companions and believed they were alone, then the actual number of visitors did not matter for each visitor's wilderness experience. On the other hand, if every visitor found the solitude ruined by strangers, then the management failed, no matter how few people visited.

Wilderness designation and management must also take into account adjacent land uses. A wilderness next to a garbage dump or a power plant spewing smoke is a contradiction in terms. Whether a wilderness can be adjacent to a high-intensity campground or near a city is a more subtle question that must be resolved by citizens.

Today, those involved in wilderness management recognize that wild areas change over time and that these changes should be allowed to occur as long as they are natural. This is different from earlier views that nature undisturbed was unchanging and should be managed so that it did not change. In addition, it is generally argued now that in choosing what activities can be allowed in a wilderness, we should emphasize activities that depend on wilderness (the experience of solitude or the observation of shy and elusive wildlife) rather than activities that can be enjoyed elsewhere (such as downhill skiing).

Another source of conflict is that wilderness areas frequently contain economically important resources, including timber, fossil fuels, and mineral ores. There has been heated debate about whether wilderness areas should be open to the extraction of these.

Still another controversy involves the need to study wilderness versus the desire to leave wilderness undisturbed. Those in favor of scientific research in the wilderness argue that it is necessary for the conservation of wilderness. Those opposed argue that scientific research contradicts the purpose of a designated wilderness as an area undisturbed by people. One solution is to establish separate research preserves.

CRITICAL THINKING ISSUE

Can Tropical Forests Survive in Bits and Pieces?

Although tropical rain forests occupy only about 7% of the world's land area, they provide habitat for at least half of the world's species of plants and animals. Approximately 100 million people live in rain forests or depend on them for their livelihood. Tropical plants provide products such as chocolate, nuts, fruits, gums, coffee, wood, rubber, pesticides, fibers, and dyes. Drugs for treating high blood pressure, Hodgkin's disease, leukemia, multiple sclerosis, and Parkinson's disease have been made from tropical plants, and medical scientists believe many more are yet to be discovered.

In the United States, most of the interest in tropical rain forests has focused on Brazil, whose forests are believed to have more species than any other geogaphic area. Estimates of destruction in the Brazilian rain forest range from 6 to 12%, but numerous studies have shown that deforested area alone does not adequately measure habitat destruction because surrounding habitats are also affected (refer back to Figure 12.14a). For example, the more fragmented a forest is, the more edges there are, and the greater the impact on the living organisms. Such edge effects vary depending on the species, the characteristics of the land surrounding the forest fragment, and the distance between fragments. For example, a forest surrounded by farmland is more deeply affected than one surrounded by abandoned land in which secondary growth presents a more gradual transition between forest and deforested areas. Some insects, small mammals, and many birds find only 80 m (262.5 ft) to be a barrier to movement from one fragment to another, whereas one small marsupial has been found to cross distances of 250 m (820.2 ft). Corridors between forested areas also help to offset the negative effects of deforestation on plants and animals of the forest.

Critical Thinking Questions

1. Look again at Figure 12.14a, the satellite image of part of the Brazilian rain forest. You are asked to make a plan that will allow 50% of the area to be cut, and the rest established as a national park. Make a design for how you think this would best be done, taking into account conservation of biological diversity, the difficulty of travel in tropical rain forests, and the needs of local people to make a living. In your plan, the areas to be harvested will not change over time once the design is in place.
2. You are asked to create a park like the one in question 1, taking into account that the forested areas cut for timber will be allowed to regenerate and during that time, until actual harvest, could be used for recreation. Modify your design to take that into account.
3. The forest fragments left uncut in Figure 12.14 are sometimes compared with islands. What are some ways in which this is an appropriate comparison? Some ways in which it is not?

SUMMARY

- In the past, land management for harvesting resources and conserving nature was mostly local, with each parcel of land considered independently.
- Today, a landscape perspective has developed, and lands used for harvesting resources are seen as part of a matrix that includes lands set aside for the conservation of biological diversity and for landscape beauty.
- Forests are among civilization's most important renewable resources. Forest management seeks a sustainable harvest and sustainable ecosystems. Because examples of success-

ful sustainable forestry are rare, "certification of sustainable forestry" has developed to determine which methods appear most consistent with sustainability and then compare the management of a specific forest with those standards.

- Given their rapid population growth, continued use of firewood as an important fuel in developing nations is a major threat to forests. It is doubtful that these nations can implement successful management programs in time to prevent serious damage to their forests and severe effects on their people.
- Clear-cutting is a major source of controversy in forestry. Some tree species require clearing to reproduce and grow, but the scope and method of cutting must be examined carefully in terms of the needs of the species and the type of forest ecosystem.
- Properly managed plantations can relieve pressure on forests.
- Managing parks for biological conservation is a relatively new idea that began in the 19th century. The manager of a park must be concerned with its shape and size. Parks that are too small or the wrong shape may have too small a population of the species for which the park was established and thus may not be able to sustain the species.
- A special extreme in conservation of natural areas is the management of wilderness. In the United States, the 1964 Wilderness Act provided a legal basis for such conservation. Managing wilderness seems a contradiction—trying to make sure it will be undisturbed by people requires interference to limit user access and to maintain the natural state, so an area that is not supposed to be influenced by people actually is.
- Parks, nature preserves, wilderness areas, and actively harvested forests affect one another. The geographic pattern of these areas on a landscape, including corridors and connections among different types, is part of the modern approach to biological conservation and the harvest of forest resources.

REEXAMINING THEMES AND ISSUES

Human Population

Forests provide essential resources for civilization. As the human population grows, there will be greater and greater demand for these resources. Because forest plantations can be highly productive, we are likely to place increasing emphasis on them as a source of timber. This would free more forestland for other uses.

Sustainability

Sustainability is the key to conservation and management of wild living resources. However, sustainable harvests have rarely been achieved for timber production, and sustained ecosystems in harvested forests are even rarer. Sustainability must be the central focus for forest resources in the future.

Global Perspective

Forests are global resources. A decline in the availability of forest products in one region affects the rate of harvest and economic value of these products in other regions. Biological diversity is also a global resource. As the human population grows, the conservation of biological diversity is likely to depend more and more on legally established parks, nature preserves, and wilderness areas.

Urban World

We tend to think of cities as separated from living resources, but urban parks are important in making cities pleasant and livable; if properly designed, they can also help to conserve wild living resources.

People and Nature

Forests have provided essential resources, and often people have viewed them as perhaps sacred but also dark and scary. Today, we value wilderness and forests, but we rarely harvest forests sustainably. Thus, the challenge for the future is to reconcile our dual and somewhat opposing views so that we can enjoy both the deep meaningfulness of forests and their important resources.

Science and Values

Many conflicts over parks, nature preserves, and legally designated wilderness areas also involve science and values. Science tells us what is possible and what is required in order to conserve both a specific species and total biological diversity. But what society desires for such areas is, in the end, a matter of values and experience, influenced by scientific knowledge.

KEY TERMS

certification of forestry **246**
clear-cutting **245**
codominants **245**
dominants **245**
intermediate **245**
old-growth forest **244**
plantation **245**
rotation time **244**
second-growth forest **244**
seed-tree cutting **245**
selective cutting **245**
shelterwood cutting **245**
silviculture **238**
site quality **245**
stand **244**
strip-cutting **245**
suppressed **245**
thinning **245**
wilderness **252**

STUDY QUESTIONS

1. What environmental conflicts might arise when a forest is managed for the multiple uses of (a) commercial timber, (b) wildlife conservation, and (c) a watershed for a reservoir? In what ways could management for one use benefit another?
2. What arguments could you offer for and against the statement "Clear-cutting is natural and necessary for forest management"?
3. Can a wilderness park be managed to supply water to a city? Explain your answer.
4. A park is being planned in rugged mountains with high rainfall. What are the environmental considerations if the purpose of the park is to preserve a rare species of deer? If the purpose is recreation, including hiking and hunting?
5. What are the environmental effects of decreasing the rotation time (accelerating the rate of cutting) in forests from an average of 60 years to 10 years? Compare these effects for (a) a woodland in a dry climate on a sandy soil and (b) a rain forest.
6. In a small but heavily forested nation, two plans are put forward for forest harvests. In Plan A, all the forests to be harvested are in the eastern part of the nation, while all the forests of the West are set aside as wilderness areas, parks, and nature preserves. In Plan B, small areas of forests to be harvested are distributed throughout the country, in many cases adjacent to parks, preserves, and wilderness areas. Which plan would you choose? Note that in Plan B, wilderness areas would be smaller than in Plan A.
7. The smallest legally designated wilderness in the United States is Pelican Island, Florida (Figure 12.18), covering 5 acres. Do you think this can meet the meaning of *wilderness* and the intent of the Wilderness Act?

FURTHER READING

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CHAPTER 13

Wildlife, Fisheries, and Endangered Species

Brown pelicans, once endangered because of DDT, have come back in abundance and are common along both the Atlantic and Pacific coasts. This pelican is fishing from a breakwater on the Atlantic coast of Florida.

LEARNING OBJECTIVES

Wildlife, fish, and endangered species are among the most popular environmental issues today. People love to see wildlife; many people enjoy fishing, make a living from it, or rely on fish as an important part of their diet; and since the 19th century the fate of endangered species has drawn public attention. You would think that by now we would be doing a good job of conserving and managing these kinds of life, but often we are not. This chapter tells you how we are doing and how we can improve our conservation and management of wildlife, fisheries, and endangered species. After reading this chapter, you should understand . . .

- Why people want to conserve wildlife and endangered species;
- The importance of habitat, ecosystems, and landscape in the conservation of endangered species;
- Current causes of extinction;
- Steps we can take to achieve sustainability of wildlife, fisheries, and endangered species;
- The concepts of species persistence, maximum sustainable yield, the logistic growth curve, carrying capacity, optimum sustainable yield, and minimum viable populations.

CASE STUDY

Stories Told by the Grizzly Bear and the Bison

The grizzly bear and the American bison illustrate many of the general problems of conserving and managing wildlife and endangered species. In Chapter 2 we pointed out that the standard scientific method sometimes does not seem suited to studies in the environmental sciences. This is also true of some aspects of wildlife management and conservation. Several examples illustrate the needs and problems.

The Grizzly Bear

A classic example of wildlife management is the North American grizzly bear. An endangered species, the grizzly has been the subject of efforts by the U.S. Fish and Wildlife Service to meet the requirements of the U.S. Endangered Species Act, which include restoring the population of these bears.

The grizzly became endangered as a result of hunting and habitat destruction. It is arguably the most dangerous North American mammal, famous for unprovoked attacks on people, and has been eliminated from much of its range for that reason. Males weigh as much as 270 kg (600 pounds), females as much as 160 kg (350 pounds). When they rear up on their hind legs, they are almost 3 m (8 ft) tall. No wonder they are frightening (see Figure 13.1). Despite this, or perhaps because of it, grizzlies intrigue people, and watching grizzlies from a safe distance has become a popular recreation.

At first glance, restoring the grizzly seems simple enough. But then that old question arises: Restore to what? One answer is to restore the species to its abundance at the time of the European discovery and settlement of North America. But it turns out that there is very little historical information about the abundance of the grizzly at that time, so it is not easy to determine how many (or what density per unit area) could be considered a "restored" population. We also lack a good estimate of the grizzly's present abundance, and thus we don't know how far we will have to take the species to "restore" it to some hypothetical past abundance. Moreover, the grizzly is difficult to study—it is large and dangerous and tends to be reclusive. The U.S. Fish and Wildlife Service attempted to count the grizzlies in Yellowstone National Park by installing automatic flash cameras that were set off when the grizzlies took a bait. This seemed a good idea, but the grizzlies didn't like the cameras and destroyed them,[1] so we still don't have a good scientific estimate of their present number. The National Wildlife Federation lists 1,200 in the contiguous states, 32,000 in Alaska, and about 25,000 in Canada, but these are crude estimates.[2]

FIGURE 13.1 **Grizzly bear**. Records of bear sightings by Lewis and Clark have been used to estimate their population at the beginning of the 19th century.

How do we arrive at an estimate of a population that existed at a time when nobody thought of counting its members? Where possible, we use historical records, as discussed in Chapter 2. We can obtain a crude estimate of the grizzly's abundance at the beginning of the 19th century from the journals of the Lewis and Clark expedition. Lewis and Clark did not list the numbers of most wildlife they saw; they simply wrote that they saw "many" bison, elk, and so forth. But the grizzlies were especially dangerous and tended to travel alone, so Lewis and Clark noted each encounter, stating the exact number they met. On that expedition, they saw 37 grizzly bears over a distance of approximately 1,000 miles (their records were in miles).[1]

Lewis and Clark saw grizzlies from near what is now Pierre, South Dakota, to what is today Missoula, Montana. A northern and southern geographic limit to the grizzly's range can be obtained from other explorers. Assuming Lewis and Clark could see a half-mile to each side of their line of travel on average, the density of the bears was approximately 3.7 per 100 square miles. If we estimate that the bears' geographic range was 320,000 square miles in the mountain and western plains states, we arrive at a total population of 320,000 x 0.37, or about 12,000 bears.

Suppose we phrase this as a hypothesis: "The number of grizzly bears in 1805 in what is now the United States was 12,000." Is this open to disproof? Not without time travel. Therefore, it is not a scientific statement; it can only be taken as an educated guess or, more formally, an assumption or premise. Still, it has some basis in historical documents, and it is better than no information, since we have few alternatives to determine what used to be. We can use this assumption to create a plan to restore the grizzly to that abundance. But is this the best approach?

Another approach is to ask what is the minimum viable population of grizzly bears—forget completely about what might have been the situation in the past and make use of modern knowledge of population dynamics and genetics, along with food requirements and potential production of that food. Studies of existing populations of brown and grizzly bears suggest that only populations larger than 450 individuals respond to protection with rapid growth.[2] Using this approach, we could estimate how many bears appear to be a "safe" number—that is, a number that carries small risk of extinction and loss of genetic diversity. More precisely, we could phrase this statement as "How many bears are necessary so that the probability that the grizzly will become extinct in the next ten years [or some other period that we consider reasonable for planning] is less than 1% [or some other percentage that we would like]?"

With appropriate studies, this approach could have a scientific basis. Consider a statement of this kind phrased as a hypothesis: "A population of 450 bears [or some other number] results in a 99% chance that at least one mature male and one mature female will be alive ten years from today." We can disprove this statement, but only by waiting for ten years to go by. Although it is a scientific statement, it is a difficult one to deal with in planning for the present.

The American Bison

Another classic case of wildlife management, or mismanagement, is the demise of the American bison, or buffalo (Figure 13.2a). The bison was brought close to extinction in the 19th century for two reasons: They were hunted because coats made of bison hides had become fashionable in Europe, and they also were killed as part of warfare against the Plains peoples (Figure 13.2b). U.S. Army Colonel R.I. Dodge was quoted in 1867 as saying, "Kill every buffalo you can. Every buffalo dead is an Indian gone."[1]

Unlike the grizzly bear, the bison has recovered, in large part because ranchers have begun to find them profitable to raise and sell for meat and other products. Informal estimates, including herds on private and public ranges, suggest there are 200,000–300,000, and bison are said to occur in every state in the United States, including Hawaii, a habitat quite different from their original Great Plains home range.[3] About 20,000 roam wild on public lands in the United States and Canada.[4]

How many bison were there before European settlement of the American West? And how low did their numbers drop? Historical records provide insight. In 1865 the U.S. Army, in response to Indian attacks in the fall of 1864, set fires to drive away the Indians and the buffalo, killing vast numbers of animals.[5] The speed with which bison were almost eliminated was surprising—even to many of those involved in hunting them.

Many early writers tell of immense herds of bison, but few counted them. One exception was General Isaac I. Stevens, who, on July 10, 1853, was surveying for the transcontinental railway in North Dakota. He and his men climbed a high hill and saw "for a great distance ahead every square mile" having "a herd of buffalo upon it." He wrote that "their number was variously estimated by the members of the party—some as high as half a million. I do not think it any exaggeration to

(a)

(b)

FIGURE 13.2 **(a) A bison ranch in the United States**. In recent years, interest in growing bison ranches has increased greatly. In part, the goal is to restore bison to a reasonable percentage of its numbers before the Civil War. In part, bison are ranched because people like them. In addition, there is a growing market for bison meat and other products, including cloth made from bison hair. **(b) Painting of a buffalo hunt** by George Catlin in 1832–1833 at the mouth of the Yellowstone River.

set it down at 200,000."[1] In short, his estimate of just one herd was about the same number of bison that exist in total today!

One of the better attempts to estimate the number of buffalo in a herd was made by Colonel R. I. Dodge, who took a wagon from Fort Zarah to Fort Larned on the Arkansas River in May 1871, a distance of 34 miles. For at least 25 of those miles, he found himself in a "dark blanket" of buffalo. He estimated that the mass of animals he saw in one day totaled 480,000. At one point, he and his men traveled to the top of a hill from which he estimated that he could see six to ten miles, and from that high point there appeared to be a single solid mass of buffalo extending over 25 miles. At ten animals per acre, not a particularly high density, the herd would have numbered 2.7–8.0 million animals.[1]

In the fall of 1868, "a train traveled 120 miles between Ellsworth and Sheridan, Wyoming, through a continuous, browsing herd, packed so thick that the engineer had to stop several times, mostly because the buffaloes would scarcely get off the tracks for the whistle and the belching smoke."[5] That spring, a train had been delayed for eight hours while a single herd passed "in one steady, unending stream." We can use accounts like this one to set bounds on the possible number of animals seen. At the highest extreme, we can assume that the train bisected a circular herd with a diameter of 120 miles. Such a herd would cover 11,310 square miles, or more than 7 million acres. If we suppose that people exaggerated the density of the buffalo, and there were only ten per acre, this single herd would still have numbered 70 million animals!

Some might say that this estimate is probably too high, because the herd would more likely have formed a broad, meandering, migrating line rather than a circle. The impression remains the same—there were huge numbers of buffalo in the American West even as late as 1868, numbering in the tens of millions and probably 50 million or more. Ominously, that same year, the Kansas Pacific Railroad advertised a "Grand Railway Excursion and Buffalo Hunt."[5] Some say that many hunters believed the buffalo could never be brought to extinction because there were so many. The same was commonly believed about all of America's living resources throughout the 19th century.

We tend to view environmentalism as a social and political movement of the 20th century, but it is said that after the Civil War there were angry protests in every legislature over the slaughter of buffalo. In 1871 the U.S. Biological Survey sent George Grinnell to survey the herds along the Platte River. He estimated that only 500,000 buffalo remained there and that at the then-current rate of killing, the animals would not last long. As late as the spring of 1883, a herd of an estimated 75,000 crossed the Yellowstone River near Miles City, Montana, but fewer than 5,000 reached the Canadian border.[5] By the end of that year—only 15 years after the Kansas Pacific train was delayed for eight hours by a huge herd of buffalo—only a thousand or so buffalo could be found, 256 in captivity and about 835 roaming the plains. A short time later, there were only 50 buffalo wild on the plains.

Today, more and more ranchers are finding ways to maintain bison, and the market for bison meat and other bison products is growing, along with an increasing interest in reestablishing bison herds for aesthetic, spiritual, and moral reasons. The history of the bison once again raises the question of what we mean by "restore" a population. Even with our crude estimates of original abundances, the numbers would have varied from year to year. So we would have to "restore" bison not to a single number independent of the ability of its habitat to support the population, but to some range of abundances. How do we approach that problem and estimate the range?

13.1 Traditional Single-Species Wildlife Management

Wildlife, fisheries, and endangered species are considered together in this chapter because they have a common history of exploitation, management, and conservation, and because modern attempts to manage and conserve them follow the same approaches. Although any form of life, from bacteria and fungi to flowering plants and animals, can become endangered, concern about endangered species has tended to focus on wildlife. We will maintain that focus, but we ask you to remember that the general principles apply to all forms of life.

Attempts to apply science to the conservation and management of wildlife and fisheries, and therefore to endangered species, began around the turn of the 20th century and viewed each species as a single population in isolation.

Carrying Capacity and Sustainable Yields

The classical, early-20th-century idea of wildlife and fisheries was formalized in the S-shaped logistic growth curve (Figure 13.3), which we discussed in Chapter 4.

As explained in that chapter, the logistic growth curve assumes that changes in the size of a population are simply the result of the population's size in relation to a maximum, called the *carrying capacity*. The logistic characterizes the population only by its total size, nothing else—not the ratio of young to old, healthy to sick, males to females, and the environment doesn't appear at all; it is just assumed to be constant. (See the accompanying box Key Characteristics of a Logistic Population.) The carrying capacity is defined simply as the maximum population that can be sustained indefinitely. Implicit in this definition is the idea that if the population exceeds the carrying capacity, it will damage its environment and/or its own ability to grow and reproduce, and therefore the population will decline.

Two management goals resulted from these ideas and the logistic equation: For a species that we intend to harvest, the goal was maximum sustainable yield (MSY); for a species that we wish to conserve, the goal was to have that species reach, and remain at, its carrying capacity. **Maximum sustainable yield** is defined as the maximum growth rate (measured either as a net increase in the number of individuals or in biomass over a specified time period) that the population could sustain indefinitely. The **maximum sustainable-yield population** is defined as the population size at which the maximum growth rate occurs. More simply, the population was viewed as a factory that could keep churning out exactly the same quantity of a product year after year.

Key Characteristics of a Logistic Population

- The population exists in an environment assumed to be constant.
- The population is small in relation to its resources and therefore grows at a nearly exponential rate.
- Competition among individuals in the population slows the growth rate.
- The greater the number of individuals, the greater the competition and the slower the rate of growth.
- Eventually, a point is reached, called the **logistic carrying capacity**, at which the number of individuals is just sufficient for the available resources.
- At this level, the number of births in a unit time equals the number of deaths, and the population is constant.
- A population can be described simply by its total number.
- Therefore, all individuals are equal.

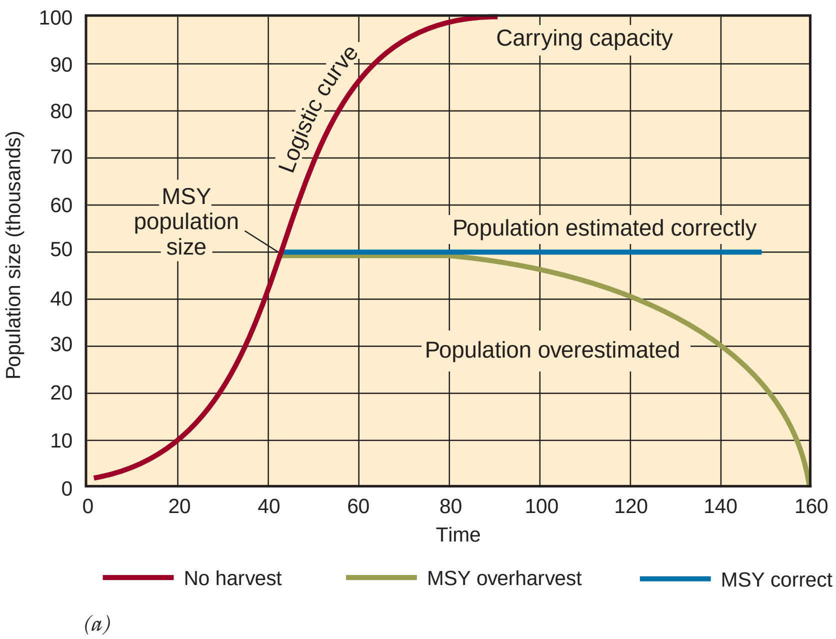
Today a broader view is developing. It acknowledges that a population exists within an ecological community and within an ecosystem, and that the environment is always, or almost always, changing (including human-induced changes). Therefore, the population you are interested in interacts with many others, and the size and condition of those can affect the one on which you are focusing. With this new understanding, the harvesting goal is to harvest sustainably, removing in each time period the maximum number of individuals (or maximum biomass) that can be harvested indefinitely without diminishing either the population that particularly interests you or its ecosystem. The preservation goal for a threatened or an endangered species becomes more open, with more choices. One is to try to keep the population at its carrying capacity. Another is to sustain a **minimum viable population**, which is the estimated smallest population that can maintain itself and its genetic variability indefinitely. A third option, which leads to a population size somewhere between the other two, is the **optimum sustainable population**.

In the logistic curve, the greatest production occurs when the population is exactly one-half of the carrying capacity (see Figure 13.3). This is nifty because it makes everything seem simple—all you have to do is figure out the carrying capacity and keep the population at one-half of it. But what seems simple can easily become troublesome. Even if the basic assumptions of the logistic curve were true, which they are not, the slightest overestimate of carrying capacity, and therefore MSY, would lead to overharvesting, a decline in production, and a decline in the abundance of the species. If a population is harvested as if it were actually at one-half its carrying capacity, then unless a logistic population is actually maintained at exactly that number, its growth will decline. Since it is almost impossible to maintain a wild population at some exact number, the approach is doomed from the start.

One important result of all of this is that a *logistic population is stable in terms of its carrying capacity*—it will return to that number after a disturbance. If the population grows beyond its carrying capacity, deaths exceed births, and the population declines back to the carrying capacity. If the population falls below the carrying capacity, births exceed deaths, and the population increases. Only if the population is exactly at the carrying capacity do births exactly equal deaths, and then the population does not change.

Despite its limitations, the logistic growth curve was used for all wildlife, especially fisheries and including endangered species, throughout much of the 20th century.

The term **carrying capacity** as used today has three definitions. The first is the carrying capacity as defined by the logistic growth curve, the *logistic carrying capacity* already discussed. The second definition contains the same idea but is not dependent on that specific equation. It states that the



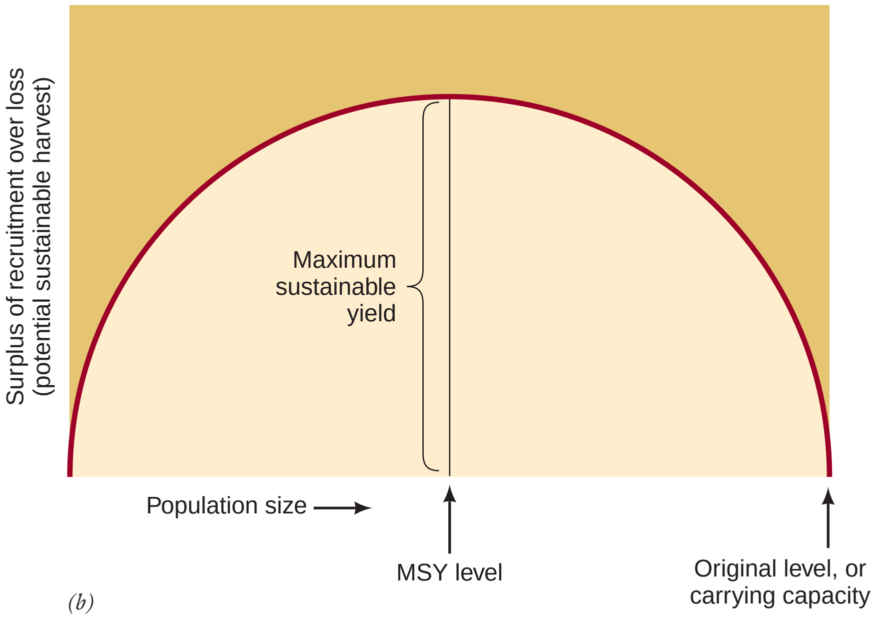


FIGURE 13.3 **(a) The logistic growth curve**, showing the carrying capacity and the maximum sustainable yield (MSY) population (where the population size is one-half the carrying capacity). The figure shows what happens to a population when we assume it is at MSY and it is not. Suppose a population grows according to the logistic curve from a small number to a carrying capacity of 100,000 with an annual growth rate of 5%. The correct maximum sustainable yield would be 50,000. When the population reaches exactly the calculated maximum sustainable yield, the population continues to be constant. But if we make a mistake in estimating the size of the population (for example, if we believe that it is 60,000 when it is only 50,000), then the harvest will always be too large, and we will drive the population to extinction. **(b) Another view of a logistic population**. Growth in the population here is graphed against population size. Growth peaks when the population is exactly at one-half the carrying capacity. This is a mathematical consequence of the equation for the curve. It is rarely, if ever, observed in nature.

carrying capacity is an abundance at which a population can sustain itself without any detrimental effects that would lessen the ability *of that species*—in the abstract, treated as separated from all others—to maintain that abundance. The third, the *optimum sustainable population*, already discussed, leads to a population size between the other two.

An Example of Problems with the Logistic Curve

Suppose you are in charge of managing a deer herd for recreational hunting in one of the 50 U.S. states. Your goal is to maintain the population at its MSY level, which, as you can see from Figure 13.3, occurs at exactly one-half of the carrying capacity. At this abundance, the population increases by the greatest number during any time period.

To accomplish this goal, first you have to determine the logistic carrying capacity. You are immediately in trouble because, first, only in a few cases has the carrying capacity ever been determined by legitimate scientific methods (see Chapter 2) and, second, we now know that the carrying capacity varies with changes in the environment. The procedure in the past was to estimate the carrying capacity by *nonscientific* means and then attempt to maintain the population at one-half that level. This method requires accurate counts each year. It also requires that the environment not vary, or, if it does, that it vary in a way that does not affect the population. Since these conditions cannot be met, the logistic curve has to fail as a basis for managing the deer herd.

An interesting example of the staying power of the logistic growth curve can be found in the United States Marine Mammal Protection Act of 1972. This act states that its primary goal is to conserve "the health and stability of marine ecosystems," which is part of the modern approach, and so the act seems to be off to a good start. But then the act states that the secondary goal is to maintain an "optimum sustainable population" of marine mammals. What is this? The wording of the act allows two interpretations. One is the logistic carrying capacity, and the other is the MSY population level of the logistic growth curve. So the act takes us back to square one, the logistic curve.

13.2 Improved Approaches to Wildlife Management

The U.S. Council on Environmental Quality (an office within the executive branch of the federal government), the World Wildlife Fund of the United States, the Ecological Society of America, the Smithsonian Institution, and the International Union for the Conservation of Nature (IUCN) have proposed four principles of wildlife conservation:

- A safety factor in terms of population size, to allow for limitations of knowledge and imperfections of procedures. An interest in harvesting a population should not allow the population to be depleted to some theoretical minimum size.
- Concern with the entire community of organisms and all the renewable resources, so that policies developed for one species are not wasteful of other resources.
- Maintenance of the ecosystem of which the wildlife are a part, minimizing risk of irreversible change and long-term adverse effects as a result of use.
- Continual monitoring, analysis, and assessment. The application of science and the pursuit of knowledge about the wildlife of interest and its ecosystem should be maintained and the results made available to the public.

These principles broaden the scope of wildlife management from a narrow focus on a single species to inclusion of the ecological community and ecosystem. They call for a safety net in terms of population size, meaning that no population should be held at exactly the MSY level or reduced to some theoretical minimum abundance. These new principles provide a starting point for an improved approach to wildlife management.

Time Series and Historical Range of Variation

As illustrated by the opening case study about the American buffalo and grizzly bears, it is best to have an estimate of population over a number of years. This set of estimates is called a **time series** and could provide us with a measure of the **historical range of variation**—the known range of abundances of a population or species over some past time interval. Such records exist for few species. One is the American whooping crane (Figure 13.4), America's tallest bird, standing about 1.6 m (5 ft) tall. Because this species became so rare and because it migrated as a single flock, people began counting the total population in the late 1930s. At that time, they saw only 14 whooping cranes. They counted not only the total number but also the number born that year. The difference between these two numbers gives the number dying each year as well. And from this time series, we can estimate the probability of extinction.

The first estimate of the probability of extinction based on the historical range of variation, made in the early 1970s, was a surprise. Although the birds were few, the probability of extinction was less than one in a billion.[6] How could this number be so low? Use of the historical range of variation carries with it the assumption that causes of variation in the future will be only those that occurred during the historical period. For the whooping cranes, one catastrophe—such as a long, unprecedented drought on the wintering grounds—could cause a population decline not observed in the past.

Not that the whooping crane is without threats—current changes in its environment may not be simply repeats of what happened in the past. According to Tom Stehn, Whooping Crane Coordinator for the U.S. Fish and Wildlife Service, the whooping crane population that winters in Aransas National Wildlife Refuge, Texas, and summers in Wood Buffalo National Park, Canada,

> *reached a record population of 270 at Aransas in December, 2008. The number would have been substantially higher but for the loss of 34 birds that left Aransas in the spring, 2008 and failed to return in the fall. Faced with food shortages from an "exceptional" drought that hammered Texas, record high mortality during the 2008–09 winter of 23 cranes (8.5% of the flock) left the AWBP at 247 in the spring, 2009. Total flock mortality for the 12 months following April, 2008 equaled 57 birds (21.4% of the flock). The refuge provided supplemental feed during the 2008–09 winter to provide some cranes with additional calories. Two whooping cranes failed to migrate north, but survived the hot and dry 2009 Aransas summer.*

A below-average 2009 production year in Canada with 22 fledged chicks from 62 nests was half the production of the previous summer and is expected to result in a break-even year for the AWBP. Threats to the flock including land and water development in Texas, the spread of black mangrove on the wintering grounds, and wind farm construction in the migration corridor all remained unabated in 2009.[7]

Even with this limitation, this method provides invaluable information. Unfortunately, at present, mathematical estimates of the probability of extinction have been done for just a handful of species. The good news is that the wild whooping cranes on the main flyway have continued to increase and in 2008 numbered 274. The total wild population (all flyways) was 382, and there were 162 in captive flocks, for a total of 534.[8, 5]

Age Structure as Useful Information

An additional key to successful wildlife management is monitoring of the population's age structure (see Chapter 4), which can provide many different kinds of information. For example, the age structures of the catch of salmon from the Columbia River in Washington for two different periods, 1941–1943 and 1961–1963, were quite different. In the first period, most of the catch (60%) consisted of four-year-olds; the three-year-olds and 5-year-olds each made up about 15% of the population. Twenty years later, in 1961 and 1962, half the catch consisted of 3-year-olds, the number of 5-year-olds had declined to about 8%, and the total catch had declined considerably. During the period 1941–1943, 1.9 million fish were caught. During the second period, 1961–1963, the total catch dropped to 849,000, just 49% of the total caught in the earlier period. The shift in catch toward younger ages, along with an overall decline in catch, suggests that the fish were being exploited to a point at which they were not reaching older ages. Such a shift in the age structure of a harvested population is an early sign of overexploitation and of a need to alter allowable catches.

Harvests as an Estimate of Numbers

Another way to estimate animal populations is to use the number harvested. Records of the number of buffalo killed were neither organized nor all that well kept, but they were sufficient to give us some idea of the number taken. In 1870, about 2 million buffalo were killed. In 1872, one company in Dodge City, Kansas, handled 200,000 hides. Estimates based on the sum of reports from such companies, together with guesses at how many

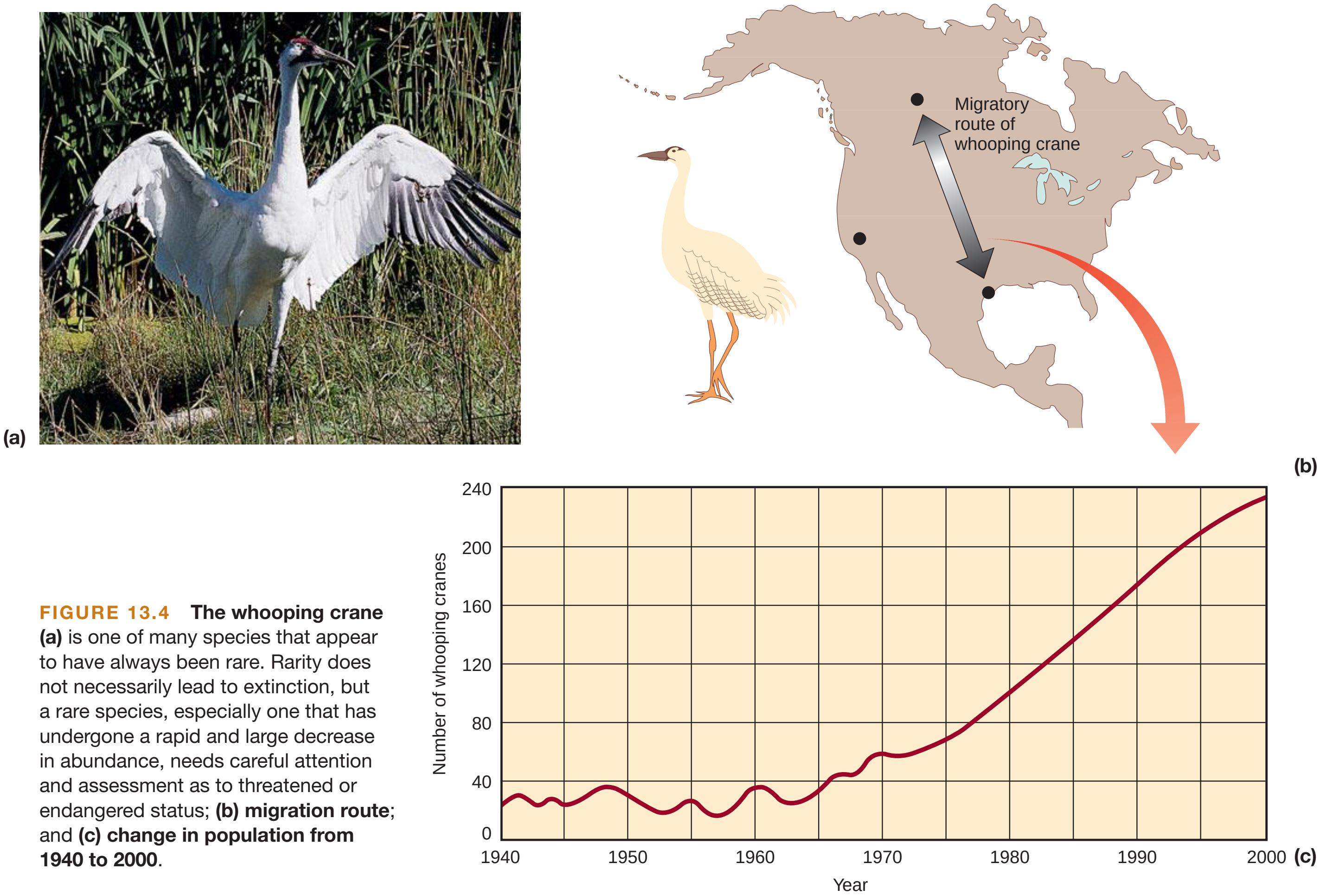


FIGURE 13.4 The whooping crane (a) is one of many species that appear to have always been rare. Rarity does not necessarily lead to extinction, but a rare species, especially one that has undergone a rapid and large decrease in abundance, needs careful attention and assessment as to threatened or endangered status; **(b) migration route**; and **(c) change in population from 1940 to 2000**.

animals were likely taken by small operators and not reported, suggest that about 1.5 million hides were shipped in 1872 and again in 1873.[5] In those years, buffalo hunting was the main economic activity in Kansas. The Indians were also killing large numbers of buffalo for their own use and for trade. Estimates range to 3.5 million buffalo killed per year, nationwide, during the 1870s.[9] The bison numbered at least in the low millions.

Still another way harvest counts are used to estimate previous animal abundance is the **catch per unit** effort. This method assumes that the same effort is exerted by all hunters/harvesters per unit of time, as long as they have the same technology. So if you know the total time spent in hunting/harvesting and you know the catch per unit of effort, you can estimate the total population. This method leads to rather crude estimates with a large observational error; but where there is no other source of information, it can offer unique insights.

An interesting application of this method is the reconstruction of the harvest of the bowhead whale and, from that, an estimate of the total bowhead population. Taken traditionally by Eskimos, the bowhead was the object of "Yankee," or American, whaling from 1820 until the beginning of World War I. (See A Closer Look 13.3 later in this chapter for a general discussion of marine mammals.) Every ship's voyage was recorded, so we know essentially 100% of all ships that went out to catch bowheads. In addition, on each ship a daily log was kept, with records including sea conditions, ice conditions, visibility, number of whales caught, and their size in terms of barrels of oil. Some 20% of these logbooks still exist, and their entries have been computerized. Using some crude statistical techniques, it was possible to estimate the abundance of the bowhead in 1820 at 20,000, plus or minus 10,000. Indeed, it was possible to estimate the total catch of whales and the catch for each year—and therefore the entire history of the hunting of this species.

13.3 Fisheries

Fish are important to our diets—they provide about 16% of the world's protein and are especially important protein sources in developing countries. Fish provide 6.6% of food in North America (where people are less interested in fish than are people in most other areas), 8% in Latin America, 9.7% in Western Europe, 21% in Africa, 22% in central Asia, and 28% in the Far East.

Fishing is an international trade, but a few countries dominate: Japan, China, Russia, Chile, and the United States are among the major fisheries nations. And commercial fisheries are concentrated in relatively few areas of the world's oceans (Figure 13.5). Continental shelves, which make up only 10% of the oceans, provide more than 90% of the fishery harvest. Fish are abundant where their food is abundant and, ultimately, where there is high production of algae at the base of the food chain. Algae are most abundant in areas with relatively high concentrations of the chemical elements necessary for life, particularly nitrogen and phosphorus. These areas occur most commonly along the continental shelf, particularly in regions of wind-induced upwellings and sometimes quite close to shore.

The world's total fish harvest has increased greatly since the middle of the 20th century. The total harvest was 35 million metric tons (MT) in 1960. It more than doubled in just 20 years (an annual increase of about 3.6%) to 72 million MT in 1980 and has since grown to 132,000 MT, but seems to be leveling off.[10] The total global fish harvest doubled in 20 years because of increases in the number of boats, improvements in technology, and especially increases in aquaculture production, which also more than doubled between 1992 and 2001, from about 15 million MT to more than 37 million MT. Aquaculture presently provides more than 20% of all fish harvested, up from 15% in 1992.

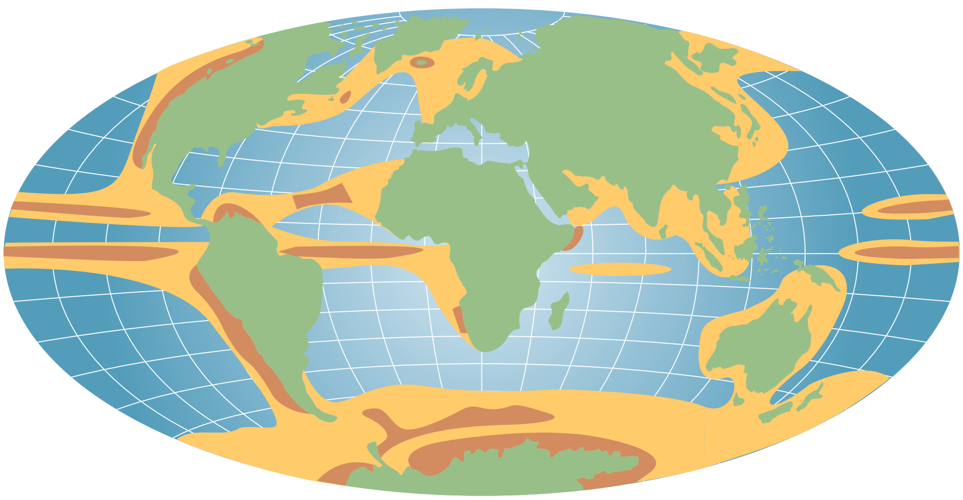


FIGURE 13.5 The world's major fisheries. Red areas are major fisheries; the darker the red, the greater the harvest and the more important the fishery. Most major fisheries are in areas of ocean upwellings, where currents rise, bringing nutrient-rich waters up from the depths of the ocean. Upwellings tend to occur near continents.[11]

Table 13.1 WORLD FISHERIES CATCH

KIND	HARVEST (MILLIONS OF METRIC TONS)	PERCENT	ACCUMULATED PERCENTAGE
Herring, sardines, and anchovies	25	19.23%	19.23%
Carp and relatives	15	11.54%	30.77%
Cod, hake, and haddock	8.6	6.62%	37.38%
Tuna and their relatives	6	4.62%	42.00%
Oysters	4.2	3.23%	45.23%
Shrimp	4	3.08%	48.31%
Squid and octopus	3.7	2.85%	51.15%
Other mollusks	3.7	2.85%	54.00%
Clams and relatives	3	2.31%	56.31%
Tilapia	2.3	1.77%	58.08%
Scallops	1.8	1.38%	59.46%
Mussels and relatives	1.6	1.23%	60.69%
Subtotal	78.9	60.69%	
TOTAL ALL SPECIES	130	100%	

Source: National Oceanic & Atmospheric Administration World

Scientists estimate that there are 27,000 species of fish and shellfish in the oceans. People catch many of these species for food, but only a few kinds provide most of the food—anchovies, herrings, and sardines account for almost 20% (Table 13.1).

In summary, new approaches to wildlife conservation and management include (1) historical range of abundance; (2) estimation of the probability of extinction based on historical range of abundance; (3) use of age-structure information; and (4) better use of harvests as sources of information. These, along with an understanding of the ecosystem and landscape context for populations, are improving our ability to conserve wildlife.

Although the total marine fisheries catch has increased during the past half-century, the effort required to catch a fish has increased as well. More fishing boats with better and better gear sail the oceans (Figure 13.6). That is why the total catch can increase while the total population of a fish species declines.

(a) (b) (c)

FIGURE 13.6 Some modern commercial fishing methods. (a) Trawling using large nets; **(b)** longlines have caught a swordfish; **(c)** workers on a factory ship.

The Decline of Fish Populations

Evidence that the fish populations were declining came from the catch per unit effort. A unit of effort varies with the kind of fish sought. For marine fish caught with lines and hooks, the catch rate generally fell from 6–12 fish caught per 100 hooks—the success typical of a previously unexploited fish population—to 0.5–2.0 fish per 100 hooks just ten years later (Figure 13.7). These observations suggest that fishing depletes fish quickly—about an 80% decline in 15 years. Many of the fish that people eat are predators, and on fishing grounds the biomass of large predatory fish appears to be only about 10% of pre-industrial levels. These changes indicate that the biomass of most major commercial fish has declined to the point where we are mining, not sustaining, these living resources.

Species suffering these declines include codfish, flatfishes, tuna, swordfish, sharks, skates, and rays. The North Atlantic, whose Georges Bank and Grand Banks have for centuries provided some of the world's largest fish harvests, is suffering. The Atlantic codfish catch was 3.7 million MT in 1957, peaked at 7.1 million MT in 1974, declined to 4.3 million MT in 2000, and climbed slightly to 4.7 in 2001.[12] European scientists called for a total ban on cod fishing in the North Atlantic, and the European Union came close to accepting this call, stopping just short of a total ban and instead establishing a 65% cut in the allowed catch for North Sea cod for 2004 and 2005.[12] (See also A Closer Look 13.1.)

Scallops in the western Pacific show a typical harvest pattern, starting with a very low harvest in 1964 at 200 MT, increasing rapidly to 5,887 MT in 1975, declining to 1,489 in 1974, rising to about 7,670 MT in 1993, and then declining to 2,964 in 2002.[13] Catch of tuna and their relatives peaked in the early 1990s at about 730,000 MT and fell to 680,000 MT in 2000, a decline of 14% (Figure 13.7).

Chesapeake Bay, America's largest estuary, was another of the world's great fisheries, famous for oysters and crabs and as the breeding and spawning ground for bluefish, sea bass, and many other commercially valuable species (Figure 13.8). The bay, 200 miles long and 30 miles wide, drains an area of more than 165,000 km^2 from New York State to Maryland and is fed by 48 large rivers and 100 small ones.

Adding to the difficulty of managing the Chesapeake Bay fisheries, food webs are complex. Typical of marine food webs, the food chain of the bluefish that spawns and breeds in Chesapeake Bay shows links to a number of other species, each requiring its own habitat within the space and depending on processes that have a variety of scales of space and time (Figure 13.9).

Furthermore, Chesapeake Bay is influenced by many factors on the surrounding lands in its watershed—runoff from farms, including chicken and turkey farms, that are highly polluted with fertilizers and pesticides; introductions of exotic species; and direct alteration of habitats from fishing and the development of shoreline homes. There is also the varied salinity of the bay's waters—freshwater inlets from rivers and streams, seawater from the Atlantic, and brackish water resulting from the mixture of these.

Just determining which of these factors, if any, are responsible for a major change in the abundance of any fish species is difficult enough, let alone finding a solution that is economically feasible and maintains traditional levels of fisheries employment in the bay. The Chesapeake Bay's fisheries resources are at the limit of what environmental sciences can deal with at this time. Scientific theory remains inadequate, as do observations, especially of fish abundance.

Ironically, this crisis has arisen for one of the living resources most subjected to science-based management. How could this have happened? First, management has been based largely on the logistic growth curve, whose problems we have discussed. Second, fisheries are an open resource, subject to the problems of Garrett Hardin's

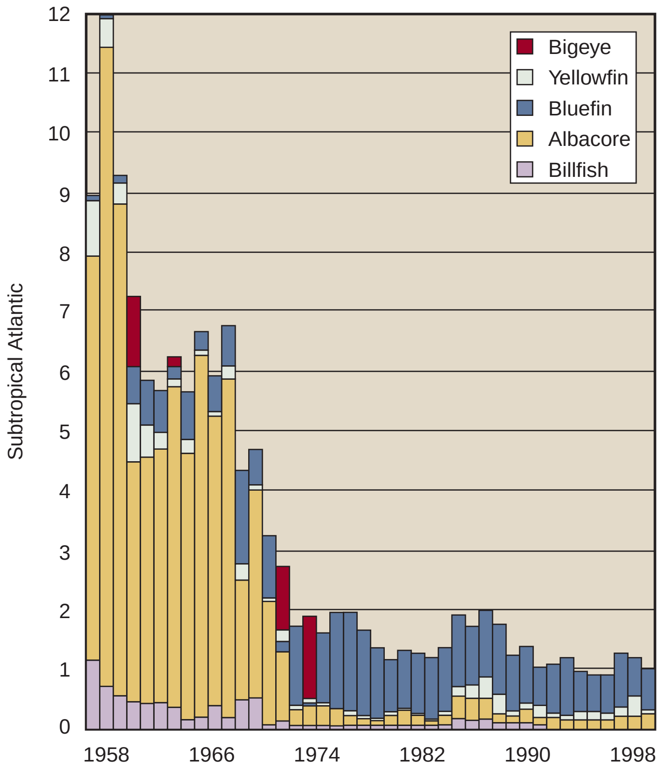


FIGURE 13.7 Tuna catch decline. The catch per unit of effort is represented here as the number of fish caught per 100 hooks for tuna and their relatives in the subtropical Atlantic Ocean. The vertical axis shows the number of fish caught per 100 hooks. The catch per unit of effort was 12 in 1958, when heavy modern industrial fishing for tuna began, and declined rapidly to about 2 by 1974. This pattern occurred worldwide in all the major fishing grounds for these species. (*Source*: Ransom A. Meyers and Boris Worm, "Rapid Worldwide Depletion of Predatory Fish Communities," *Nature* [May 15, 2003].)

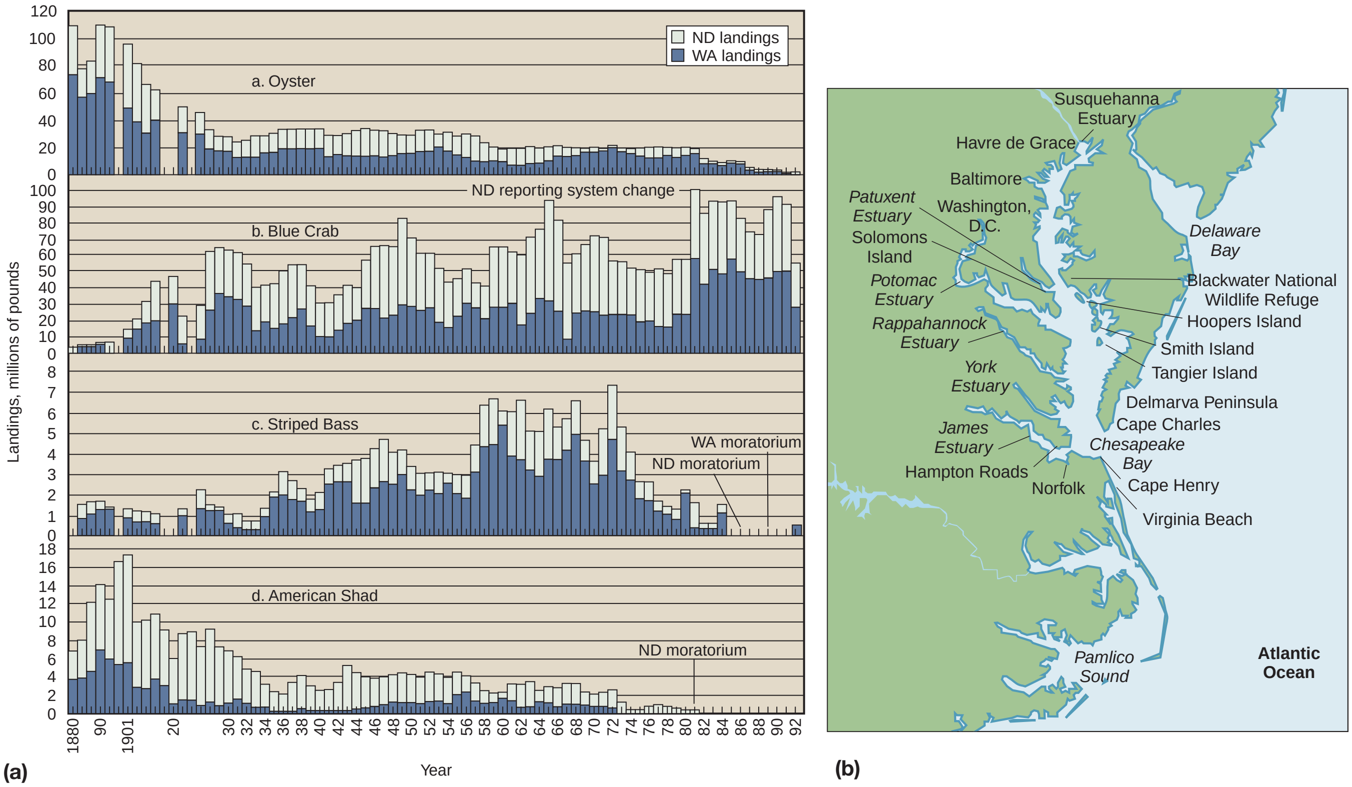


FIGURE 13.8 **(a) Fish catch in the Chesapeake Bay**. Oysters have declined dramatically. (*Source:* The Chesapeake Bay Foundation.) **(b) Map of the Chesapeake Bay Estuary**. (*Source:* U.S. Geological Survey, "The Chesapeake Bay: Geological Product of Rising Sea Level," 1998.)

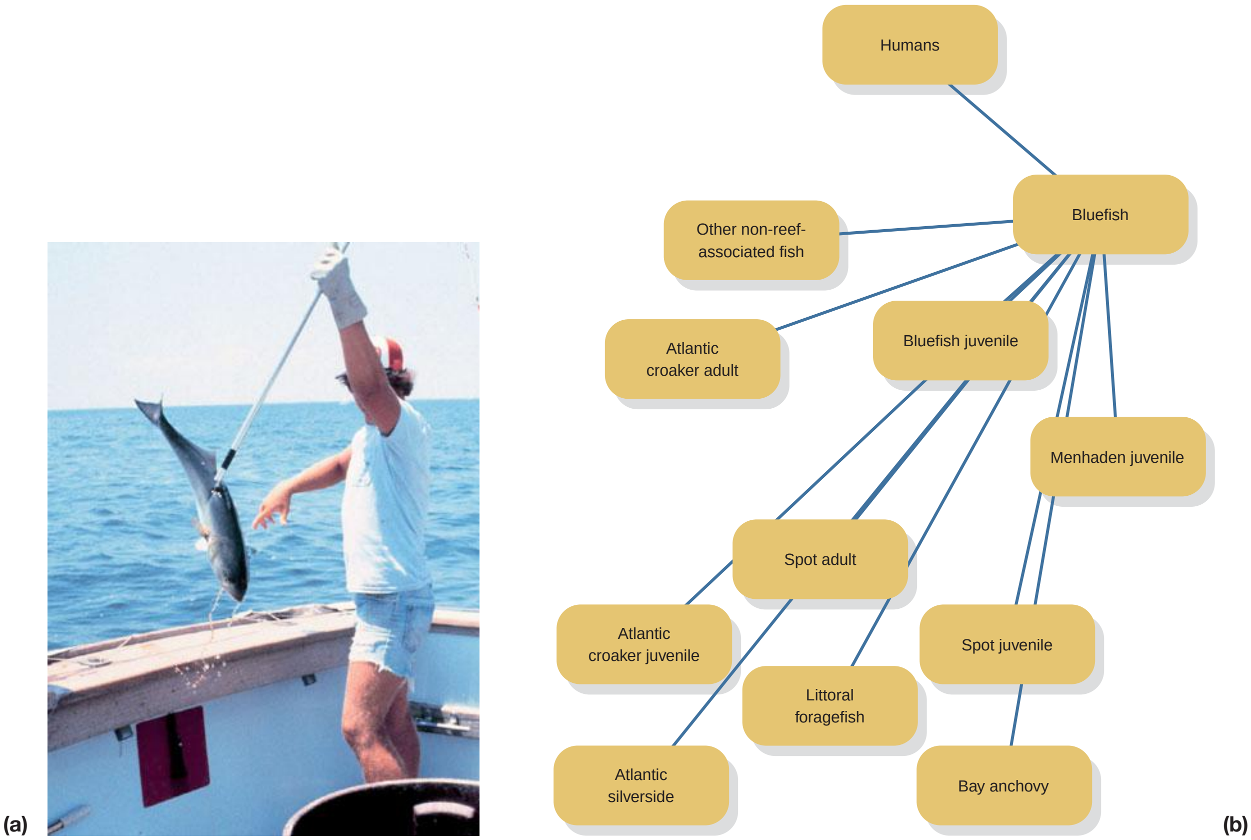


FIGURE 13.9 **(a) Bluefish; (b) food chain of the bluefish in Chesapeake Bay** (*Source*: Chesapeake Bay Foundation.)

"tragedy of the commons," discussed in Chapter 7. In an open resource, often in international waters, the numbers of fish that may be harvested can be limited only by international treaties, which are not tightly binding. Open resources offer ample opportunity for unregulated or illegal harvest, or harvest contrary to agreements.

Exploitation of a new fishery usually occurs before scientific assessment, so the fish are depleted by the time any reliable information about them is available. Furthermore, some fishing gear is destructive to the habitat. Ground-trawling equipment destroys the ocean floor, ruining habitat for both the target fish and its food. Longline fishing kills sea turtles and other nontarget surface animals. Large tuna nets have killed many dolphins that were hunting the tuna.

In addition to highlighting the need for better management methods, the harvest of large predators raises questions about ocean ecological communities, especially whether these large predators play an important role in controlling the abundance of other species.

Human beings began as hunter-gatherers, and some hunter-gatherer cultures still exist. Wildlife on the land used to be a major source of food for hunter-gatherers. It is now a minor source of food for people of developed nations, although still a major food source for some indigenous peoples, such as the Eskimo. In contrast, even developed nations are still primarily hunter-gatherers in the harvesting of fish (see the discussion of aquaculture in Chapter 11).

Can Fishing Ever Be Sustainable?

Suppose you went into fishing as a business and expected reasonable growth in that business in the first 20 years. The world's ocean fish catch rose from 39 million MT in 1964 to 68 million MT in 2003, an average of 3.8% per year for a total increase of 77%.[15] From a business point of view, even assuming all fish caught are sold, that is not considered rapid sales growth. But it is a heavy burden on a living resource.

There is a general lesson to be learned here: Few wild biological resources can sustain a harvest large enough to meet the requirements of a growing business. Although when the overall economy is poor, such as during the economic downturn of 2008–2009, these growth rates begin to look pretty good, most wild biological resources really aren't a good business over the long run. We learned this lesson also from the demise of the bison, discussed earlier, and it is true for whales as well (see A Closer Look 13.3). There have been a few exceptions, such as the several hundred years of fur trading by the Hudson's Bay Company in northern Canada. However, past experience suggests that economically beneficial sustainability is unlikely for most wild populations.

With that in mind, we note that farming fish—aquaculture, discussed in Chapter 11—has been an important source of food in China for centuries and is an increasingly important food source worldwide. But aquaculture can create its own environmental problems (see A Closer Look 13.1).

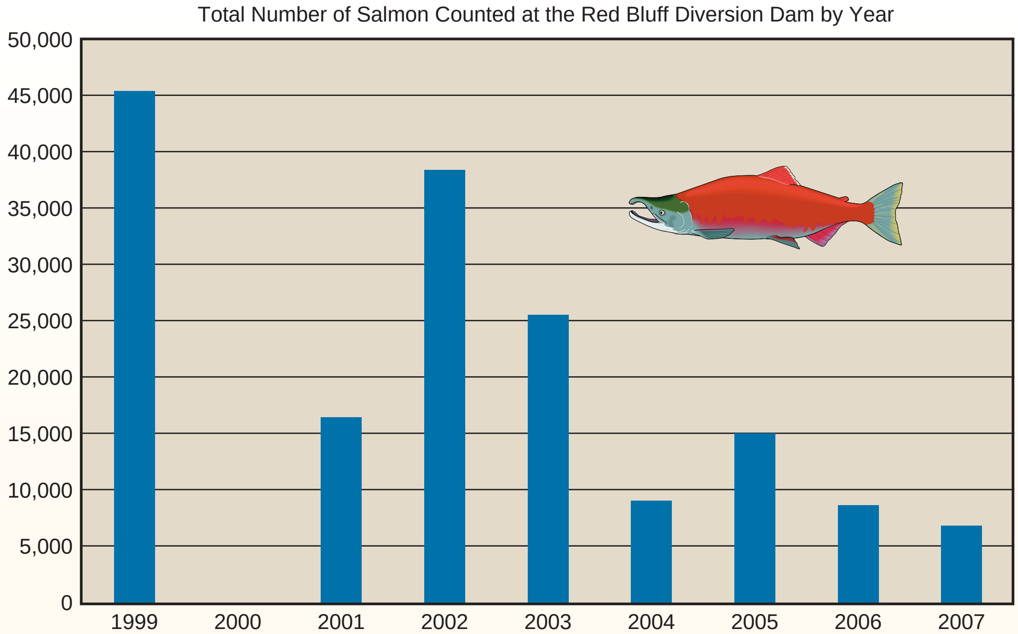
A CLOSER LOOK 13.1

King Salmon Fishing Season Canceled: Can We Save Them from Extinction?

On May 1, 2008, Secretary of Commerce Carlos M. Gutierrez declared "a commercial fishery failure for the West Coast salmon fishery due to historically low salmon returns," and ordered that salmon fishing be closed. It was an unprecedented decision, the first time since California and Oregon became states, because experts decided that numbers of salmon on the Sacramento River had dropped drastically. The decision was repeated in April 2009, halting all king salmon catch off of California but allowing a small catch off of Oregon, and also allowing a small salmon season on the Sacramento River from mid-November to December 31.[12] Figure 13.10 shows an example of the counts that influenced the decision. These counts were done at the Red Bluff Dam, an irrigation dam for part of the flow of the Sacramento River, completed in 1966. There the fish could be observed as they traversed a fish ladder. Between 1967 and 1969, an average of more than 85,000 adult king salmon crossed the dam. In 2007, there were fewer than 7,000.[13]

While the evidence from Red Bluff Dam seems persuasive, there are several problems. First, the number of salmon varies greatly from year to year, as you can see from the graph. Second, there is no single, consistent way that all the salmon on the Sacramento River system are counted, and in some places the counts are much more ambiguous, suggesting that the numbers may not have dropped severely, as shown in Figure 13.11.

Lacking the best long-term observations, those in charge of managing the salmon decided to err on the side of caution:



(a)

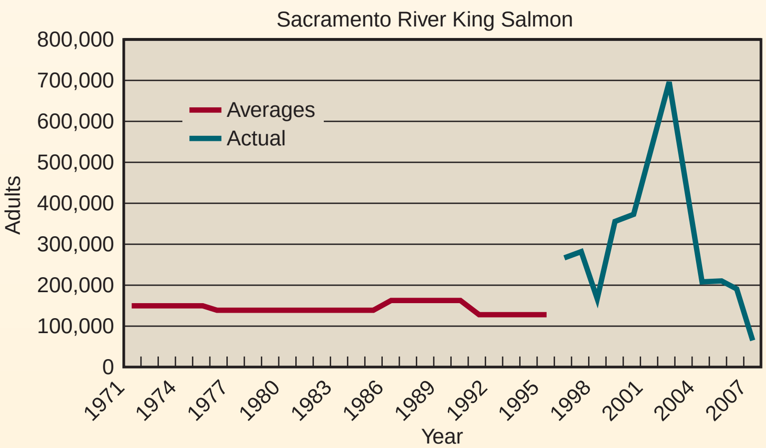
(b)

FIGURE 13.10 Salmon on the Sacramento River. (a) Counted at the Red Bluff Diversion Dam, Red Bluff, California, between May 14 and September 15 each year as they traverse a fish ladder. (*Source*: http://www.rbuhsd.k12.ca.us/~mpritcha/salmoncount.html); **(b)** Red Bluff Dam photo.

for the fish. As California governor Arnold Schwarzenegger said, "These restrictions will have significant impacts to California's commercial and recreational ocean salmon and Central Valley in-river recreation salmon fisheries and will result in severe economic losses throughout the State, including an estimated $255 million economic impact and the loss of an estimated 2,263 jobs."[14]

It was a difficult choice and typical of the kinds of decisions that arise over the conservation of wildlife, fisheries, and endangered species. Far too often, the data necessary for the wisest planning and decisions are lacking. As we learned in earlier chapters, populations and their environment are always changing, so we can't assume there is one single, simple number that represents the natural state of affairs. Look at the graph of the counts of salmon at Red Bluff Dam. What would you consider an average number of salmon? Is there such a thing? What decision would you have made?

This chapter provides the background necessary to conserve and manage these kinds of life, and raises the important questions that our society faces about wildlife, fisheries, and endangered species in the next decades.



(a)

(b)

FIGURE 13.11 Less precise estimates of king salmon for the entire Sacramento River.[16]

In sum, fish are an important food, and world harvests of fish are large, but the fish populations on which the harvests depend are generally declining, easily exploited, and difficult to restore. We desperately need new approaches to forecasting acceptable harvests and establishing workable international agreements to limit catch. This is a major environmental challenge, needing solutions within the next decade.

13.4 Endangered Species: Current Status

When we say that we want to save a species, what is it that we really want to save? There are four possible answers:

- A wild creature in a wild habitat, as a symbol to us of wilderness.
- A wild creature in a managed habitat, so the species can feed and reproduce with little interference and so we can see it in a naturalistic habitat.
- A population in a zoo, so the genetic characteristics are maintained in live individuals.
- Genetic material only—frozen cells containing DNA from a species for future scientific research.

Which of these goals we choose involves not only science but also values. People have different reasons for wishing to save endangered species—utilitarian, ecological, cultural, recreational, spiritual, inspirational, aesthetic, and moral (see A Closer Look 13.2). Policies and actions differ widely, depending on which goal is chosen.

We have managed to turn some once-large populations of wildlife, including fish, into endangered species. With the expanding public interest in rare and endangered species, especially large mammals and birds, it is time for us to turn our attention to these species.

First some facts. The number of species of animals listed as threatened or endangered rose from about 1,700 in 1988 to 3,800 in 1996 and 5,188 in 2004, the most recent assessment by the International Union for the Conservation of Nature (IUCN).[16] The IUCN's *Red List of Threatened Species* reports that about 20% of all known species of mammals are at risk of extinction, as are 12% of known birds, 4% of known reptiles, 31% of amphibians, and 3% of fish, primarily freshwater fish (see Table 13.2).[18] The *Red List* also estimates that 33,798 species of vascular plants (the familiar kind of plants—trees, grasses, shrubs, flowering herbs), or 12.5% of those known, have recently become extinct or endangered.[17] It lists more than 8,000 plants that are threatened, approximately 3% of all plants.[18]

Table 13.2 NUMBER OF THREATENED SPECIES

LIFE-FORM	NUMBER THREATENED	PERCENT OF SPECIES KNOWN
Vertebrates	5,188	9
Mammals	1,101	20
Birds	1,213	12
Reptiles	304	4
Amphibians	1,770	31
Fish	800	3
Invertebrates	1,992	0.17
Insects	559	0.06
Mollusks	974	1
Crustaceans	429	1
Others	30	0.02
Plants	8,321	2.89
Mosses	80	0.5
Ferns and "Allies"	140	1
Gymnosperms	305	31
Dicots	7,025	4
Monocots	771	1
Total Animals and Plants	**31,002**	**2%**

Source: IUCN Red List www.iuenredlist.org/info/table/table1 (2004)

What does it mean to call a species "threatened" or "endangered"? The terms can have strictly biological meanings, or they can have legal meanings. The U.S. Endangered Species Act of 1973 defines *endangered species* as "any species which is in danger of extinction throughout all or a significant portion of its range other than a species of the Class Insecta determined by the Secretary to constitute a pest whose protection under the provisions of this Act would present an overwhelming and overriding risk to man." In other words, if certain insect species are pests, we want to be rid of them. It is interesting that insect pests can be excluded from protection by this legal definition, but there is no mention of disease-causing bacteria or other microorganisms.

Threatened species, according to the Act, "means any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range."

A CLOSER LOOK 13.2

Reasons for Conserving Endangered Species—and All Life on Earth

Important reasons for conserving endangered species are of two types: those having to do with tangible qualities and those dealing with intangible ones (see Chapter 7 for an explanation of tangible and intangible qualities). The tangible ones are utilitarian and ecological. The intangible are aesthetic, moral, recreational, spiritual, inspirational, and cultural.[18]

Utilitarian Justification

Many of the arguments for conserving endangered species, and for conserving biological diversity in general, have focused on the utilitarian justification: that many wild species have proved useful to us and many more may yet prove useful now or in the future, and therefore we should protect every species from extinction.

One example is the need to conserve wild strains of grains and other crops because disease organisms that attack crops evolve continually, and as new disease strains develop, crops become vulnerable. Crops such as wheat and corn depend on the continued introduction of fresh genetic characteristics from wild strains to create new, disease-resistant genetic hybrids. Related to this justification is the possibility of finding new crops among the many species of plants (see Chapter 11).

Another utilitarian justification is that many important chemical compounds come from wild organisms. Medicinal use of plants has an ancient history, going back into human prehistory. For example, a book titled *Materia Medica*, about the medicinal use of plants, was written in the 6th century A.D. in Constantinople by a man named Dioscorides (Figure 13.12).[19] To avoid scurvy, Native Americans advised early European explorers to chew on the bark of eastern hemlock trees (*Tsuga canadensis*); we know today that this was a way to get a little vitamin C.

Digitalis, an important drug for treating certain heart ailments, comes from purple foxglove, and aspirin is a derivative of willow bark. A more recent example was the discovery of a cancer-fighting chemical, paclitaxel, in the Pacific yew tree (genus name *Taxus*; hence the trade name Taxol). Well-known medicines derived from tropical forests include anticancer drugs from rosy periwinkles, steroids from Mexican yams, antihypertensive drugs from serpentwood, and antibiotics from tropical fungi.[20] Some 25% of prescriptions dispensed in the United States today contain ingredients extracted from vascular plants,[21] and these represent only a small fraction of the estimated 500,000 existing plant species. Other plants and organisms may produce useful medical compounds that are as yet unknown.

Scientists are testing marine organisms for use in pharmaceutical drugs. Coral reefs offer a promising area of study for such compounds because many coral-reef species produce toxins to defend themselves. According to the National Oceanic and Atmospheric Administration (NOAA), "Creatures found in coral ecosystems are important sources of new medicines being developed to induce and ease labor; treat cancer, arthritis, asthma, ulcers, human bacte-

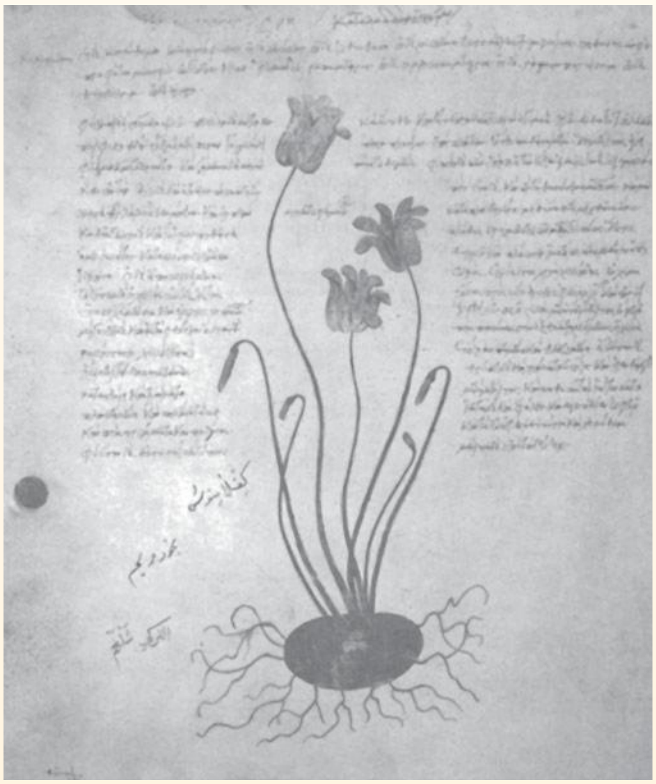


FIGURE 13.12 **Sowbread** (*Sow cyclamen*), a small flowering plant, was believed useful medically at least 1,500 years ago, when this drawing of it appeared in a book published in Constantinople. Whether or not it is medically useful, the plant illustrates the ancient history of interest in medicinal plants. (*Source*: James J. O'Donnell, *The Ruin of the Roman Empire* [New York: ECCO (HarperCollins), 2008], from *Materia Medica* by Dioscorides.)

rial infections, heart disease, viruses, and other diseases; as well as sources of nutritional supplements, enzymes, and cosmetics."[22, 23]

Some species are also used directly in medical research. For example, the armadillo, one of only two animal species (the other is us) known to contract leprosy, is used to study cures for that disease. Other animals, such as horseshoe crabs and barnacles, are important because of physiologically active compounds they make. Still others may have similar uses as yet unknown to us.

Tourism provides yet another utilitarian justification. Ecotourism is a growing source of income for many countries. Ecotourists value nature, including its endangered species, for aesthetic or spiritual reasons, but the result can be utilitarian.

Ecological Justification

When we reason that organisms are necessary to maintain the functions of ecosystems and the biosphere, we are using an ecological justification for conserving these organisms. Individual species, entire ecosystems, and the biosphere provide public-service functions essential or important to the persistence of life, and as such they are indirectly necessary for our survival. When bees pollinate flowers, for example, they provide a benefit to us that would be costly to replace with human labor. Trees remove certain pollutants from the air; and some soil bacteria fix nitrogen, converting it from molecular nitrogen in the atmosphere to nitrate and ammonia that can be taken up by other living things. That some such functions involve the entire biosphere reminds us of the global perspective on conserving nature and specific species.

Aesthetic Justification

An aesthetic justification asserts that biological diversity enhances the quality of our lives by providing some of the most beautiful and appealing aspects of our existence. Biological diversity is an important quality of landscape beauty. Many organisms—birds, large land mammals, and flowering plants, as well as many insects and ocean animals—are appreciated for their beauty. This appreciation of nature is ancient. Whatever other reasons Pleistocene people had for creating paintings in caves in France and Spain, their paintings of wildlife, done about 14,000 years ago, are beautiful. The paintings include species that have since become extinct, such as mastodons. Poetry, novels, plays, paintings, and sculpture often celebrate the beauty of nature. It is a very human quality to appreciate nature's beauty and is a strong reason for the conservation of endangered species.

Moral Justification

Moral justification is based on the belief that species have a right to exist, independent of our need for them; consequently, in our role as global stewards, we are obligated to promote the continued existence of species and to conserve biological diversity. This right to exist was stated in the U.N. General Assembly World Charter for Nature, 1982. The U.S. Endangered Species Act also includes statements concerning the rights of organisms to exist. Thus, a moral justification for the conservation of endangered species is part of the intent of the law.

Moral justification has deep roots within human culture, religion, and society. Those who focus on cost-benefit analyses tend to downplay moral justification, but although it may not seem to have economic ramifications, in fact it does. As more and more citizens of the world assert the validity of moral justification, more actions that have economic effects are taken to defend a moral position.

The moral justification has grown in popularity in recent decades, as indicated by the increasing interest in the deep-ecology movement. Arne Næss, one of its principal philosophers, explains: "The right of all the forms [of life] to live is a universal right which cannot be quantified. No single species of living being has more of this particular right to live and unfold than any other species."[24]

Cultural Justification

Certain species, some threatened or endangered, are of great importance to many indigenous peoples, who rely on these species of vegetation and wildlife for food, shelter, tools, fuel, materials for clothing, and medicine. Reduced biological diversity can severely increase the poverty of these people. For poor indigenous people who depend on forests, there may be no reasonable replacement except continual outside assistance, which development projects are supposed to eliminate. Urban residents, too, share in the benefits of biological diversity, even if these benefits may not be apparent or may become apparent too late.

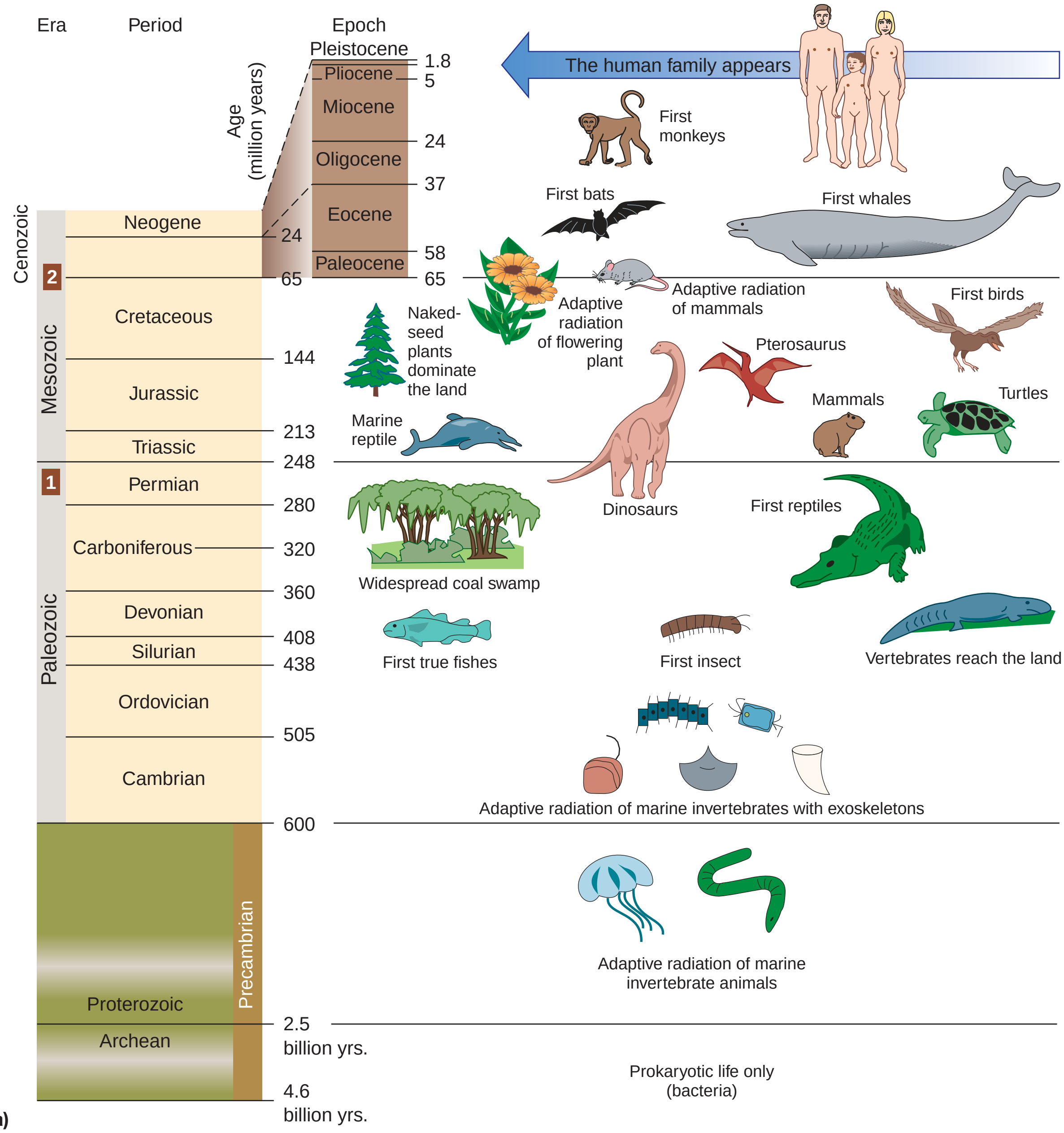
Other Intangible Justifications: Recreational, Spiritual, Inspirational

As any mountain biker, scuba diver, or surfer will tell you, the outdoors is great for recreation, and the more natural, the better. Beyond improving muscle tone and cardiovascular strength, many people find a spiritual uplifting and a connectedness to nature from the outdoors, especially where there is a lot of diversity of living things. It has inspired poets, novelists, painters, and even scientists.

13.5 How a Species Becomes Endangered and Extinct

Extinction is the rule of nature (see the discussion of biological evolution in Chapter 7). **Local extinction** means that a species disappears from a part of its range but persists elsewhere. **Global extinction** means a species can no longer be found anywhere. Although extinction is the ultimate fate of all species, the rate of extinctions has varied greatly over geologic time and has accelerated since the Industrial Revolution.

From 580 million years ago until the beginning of the Industrial Revolution, about one species per year, on average, became extinct. Over much of the history of life on Earth, the rate of evolution of new species equaled or slightly exceeded the rate of extinction. The average longevity of a species has been about 10 million years.[25] However, as discussed in Chapter 7, the fossil record suggests that there have been periods of catastrophic losses of species and other periods of rapid evolution of new species (see Figures 13.13 and 13.14), which some refer to as "punctuated extinctions." About 250 million years ago, a mass extinction occurred in which approximately 53% of marine animal species disappeared; and about 65 million years ago, most of the dinosaurs became extinct. Interspersed with the episodes of mass extinctions, there seem to have been periods of hundreds of thousands of years with comparatively low rates of extinction.



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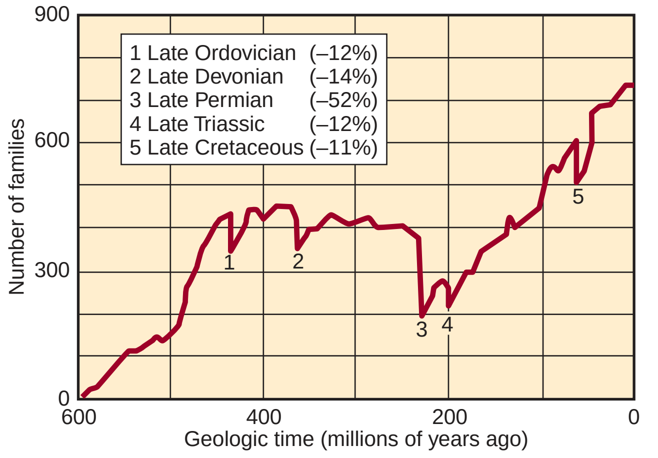

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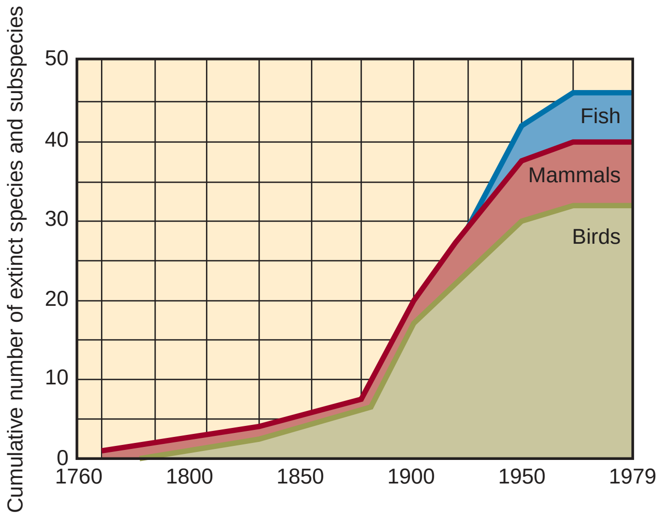

(c)

FIGURE 13.13 **(a) A brief diagrammatic history of evolution and extinction of life on Earth.** There have been periods of rapid evolution of new species and episodes of catastrophic losses of species. Two major catastrophes were the Permian loss, which included 52% of marine animals, as well as land plants and animals, and the Cretaceous loss of dinosaurs. **(b) Graph of the number of families of marine animals in the fossil records,** showing long periods of overall increase in the number of families punctuated by brief periods of major declines. **(c) Extinct vertebrate species and subspecies, 1760–1979**. The number of species becoming extinct increases rapidly after 1860. Note that most of the increase is due to the extinction of birds. (*Sources*: [a] D.M. Raup, "Diversity Crisis in the Geological Past," in E.O. Wilson, ed., *Biodiversity* [Washington, DC: National Academy Press, 1988], p. 53; derived from S.M. Stanley, *Earth and Life through Time* [New York: W.H. Freeman, 1986]. Reprinted with permission. [b] D.M. Raup and J.J. Sepkoski Jr., "Mass Extinctions in the Marine Fossil Record," *Science* 215 [1982]:1501–1502. [c] Council on Environmental Quality; additional data from B. Groombridge England: IUCN, 1993].)

An intriguing example of punctuated extinctions occurred about 10,000 years ago, at the end of the last great continental glaciation. At that time, massive extinctions of large birds and mammals occurred: 33 genera of large mammals—those weighing 50 kg (110 lb) or more—became extinct, whereas only 13 genera had become extinct in the preceding 1 or 2 million years (Figure 13.13a). Smaller mammals were not as affected, nor were marine mammals. As early as 1876, Alfred Wallace, an English biological geographer, noted that "we live in a zoologically impoverished world, from which all of the hugest, and fiercest, and strangest forms have recently disappeared." It has been suggested that these sudden extinctions coincided with the arrival, on different continents at different times, of Stone Age people and therefore may have been caused by hunting.[26]

FIGURE 13.14 **Artist's restoration of an extinct saber-toothed cat with prey.** The cat is an example of one of the many large mammals that became extinct about 10,000 years ago.

Causes of Extinction

Causes of extinction are usually grouped into four risk categories: population risk, environmental risk, natural catastrophe, and genetic risk. *Risk* here means the chance that a species or population will become extinct owing to one of these causes.

Population Risk

Random variations in population rates (birth rates and death rates) can cause a species in low abundance to become extinct. This is termed *population risk*. For example, blue whales swim over vast areas of ocean. Because whaling once reduced their total population to only several hundred individuals, the success of individual blue whales in finding mates probably varied from year to year. If in one year most whales were unsuccessful in finding mates, then births could be dangerously low. Such random variation in populations, typical among many species, can occur without any change in the environment. It is a risk especially to species that consist of only a single population in one habitat. Mathematical models of population growth can help calculate the population risk and determine the minimum viable population size.

Environmental Risk

Population size can be affected by changes in the environment that occur from day to day, month to month, and year to year, even though the changes are not severe enough to be considered environmental catastrophes. Environmental risk involves variation in the physical or biological environment, including variations in predator, prey, symbiotic species, or competitor species. Some species are so rare and isolated that such normal variations can lead to their extinction.

For example, Paul and Anne Ehrlich described the local extinction of a population of butterflies in the Colorado mountains.[27] These butterflies lay their eggs in the unopened buds of a single species of lupine (a member of the legume family), and the hatched caterpillars feed on the flowers. One year, however, a very late snow and freeze killed all the lupine buds, leaving the caterpillars without food and causing local extinction of the butterflies. Had this been the only population of that butterfly, the entire species would have become extinct.

Natural Catastrophe

A sudden change in the environment that is not caused by human action is a natural catastrophe. Fires, major storms, earthquakes, and floods are natural catastrophes on land; changes in currents and upwellings are ocean catastrophes. For example, the explosion of a volcano on the island of Krakatoa in Indonesia in 1883 caused one of recent history's worst natural catastrophes. Most of the island was blown to bits, bringing about local extinction of most life-forms there.

Genetic Risk

Detrimental change in genetic characteristics, not caused by external environmental changes, is called *genetic risk*. Genetic changes can occur in small populations from reduced genetic variation and from genetic drift and mutation (see Chapter 8). In a small population, only some of the possible inherited characteristics will be found. The species is vulnerable to extinction because it lacks variety or because a mutation can become fixed in the population.

Consider the last 20 condors in the wild in California. It stands to reason that this small number was likely to have less genetic variability than the much larger population that existed several centuries ago. This increased the condors' vulnerability. Suppose that the last 20 condors, by chance, had inherited characteristics that made them less able to withstand lack of water. If left in the wild, these condors would have been more vulnerable to extinction than a larger, more genetically varied population.

13.6 The Good News: We Have Improved the Status of Some Species

Thanks to the efforts of many people, a number of previously endangered species, such as the Aleutian goose, have recovered. Other recovered species include the following:

- The elephant seal, which had dwindled to about a dozen animals around 1900 and now numbers in the hundreds of thousands.
- The sea otter, reduced in the 19th century to several hundred and now numbering approximately 10,000.
- Many species of birds endangered because the insecticide DDT caused thinning of eggshells and failure of reproduction. With the elimination of DDT in the United States, many bird species recovered, including the bald eagle, brown pelican, white pelican, osprey, and peregrine falcon.
- The blue whale, thought to have been reduced to about 400 when whaling was still actively pursued by a number of nations. Today, 400 blue whales are sighted annually in the Santa Barbara Channel along the California coast, a sizable fraction of the total population.
- The gray whale, which was hunted to near-extinction but is now abundant along the California coast and in its annual migration to Alaska.

Since the U.S. Endangered Species Act became law in 1973, 13 species within the United States have officially recovered (Table 13.3), according to the U.S. Fish and Wildlife Service, which has also "delisted" from protection of the Act 9 species because they have gone extinct, and 17 because they were listed in error or because it was decided that they were not a unique species or a genetically significant unit within a species. (The Act allows listing of subspecies so genetically different from the rest of the species that they deserve protection.)[28]

Table 13.3 RECOVERED SPECIES IN THE UNITED STATES

	DATE SPECIES		
N	FIRST LISTED	DATE DELISTED	SPECIES NAME
1	7/27/1979	6/4//1987	Alligator, American (Alligator mississippiensis)
2	9/17/1980	8/27/2002	Cinquefoil, Robbins' (Potentilla robbinsiana)
3	7/24/2003	7/24/2003	Deer, Columbian white-tailed Douglas County DPS (Odocoileus Virginianus leucurus)
4	3/11/1967	7/9/2007	Eagle, bald lower 48 states (Haliaeetus leucocephalus)
5	6/2/1970	8/25/1999	Falcon, Amercian peregrine (Falco peregrinus anatum)
6	6/2/1970	10/5/1994	Falcon, Arctic peregrine (Falco peregrinus tundrius)
7	3/11/1967	3/20/2001	Goose, Aleutian Canada (Branta Canadensis leucopareia)
8	6/2/1970	2/4/1985	Pelican brown U.S. Atlantic coast, FL, AL (Pelecanus occidentails)
9	7/1/1985	8/26/2008	Squirrel, Virginia northern flying (Glaucomys sabrinus fuscus)
10	5/22/1997	8/18/2005	Sunflower, Eggert's (Helianthus eggertii)
11	6/16/1994	6/16/1994	Whale, gray except where listed (Eschrichtius robustus)
12	3/28/2008	4/2/2009	Wolf, gray Northern Rocky Mountain DPS (Canis lupus)
13	7/19/1990	10/7/2003	Woolly-star, Hoover's (Eriastrum hooveri)

Source: U.S. Fish and Wildlife Service, Delisting Report, http://ecos.fws.gov/tess_public/DelistingReport.do.

A CLOSER LOOK 13.3

Conservation of Whales and Other Marine Mammals

Fossil records show that all marine mammals were originally inhabitants of the land. During the last 80 million years, several separate groups of mammals returned to the oceans and underwent adaptations to marine life. Each group of marine mammals shows a different degree of transition to ocean life. Understandably, the adaptation is greatest for those that began the transition longest ago. Some marine mammals—such as dolphins, porpoises, and great whales—complete their entire life cycle in the oceans and have organs and limbs that are highly adapted to life in the water; they cannot move on the land. Others, such as seals and sea lions, spend part of their time on shore.

Cetaceans

Whales

Whales fit into two major categories: baleen and toothed (Figure 13.15a and b). The sperm whale is the only great whale that is toothed; the rest of the toothed group are smaller whales, dolphins, and porpoises. The other great whales, in the baleen group, have highly modified teeth that look like giant combs and act as water filters. Baleen whales feed by filtering ocean plankton.

Drawings of whales have been dated as early as 2200 B.C.[29] Eskimos used whales for food and clothing as long ago as 1500 B.C. In the 9th century, whaling by Norwegians was reported by travelers whose accounts were written down in the court of the English king Alfred. The earliest whale hunters killed these huge mammals from the shore or from small boats near shore, but gradually whale hunters ventured farther out. In the 11th and 12th centuries, Basques hunted the Atlantic right whale from open boats in the Bay of Biscay, off the western coast of France. Whales were brought ashore for processing, and the boats returned to land once the search for whales was finished.

The Industrial Revolution eventually made whaling pelagic—almost entirely conducted on the open sea. Whalers searched for whales from ships that remained at sea for long periods, and the whales were brought on board and processed

(a)

(b)

FIGURE 13.15
(a) A sperm whale; (b) a blue whale.

Table 13.4 ESTIMATES OF THE NUMBER OF WHALES

Whales are difficult to count, and the wide range of estimates indicates this difficulty. Of the baleen whales, the most numerous are the smallest—the minke and the pilot. The only toothed great whale, the sperm whale, is thought to be relatively numerous, but actual counts of this species have been made only in comparatively small areas of the ocean.

	RANGE OF ESTIMATES	
SPECIES	MINIMUM	MAXIMUM
Blue	400	1,400
Bowhead	6,900	9,200
Fin	27,700	82,000
Gray	21,900	32,400
Humpback	5,900	16,800
Minke	510,000	1,140,000
Pilot	440,000	1,370,000
Sperm	200,000	1,500,000

Source: International Whaling Commission, August 29, 2006, http://www.iwcoffice.org/conservation/estimate.htm. The estimate for sperm whale is from U.S. NOAA http://www.nmfs.noaa.gov/pr/species/mammals/cetaceans/spermwhale.htm

there by newly invented furnaces and boilers for extracting whale oil at sea. With these inventions, whaling grew as an industry. American fleets developed in the 18th century in New England, and by the 19th century the United States dominated the industry, providing most of the whaling ships and even more of the crews.[30, 31]

Whales provided many 19th-century products. Whale oil was used for cooking, lubrication, and lamps. Whales provided the main ingredients for the base of perfumes. The elongated teeth (whale-bone or baleen) that enable baleen whales to strain the ocean waters for food are flexible and springy and were used for corset stays and other products before the invention of inexpensive steel springs.

Although the 19th-century whaling ships were made famous by novels such as *Moby Dick*, more whales were killed in the 20th century than in the 19th. The resulting worldwide decline in most species of whales made this a global environmental issue.

Conservationists have been concerned about whales for many years. Attempts to control whaling began with the League of Nations in 1924. The first agreement, the Convention for the Regulation of Whaling, was signed by 21 countries in 1931. In 1946 a conference in Washington, DC, initiated the International Whaling Commission (IWC), and in 1982 the IWC established a moratorium on commercial whaling. Currently, 12 of approximately 80 species of whales are protected.[32]

The IWC has played a major role in reducing (almost eliminating) the commercial harvesting of whales. Since its formation, no whale species has become extinct, the total take of whales has decreased, and harvesting of whale species considered endangered has ceased. Endangered species protected from hunting have had a mixed history (see Table 13.4). Blue whales appear to have recovered somewhat but remain rare and endangered. Gray whales are now relatively abundant, numbering about 26,000.[34] However, global climate change, pollution, and ozone depletion now pose greater risks to whale populations than does whaling.

The establishment of the IWC was not only vitally important to whales but also a major landmark in wildlife conservation. It was one of the first major attempts by a group of nations to agree on a reasonable harvest of a biological resource. The annual meeting of the IWC has become a forum for discussing international conservation, working out basic concepts of maximum and optimum sustainable yields, and formulating a scientific basis for commercial harvesting. The

IWC demonstrates that even an informal commission whose decisions are accepted voluntarily by nations can function as a powerful force for conservation.

In the past, each marine mammal population was treated as if it were isolated, had a constant supply of food, and was subject only to the effects of human harvesting. That is, its growth was assumed to follow the logistic curve. We now realize that management policies for marine mammals must be expanded to include ecosystem concepts and the understanding that populations interact in complex ways.

The goal of marine mammal management is to prevent extinction and maintain large population sizes rather than to maximize production. For this reason, the Marine Mammal Protection Act, enacted by the United States in 1972, has as its goal an optimum sustainable population (OSP) rather than a maximum or an optimum sustainable yield. An OSP is the largest population that can be sustained indefinitely without deleterious effects on the ability of the population or its ecosystem to continue to support that same level.

Some of the great whales remain rare.

Dolphins and Other Small Cetaceans

Among the many species of small "whales" are dolphins and porpoises, more than 40 species of which have been hunted commercially or have been killed inadvertently by other fishing efforts.[33] A classic case is the inadvertent catch of the spinner, spotted, and common dolphins of the eastern Pacific. Because these carnivorous, fish-eating mammals often feed with yellowfin tuna, a major commercial fish, more than 7 million dolphins have been netted and killed inadvertently in the past 40 years.[34]

The U.S. Marine Mammal Commission and commercial fishermen have cooperated in seeking ways to reduce dolphin mortality. Research into dolphin behavior helped in the design of new netting procedures that trapped far fewer dolphins. The attempt to reduce dolphin mortality illustrates cooperation among fishermen, conservationists, and government agencies and indicates the role of scientific research in managing renewable resources.

13.7 Can a Species Be Too Abundant? If So, What to Do?

All marine mammals are protected in the United States by the Federal Marine Mammal Protection Act of 1972, which has improved the status of many marine mammals. Sometimes, however, we succeed too well in increasing the populations of a species. Case in point: Sea lions now number more than 190,000 and have become so abundant as to be local problems.[35, 36] In San Francisco Harbor and in Santa Barbara Harbor, for example, sea lions haul out and sun themselves on boats and pollute the water with their excrement near shore. In one case, so many hauled out on a sailboat in Santa Barbara Harbor that they sank the boat, and some of the animals were trapped and drowned.

Mountain lions, too, have become locally overabundant. In the 1990s, California voters passed an initiative that protected the endangered mountain lion but contained no provisions for managing the lion if it became overabundant, unless it threatened human life and property. Few people thought the mountain lion could ever recover enough to become a problem, but in several cases in recent years mountain lions have attacked and even killed people. Current estimates suggest there may be as many as 4,000 to 6,000 in California.[37] These attacks become more frequent as the mountain lion population grows and as the human population grows and people build houses in what was mountain lion habitat.

13.8 How People Cause Extinctions and Affect Biological Diversity

People have become an important factor in causing species to become threatened, endangered, and finally extinct. We do this in several ways:

- By intentional hunting or harvesting (for commercial purposes, for sport, or to control a species that is considered a pest).
- By disrupting or eliminating habitats.
- By introducing exotic species, including new parasites, predators, or competitors of a native species.
- By creating pollution.

People have caused extinctions over a long time, not just in recent years. The earliest people probably caused extinctions through hunting. This practice continues, especially for specific animal products considered valuable, such as elephant ivory and rhinoceros horns. When people learned to use fire, they began to change habitats over large areas. The development of agriculture and the rise of civilization led to rapid deforestation and other habitat changes. Later, as people explored new areas, the introduction of exotic species became a greater cause of extinction (see Chapter 8), especially after Columbus's voyage to the New World, Magellan's circumnavigation of the globe, and the resulting spread of European civilization and technology. The introduction of thousands of novel chemicals into the environment made pollution an increasing cause of extinction in the 20th century, and pollution control has proved a successful way to help species.

The IUCN estimates that 75% of the extinctions of birds and mammals since 1600 have been caused by human beings. Hunting is estimated to have caused 42% of the extinctions of birds and 33% of the extinctions of mammals. The current extinction rate among most groups of mammals is estimated to be 1,000 times greater than the extinction rate at the end of the Pleistocene epoch.[22]

13.9 Ecological Islands and Endangered Species

The history of the Kirtland's warbler illustrates that a species may inhabit "ecological islands," which the isolated jack-pine stands of the right age range are for that bird. Recall from our discussion in Chapter 8 that an ecological island is an area that is biologically isolated, so that a species living there cannot mix (or only rarely mixes) with any other population of the same species (Figure 13.16). Mountaintops and isolated ponds are ecological islands. Real geographic islands may also be ecological islands. Insights gained from studies of the biogeography of islands have important implications for the conservation of endangered species and for the design of parks and preserves for biological conservation.

Almost every park is a biological island for some species. A small city park between buildings may be an island for trees and squirrels. At the other extreme, even a large national park is an ecological island. For example, the Masai Mara Game Reserve in the Serengeti Plain, which stretches from Tanzania to Kenya in East Africa, and other great wildlife parks of eastern and southern Africa are becoming islands of natural landscape surrounded by human settlements. Lions and other great cats exist in these parks as isolated populations, no longer able to roam completely freely and to mix over large areas. Other examples are islands of uncut forests left by logging operations, and oceanic islands, where intense fishing has isolated parts of fish populations.

How large must an ecological island be to ensure the survival of a species? The size varies with the species but can be estimated. Some islands that seem large to us are too small for species we wish to preserve. For example, a preserve was set aside in India in an attempt to reintroduce the Indian lion into an area where it had been eliminated by hunting and by changing patterns of land use. In 1957, a male and two females were introduced into a 95 km^2 (36 mi^2) preserve in the Chakia forest, known as the Chandraprabha Sanctuary. The introduction was carried out carefully and the population was counted annually. There were four lions in 1958, five in 1960, seven in 1962, and eleven in 1965, after which they disappeared and were never seen again.

Why did they go? Although 95 km^2 seems large to us, male Indian lions have territories of 130 km^2


(a)


(b)


(c)

FIGURE 13.16 **Ecological islands: (a)** Central Park in New York City; **(b)** a mountaintop in Arizona where there are bighorn sheep; **(c)** an African wildlife park.

(50 mi^2), within which females and young also live. A population that could persist for a long time would need a number of such territories, so an adequate preserve would require 640–1,300 km^2 (247–500 mi^2). Various other reasons were also suggested for the disappearance of the lions, including poisoning and shooting by villagers. But regardless of the immediate cause, a much larger area was required for long-term persistence of the lions.

13.10 Using Spatial Relationships to Conserve Endangered Species

The red-cockaded woodpecker (Figure 13.17a) is an endangered species of the American Southeast, numbering approximately 15,000.[38] The woodpecker makes its nests in old dead or dying pines, and one of its foods is the pine bark beetle (Figure 13.17b). To conserve this species of woodpecker, these pines must be preserved. But the old pines are home to the beetles, which are pests to the trees and damage them for commercial logging. This presents an intriguing problem: How can we maintain the woodpecker and its food (which includes the pine bark beetle) and also maintain productive forests?

The classic 20th-century way to view the relationship among the pines, the bark beetle, and the woodpecker would be to show a food chain (see Chapter 6). But this alone does not solve the problem for us. A newer approach is to consider the habitat requirements of the pine bark beetle and the woodpecker. Their requirements are somewhat different, but if we overlay a map of one's habitat requirements over a map of the other's, we can compare the co-occurrence of habitats. Beginning with such maps, it becomes possible to design a landscape that would allow the maintenance of all three—pines, beetles, and birds.


(a)


(b)

FIGURE 13.17 **(a) Endangered red-cockaded woodpecker, and (b) the pine bark beetle, food for the woodpecker.**

CRITICAL THINKING ISSUE

Should Wolves Be Reestablished in the Adirondack Park?

With an area slightly over 24,000 km^2, the Adirondack Park in northern New York is the largest park in the lower 48 states. Unlike most parks, however, it is a mixture of private (60%) and public (40%) land and is home to 130,000 people. When European colonists first came to the area, it was, like much of the rest of North America, inhabited by gray wolves. By 1960, wolves had been exterminated in all of the lower 48 states except for northern Minnesota. The last official sighting of a wolf in the Adirondacks was in the 1890s.

Although the gray wolf was not endangered globally—there were more than 60,000 in Canada and Alaska—it was one of the first animals listed as endangered under the 1973 Endangered Species Act. As required, the U.S. Fish and Wildlife Service developed a plan for recovery that included protection of the existing population and reintroduction of wolves to wilderness areas. The recovery plan would be considered a success if survival of the Minnesota wolf population was assured and at least one other population of more than 200 wolves had been established at least 320 km from the Minnesota population.

Under the plan, Minnesota's wolf population increased, and some wolves from that population, as well as others from southern Canada, dispersed into northern Michigan and Wisconsin, each of which had populations of approximately 100 wolves in 1998. Also, 31 wolves from Canada were introduced into Yellowstone National Park in 1995, and that population grew to over 100. By the end of 1998, it seemed fairly certain that the criteria for removing the wolf from the Endangered Species list would soon be met.

In 1992, when the results of the recovery plan were still uncertain, the Fish and Wildlife Service proposed to investigate the possibility of reintroducing wolves to northern Maine and the Adirondack Park. A survey of New York State residents in 1996 funded by Defenders of Wildlife found that 76% of people living in the park supported reintroduction. However, many residents and organizations within the park vigorously opposed reintroduction and questioned the validity of the survey. Concerns focused primarily on the potential dangers to people, livestock, and pets and the possible impact on the deer population. In response to the public outcry, Defenders of Wildlife established a citizens' advisory committee that initiated two studies by outside experts, one on the social and economic aspects of reintroduction and another on whether there were sufficient prey and suitable habitat for wolves.

Wolves prey primarily on moose, deer, and beaver. Moose have been returning to the Adirondacks in recent years and now number about 40, but this is far less than the moose population in areas where wolves are successfully reestablishing. Beaver are abundant in the Adirondacks, with an estimated population of over 50,000. Because wolves feed on beaver primarily in the spring and the moose population is small, the main food source for Adirondack wolves would be deer.

Deer thrive in areas of early-successional forest and edge habitats, both of which have declined in the Adirondacks as logging has decreased on private forestland and has been eliminated altogether on public lands. Furthermore, the Adirondacks are at the northern limit of the range for white-tailed deer, where harsh winters can result in significant mortality. Deer density in the Adirondacks is estimated at 3.25 per square kilometer, fewer than in the wolf habitat in Minnesota, which also has 8,500 moose. If deer were the only prey available, wolves would kill between 2.5% and 6.5% of the deer population, while hunters take approximately 13% each year. Determining whether there is a sufficient prey base to support a population of wolves is complicated by the fact that coyotes have moved into the Adirondacks and occupy the niche once filled by wolves. Whether wolves would add to the deer kill or replace coyotes, with no net impact on the deer population, is difficult to predict.

An area of 14,000 km^2 in various parts of the Adirondack Park meets criteria established for suitable wolf habitat, but this is about half of the area required to maintain a wolf population for the long term. Based on the average deer density and weight, as well as the food requirements of wolves, biologists estimate that this habitat could support about 155 wolves. However, human communities are scattered throughout much of the park, and many residents are concerned that wolves would not remain on public land and would threaten local residents as well as back-country hikers and hunters. Also, private lands around the edges of the park, with their greater density of deer, dairy cows, and people, could attract wolves.

Critical Thinking Questions

1. Who should make decisions about wildlife management, such as returning wolves to the Adirondacks—scientists, government officials, or the public?
2. Some people advocate leaving the decision to the wolves—that is, waiting for them to disperse from southern Canada and Maine into the Adirondacks. Study a map of the northeastern United States and southeastern Canada. What do you think is the likelihood of natural recolonization of the Adirondacks by wolves?
3. Do you think wolves should be reintroduced to the Adirondack Park? If you lived in the park, would that affect your opinion? How would removal of the wolf from the Endangered Species list affect your opinion?
4. Some biologists recently concluded that wolves in Yellowstone and the Great Lakes region belong to a different subspecies, the Rocky Mountain timber wolf, from those that formerly lived in the northeastern United States, the eastern timber wolf. This means that the eastern timber wolf is still extinct in the lower 48 states. Would this affect your opinion about reintroducing wolves into the Adirondacks?

SUMMARY

- Modern approaches to management and conservation of wildlife use a broad perspective that considers interactions among species as well as the ecosystem and landscape contexts.
- To successfully manage wildlife for harvest, conservation, and protection from extinction, we need certain quantitative information about the wildlife population, including measures of total abundance and of births and deaths, preferably recorded over a long period. The age structure of a population can also help. In addition, we have to characterize the habitat in quantitative terms. However, it is often difficult to obtain these data.

- A common goal of wildlife conservation today is to "restore" the abundance of a species to some previous number, usually a number thought to have existed prior to the influence of modern technological civilization. Information about long-ago abundances is rarely available, but sometimes we can estimate numbers indirectly—for example, by using the Lewis and Clark journals to reconstruct the 1805 population of grizzly bears, or using logbooks from whaling ships. Adding to the complexity, wildlife abundances vary over time even in natural systems uninfluenced by modern civilization. Also, historical information often cannot be subjected to formal tests of disproof and therefore does not by itself qualify as scientific. Adequate information exists for relatively few species.
- Another approach is to seek a minimum viable population, a carrying capacity, or an optimal sustainable population or harvest based on data that can be obtained and tested today. This approach abandons the goal of restoring a species to some hypothetical past abundance.
- The good news is that many formerly endangered species have been restored to an abundance that suggests they are unlikely to become extinct. Success is achieved when the habitat is restored to conditions required by a species. The conservation and management of wildlife present great challenges but also offer great rewards of long-standing and deep meaning to people.

REEXAMINING THEMES AND ISSUES

Human Population

Human beings are a primary cause of species extinctions today and also contributed to extinctions in the past. Nonindustrial societies have caused extinction by such activities as hunting and the introduction of exotic species into new habitats. With the age of exploration in the Renaissance and with the Industrial Revolution, the rate of extinctions accelerated. People altered habitats more rapidly and over greater areas. Hunting efficiency increased, as did the introduction of exotic species into new habitats. As the human population grows, conflicts over habitat between people and wildlife increase. Once again, we find that the human population problem underlies this environmental issue.

Sustainability

At the heart of issues concerning wild living resources is the question of sustainability of species and their ecosystems. One of the key questions is whether we can sustain these resources at a constant abundance. In general, it has been assumed that fish and other wildlife that are hunted for recreation, such as deer, could be maintained at some constant, highly productive level. Constant production is desirable economically because it would provide a reliable, easily forecast income each year. But despite attempts at direct management, few wild living resources have remained at constant levels. New ideas about the intrinsic variability of ecosystems and populations lead us to question the assumption that such resources can or should be maintained at constant levels.

Global Perspective

Although the final extinction of a species takes place in one locale, the problem of biological diversity and the extinction of species is global because of the worldwide increase in the rate of extinction and because of the growth of the human population and its effects on wild living resources.

Urban World

We have tended to think of wild living resources as existing outside of cities, but there is a growing recognition that urban environments will be more and more important in conserving biological diversity. This is partly because cities now occupy many sensitive habitats around the world, such as coastal and inland wetlands. It is also because appropriately designed parks and backyard plantings can provide habitats for some endangered species. As the world becomes increasingly urbanized, this function of cities will become more important.

People and Nature

Wildlife, fish, and endangered species are popular issues. We seem to have a deep feeling of connectedness to many wild animals—we like to watch them, and we like to know that they still exist even when we cannot see them. Wild animals have always been important symbols to people, sometimes sacred ones. The conservation of wildlife of all kinds is therefore valuable to our sense of ourselves, both as individuals and as members of a civilization.

Science and Values

The reasons that people want to save endangered species begin with human values, including values placed on the continuation of life and on the public-service functions of ecosystems. Among the most controversial environmental issues in terms of values are the conservation of biological diversity and the protection of endangered species. Science tells us what is possible with respect to conserving species, which species are likely to persist, and which are not. Ultimately, therefore, our decisions about where to focus our efforts in sustaining wild living resources depend on our values.

KEY TERMS

carrying capacity **261**
catch per unit effort **265**
global extinction **274**
historical range of variation **263**
local extinction **274**
logistic carrying capacity **261**
maximum sustainable yield **261**
maximum-sustainable-yield population **261**
minimum viable population **261**
optimum sustainable population **261**
time series **263**

STUDY QUESTIONS

1. Why are we so unsuccessful in making rats an endangered species?

2. What have been the major causes of extinction (a) in recent times and (b) before people existed on Earth?

3. Refer back to the introductory case study about the American buffalo and grizzly bear. The U.S. Fish and Wildlife Service suggested three key indicators of the status of the grizzly bear: (1) sufficient reproduction to offset the existing levels of human-caused mortality, (2) adequate distribution of breeding animals throughout the area, and (3) a limit on total human-caused mortality. Are these indicators sufficient to assure the recovery of this species? What would you suggest instead?

4. This chapter discussed eight justifications for preserving endangered species. Which of them apply to the following? (You can decide that none apply.)
(a) the black rhinoceros of Africa
(b) the Furbish lousewort, a rare small flowering plant of New England, seen by few people
(c) an unnamed and newly discovered beetle from the Amazon rain forest
(d) smallpox
(e) wild strains of potatoes in Peru
(f) the North American bald eagle

5. Locate an ecological island close to where you live and visit it. Which species are most vulnerable to local extinction?

6. Oysters were once plentiful in the waters around New York City. Create a plan to restore them to numbers that could be the basis for commercial harvest.

7. Using information available in libraries, determine the minimum area required for a minimum viable population of the following:
(a) domestic cats
(b) cheetahs
(c) the American alligator
(d) swallowtail butterflies

8. Both a ranch and a preserve will be established for the North American bison. The goal of the ranch owner is to show that bison can be a better source of meat than introduced cattle and at the same time have a less detrimental effect on the land. The goal of the preserve is to maximize the abundance of the bison. How will the plans for the ranch and preserve differ, and how will they be similar?

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CHAPTER 14

Energy: Some Basics

Manhattan Island from New Jersey during the blackout of August 14, 2003. During rush hour, millions of people walked dark streets to go home.

LEARNING OBJECTIVES

Understanding the basics of what energy is, as well as the sources and uses of energy, is essential for effective energy planning. After reading this chapter, you should understand . . .

- That energy is neither created nor destroyed but is transformed from one kind to another;
- Why, in all transformations, energy tends to go from a more usable to a less usable form;
- What energy efficiency is and why it is always less than 100%;
- That people in industrialized countries consume a disproportionately large share of the world's total energy, and how efficient use and conservation of energy can help us make better use of global energy resources;
- Why some energy planners propose a business-as-usual approach to energy (based on large power plants using fossil fuels, especially coal), and others a new approach (based on more disseminated and renewable energy sources), and why both of these approaches have positive and negative points;
- Why moving toward global sustainable energy planning with integrated energy planning is an important goal;
- What elements are needed to develop integrated energy planning.

CASE STUDY

National Energy Policy: From Coast-to-Coast Energy Crisis to Promoting Energy Independence

The most serious blackout in U.S. history occurred on August 14, 2003. New York City, along with eight states and parts of Canada, suddenly lost electric power at about 4:00 p.m. More than 50 million people were affected, some trapped in elevators or electric trains underground. People streamed into the streets of New York, unsure whether or not the power failure was due to a terrorist attack. Power was restored within 24 hours to most places, but the event was an energy shock that demonstrated our dependence on aging power distribution systems and centralized electric power generation. Terrorists had nothing to do with the blackout, but the event caused harm, anxiety, and financial loss to millions of people.

Seven presidents of the United States since the mid-1970s have attempted to address energy problems and how to become independent of foreign energy sources. The Energy Policy Act of 2005, passed by Congress and signed into law by President George W. Bush in the summer of 2005, has been followed by heated debate about energy policy in the 21st century. A number of topics related to energy are being discussed, including the American Clean Energy and Security Act of 2009, which took a serious step toward energy self-sufficiency in the United States.

The 2009 Act has four parts: (1) *clean energy,* which involves renewable energy, sequestration of carbon, development of clean fuels and vehicles, and a better electricity transmission grid; (2) *energy efficiency,* for buildings, homes, transportation, and utilities; (3) *reduction of carbon dioxide and other greenhouse gases associated with global warming,* including programs to reduce global warming by reducing emissions of carbon dioxide in coming years; and (4) *making the transition to a clean energy economy,* including economic incentives for development of green-energy jobs, exporting clean technology, increasing domestic competitiveness, and finding ways to adapt to global warming.

Today we are more dependent than ever on imported oil. We import about 65% of our oil, often from countries that do not particularly like us. This presents a security risk. Since the 1970s, U.S. consumption of gasoline (for which most oil is used) has risen 50%, while domestic production of oil has dropped by nearly one-half, due in part to a dramatic 50% reduction in Alaska's oil production since the late 1980s. One result was that gasoline prices rose to a peak of $4 per gallon in 2008.

Natural gas has followed a similar pattern with respect to production and consumption since the late 1980s. New power plants today use natural gas as the desired fuel because it is cleaner-burning, resulting in fewer pollutants, and the United States has abundant potential supplies. The problem with natural gas will be to bring production in line with consumption in the future.

Energy planning at the national level in the first five years of the 21st century was marked by an ongoing debate about future supplies of fossil fuels, including coal, oil, and natural gas. Planning objectives have centered on providing a larger supply of coal, natural gas, and, to a lesser extent, oil. Planners concluded that if the United States is to meet electricity demands by the year 2020, over 1,000 new power plants will have to be constructed. When we work out the numbers, this means building about 60 per year between now and 2020—more than one new facility per week!

The key to energy planning is a diversity of energy sources with a better mix of fossil fuels and alternative sources that must eventually replace them. What is apparent is that in the first decades of the 21st century we are going to be continually plagued by dramatic price changes in energy and accompanying shortages. This pattern will continue until we become much more independent from foreign energy sources. Using our remaining fossil fuels, particularly the cleaner fuels such as natural gas, will represent a transitional phase to more sustainable sources. What is really necessary is a major program to develop sources such as wind and solar much more vigorously than has been done in the past or, apparently, will be done in the next few years. If we are unable to make the transition as world production of petroleum peaks and declines, then we will face an energy crisis unsurpassed in our history.

The United States faces serious energy problems. Energy policy, from local to global, has emerged as a central economic concern, national security issue, and environmental question.[1] How we respond to energy issues will largely define who and what we are and will become in the 21st century. With this in mind, in this chapter we explore some of the basic principles associated with what energy is, how much energy we consume, and how we might manage energy for the future.

14.1 Outlook for Energy

Energy crises are nothing new. People have faced energy problems for thousands of years, as far back as the early Greek and Roman cultures.

Energy Crises in Ancient Greece and Rome

The climate in Greece's coastal areas 2,500 years ago was characterized by warm summers and cool winters, much as it is today. To warm their homes in winter, the Greeks used small, charcoal-burning heaters that were not very efficient. Since charcoal is produced from burning wood, wood was their primary source of energy, as it is today for half the world's people.

By the 5th century B.C., fuel shortages had become common, and much of the forested land in many parts of Greece was depleted of firewood. As local supplies diminished, it became necessary to import wood from farther away. Olive groves became sources of fuel; olive wood was turned into charcoal for burning, reducing a valuable resource. By the 4th century B.C., the city of Athens had banned the use of olive wood for fuel.

At about this time, the Greeks began to build their houses facing south, designing them so that the low winter sun entered the houses, providing heat, and the higher summer sun was partially blocked, cooling the houses. Recent excavations of ancient Greek cities suggest that large areas were planned so that individual homes could make maximum use of solar energy, which was a logical answer to their energy problem.[2]

FIGURE 14.1 Roman bathhouse (lower level) in the town of Bath, England. The orientation of the bathhouse and the placement of windows are designed to maximize the benefits of passive solar energy.

The use of wood in ancient Rome is somewhat analogous to the use of oil and gas in the United States today. The homes of wealthy Romans about 2,000 years ago had central heating that burned as much as 125 kg (275 lb) of wood every hour. Not surprisingly, local wood supplies were exhausted quickly, and the Romans had to import wood from outlying areas, eventually from as far away as 1,600 km (about 1,000 mi).[2]

The Romans turned to solar energy for the same reasons as the Greeks but with much broader application and success. They used glass windows to increase the effectiveness of solar heat, developed greenhouses to raise food during the winter, and oriented large public bathhouses (some accommodated up to 2,000 people) to use passive solar energy (Figure 14.1). The Romans believed that sunlight in bathhouses was healthy, and it also saved greatly on fuel costs. The use of solar energy in ancient Rome was widespread and resulted in laws to protect a person's right to solar energy. In some areas, it was illegal for one person to construct a building that shaded another's.[2]

The ancient Greeks and Romans experienced an energy crisis in their urban environments. In turning to solar energy, they moved toward what today we call *sustainability*. We are on that same path today as fossil fuels become scarce.

Energy Today and Tomorrow

The energy situation facing the United States and the world today is in some ways similar to that faced by the early Greeks and Romans. The use of wood in the United States peaked in the 1880s, when the use of coal became widespread. The use of coal, in turn, began to decline after 1920, when oil and gas started to become available. Today, we are facing the global peak of oil production, which is expected by about 2020. Fossil fuel resources, which took millions of years to form, may be essentially exhausted in just a few hundred years.

The decisions we make today will affect energy use for generations. Should we choose complex, centralized energy-production methods, or simpler and widely dispersed methods, or a combination of the two? Which energy sources should be emphasized? Which uses of energy should be emphasized for increased efficiency? How can we develop a sustainable energy policy? There are no easy answers.

The use of fossil fuels, especially oil, improved sanitation, medicine, and agriculture, helping to make possible the global human population increase that we have discussed in other chapters. Many of us are living longer, with a higher standard of living, than people before us. However, burning fossil fuels imposes growing environmental costs, ranging from urban pollution to a change in the global climate.

One thing certain about the energy picture for tomorrow is that it will involve living with uncertainty when it comes to energy availability and cost. The sources of energy and the patterns of energy use will undoubtedly change. We can expect problems, with growing demand and insufficient supply leading to higher costs. Supplies will continue to be regulated and could be disrupted. Oil embargoes could cause significant economic impact in the United States and other countries, and a war or revolution in a petroleum-producing country would significantly reduce petroleum exports.

It is clear that we need to rethink our entire energy policy in terms of sources, supply, consumption, and environmental concerns. We can begin by understanding basic facts about what energy is.

14.2 Energy Basics

The concept of energy is somewhat abstract: You cannot see it or feel it, even though you have to pay for it.[3] To understand energy, it is easiest to begin with the idea of a force. We all have had the experience of exerting force by pushing or pulling. The strength of a force can be measured by how much it accelerates an object.

What if your car stalls going up a hill and you get out to push it uphill to the side of the road (Figure 14.2)? You apply a force against gravity, which would otherwise cause the car to roll downhill. If the brake is on, the brakes, tires, and bearings may heat up from friction. The longer the distance over which you exert force in pushing the car, the greater the change in the car's position and the greater the amount of heat from friction in the brakes, tires, and bearings. In physicists' terms, exerting the force over the distance moved is work. That is, **work** is the product of a force times a distance. Conversely, energy is the ability to do work. Thus, if you push hard but the car doesn't move, you have exerted a force but have not done any work (according to the definition), even if you feel very tired and sweaty.[3]

In pushing your stalled car, you have moved it against gravity and caused some of its parts (brakes, tires, bearings) to be heated. These effects have something in common: They are forms of energy. You have converted chemical energy in your body to the energy of motion of the car (kinetic energy). When the car is higher on the hill, the potential energy of the car has been increased, and friction produces heat energy.

Energy is often converted or transformed from one kind to another, but the total energy is always conserved. The principle that energy cannot be created or destroyed but is always conserved is known as the **first law of thermodynamics.** Thermodynamics is the science that keeps track of energy as it undergoes various transformations from one type to another. We use the first law to keep track of the quantity of energy.[4]

To illustrate the conservation and conversion of energy, think about a tire swing over a creek (Figure 14.3). When the tire swing is held in its highest position, it is not moving. It does contain stored energy, however, owing to its position. We refer to the stored energy as *potential energy*. Other examples of potential energy are the gravitational energy in water behind a dam; the chemical energy in coal, fuel oil, and gasoline, as well as in the fat in your body; and nuclear energy, which is related to the forces binding the nuclei of atoms.[3]

The tire swing, when released from its highest position, moves downward. At the bottom (straight down), the speed of the tire swing is greatest, and no potential energy remains. At this point, all the swing's energy is the energy of motion, called *kinetic energy*. As the tire swings back and forth, the energy continuously changes between the two forms, potential and kinetic. However, with each swing, the tire slows down a little more and goes a little less high because of friction created by the movement of the tire and rope through air and friction at the pivot where the rope is tied to the tree. The friction slows the swing, generating *heat energy*, which is energy from random motion of atoms and molecules. Eventually, all the energy is converted to heat and emitted to the environment, and the swing stops.[3]

The example of the swing illustrates the tendency of energy to dissipate and end up as heat. Indeed, physicists have found that it is possible to change all the gravitational energy in a tire swing (a type of pendulum) to heat. However, it is impossible to change all the

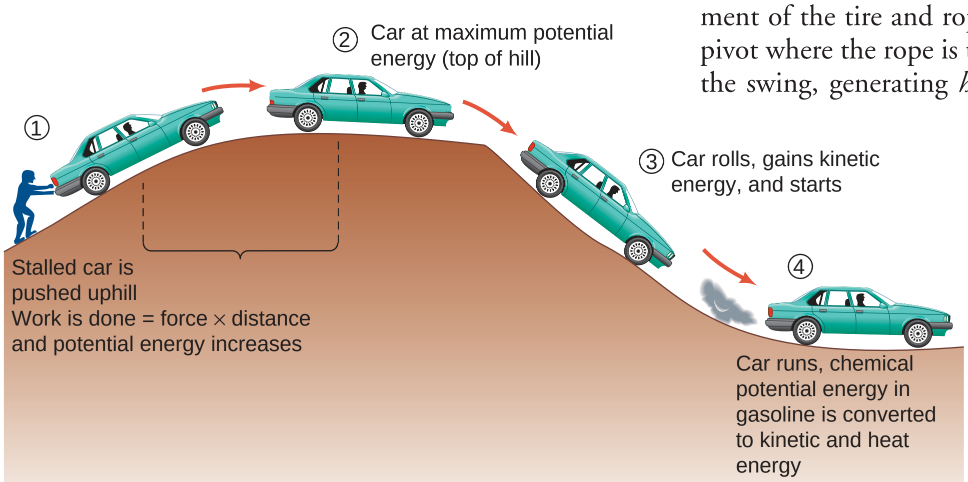


FIGURE 14.2 Some basic energy concepts, including potential energy, kinetic energy, and heat energy.

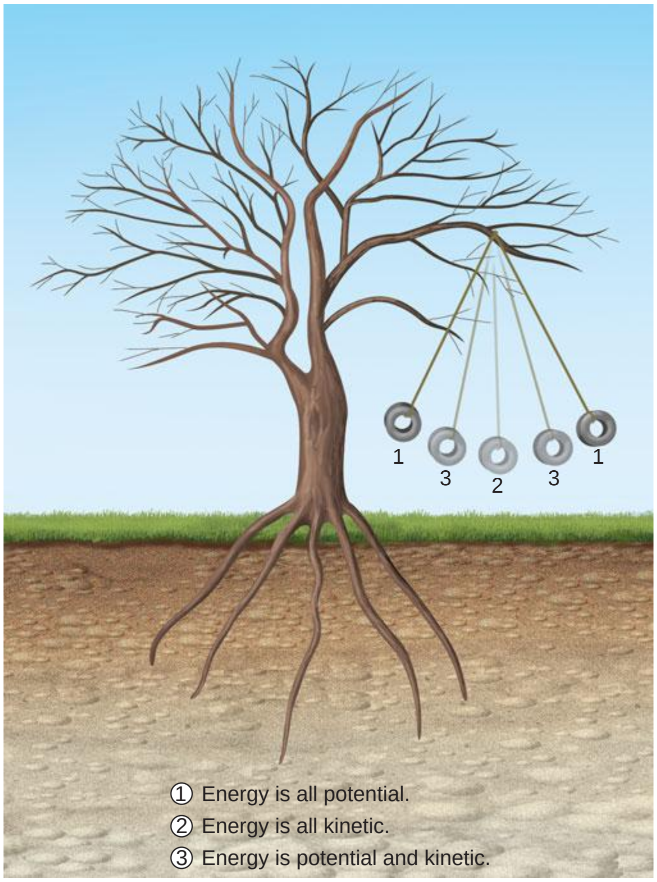


FIGURE 14.3 Diagram of a tire swing, illustrating the relation between potential and kinetic energy.

heat energy thus generated back into potential energy. Energy is conserved in the tire swing. When the tire swing finally stops, all the initial gravitational potential energy has been transformed by way of friction to heat energy. If the same amount of energy, in the form of heat, were returned to the tire swing, would you expect the swing to start again? The answer is no! What, then, is used up? It is not energy because energy is always conserved. What is used up is the energy *quality*—the availability of the energy to perform work. The higher the quality of the energy, the more easily it can be converted to work; the lower the energy quality, the more difficult to convert it to work.

This example illustrates another fundamental property of energy: Energy always tends to go from a more usable (higher-quality) form to a less usable (lower-quality) form. This is the **second law of thermodynamics**, and it means that when you use energy, you lower its quality.

Let's return to the example of the stalled car, which you have now pushed to the side of the road. Having pushed the car a little way uphill, you have increased its potential energy. You can convert this to kinetic energy by letting it roll back downhill. You engage the gears to restart the car. As the car idles, the potential chemical energy (from the gasoline) is converted to waste heat energy and other energy forms, including electricity to charge the battery and play the radio.

Why can't we collect the wasted heat and use it to run the engine? Again, as the second law of thermodynamics tells us, once energy is degraded to low-quality heat, it can never regain its original availability or energy grade. When we refer to low-grade heat energy, we mean that relatively little of it is available to do useful work. High-grade energy, such as that of gasoline, coal, or natural gas, has high potential to do useful work. The biosphere continuously receives high-grade energy from the sun and radiates low-grade heat to the depths of space.[3, 4]

14.3 Energy Efficiency

Two fundamental types of energy efficiencies are derived from the first and second laws of thermodynamics: first-law efficiency and second-law efficiency. **First-law efficiency** deals with the amount of energy without any consideration of the quality or availability of the energy. It is calculated as the ratio of the actual amount of energy delivered where it is needed to the amount of energy supplied to meet that need. Expressions for efficiencies are given as fractions; multiplying the fraction by 100 converts it to a percentage. As an example, consider a furnace system that keeps a home at a desired temperature of 18°C (65°F) when the outside temperature is 0°C (32°F). The furnace, which burns natural gas, delivers 1 unit of heat energy to the house for every 1.5 units of energy extracted from burning the fuel. That means it has a first-law efficiency of 1 divided by 1.5, or 67% (see Table 14.1 for other examples).[4] The "unit" of energy for our furnace is arbitrary for the purpose of discussion; we also could use the British thermal unit (Btu) or some other units (see A Closer Look 14.1).

First-law efficiencies are misleading because a high value suggests (often incorrectly) that little can be done to save energy through additional improvements in efficiency. This problem is addressed by the use of second-law efficiency. **Second-law efficiency** refers to how well matched the energy end use is with the quality of the energy source. For our home-heating example, the second-law efficiency would compare the minimum energy necessary to heat the home to the energy actually used by the gas furnace. If we calculated the second-law efficiency (which is beyond the scope of this discussion), the result might be 5%—much lower than the first-law efficiency of 67%.[4] (We will see why later.) Table 14.1 also lists some second-law efficiencies for common uses of energy.

Values of second-law efficiency are important because low values indicate where improvements in energy technology and planning may save significant amounts of high-quality energy. Second-law efficiency tells us whether the energy quality is appropriate to the task. For example, you could use a welder's acetylene blowtorch to light a candle, but a match is much more efficient (and safer as well).

Table 14.1 EXAMPLES OF FIRST- AND SECOND-LAW EFFICIENCIES

ENERGY (END USE)	FIRST-LAW EFFICIENCY (%)	WASTE HEAT (%)	SECOND-LAW EFFICIENCY (%)	POTENTIAL FOR SAVINGS
Incandescent lightbulb	5	95		
Fluorescent light	20	80		
Automobile	20-25	75-80	10	Moderate
Power plants (electric); fossil fuel and nuclear	30-40	60-70	30	Low to moderate
Burning fossil fuels (used directly for heat)	65	35		
Water heating			2	Very high
Space heating and cooling			6	Very high
All energy (U.S.)	50	50	10-15	High

A CLOSER LOOK 14.1

Energy Units

When we buy electricity by the kilowatt-hour, what are we buying? We say we are buying energy, but what does that mean? Before we go deeper into the concepts of energy and its uses, we need to define some basic units.

The fundamental energy unit in the metric system is the *joule;* 1 joule is defined as a force of 1 newton* applied over a distance of 1 meter. To work with large quantities, such as the amount of energy used in the United States in a given year, we use the unit *exajoule*, which is equivalent to 10^{18} (a billion billion) joules, roughly equivalent to 1 quadrillion, or 10^{15}, Btu, referred to as a *quad*. To put these big numbers in perspective, the United States today consumes approximately 100 exajoules (or quads) of energy per year, and world consumption is about 425 exajoules (quads) annually.

In many instances, we are particularly interested in the rate of energy use, or *power*, which is energy divided by time. In the metric system, power may be expressed as joules per second, or *watts* (W); 1 joule per second is equal to 1 watt. When larger power units are required, we can use multipliers, such as *kilo*-(thousand), *mega*- (million), and *giga*-(billion). For example, a modern nuclear power plant's electricity production rate is 1,000 megawatts (MW) or 1 gigawatt (GW).

Sometimes it is useful to use a hybrid energy unit, such as the watt-hour (Wh); remember, energy is power multiplied by time. Electrical energy is usually expressed and sold in *kilowatt-hours* (kWh, or 1,000 Wh). This unit of energy is 1,000 W applied for 1 hour (3,600 seconds), the equivalent energy of 3,600,000 J (3.6 MJ).

The average estimated electrical energy in kilowatt-hours used by various household appliances over a period of a year is shown in Table 14.2. The total energy used annually is the power rating of the appliance multiplied by the time the appliance was actually used. The appliances that use most of the electrical energy are water heaters, refrigerators, clothes driers, and washing machines. A list of common household appliances and the amounts of energy they consume is useful in identifying the ones that might help save energy through conservation or improved efficiency.

* A newton (N) is the force necessary to produce an acceleration of 1 m per sec (m/s^2) to a mass of 1 kg.

Table 14.2 POWER USE OF TYPICAL HOUSEHOLD APPLIANCES IN WATTS (W)

APPLIANCE	POWER (W)
Clock	2
Coffee maker	900–1200
Clothes washer	350–500
Clothes dryer	1800–5000
Dishwasher	1200–2400 (using the drying feature greatly increases energy consumption)
Electric blanket - *Single/Double*	60/100
Fans	
Ceiling	65–175
Window	55–250
Furnace	750
Whole house	240–750
Hair dryer	1200–1875
Heater (*portable*)	750–1500
Clothes iron	1000–1800
Microwave oven	750–1100
Personal computer	
CPU - awake/asleep	120/30 or less
Monitor - awake/asleep	150/30 or less
Laptop	50
Radio (*stereo*)	70–400
Refrigerator (*frost-free, 16 cubic feet*)	725
Televisions (color)	
19”	65–110
36” = 133 W	
53”–61” Projection	170
Flat screen	120
Toaster	800–1400
Toaster oven	1225
VCR/DVD	17–21/20–25
Vacuum cleaner	1000–1440
Water heater (*40 gallon*)	4500–5500
Water pump (*deep well*)	250–1100
Water bed (*with heater, no cover*)	120–380

*You can use this formula below to estimate an appliance's energy use:

Wattage $\times$ Hours Used Per Day $\div$ 1000 $=$ Daily Kilowatt-hour (kWh) consumption: remember 1kW = 1,000 watts, which is why we divide by 1,000

Multiply by the number of days you use a particular appliance during the year for the annual energy consumption.

You can calculate the annual cost to run an appliance by multiplying the kWh per year by your local utility's rate per kWh consumed.

Example: Personal Computer and Monitor: (120 $+$ 150 Watts $\times$ 4 hours/day $\times$ 365 days/year) $\div$ 1000 $\cong$ 394 kWh $\times$ 11 cents/kWh (approx national average) $\cong$ \$43.34/year

*Note: To estimate the number of hours that a refrigerator actually operates at its maximum wattage, divide the total time the refrigerator is plugged in by three. Refrigerators, although turned “on” all the time, cycle on and off as needed to maintain interior temperatures.

Source: Modified from U.S. Department of Energy. Your Home. accessed January 27, 2010 at http://www.energysavers.gov

We are now in a position to understand why the second-law efficiency is so low (5%) for the house-heating example discussed earlier. This low efficiency implies that the furnace is consuming too much high-quality energy in carrying out the task of heating the house. In other words, the task of heating the house requires heat at a relatively low temperature, near 18°C (65°F), not heat with temperatures in excess of 1,000°C (1,832°F), such as is generated inside the gas furnace. Lower-quality energy, such as solar energy, could do the task and yield a higher second-law efficiency because there is a better match between the required energy quality and the house-heating end use. Through better energy planning, such as matching the quality of energy supplies to the end use, higher second-law efficiencies can be achieved, resulting in substantial savings of high-quality energy.

Examination of Table 14.1 indicates that electricity-generating plants have nearly the same first-law and second-law efficiencies. These generating plants are examples of heat engines. A heat engine produces work from heat. Most of the electricity generated in the world today comes from *heat engines* that use nuclear fuel, coal, gas, or other fuels. Our own bodies are examples of heat engines, operating with a capacity (power) of about 100 watts and fueled indirectly by solar energy. (See A Closer Look 14.1 for an explanation of watts and other units of energy.) The internal combustion engine (used in automobiles) and the steam engine are additional examples of heat engines. A great deal of the world's energy is used in heat engines, with profound environmental effects, such as thermal pollution, urban smog, acid rain, and global warming.

The maximum possible efficiency of a heat engine, known as *thermal efficiency*, was discovered by the French engineer Sadi Carnot in 1824, before the first law of thermodynamics was formulated.[5] Modern heat engines have thermal efficiencies that range between 60 and 80% of their ideal Carnot efficiencies. Modern 1,000-megawatt (MW) electrical generating plants have thermal efficiencies ranging between 30 and 40%; that means at least 60–70% of the energy input to the plant is rejected as waste heat. For example, assume that the electric power output from a large generating plant is 1 unit of power (typically 1,000 MW). Producing that 1 unit of power requires 3 units of input (such as burning coal) at the power plant, and the entire process produces 2 units of waste heat, for a thermal efficiency of 33%. The significant number here is the waste heat, 2 units, which amounts to twice the actual electric power produced.

Electricity may be produced by large power plants that burn coal or natural gas, by plants that use nuclear fuel, or by smaller producers, such as geothermal, solar, or wind sources (see Chapters 15, 16, and 17). Once produced, the electricity is fed into the grid, which is the network of power lines, or the distribution system. Eventually it reaches homes, shops, farms, and factories, where it provides light and heat and also drives motors and other machinery used by society. As electricity moves through the grid, losses take place. The wires that transport electricity (power lines) have a natural resistance to electrical flow. Known as *electrical resistivity*, this resistance converts some of the electric energy in the transmission lines to heat energy, which is radiated into the environment surrounding the lines.

14.4 Energy Sources and Consumption

People living in industrialized countries make up a relatively small percentage of the world's population but consume a disproportionate share of the total energy consumed in the world. For example, the United States, with only 5% of the world's population, uses approximately 20% of the total energy consumed in the world. There is a direct relationship between a country's standard of living (as measured by gross national product) and energy consumption per capita.

After the peak in oil production, expected in 2020–2050, oil and gasoline will be in shorter supply and more expensive. Before then, use of these fuels may be curtailed in an effort to lessen global climate change. As a result, within the next 30 years both developed and developing countries will need to find innovative ways to obtain energy. In the future, affluence may be related as closely to more efficient use of a wider variety of energy sources as it is now to total energy consumption.

Fossil Fuels and Alternative Energy Sources

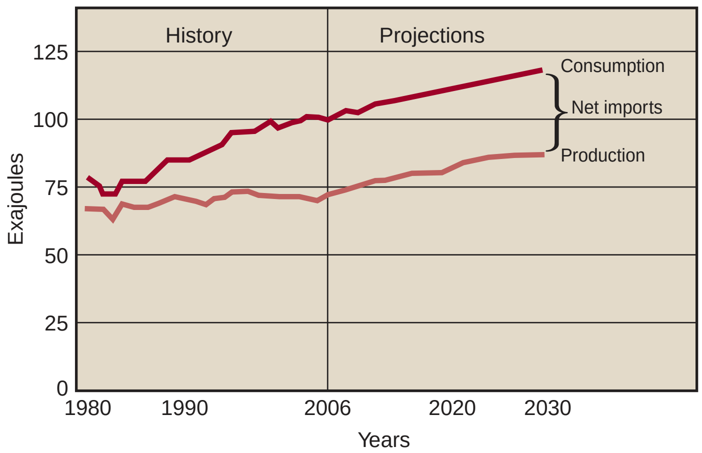
Today, approximately 90% of the energy consumed in the United States is derived from petroleum, natural gas, and coal. Because they originated from plant and animal material that existed millions of years ago, they are called fossil fuels. They are forms of stored solar energy that are part of our geologic resource base, and they are essentially nonrenewable. Other sources of energy—geothermal, nuclear, hydropower, and solar, among others—are referred to as *alternative* energy sources because they may serve as alternatives to fossil fuels in the future. Some of them, such as solar and wind, are not depleted by consumption and are known as *renewable energy* sources.

The shift to alternative energy sources may be gradual as fossil fuels continue to be used, or it could be accelerated by concern about potential environmental effects of burning fossil fuels. Regardless of which path we take, one thing is certain: Fossil fuels are finite. It took millions of years to form them, but they will be depleted in only a few hundred years of human history. Using even the most optimistic predictions, the fossil fuel epoch that started with the Industrial Revolution will represent only about 500 years of human history. Therefore, although fossil fuels have been extremely significant in the development of modern civilization, their use will be a brief event in the span of human history.[6, 7]

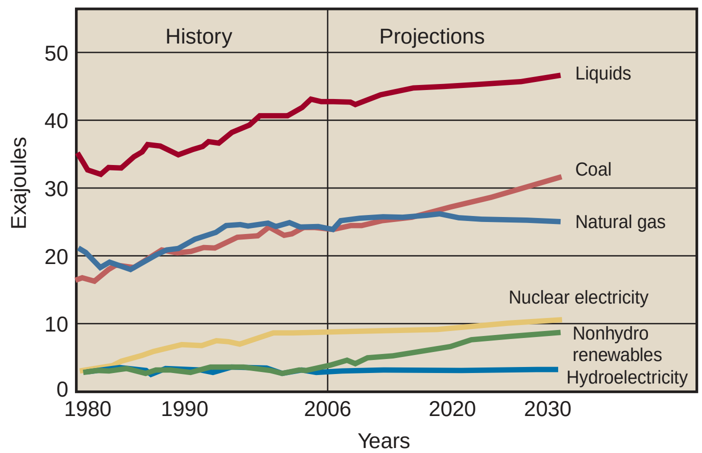
Energy Consumption in the United States

Energy consumption in the United States from 1980 and projected to 2030 is shown in Figure 14.4. The figure dramatically illustrates our ongoing dependence on the three major fossil fuels: coal, natural gas, and petroleum. From approximately 1950 through the late 1970s, energy consumption soared, from about 30 exajoules to 75 exajoules. (Energy units are defined in A Closer Look 14.1.) Since about 1980, energy consumption has risen by only about 25 exajoules. This is encouraging because it suggests that policies promoting energy-efficiency improvements (such as requiring new automobiles to be more fuel-efficient and buildings to be better insulated) have been at least partially successful.

What is not shown in the figure, however, is the huge energy loss. For example, energy consumption in the United States in 1965 was approximately 50 exajoules, of which only about half was used effectively. Energy losses were about 50% (the number shown earlier in Table 14.1 for all energy). In 2009, energy consumption in the United States was about 100 exajoules, and again about 50% was lost in conversion processes. Energy losses in 2009 were about equal to total U.S. energy consumption in 1965! The largest energy losses are associated with the production of electricity and with transportation, mostly through the use of heat engines, which produce waste heat that is lost to the environment.



(a) Total energy production and consumption, 1980-2030 (quadrillion Btu)



(b) Energy consumption by fuel, 1980-2030 (quadrillion Btu)

FIGURE 14.4 U.S. energy from 1980 and projected to 2030. **(a)** Total consumption and production; **(b)** consumption by source. (*Source:* Department of Energy, Energy Information Agency, *Annual Report 2008*.) These forecasts are conservative in terms of expected increases in alternative energy.

Another way to examine energy use is to look at the generalized energy flow of the United States by end use for a particular year (Figure 14.5). In 2008 we imported considerably more oil than we produced (we import about 65% of the oil we use), and our energy consumption was fairly evenly distributed in three sectors: residential/commercial, industrial, and transportation. It is clear that we remain dangerously vulnerable to changing world conditions affecting the production and delivery of crude oil. We need to evaluate the entire spectrum of potential energy sources to ensure that sufficient energy will be available in the future, while sustaining environmental quality.

14.5 Energy Conservation, Increased Efficiency, and Cogeneration

There is a movement to change patterns of energy consumption in the United States through such measures as conservation, improved energy efficiency, and cogeneration. **Conservation** of energy refers simply to using less energy and adjusting our energy needs and uses to minimize the amount of high-quality energy necessary for a given task.[8] Increased **energy efficiency** involves designing equipment to yield more energy output from a given amount of energy input (first-law efficiency) or better matches between energy source and end use (second-law efficiency). **Cogeneration** includes a number of processes designed to capture and use waste heat, rather than simply releasing it into the atmosphere, water, or other parts of the environment as a thermal pollutant. In other words, we design energy systems and power plants to provide energy more than once[9]—that is, to use it a second time, at a lower temperature, but possibly to use it in more than one way as well.

An example of cogeneration is the *natural gas combined cycle power plant* that produces electricity in two ways: gas cycle and steam cycle. In the gas cycle, the natural gas fuel is burned in a gas turbine to produce electricity. In the steam cycle, hot exhaust from the gas turbine is used to create steam that is fed into a steam generator to produce additional electricity. The combined cycles capture waste heat from the gas cycle, nearly doubling the efficiency of the power plant from about 30 to 50–60%. Energy conservation is particularly attractive because it provides more than a one-to-one savings. Remember that it takes 3 units of fuel such as coal to produce 1 unit of power such as electricity (two-thirds is waste heat). Therefore, not using (conserving) 1 unit of power saves 3 units of fuel!

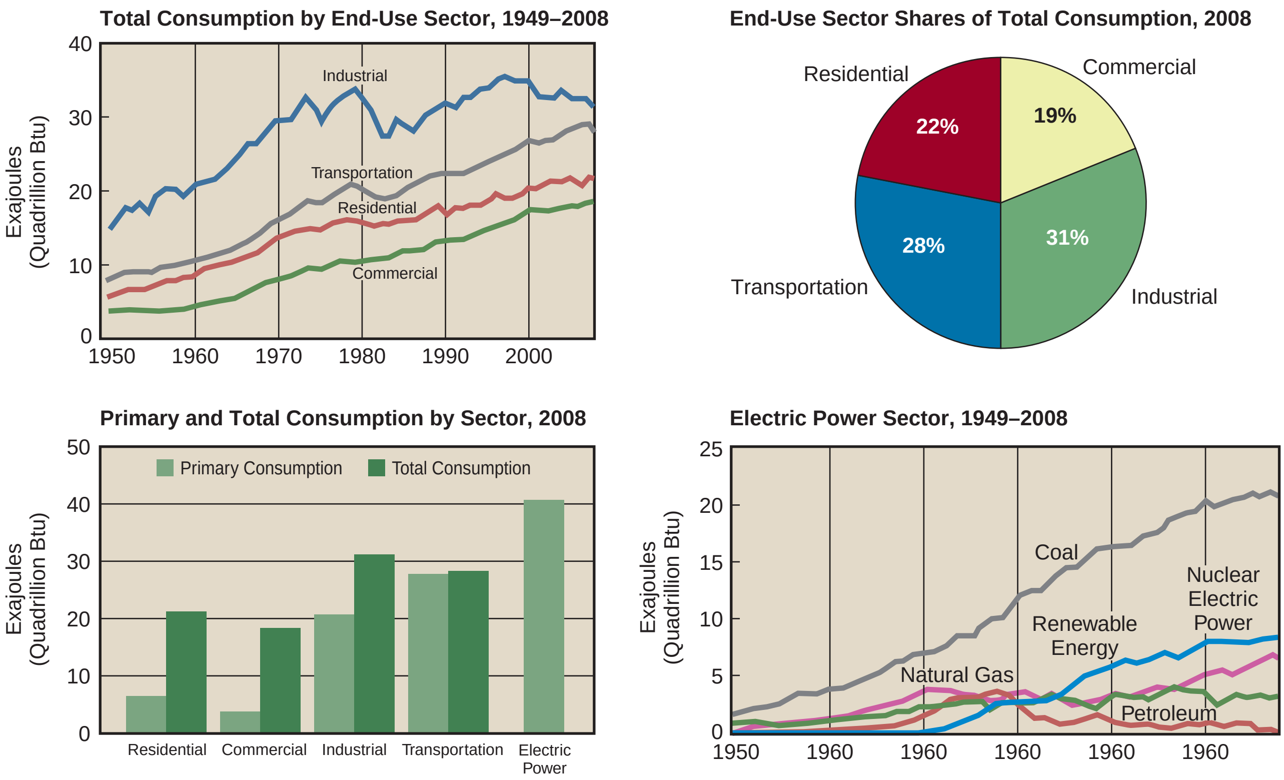


FIGURE 14.5 **Energy consumption in the United States by sector (approximate).** Total primary consumption is the amount of fossil and renewable fuels consumed. Total consumption refers to fossil and renewable fuels consumed plus electricity used. (*Source:* U.S. Energy Information Administration, *Annual Energy Review, 2008.*)

These three concepts—energy conservation, energy efficiency, and cogeneration—are all interlinked. For example, when big, coal-burning power stations produce electricity, they may release large amounts of heat into the atmosphere. Cogeneration, by using that waste heat, can increase the overall efficiency of a typical power plant from 33% to as much as 75%, effectively reducing losses from 67 to 25%. Cogeneration also involves generating electricity as a by-product of industrial processes that produce steam as part of their regular operations. Optimistic energy forecasters estimate that eventually we may meet approximately one-half the electrical power needs of industry through cogeneration.[8, 9] Another source has estimated that cogeneration could provide more than 10% of the power capacity of the United States.

The average first-law efficiency of only 50% (Table 14.1) illustrates that large amounts of energy are currently lost in producing electricity and in transporting people and goods. Innovations in how we produce energy for a particular use can help prevent this loss, raising second-law efficiencies. Of particular importance will be energy uses with applications below 100°C (212°F), because a large portion of U.S. energy consumption for uses below 300°C, or 572°F, is for space heating and water heating.

In considering where to focus our efforts to improve energy efficiency, we need to look at the total energy-use picture. In the United States, space heating and cooling of homes and offices, water heating, industrial processes (to produce steam), and automobiles account for nearly 60% of the total energy use, whereas transportation by train, bus, and airplane accounts for only about 5%. Therefore, the areas we should target for improvement are building design, industrial energy use, and automobile design. We note, however, that debate continues as to how much efficiency improvements and conservation can reduce future energy demands and the need for increased energy production from traditional sources, such as fossil fuel.

Building Design

A spectrum of possibilities exists for increasing energy efficiency and conservation in residential buildings. For new homes, the answer is to design and construct homes that require less energy for comfortable living.[8] For example, we can design buildings to take advantage of passive solar potential, as did the early Greeks and Romans and the Native American cliff dwellers. (Passive solar energy systems collect solar heat without using moving parts.) Windows and overhanging structures can be positioned so that the overhangs shade the windows from solar energy in summer, thereby keeping the house cool, while allowing winter sun to penetrate the windows and warm the house.

The potential for energy savings through architectural design for older buildings is extremely limited. The position of the building on the site is already established, and reconstruction and modifications are often not

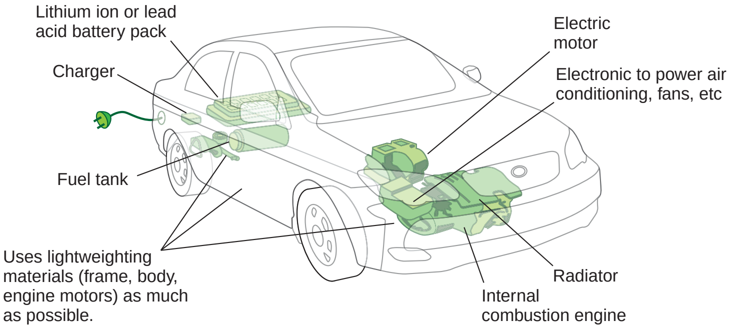


FIGURE 14.6 Idealized diagram of a plug-in hybrid car.

cost-effective. The best approach to energy conservation for these buildings is insulation, caulking, weather stripping, installation of window coverings and storm windows, and regular maintenance.

Ironically, buildings constructed to conserve energy are more likely to develop indoor air pollution due to reduced ventilation. In fact, air pollution is emerging as one of our most serious environmental problems. Potential difficulties can be reduced by better designs for air-circulation systems that purify indoor air and bring in fresh, clean air. Construction that incorporates environmental principles is more expensive owing to higher fees for architects and engineers, as well as higher initial construction costs. Nevertheless, moving toward improved design of homes and residential buildings to conserve energy remains an important endeavor.

Industrial Energy

The rate of increase in energy use (consumption) leveled off in the early 1970s. Nevertheless, industrial production of goods (automobiles, appliances, etc.) continued to grow significantly. Today, U.S. industry consumes about one-third of the energy produced. The reason we have had higher productivity with lower growth of energy use is that more industries are using cogeneration and more energy-efficient machinery, such as motors and pumps designed to use less energy.[8, 10]

Automobile Design

The development of fuel-efficient automobiles has steadily improved during the last 30 years. In the early 1970s, the average U.S. automobile burned approximately 1 gallon of gas for every 14 miles traveled. By 1996, the miles per gallon (mpg) had risen to an average of 28 for highway driving and as high as 49 for some automobiles.[11] Fuel consumption rates did not improve much from 1996 to 1999. In 2004, many vehicles sold were SUVs and light trucks with fuel consumption of 10–20 mpg. A loophole in regulations permits these vehicles to have poorer fuel consumption than conventional automobiles.[11] As a result of higher gasoline prices, sales of larger SUVs declined in 2006, but smaller SUVs remain popular as consumers are apparently sacrificing size for economy (up to a point). Today the fuel consumption of some hybrid (gasoline-electric) vehicles exceeds 90 mpg on the highway and 60 mpg in the city. This improvement stems from increased fuel efficiency; smaller cars with engines constructed of lighter materials; and hybrid cars, which combine a fuel-burning engine and an electric motor. Demand for hybrid vehicles is growing rapidly and will be met with the development of more advanced rechargeable batteries (plug-in hybrids; see Figure 14.6).

The real change in cars is coming. What it will be and when are not entirely known, but it may be a transformation to all-electric cars. Miles per gallon will not be the issue, but where and how we produce the electricity will be.

Values, Choices, and Energy Conservation

A potentially effective method of conserving energy is to change our behavior by using less energy. This involves our values and the choices we make to act at a local level to address global environmental problems, such as human-induced warming caused by burning fossil fuels. For example, we make choices as to how far we commute to school or work and what method of transport we use to get there. Some people commute more than an hour by car to get to work, while others ride a bike, walk, or take a bus or train. Other ways of modifying behavior to conserve energy include the following:

- Using carpools to travel to and from work or school
- Purchasing a hybrid car (gasoline-electric)
- Turning off lights when leaving rooms
- Taking shorter showers (conserves hot water)
- Putting on a sweater and turning down the thermostat in winter
- Using energy-efficient compact fluorescent lightbulbs
- Purchasing energy-efficient appliances
- Sealing drafts in buildings with weather stripping and caulk
- Better insulating your home
- Washing clothes in cold water whenever possible
- Purchasing local foods rather than foods that must be brought to market from afar
- Reducing standby power for electronic devices and appliances by using power strips and turning them off when not in use

What other ways of modifying your behavior would help conserve energy?

14.6 Sustainable-Energy Policy

Energy policy today is at a crossroads. One path leads to the "business-as-usual" approach—find greater amounts of fossil fuels, build larger power plants, and go on using energy as freely as we always have. The business-as-usual path is more comfortable—it requires no new thinking; no realignment of political, economic, or social conditions; and little anticipation of coming reductions in oil production.

People heavily invested in the continued use of fossil fuels and nuclear energy often favor the traditional path. They argue that much environmental degradation around the world has been caused by people who have been forced to use local resources, such as wood, for energy, leading to the loss of plant and animal life and increasing soil erosion. They argue that the way to solve these environmental problems is to provide cheap, high-quality energy, such as fossil fuels or nuclear energy.

In countries like the United States, with sizable resources of coal and natural gas, people supporting the business-as-usual path argue that we should exploit those resources while finding ways to reduce their environmental impact. According to these proponents, we should (1) let the energy industry develop the available energy resources and (2) let industry, free from government regulations, provide a steady supply of energy with less total environmental damage.

The previous U.S. energy plan, suggested by then President George W. Bush, was largely a business-as-usual proposal: Find and use more coal, oil, and natural gas; use more nuclear power; and build more than 1,000 new fossil fuel plants in the next 20 years. Energy conservation and development of alternative energy sources, while encouraged, were not considered of primary importance.

A visionary path for energy policy was suggested more than 30 years ago by Amory Lovins.[12] That path focuses on energy alternatives that emphasize energy quality and are renewable, flexible, and environmentally more benign than those of the business-as-usual path. As defined by Lovins, these alternatives have the following characteristics:

- They rely heavily on renewable energy resources, such as sunlight, wind, and biomass (wood and other plant material).
- They are diverse and are tailored for maximum effectiveness under specific circumstances.
- They are flexible, accessible, and understandable to many people.
- They are matched in energy quality, geographic distribution, and scale to end-use needs, increasing second-law efficiency.

Lovins points out that people are not particularly interested in having a certain amount of oil, gas, or electricity delivered to their homes; they are interested in having comfortable homes, adequate lighting, food on the table, and energy for transportation.[12] According to Lovins, only about 5% of end uses require high-grade energy, such as electricity. Nevertheless, a lot of electricity is used to heat homes and water. Lovins shows that there is an imbalance in using nuclear reactions at extremely high temperatures and in burning fossil fuels at high temperatures simply to meet needs where the necessary temperature increase may be only a few 10s of degrees. He considers such large discrepancies wasteful and a misallocation of high-quality energy.

Energy for Tomorrow

The availability of energy supplies and the future demand for energy are difficult to predict because the technical, economic, political, and social assumptions underlying predictions are constantly changing. In addition, seasonal and regional variations in energy consumption must also be considered. For example, in areas with cold winters and hot, humid summers, energy consumption peaks during the winter months (from heating) and again in the summer (from air-conditioning). Regional variations in energy consumption are significant. For example, in the United States as a whole, the transportation sector uses about one-fourth of the energy consumed. However, in California, where people often commute long distances to work, about one-half of the energy is used for transportation, more than double the national average. Energy sources, too, vary by region. For example, in the eastern and southwestern United States, the fuel of choice for power plants is often coal, but power plants on the West Coast are more likely to burn oil or natural gas or use hydropower from dams to produce electricity.

Future changes in population densities, as well as intensive conservation measures, will probably alter existing patterns of energy use. This might involve a shift to more reliance on alternative (particularly renewable) energy sources.[13, 14] Energy consumption in the United States in the year 2050 may be about 160 exajoules. What will be the energy sources for the anticipated growth in energy consumption? Will we follow our past policy of business as usual (coal, oil, nuclear), or will we turn more to alternative energy sources (wind, solar, geothermal)? What is clear is that the mix of energy sources in 2030 will be different from today's and more diversified.[13-15]

All projections of specific sources and uses of energy in the future must be considered speculative. Perhaps most speculative of all is the idea that we really can meet most of our energy needs with alternative, renewable energy sources in the next several decades. From an energy viewpoint, the next 20 to 30 years, as we move through the maximum production of petroleum, will be crucial to the United States and to the rest of the industrialized world.

The energy decisions we make in the very near future will greatly affect both our standard of living and our quality of life. From an optimistic point of view, we have the necessary information and technology to ensure a bright, warm, lighted, and mobile future. But time may be running out, and we need action now. We can continue to take things as they come and live with the results of our present dependence on fossil fuels, or we can build a sustainable energy future based on careful planning, innovative thinking, and a willingness to move from our dependence on petroleum.

U.S. energy policy for the 21st century is being discussed seriously, and significant change in policy is likely. Some of the recommendations are as follows:

- Promote conventional energy sources: Use more natural gas to reduce our reliance on energy from foreign countries.
- Encourage alternative energy: Support and subsidize wind, solar, geothermal, hydrogen, and biofuels (ethanol and biodiesel).
- Provide for energy infrastructure: Ensure that electricity is transmitted over dependable, modern infrastructure.
- Promote conservation measures: Set higher efficiency standards for buildings and for household products. Require that waste heat from power generation and industrial processes be used to produce electricity or other products. Recommend stronger fuel-efficiency standards for cars, trucks, and SUVs. Provide tax credits for installing energy-efficient windows and appliances in homes and for purchasing fuel-efficient hybrids or clean-diesel vehicles.
- Carefully evaluate the pros and cons of nuclear power, which can generate large amounts of electricity without emitting greenhouse gases, but has serious negatives as well.
- Promote research: Develop new alternative energy sources; find new, innovative ways to improve existing coal plants and to help construct cleaner coal plants; determine whether it is possible to extract vast amounts of oil trapped in oil shale and tar sands without harming the environment; and develop pollution-free, electric automobiles.

Which of the above points will become policy in future years is not known, but parts of the key ideas will move us toward sustainable energy.

Integrated, Sustainable Energy Management The concept of **integrated energy management** recognizes that no single energy source can provide all the energy required by the various countries of the world.[16] A range of options that vary from region to region will have to be employed. Furthermore, the mix of technologies and sources of energy will involve both fossil fuels and alternative, renewable sources.

A basic goal of integrated energy management is to move toward **sustainable energy development** that is implemented at the local level. Sustainable energy development would have the following characteristics:

- It would provide reliable sources of energy.
- It would not destroy or seriously harm our global, regional, or local environments.
- It would help ensure that future generations inherit a quality environment with a fair share of the Earth's resources.

To implement sustainable energy development, leaders in various regions of the world will need energy plans based on local and regional conditions. The plans will integrate the desired end uses for energy with the energy sources that are most appropriate for a particular region and that hold potential for conservation and efficiency. Such plans will recognize that preserving resources can be profitable and that degradation of the environment and poor economic conditions go hand in hand.[16] In other words, degradation of air, water, and land resources depletes assets and ultimately will lower both the standard of living and the quality of life. A good energy plan recognizes that energy demands can be met in environmentally preferred ways and is part of an aggressive environmental policy whose goal is a quality environment for future generations. The plan should do the following:[16]

- Provide for sustainable energy development.
- Provide for aggressive energy efficiency and conservation.
- Provide for diversity and integration of energy sources.
- Develop and use the "smart grid" to optimally manage energy flow on the scale of buildings to regions.
- Provide for a balance between economic health and environmental quality.
- Use second-law efficiencies as an energy policy tool—that is, strive to achieve a good balance between the quality of an energy source and end uses for that energy.

An important element of the plan involves the energy used for automobiles. This builds on policies of the past 30 years to develop hybrid vehicles that use both an electric motor and an internal combustion engine, and to improve fuel technology to reduce both fuel consumption and emission of air pollutants. Finally, the plan should factor in the marketplace through pricing that reflects the economic cost of using the fuel, as well as its cost to the environment. In sum, the plan should be an integrated energy-management statement that moves toward sustainable development. Those who develop such plans recognize that a diversity of energy supplies will be necessary and that the key components are (1) improvements in energy efficiency and conservation and (2) matching energy quality to end uses.[16]

The global pattern of ever-increasing energy consumption led by the United States and other nations cannot be sustained without a new energy paradigm that includes changes in human values, not just a breakthrough in technology. Choosing to own lighter, more fuel-efficient automobiles and living in more energy-efficient homes is consistent with a sustainable energy system that focuses on providing and using energy to improve human welfare. A sustainable energy paradigm establishes and maintains multiple linkages among energy production, energy consumption, human well-being, and environmental quality.[17] It might also involve using smaller generating facilities that are more widely distributed (see A Closer Look 14.2).

A CLOSER LOOK 14.2

Micropower

It is likely that sustainable energy management will include the emerging concept of **micropower**—smaller, distributed systems for production of electricity. Such systems are not new; the inventor Thomas Edison evidently anticipated that electricity-generating systems would be dispersed. By the late 1890s, many small electrical companies were marketing and building power plants, often located in the basements of businesses and factories. These early plants evidently used cogeneration principles, since waste heat was reused for heating buildings.[18] Imagine if we had followed this early model: Homes would have their own power systems, power lines wouldn't snake through our neighborhoods, and we could replace older, less efficient systems as we do refrigerators.

Instead, in the 20th century U.S. power plants grew larger. By the 1930s, industrializing countries had set up utility systems based on large-scale central power plants, as diagrammed in Figure 14.7a. Today, however, we are again evaluating the merits of distributive power systems, as shown in Figure 14.7b.

Large, centralized power systems are consistent with the hard path, while the distributive power system is more aligned with the soft path. Micropower devices rely heavily on renewable energy sources such as wind and sunlight, which feed into the electric grid system, as shown in Figure 14.7b. Use of micropower systems in the future is being encouraged because they are reliable and are associated with less environmental damage than are large fossil-fuel-burning power plants.[18]

Uses for micropower are emerging in both developed and developing countries. In countries that lack a centralized power-generating capacity, small-scale electrical power generation from solar and wind has become the most economical option. In nations with a high degree of industrialization, micropower may emerge as a potential replacement for aging electric power plants. For micropower to be a significant factor in energy production, a shift in policies and regulations to allow micropower devices to be more competitive with centralized generation of electrical power will be required. Regardless of the obstacles that micropower devices face, distributive power systems will probably play an important role in achieving our goal of integrated, sustainable energy management for the future.

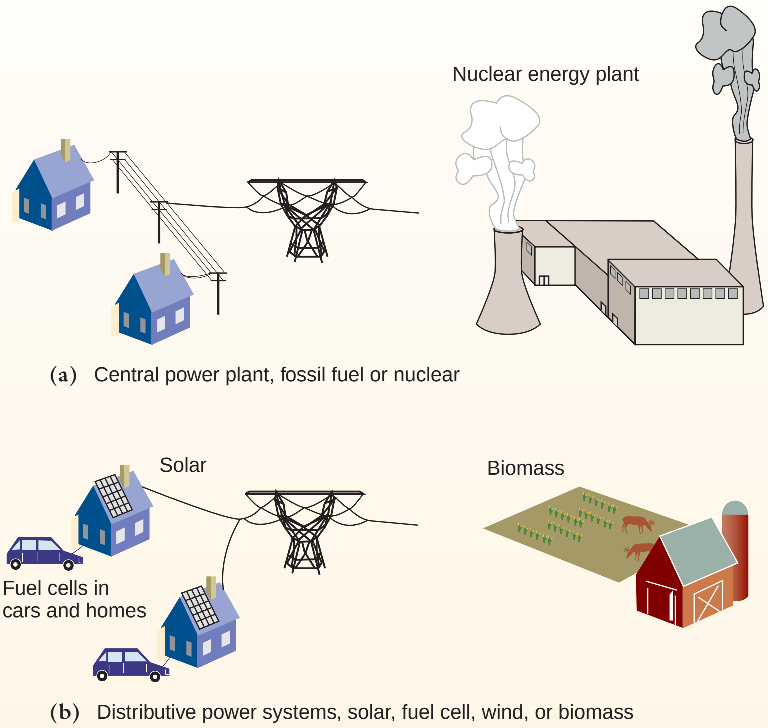


FIGURE 14.7 Idealized diagram comparing **(a)** a centralized power system, such as those used in industrial developed countries today, with **(b)** a distributive power system based on generating electricity from biomass, wind, solar, and other sources, all of which feed into the transmission and distribution system. (*Source*: Modified from S. Dunn, *Micropower, the Next Electrical Era*, Worldwatch Paper 151 [Washington, DC: Worldwatch Institute, 2000].)

CRITICAL THINKING ISSUE

Use of Energy Today and in 2030

Note: Before proceeding with this exercise, refer back to A Closer Look 4.1 to be sure you are comfortable with the units and big numbers.

The Organization for Economic Cooperation and Development (OECD) is a group of 30 countries, 27 of which are classified by the World Bank as having high-income economies. Non-OECD members are not all low-income countries, but many are. The developing countries (all of which are non-OECD) have most of the world's 6.8 billion people and are growing in population faster than the more affluent countries. The average rate of energy use in 2010 for an individual in non-OECD countries is 46 billion joules per person per year (1.5 kW per person), whereas for the OECD countries it is 210 billion joules per person per year (6.7 kW per person). In other words, people in OECD countries use about 4.5 times more energy per person than those in non-OECD countries. In 2010 each group—OECD and non-OECD—used about 250 EJ (1 EJ is 10^{18} J). The world average is 74 billion joules per person per year (2.3 kW per person).[19]

If the current annual population growth rate of 1.1% continues, the world's population will double in 64 years. However, as we learned in Chapters 1 and 4, the human population may not double again. It is expected to be about 8.5 billion by 2030. More people will likely mean more energy use. People in non-OECD countries will need to consume more energy per capita if the less developed countries are to achieve a higher standard of living; thus, energy consumption in non-OECD countries as a group is projected to increase by 2030 to about 55 billion joules per person per year (1.7 kW per person). On the other hand, energy use in OECD countries is projected to decline to about 203 billion joules per person per year (6.4 kW per person). This would bring the global average in 2030 to about 80 billion joules per person per year (2.5 kW per person), up from 74 billion joules in 2010. If these projections are correct, 58% of the energy will be consumed in the non-OECD countries, compared with 50% today.

With worldwide average energy use of 2.3 kW per person in 2010, the 6.8 billion people on Earth use about 16 trillion watts annually. A projected population of 8.5 billion in 2030 with an estimated average per capita energy use rate of 2.5 kW would use about 21 trillion watts annually, an increase of about 33% from today.[19]

A realistic goal is for annual per capita energy use to remain about 2.5 kW, with the world population peaking at 8.5 billion people by the year 2030. If this goal is to be achieved, non-OECD countries will be able to increase their populations by no more than about 50% and their energy use by about 70%; OECD nations can increase their population by only a few percent and will have to reduce their energy use slightly.

Critical Thinking Questions

1. Using only the data presented in this exercise, how much energy, in exajoules, did the world use in 2010 and what would you project global energy use to be in 2030?
2. The average person emits as heat 100 watts of power (the same as a 100 W bulb). If we assume that 25% of it is emitted by the brain, how much energy does your brain emit as heat in a year? Calculate this in joules and kWh. What is the corresponding value for all people today, and how does that value compare with world energy use per year? Can this help explain why a large, crowded lecture hall (independent of the professor pontificating) might get warm over an hour?
3. Can the world supply one-third more energy by 2030 without unacceptable environmental damage? How?
4. What would the rate of energy use be if all people on Earth had a standard of living supported by energy use of 10 kW per person, as in the United States today? How do these totals compare with the present energy-use rate worldwide?
5. In what specific ways could energy be used more efficiently in the United States? Make a list of the ways and compare your list with those of your classmates. Then compile a class list.
6. In addition to increasing efficiency, what other changes in energy consumption might be required to provide an average energy-use rate in 2030 of 6.4 kW per person in OECD countries?
7. Would you view the energy future in 2030 as a continuation of the business-as-usual approach with more large, centralized energy production based on fossil fuels, or a softer path, with more use of alternative, distributed energy sources? Justify your view.

SUMMARY

- The first law of thermodynamics states that energy is neither created nor destroyed but is always conserved and is transformed from one kind to another. We use the first law to keep track of the quantity of energy.
- The second law of thermodynamics tells us that as energy is used, it always goes from a more usable (higher-quality) form to a less usable (lower-quality) form.

- Two fundamental types of energy efficiency are derived from the first and second laws of thermodynamics. In the United States today, first-law efficiencies average about 50%, which means that about 50% of the energy produced is returned to the environment as waste heat. Second-law efficiencies average 10–15%, so there is a high potential for saving energy through better matching of the quality of energy sources with their end uses.
- Energy conservation and improvements in energy efficiency can have significant effects on energy consumption. It takes three units of a fuel such as oil to produce one unit of electricity. As a result, each unit of electricity conserved or saved through improved efficiency saves three units of fuel.
- There are arguments for both the business-as-usual path and changing to a new path. The first path has a long history of success and has produced the highest standard of living ever experienced. However, present sources of energy (based on fossil fuels) are causing serious environmental degradation and are not sustainable (especially with respect to conventional oil). A second path, based on alternative energy sources that are renewable, decentralized, diverse, and flexible, provides a better match between energy quality and end use, and emphasizes second-law efficiencies.
- The transition from fossil fuels to other energy sources requires sustainable, integrated energy management. The goal is to provide reliable sources of energy that do not cause serious harm to the environment and ensure that future generations will inherit a quality environment.

REEXAMINING THEMES AND ISSUES

Human Population

The industrialized and urbanized countries produce and use most of the world's energy. As societies change from rural to urban, energy demands generally increase. Controlling the increase of human population is an important factor in reducing total demand for energy (total demand is the product of average demand per person and number of people).

Sustainability

It will be impossible to achieve sustainability in the United States if we continue with our present energy policies. The present use of fossil fuels is not sustainable. We need to rethink the sources, uses, and management of energy. Sustainability is the central issue in our decision to continue on the hard path or change to the soft path.

Global Perspective

Understanding global trends in energy production and consumption is important if we are to directly address the global impact of burning fossil fuels with respect to air pollution and global warming. Furthermore, the use of energy resources greatly influences global economics, as these resources are transported and utilized around the world.

Urban World

A great deal of the total energy demand is in urban regions, such as Tokyo, Beijing, London, New York, and Los Angeles. How we choose to manage energy in our urban regions greatly affects the quality of urban environments. Burning cleaner fuels results in far less air pollution. This has been observed in several urban regions, such as London. Burning of coal in London once caused deadly air pollution; today, natural gas and electricity heat homes, and the air is cleaner. Burning coal in Beijing continues to cause significant air pollution and health problems for millions of people living there.

People and Nature

Our development and use of energy are changing nature in significant ways. For example, burning fossil fuels is changing the composition of the atmosphere, particularly through the addition of carbon dioxide. The carbon dioxide is contributing to the warming of the atmosphere, water, and land (see Chapter 20 for details). A warmer Earth is, in turn, changing the climates of some regions and affecting weather patterns and the intensity of storms.

Science and Values

Public-opinion polls consistently show that people value a quality environment. In response, energy planners are evaluating how to use our present energy resources more efficiently, practice energy conservation, and reduce adverse environmental effects of energy consumption. Science is providing options in terms of energy sources and uses; our choices will reflect our values.

KEY TERMS

cogeneration **294**
conservation **294**
energy efficiency **294**
first-law efficiency **290**
first law of thermodynamics **289**
integrated energy management **298**
micropower **299**
second-law efficiency **290**
second law of thermodynamics **290**
sustainable energy development **298**
work **289**

STUDY QUESTIONS

1. What evidence supports the notion that, although present energy problems are not the first in human history, they are unique in other ways?
2. How do the terms *energy*, *work*, and *power* differ in meaning?
3. Compare and contrast the potential advantages and disadvantages of a major shift from hard-path to soft-path energy development.
4. You have just purchased a 100-hectare wooded island in Puget Sound. Your house is built of raw timber and is uninsulated. Although the island receives some wind, trees over 40 m tall block most of it. You have a diesel generator for electric power, and hot water is produced by an electric heater run by the generator. Oil and gas can be brought in by ship. What steps would you take in the next five years to reduce the cost of the energy you use with the least damage to the island's natural environment?
5. How might better matching of end uses with potential sources yield improvements in energy efficiency?
6. Complete an energy audit of the building you live in, then develop recommendations that might lead to lower utility bills.
7. How might plans using the concept of integrated energy management differ for the Los Angeles area and the New York City area? How might both of these plans differ from an energy plan for Mexico City, which is quickly becoming one of the largest urban areas in the world?
8. A recent energy scenario for the United States suggests that in the coming decades energy sources might be natural gas (10%), solar power (30%), hydropower (20%), wind power (20%), biomass (10%), and geothermal energy (10%). Do you think this is a likely scenario? What would be the major difficulties and points of resistance or controversy?

FURTHER READING

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