SUSTAINING THE EARTH | G. TYLER MILLER | SCOTT E. SPOOLMAN

Sustaining the Earth

ELEVENTH EDITION

G. Tyler Miller

Scott E. Spoolman

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G. Tyler Miller, Scott E. Spoolman

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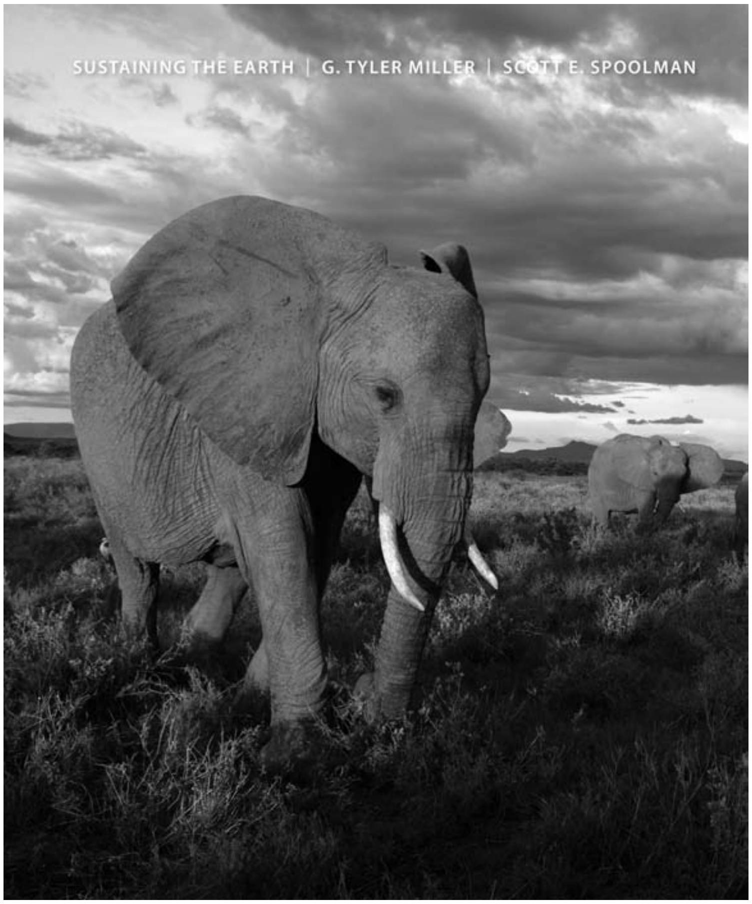
Brief Contents

About the Cover Photo



The elephant is the world's largest land animal. There are two recognized species of elephant: the African elephant (shown here) and Asian elephant. The Asian elephant is the smaller of the two and has smaller ears. Elephants, which can live for over 70 years in the wild, are considered to be intelligent animals, having large brains and excellent memories. They have been known to show signs of joy, anger, and grief, and they appear to value play.

Elephants are herbivores that can live in various habitats, including savannahs, forests, deserts, and marshes, although they prefer to be near water. They are viewed as a *keystone species* because, in shaping their habitats, they also help to maintain a diversity of habitats suitable for other species. They affect vegetation in their habitats by dispersing seeds in their dung and by uprooting trees and undergrowth. In the savannah, this helps to maintain grasslands for grazing animals and their predators. During drought they dig for water, often creating or enlarging waterholes that are used by other animals.

The African elephant is classified as vulnerable, whereas the Asian elephant is an endangered species. In 1979 there were an estimated 1.3 million wild African elephants. Today, an estimated 400,000 remain in the wild. There are only 35,000 to 40,000 remaining wild Asian elephants. Wild elephant populations are in sharp decline, mostly because elephants are illegally killed for their ivory tusks. Since 1990, there has been an international ban of the sale of ivory and in some areas, elephants are protected as threatened or endangered species, but the illegal killing of elephants for their valuable ivory continues.

Another major threat to elephants is the loss and fragmentation of their habitats as human populations have spread and taken over more land. Elephants are eating or trampling the crops of settlers who have moved into elephant habitat areas, and this has caused the killing of some elephants by farmers. If these threats are not curtailed, elephants may disappear from the wild within your lifetime.

Detailed Contents

SUSTAINING BIODIVERSITY

SUSTAINING NATURAL RESOURCES

PREFACE

For Instructors

We wrote this book to help instructors achieve three important goals: *first*, to explain to their students the basics of earth science, including how life on the earth has survived for billions of years; *second*, to help students to use this scientific foundation in order to understand the multiple environmental problems that we face and to evaluate possible solutions to them; and *third*, to inspire their students to make a difference in how we treat the earth on which our lives and economies depend, and thus make a difference in how we treat ourselves and our descendants.

To help achieve these goals, we view environmental problems and possible solutions to them through the lens of *sustainability*—the integrating theme of this book. We believe that most people can live comfortable and fulfilling lives, and that societies will be more prosperous and peaceful when sustainability becomes the chief measure by which personal choices and public policies are made.

The news media tend to be full of bad news about the environment. But environmental science is a study that also includes a lot of good news and promise for a better future. We base this vision of a better world on realistic hopes. To emphasize this positive approach, we use *Good News* icons to mark areas in this text that present positive developments in humanity's efforts to deal with environmental problems.

What's New in This Edition?

Our texts have been widely praised for keeping users up-to-date in the rapidly changing field of environmental science. We continue to maintain this and other strengths, and in this edition, we have added new updated materials and features, including the following:

- *Three social science principles of sustainability*. These complement the three scientific principles of sustainability that we have long used to explain how life on Earth has sustained itself for billions of years, and they act as guidelines for making a possible transition to more sustainable economies and societies.
- *Thinking About* exercises, interspersed throughout the chapters, ask students to analyze material immediately after it is presented.
- *Connections* boxes located in several chapters; these brief pieces stimulate critical thinking by exploring the often surprising connections related to environmental problems.
- *Doing Environmental Science* exercises, one at the end of each chapter, give students challenging new ways to apply the material by doing the work of environmental scientists.

Sustainability Is the Integrating Theme of This Book

Sustainability, a watchword of the 21st century for those concerned about the environment, is the overarching theme of this textbook. You can see the sustainability emphasis by looking at the Brief Contents (p. iii).

Six **principles of sustainability** play a major role in carrying out this book's sustainability theme. These principles are introduced in Chapter 1, depicted in Figure 1-1 (p. 3) and Figure 1-4 (p. 5) and on the back cover of the student edition. They are used throughout the book, with each reference marked in the margin by . (See Chapter 6, pp. 114 and 121.)

We use the following five major subthemes to integrate material throughout this book (see diagram on back cover).

- ***Natural capital.*** Sustainability depends on the natural resources and natural services that support all life and economies. Examples of diagrams that illustrate this subtheme are Figures 3-1, p. 49, and 3-8, p. 59.
- ***Natural capital degradation.*** We describe how human activities can degrade natural capital. Examples of diagrams that illustrate this subtheme are Figures 3-6, p. 58, and 6-7, p. 115.
- ***Solutions.*** We pay a great deal of attention to the search for *solutions* to natural capital degradation and other environmental problems. We present proposed solutions in a balanced manner and challenge students to use critical thinking to evaluate them. Some figures and many chapter sections and subsections present possible solutions to various environmental problems. Examples are Figures 6-9, p. 117, and 8-8, p. 163.
- ***Trade-Offs.*** The search for solutions involves *trade-offs*, because any solution requires weighing advantages against disadvantages. Our Trade-Offs diagrams present the advantages and disadvantages of various environmental technologies and solutions to environmental problems. Examples are Figures 8-6, p. 162, and 10-6, p. 214.

- ***Individuals Matter.*** In a number of chapters, *Individuals Matter* boxes describe what various scientists and concerned citizens have done to help us achieve sustainability (see pp. 117 and 265). Also, a number of *What Can You Do?* diagrams describe how readers can deal with the problems we face. Examples are Figures 8-16, p. 170, and 10-19, p. 225. Eight especially important steps that individuals can take are summarized in Figure 14-17 (p. 329).

Other Key Features of This Textbook

- ***Up-to-Date Coverage.*** Our textbooks have been widely praised for keeping users up-to-date in the rapidly changing field of environmental science. We have used hundreds of articles and reports published in 2010–2013 to update the information and concepts in our books. Major new or updated topics in this book include the decline of many amphibian species (p. 69); the decline of honeybees (p. 97); how damming a river can kill an estuary (p. 163); and hydraulic fracturing (fracking) in oil and natural gas production and its harmful effects (p. 193), along with many other important topics.
- ***Concept-Centered Approach.*** To help students focus on the main ideas, we built each major chapter section around a *key question* and one to three *key concepts*, which state the most important take-away messages of each chapter section. At the front of each chapter, all key questions and concepts are listed and serve as a chapter outline, and each chapter section begins with a key question and concepts (see pp. 48 and 156), which are highlighted and referenced throughout each chapter. Also, concept applications are highlighted and referenced throughout each chapter.
- ***Science-Based Coverage.*** Chapters 1–4 discuss how scientists work and introduce the scientific principles (see Brief Contents, p. iii) needed for a basic understanding of how natural systems work and for evaluating proposed solutions to environmental problems. Important environmental science topics are explored in depth in *Science Focus* boxes distributed among the chapters (see pp. 82 and 126). Science is also integrated throughout the book in various *Case Studies* (see pp. 122 and 165) and in figures (see Figures 5-11, p. 103, and 8-19, p. 174).
- ***Global Perspective.*** This book also provides a global perspective, first on the ecological level, revealing how all the world's life is connected and sustained within the biosphere, and second, through the use of information and images from around the world.
- ***Case Studies.*** These appear throughout the book (see pp. 101 and 251 and the Detailed Contents, pp. v–viii, where case studies are highlighted in bold.) Each provides an in-depth look at a specific environmental problem and its possible solutions. We include two other forms of case studies in *Science Focus* and *Individuals Matter* boxes. Each Science Focus box provides a closer look at some specific scientific process that has focused on an environmental problem or solution (see p. 119). Each Individuals Matter box tells a story of someone who has made a difference in some part of the world in the general quest for a higher level of sustainability (see p. 117).
- ***Critical Thinking.*** The introduction on *Learning Skills* describes critical thinking skills for students (pp. xviii-xix). Specific critical thinking exercises are used throughout the book in several ways:
    - In *Thinking About* exercises scattered throughout the chapters
    - In all *Science Focus* boxes
    - In the captions of many of the book's figures (see Figures 3-1, p. 49; and 8-17, p. 171)
    - As end-of-chapter questions (see pp. 109 and 227)
- ***Flexibility.*** There are hundreds of ways to organize the content of this course to fit the needs of different instructors with a wide variety of professional backgrounds as well as course lengths and goals. To meet these diverse needs, we have designed a highly flexible book that allows instructors to vary the order of chapters and sections within chapters without exposing students to terms and concepts that could confuse them. We recommend that instructors start with Chapter 1 because it defines basic terms and gives an overview of sustainability, population, pollution, resources, and economic development issues that are discussed throughout the book. This provides a springboard for instructors to use other chapters in almost any order. One often-used strategy is to follow Chapter 1 with Chapters 2 through 6, which introduce basic science and ecological concepts. Instructors can then use the remaining chapters in any order desired. Some instructors follow Chapter 1 with Chapter 14 on environmental economics, politics, and worldviews, before proceeding to the chapters on basic science and ecological concepts.
- ***In-Text Study Aids.*** Each chapter begins with a list of *Key Questions and Concepts* showing how the chapter is organized and what students will be learning. When a new term is introduced and defined, it is printed in boldface type and all such terms are summarized in the glossary at the end of the book and highlighted in review questions at the end of each chapter. Many chapters contain *Thinking About* exercises and brief *Connections* boxes to get students thinking about what they have just read. Each chapter ends with a *Review* section containing a detailed set of review questions that include all the chapter's key terms in **bold** type

(p. 154), followed by a set of *Critical Thinking* questions (p. 155) to encourage students to think critically and apply what they have learned to their lives. Finally, students get a chance to apply each chapter's material in a *Doing Environmental Science* exercise (p. 155) intended to give them a sample of the sorts of work that environmental scientists do.

Supplements for Students

A multitude of electronic supplements available to students take the learning experience beyond the textbook:

- *Environmental Science CourseMate* brings course concepts to life with interactive learning, study, and exam preparation tools that support the printed textbook. Find flashcards, quizzes, videos, and more.
- *Global Environment Watch*, updated several times a day, is a focused portal into GREENR—the Global Reference on the Environment, Energy, and Natural Resources—an ideal, one-stop site for classroom discussion and research projects. This resource center keeps courses up-to-date with the most current news on the environment. Students can access information from trusted academic journals, news outlets, and magazines, as well as statistics, an interactive world map, videos, primary sources, case studies, podcasts, and much more.

Other student learning tools include:

- *Essential Study Skills for Science Students* by Daniel D. Chiras. This book includes chapters on developing good study habits; sharpening memory; getting the most out of lectures, labs, and reading assignments; improving test-taking abilities; and becoming a critical thinker. Available for students upon instructor request.
- *Lab Manual*. This lab manual includes both hands-on and data analysis labs to help your students develop a range of skills. Create a custom version of this Lab Manual by adding labs you have written or ones from our collection with Cengage Custom Publishing. An Instructor's Manual for the labs is available to adopters.
- *What Can You Do?* This guide presents students with a variety of ways through which they can affect the environment, and shows them how to track the effect their actions have on their carbon footprint.

Supplements for Instructors

- *Instructor Companion Site* has everything you need for your course in one place! This collection of book-specific lecture and class tools is available. Access and download PowerPoint presentations, images, instructor's manual, videos, and more.
- *Cengage Learning Testing Powered by Cognero* is a flexible, online system that allows you to:
  - author, edit, and manage test bank content from multiple Cengage Learning solutions;
  - create multiple test versions in an instant; and
  - deliver tests from your LMS, your classroom, or wherever you want.

Start right away! Cengage Learning Testing Powered by Cognero works on any operating system or browser.

- No special installs or downloads needed
- Create tests from school, home, the coffee shop – anywhere with Internet access

What will you find?

- *Simplicity at every step*. A desktop-inspired interface features drop-down menus and familiar, intuitive tools that take you through content creation and management with ease.
- *Full-featured test generator*. Create ideal assessments with your choice of 15 question types (including true/false, multiple choice, opinion scale/likert, and essay). Multi-language support, an equation editor, and unlimited metadata help ensure your tests are complete and compliant.
- *Cross-compatible capability*. Import and export content into other systems.

Other Textbook Options

Instructors who want a book with a different length and emphasis can use one of our three other books that we have written for various types of environmental science courses: *Living in the Environment*, 18th edition (832 pages, Brooks/Cole, 2015), *Environmental Science*, 14th edition (452 pages, Brooks/Cole 2013), and *Essentials of Ecology*, 7th edition (416 pages, Brooks/Cole, 2015).

Help Us Improve This Book or Its Supplements

Let us know how you think we can improve this book. If you find any errors, bias, or confusing explanations, please e-mail us about your concerns at:

mtg89@hotmail.com
spoolman@tds.net

We can correct most errors in subsequent printings of this edition, as well as in future editions.

Acknowledgments

We wish to thank the many students and teachers who have responded so favorably to the ten previous editions of *Sustaining the Earth*, the 17 editions of *Living in* *the Environment*, the 14 editions of *Environmental Science*, and the 6 editions of *Essentials of Ecology*, and who have corrected errors and offered many helpful suggestions for improvement. We are also deeply indebted to the more than 300 reviewers, who pointed out errors and suggested many important improvements in the various editions of these three books.

It takes a village to produce a textbook, and the members of the talented production team, listed on the copyright page, have made vital contributions. Our special thanks go to development editor Jake Warde, production editors Hal Humphrey, Mallory Skinner, and Andrea Lewis, copy editor Michael McConnell, page compositor Michele Margenau, photo researcher Sree Meenakshi Ragothaman, artist Patrick Lane, media developer Alexandria Brady, content coordinator Kellie Petruzzelli, product assistant Chelsea Joy, and Brooks/Cole's hard-working sales staff. Finally, we are very fortunate to have the guidance, inspiration, and unfailing support of Life Sciences Senior Product Team Manager Yolanda Cossio and her dedicated team of highly talented people who have made this and other book projects such a pleasure to work on.

We also thank Ed Wells and the team who developed the *Laboratory Manual* to accompany this book, and the people who have translated it into eight languages for use throughout much of the world.

G. Tyler Miller
Scott E. Spoolman

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About the Authors

G. Tyler Miller

G. Tyler Miller has written 62 textbooks for introductory courses in environmental science, basic ecology, energy, and environmental chemistry. Since 1975, Miller's books have been the most widely used textbooks for environmental science in the United States and throughout the world. They have been used by almost 3 million students and have been translated into eight languages.

Miller has a professional background in chemistry, physics, and ecology. He has PhD from the University of Virginia and has received two honorary doctoral degrees for his contributions to environmental education. He taught college for 20 years, developed one of the nation's first environmental studies programs, and developed an innovative interdisciplinary undergraduate science program before deciding to write environmental science textbooks full time in 1975. Currently, he is the president of Earth Education and Research, devoted to improving environmental education.

He describes his hopes for the future as follows:

If I had to pick a time to be alive, it would be the next 75 years. Why? First, there is overwhelming scientific evidence that we are in the process of seriously degrading our own life-support system. In other words, we are living unsustainably. Second, within your lifetime we have the opportunity to learn how to live more sustainably by working with the rest of nature, as described in this book.

I am fortunate to have three smart, talented, and wonderful sons—Greg, David, and Bill. I am especially privileged to have Kathleen as my wife, best friend, and research associate. It is inspiring to have a brilliant, beautiful (inside and out), and strong woman who cares deeply about nature as a lifemate. She is my hero. I dedicate this book to her and to the earth.

Scott E. Spoolman

Scott Spoolman is a writer and textbook editor with more than 30 years of experience in educational publishing. He has worked with Tyler Miller since 2003 as a contributing editor on earlier editions of *Living in the Environment*, *Environmental Science*, and *Sustaining the Earth*. With Norman Myers, he also coauthored *Environmental Issues and Solutions: A Modular Approach*.

Spoolman holds a master's degree in science journalism from the University of Minnesota. He has authored numerous articles in the fields of science, environmental engineering, politics, and business. He worked as an acquisitions editor on a series of college forestry textbooks. He has also worked as a consulting editor in the development of over 70 college and high school textbooks in fields of the natural and social sciences.

In his free time, he enjoys exploring the forests and waters of his native Wisconsin along with his family—his wife, environmental educator Gail Martinelli, and his children, Will and Katie. Spoolman has the following to say about his collaboration with Tyler Miller.

I am honored to be working with Tyler Miller as a coauthor to continue the Miller tradition of thorough, clear, and engaging writing about the vast and complex field of environmental science. I share Tyler Miller's passion for ensuring that these textbooks and their multimedia supplements will be valuable tools for students and instructors. To that end, we strive to introduce this interdisciplinary field in ways that will be informative and sobering, but also tantalizing and motivational.

If the flip side of any problem is indeed an opportunity, then this truly is one of the most exciting times in history for students to start an environmental career. Environmental problems are numerous, serious, and daunting, but their possible solutions generate exciting new career opportunities. We place high priorities on inspiring students with these possibilities, challenging them to maintain a scientific focus, pointing them toward rewarding and fulfilling careers, and in doing so, working to help sustain life on the earth.

My Environmental Journey

G. Tyler Miller

My environmental journey began in 1966 when I heard a lecture on population and pollution problems by Dean Cowie, a biophysicist with the U.S. Geological Survey. It changed my life. I told him that if even half of what he said was valid, I would feel ethically obligated to spend the rest of my career teaching and writing to help students learn about the basics of environmental science. After spending six months studying the environmental literature, I concluded that he had greatly underestimated the seriousness of these problems.

I developed an undergraduate environmental studies program and in 1971 published my first introductory environmental science book, an interdisciplinary study of the connections between energy laws (thermodynamics), chemistry, and ecology. In 1975, I published the first edition of *Living in the Environment*. Since then, I have completed multiple editions of this textbook, and of three others derived from it, along with other books.

Beginning in 1985, I spent ten years in the deep woods living in an adapted school bus that I used as an environmental science laboratory and writing environmental science textbooks. I evaluated the use of passive solar energy design to heat the structure; buried earth tubes to bring in air cooled by the earth (geothermal cooling) at a cost of about $1 per summer; set up active and passive systems to provide hot water; installed an energy-efficient instant hot water heater powered by LPG; installed energy-efficient windows and appliances and a composting (waterless) toilet; employed biological pest control; composted food wastes; used natural planting (no grass or lawnmowers); gardened organically; and experimented with a host of other potential solutions to major environmental problems that we face.

I also used this time to learn and think about how nature works by studying the plants and animals around me. My experience from living in nature is reflected in much of the material in this book. It also helped me to develop the three simple principles of sustainability that serve as the integrating theme for this textbook and to apply these principles to living my life more sustainably.

I came out of the woods in 1995 to learn about how to live more sustainably in an urban setting where most people live. Since then, I have lived in two urban villages, one in a small town and one within a large metropolitan area.

Since 1970, my goal has been to use a car as little as possible. Since I work at home, I have a "low-pollute commute" from my bedroom to a chair and a laptop computer. I usually take one airplane trip a year to visit my sister and my publisher.

As you will learn in this book, life involves a series of environmental trade-offs. Like most people, I still have a large environmental impact, but I continue to struggle to reduce it. I hope you will join me in striving to live more sustainably and sharing what you learn with others. It is not always easy, but it sure is fun.

Cengage Learning's Commitment to Sustainable Practices

We, the authors of this textbook, and Cengage Learning, the publisher, are committed to making the publishing process as sustainable as possible. This involves four basic strategies:

- *Using sustainably produced paper*. The book publishing industry is committed to increasing the use of recycled fibers, and Cengage Learning is always looking for ways to increase this content. Cengage Learning works with paper suppliers to maximize the use of paper that contains only wood fibers that are certified as sustainably produced, from the growing and cutting of trees all the way through paper production.
- *Reducing resources used per book*. The publisher has an ongoing program to reduce the amount of wood pulp, virgin fibers, and other materials that go into each sheet of paper used. New, specially designed printing presses also reduce the amount of scrap paper produced per book.
- *Recycling*. Printers recycle the scrap paper that is produced as part of the printing process. Cengage Learning also recycles waste cardboard from shipping cartons, along with other materials used in the publishing process.
- *Process improvements*. In years past, publishing has involved using a great deal of paper and ink for the writing and editing of manuscripts, copyediting, reviewing page proofs, and creating illustrations. Almost all of these materials are now saved through use of electronic files. Very little paper and ink were used in the preparation of this textbook.

Learning Skills

Students who can begin early in their lives to think of things as connected, even if they revise their views every year, have begun the life of learning.

MARK VAN DOREN

Why Is It Important to Study Environmental Science?

Welcome to **environmental science**—an *interdisciplinary* study of how the earth works, how we interact with the earth, and how we can deal with the environmental problems we face. Because environmental issues affect every part of your life, the concepts, information, and issues discussed in this book and the course you are taking will be useful to you now and throughout your life.

Understandably, we are biased, but *we strongly believe that environmental science is the single most important course in your education*. What could be more important than learning how the earth works, how we affect its life-support system, and how we can reduce our environmental impact?

Evidence indicates strongly that we will have to learn to live more sustainably by reducing our degradation of the planet's life-support system. We hope this book will inspire you to become involved in this change in the way we view and treat the earth, which sustains us, our economies, and all other living things.

You Can Improve Your Study and Learning Skills

Maximizing your ability to learn involves trying to *improve your study and learning skills*. Here are some suggestions for doing so:

Develop a passion for learning. As the famous physicist and philosopher Albert Einstein put it, "I have no special talent. I am only passionately curious."

Get organized. Becoming more efficient at studying gives you more time for other interests.

Make daily to-do lists. Put items in order of importance, focus on the most important tasks, and assign a time to work on these items. Shift your schedule as needed to accomplish the most important items.

Set up a study routine in a distraction-free environment. Study in a quiet, well-lighted space. Take breaks every hour or so. During each break, take several deep breaths and move around; this will help you to stay more alert and focused.

Avoid procrastination. Keep up with your reading and other assignments. Set aside a particular time for studying each day and make it a part of your daily routine.

Make hills out of mountains. It can be psychologically challenging to read an entire book or a chapter in a book, to write a paper, or to study for a big test. It often helps to break these large tasks (mountains) down into a series of small tasks (hills). Each day, read a few pages of the assigned book or chapter, write a few paragraphs of the paper, and review what you have studied and learned.

Look at the big picture first. Get an overview of an assigned reading in this book by looking at the *Key Questions and Concepts* box at the beginning of each chapter. It lists both the key questions explored in the chapter sections and their corresponding key concepts, which are the critical lessons to learn in the chapter. Use this list as a chapter roadmap. When you finish a chapter you can also use the list to review.

Ask and answer questions as you read. For example, "What is the main point of a particular subsection or paragraph?" Relate your own questions to the key questions and key concepts addressed in each major chapter section. In this way, you can flesh out a chapter outline to help you understand the chapter material. You may even want to write out such an outline.

Focus on key terms. Use the glossary in your textbook to look up the meanings of terms or words you do not understand. This book shows all key terms in **boldface** type and lesser, but still important, terms in *italicized* type. The review questions at the end of each chapter also include the chapter's key terms in boldface. Flash cards for testing your mastery of key terms for each chapter are available on the website for this book, or you can make your own by putting a term on one side of an index card or piece of paper and its meaning on the other side.

Interact with what you read. Highlight key sentences and paragraphs and make notes in the margins. You might also mark important pages that you want to return to.

Review to reinforce learning. Before each class session, review the material you learned in the previous session and read the assigned material.

Become a good note taker. Learn to write down the main points and key facts from any lecture using your own shorthand system. Review, fill in, and organize your notes as soon as possible after each class.

Write out answers to questions to focus and reinforce learning. Answer the critical thinking questions found in *Thinking About* boxes throughout the chapters, in many figure captions, and at the end of each chapter. These questions are designed to inspire you to think about key ideas and connect them to other ideas and your own life. Also answer the review questions found at the end of each chapter. The website for each chapter has an additional detailed list of review questions. Writing out your answers to the critical thinking and review questions can reinforce your learning. Save your answers for review and test preparation.

Use the buddy system. Study with a friend or become a member of a study group to compare notes, review material, and prepare for tests. Explaining something to someone else is a great way to focus your thoughts and reinforce your learning. Attend any review sessions offered by instructors or teaching assistants.

Learn your instructor's test style. Does your instructor emphasize multiple-choice, fill-in-the-blank, true-or-false, factual, or essay questions? How much of the test will come from the textbook and how much from lecture material? Adapt your learning and studying methods to this style.

Become a good test taker. Avoid cramming by studying for tests well ahead of time. Eat well and get plenty of sleep before a test. Arrive on time or early. Calm yourself and increase your oxygen intake by taking several deep breaths. (Do this also about every 10–15 minutes while taking the test.) Look over the test and answer the questions you know well first. Then work on the harder ones. Use the process of elimination to narrow down the choices for multiple-choice questions. For essay questions, organize your thoughts before you start writing. If you have no idea what a question means, make an educated guess. You might earn some partial credit and avoid getting a zero. Another strategy for getting some credit is to show your knowledge and reasoning by writing something like this: "If this question means so and so, then my answer is ________."

Take time to enjoy life. Every day, take time to laugh and enjoy nature, beauty, and friendship. By balancing work and leisure, you can become more effective in everything you do.

You Can Improve Your Critical Thinking Skills

Critical thinking involves developing the skills to analyze information and ideas, judge their validity, and make decisions. Critical thinking helps you to distinguish between facts and opinions, evaluate evidence and arguments, take and defend informed positions on issues, integrate information and see relationships, and apply your knowledge to dealing with new and different problems, and to your own lifestyle choices. Here are some basic skills for learning how to think more critically.

Question everything and everybody. Be skeptical, as any good scientist is. Do not believe everything you hear and read, including the content of this textbook, without evaluating the information you receive. Seek other sources and opinions.

Identify and evaluate your personal biases and beliefs. Each of us has biases and beliefs taught to us by our parents, teachers, friends, role models, and our own experience. What are your basic beliefs, values, and biases? Where did they come from? What assumptions are they based on? How sure are you that your beliefs, values, and assumptions are right and why? According to the American psychologist and philosopher William James, "A great many people think they are thinking when they are merely rearranging their prejudices."

Be open-minded and flexible. Be open to considering different points of view. Suspend judgment until you gather more evidence, and be willing to change your mind. Recognize that there may be a number of useful and acceptable solutions to a problem, and that very few issues are black or white. Try to take the viewpoints of those you disagree with. Understand that there are trade-offs involved in dealing with any environmental issue, as you will learn in reading this book.

Be humble about what you know. Some people are so confident in what they know that they stop thinking and questioning. To paraphrase American writer Mark Twain, "It's what we know is true, but just ain't so, that hurts us."

Evaluate how the information related to an issue was obtained. Are the statements you heard or read based on firsthand knowledge and research or on hearsay? Are unnamed sources used? Is the information based on reproducible and widely accepted scientific studies or on preliminary scientific results that may be valid but need further testing? Is the information based on a few isolated stories or experiences or on carefully controlled studies whose results were reviewed by experts in the field involved? Is it based on unsubstantiated and dubious scientific information or beliefs?

Question the evidence and conclusions presented. What are the conclusions or claims? What evidence is presented to support them? Does the evidence support them? Is there a need to gather more evidence to test the conclusions? Are there other, more reasonable conclusions?

Try to uncover differences in basic beliefs and assumptions. On the surface, most arguments or disagreements involve differences in opinions about the validity or meaning of certain facts or conclusions. Scratch a little deeper and you will find that most disagreements are usually based on different (and often hidden) basic assumptions concerning how we look at and interpret the world around us. Uncovering these basic differences can allow the parties involved to understand where each is coming from, and to agree to disagree about their basic assumptions, beliefs, or principles.

Try to identify and assess any motives on the part of those presenting evidence and drawing conclusions. What is their expertise in this area? Do they have any unstated assumptions, beliefs, biases, or values? Do they have a personal agenda? Can they benefit financially or politically from acceptance of their evidence and conclusions? Would investigators with different basic assumptions or beliefs take the same data and come to different conclusions?

Expect and tolerate uncertainty. Recognize that scientists cannot establish absolute proof or certainty about anything. However, the results of reliable science have a high degree of certainty.

Do the arguments used involve logical fallacies or debating tricks? Here are six of many examples of such tricks. *First*, attack the presenter of an argument rather than the argument itself. *Second*, appeal to emotion rather than facts and logic. *Third*, claim that if one piece of evidence or one conclusion is false, then all other related pieces of evidence and conclusions are false. *Fourth*, insist that a conclusion is false because it has not been scientifically proved. (Again, scientists never prove anything absolutely, even though they can establish high degrees of certainty.) *Fifth*, inject irrelevant or misleading information to divert attention from important points. *Sixth*, present only either/or alternatives when there may be a number of options.

Do not believe everything you read on the Internet. The Internet is a wonderful and easily accessible source of information, including alternative explanations and opinions on almost any subject or issue—much of it not available in the mainstream media and scholarly articles. Web logs, or blogs, have become a major source of information, and are even more important than standard news media for some people. However, because the Internet is so open, anyone can post anything they want to some blogs and other websites with no editorial control or review by experts. As a result, evaluating information on the Internet is one of the best ways to put into practice the principles of critical thinking discussed here. Use and enjoy the Internet, but think critically and proceed with caution.

Develop principles or rules for evaluating evidence. Develop a written list of principles to serve as guidelines for evaluating evidence and claims (such as the list we are presenting here). Continually evaluate and modify this list on the basis of your experience.

Become a seeker of wisdom, not a vessel of information. Many people believe that the main goal of education is to learn as much as you can by gathering more and more information. We believe that the primary goal is to learn how to sift through mountains of facts and ideas to find the few *nuggets of wisdom* that are the most useful for understanding the world and for making decisions. This book is full of facts and numbers, but they are useful only to the extent that they lead to an understanding of key ideas, scientific laws, theories, concepts, and connections. The major goals of the study of environmental science are to find out how nature works and sustains itself and to use this information to help make human societies and economies more sustainable, more just, and more beneficial and enjoyable for all. As writer Sandra Carey observed, "Never mistake knowledge for wisdom. One helps you make a living; the other helps you make a life." Or as American writer Walker Percy suggested, "Some individuals with a high intelligence but lacking wisdom can get all A's and flunk life."

To help you practice critical thinking, we have supplied questions throughout this book—in the captions of many figures, and at the end of each chapter. There are no right or wrong answers to many of these questions. A good way to improve your critical thinking skills is to compare your answers with those of your classmates and to discuss how you arrived at your answers.

Know Your Own Learning Style

People have different ways of learning, and it can be helpful to know your own learning style. *Visual learners* learn best by reading and viewing illustrations and diagrams. They can benefit from using flash cards (available on the website for this book) to memorize key terms and ideas. This is a highly visual book with many carefully selected photographs and diagrams designed to illustrate important ideas, concepts, and processes.

Auditory learners learn best by listening and discussing. They might benefit from reading aloud while studying and using a tape recorder in lectures for study and review. *Logical learners* learn best by using concepts and logic to uncover and understand a subject rather than relying mostly on memory.

Part of what determines your learning style is how your brain works. According to the *split-brain hypothesis*, the left hemisphere of the brain is good at logic, analysis, and evaluation, whereas the right half of the brain is good at visualizing, synthesizing, and creating. One of our goals is to provide material that stimulates both sides of your brain.

When you are trying to solve a problem, try to rest, meditate, take a walk, exercise, or do something to shut down your controlling left-brain activity. This will allow the right side of your brain to work on the problem in a less controlled and more creative manner.

This Book Presents a Positive and Realistic Environmental Vision of the Future

There are always *trade-offs* involved in making and implementing environmental decisions. Our challenge is to give a balanced presentation of different viewpoints, the advantages and disadvantages of various technologies and proposed solutions to environmental problems, and the good and bad news about environmental problems, and to do this without injecting personal bias.

When a student studies a subject as important as environmental science and ends up with no conclusions, opinions, or beliefs, it means that both the teacher and the student have failed. However, any conclusions one does reach must be found through a process of thinking critically to evaluate different ideas and to understand the trade-offs involved. Our goal is to present a positive vision of our environmental future based on realistic optimism.

Help Us Improve This Book

Researching and writing a book that covers and connects ideas in a wide variety of disciplines is a challenging and exciting task. Almost every day, we learn about some new connection in nature.

In a book this complex, there are bound to be some errors—some typographical mistakes that slip through and some statements that you might question, based on your knowledge and research. We invite you to contact us to point out any bias, to correct any errors you find, and to suggest ways to improve this book. Please e-mail your suggestions to Tyler Miller at mtg89@hotmail.com or Scott Spoolman at spoolman@tds.net.

Now start your journey into this fascinating and important study of how the earth works and how we can leave the planet in a condition at least as good as what we found. Have fun.

Study nature, love nature,
stay close to nature. It will never fail you.

FRANK LLOYD WRIGHT

Environmental Problems, Their Causes, and Sustainability

1

Key Questions and Concepts

1-1 What are some principles of sustainability?

CONCEPT 1-1A Nature has sustained itself for billions of years by relying on solar energy, biodiversity, and chemical cycling.

CONCEPT 1-1B We could shift toward living more sustainably by applying full-cost pricing, searching for win-win solutions, and committing to sustaining the earth's life-support system for future generations.

1-2 How are our ecological footprints affecting the earth?

CONCEPT 1-2 As our ecological footprints grow, we are depleting and degrading more of the earth's natural capital.

1-3 Why do we have environmental problems?

CONCEPT 1-3 Major causes of environmental problems are population growth, unsustainable resource use, poverty, avoidance of full-cost pricing, and increasing isolation from nature.

1-4 What is an environmentally sustainable society?

CONCEPT 1-4 Living sustainably means living off the earth's natural income without depleting or degrading the natural capital that supplies it.

*This is a *concept-centered* book, with each major chapter section built around one or two key concepts derived from the natural or social sciences. Key questions and concepts are summarized at the beginning of each chapter. You can use this list as a preview and as a review of the key ideas in each chapter.

No civilization has survived the ongoing destruction of its natural support system. Nor will ours.

LESTER R. BROWN

Links: SUSTAINABILITY refers to the book's sustainability theme. GOOD NEWS refers to good news about the environmental challenges we face.

1-1 What Are Some Principles of Sustainability?

▶ **CONCEPT 1-1A Nature has sustained itself for billions of years by relying on solar energy, biodiversity, and nutrient cycling.**

▶ **CONCEPT 1-1B We could shift toward living more sustainably by applying full-cost pricing, searching for win-win solutions, and committing to sustaining the earth's life-support system for future generations.**

Environmental Science Is a Study of Connections in Nature

The **environment** is everything around us, including the living and nonliving things (air, water, and energy) with which we interact in a complex web that connects us to one another and to the world we live in. Despite our many scientific and technological advances, we are utterly dependent on the earth for clean air and water, food, shelter, energy, and everything else in the planet's *life-support system*. As a result, we are part of, and not apart from, the rest of nature.

This textbook is an introduction to **environmental science**, an *interdisciplinary* study of how humans interact with the living and nonliving parts of their environment. It integrates information and ideas from the *natural sciences* (such as biology, chemistry, and geology); the *social sciences* (such as geography, economics, and political science); and the *humanities* (such as philosophy and ethics). The three goals of environmental science are **(1)** to learn how life on the earth has survived and thrived, **(2)** to understand how we interact with the environment, and **(3)** to find ways to deal with environmental problems and live more sustainably.

A key component of environmental science is **ecology**, the biological science that studies how **organisms**, or living things, interact with one another and with their environment. Every organism is a member of a certain **species**, a group of organisms that have a unique set of characteristics that distinguish them from all other organisms.

A major focus of ecology is the study of ecosystems. An **ecosystem** is a set of organisms within a defined area or volume that interact with one another and with the nonliving matter and energy in their environment. For example, a forest ecosystem consists of plants (especially trees), animals, and various other organisms that decompose organic materials, all interacting with one another, with solar energy, and with the chemicals in the forest's air, water, and soil.

We should not confuse environmental science or ecology with **environmentalism**, a social movement dedicated to protecting the earth's life-support systems for all forms of life. Environmentalism is practiced more in the political and ethical arenas than in the realm of science.

Three Scientific Principles of Sustainability

How has an incredible variety of life on the earth been sustained for at least 3.5 billion years in the face of catastrophic changes in environmental conditions? Such changes included gigantic meteorites impacting the earth, ice ages lasting for hundreds of millions of years, and long warming periods during which melting ice raised sea levels by hundreds of feet.

The latest version of our species has been around for only about 200,000 years—less than the blink of an eye relative to the 3.5 billion years that life has existed on the earth. Given the fact that we are newcomers, it makes sense that we could learn a lot from the rest of nature.

Many scientists contend that the earth is the only real example of a sustainable system. Our science-based research leads us to believe that three major natural factors have played the key roles in the long-term sustainability of life on this planet, as summarized below and in Figure 1-1 (**Concept 1-1A**). We use these three **scientific principles of sustainability**, or *lessons from nature*, throughout the book to suggest how we might move toward a more sustainable future.

- **Reliance on solar energy:** The sun warms the planet and provides energy that plants use to produce **nutrients**, or the chemicals necessary for their own life processes along with those of most other animals, including humans. The sun also powers indirect forms of solar energy such as wind and flowing water, which would not exist without solar energy.
- **Biodiversity** (short for *biological diversity*) is the variety of genes, organisms, species, and ecosystems in which organisms exist and interact. The interactions among species, especially the feeding relationships, provide vital natural services, including natural limits that keep any population from growing too large. Biodiversity also provides countless ways for life to adapt to changing environmental conditions, even catastrophic changes that wipe out large numbers of species.
- **Chemical cycling**, also referred to as **nutrient cycling**, is the circulation of chemicals that are nec-

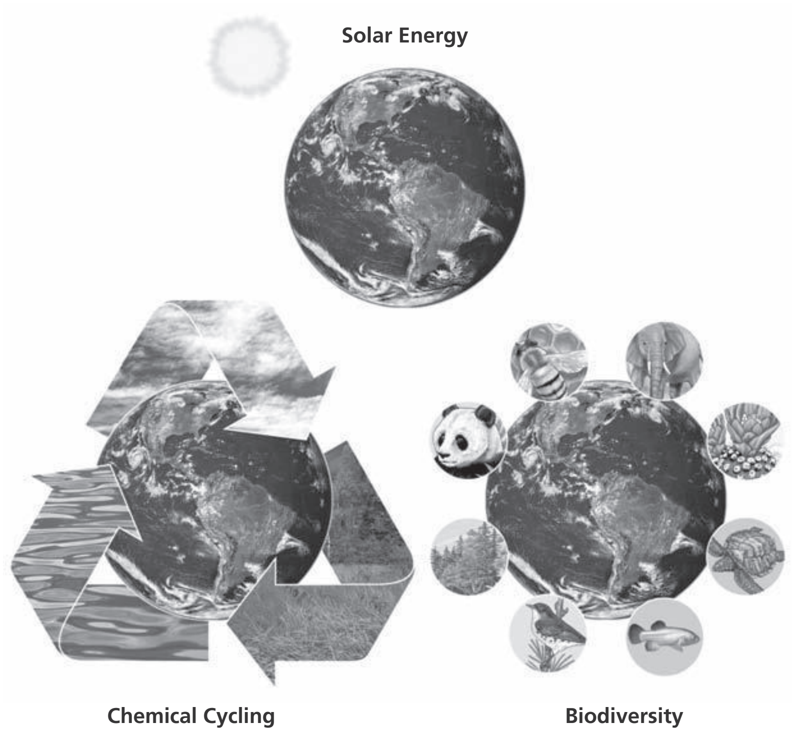


Figure 1-1 Three scientific principles of sustainability: We derive these three interconnected **principles of sustainability** from learning how nature has sustained a huge variety of life on the earth for at least 3.5 billion years, despite drastic changes in environmental conditions (**Concept 1-1A**).

essary for life from the environment through organisms and back to the environment. Because the earth receives no new supplies of these chemicals, organisms must recycle them continuously to survive. This means that there is little waste in nature, other than in the human world, because the wastes of any organism become nutrients or raw materials for other organisms.

Sustainability Has Certain Key Components

Sustainability, the central integrating theme of this book, has several critical components that we use as subthemes. One such component is **natural capital**—the natural resources and ecosystem services that keep us and other species alive and support our human economies (Figure 1-2).

Natural resources are materials and energy in nature that are essential or useful to humans. They often are classified as *renewable resources* (such as air, water, soil, plants, and wind) or *nonrenewable resources* (such as copper, oil, and coal). **Ecosystem services** are processes in nature, such as pollination, purification of air and water, and renewal of topsoil, that support life and human economies.

In economic terms, *capital* refers to money and other forms of wealth that can support a person, a population, or an economy. It can provide a sustainable income if we use it properly—that is, if we do not spend it too quickly. If we protect capital by careful investment and spending, it can last indefinitely. Similarly, natural capital can support the earth's diversity of species as long as we use its natural resources and services in a sustainable fashion.

One vital ecosystem service is nutrient cycling (Figure 1-3). An important component of nutrient cycling is *topsoil*, the upper layer of any soil in which plants can grow. It is the vital natural resource that provides the nutrients that support the plants, animals, and microorganisms that live on land. Without nutrient cycling in topsoil, land-dwelling life as we know it could not exist. Hence, we consider it to be the basis for one of the three **principles of sustainability**.

A second major component of sustainability—and another subtheme of this text—is to recognize that many human activities can *degrade natural capital* by using normally renewable resources faster than natural processes can restore them and by overloading natural systems with pollution and wastes. For example, in some parts of the world, we are clearing mature forests much faster than they can grow back and withdrawing groundwater (stored thousands of years ago) faster than nature can replenish it. We are also loading some rivers, lakes, and oceans with chemical and animal wastes faster than these bodies of water can cleanse themselves.

This leads us to a third component of sustainability: *solutions*. Although environmental scientists search for solutions to problems such as the unsustainable

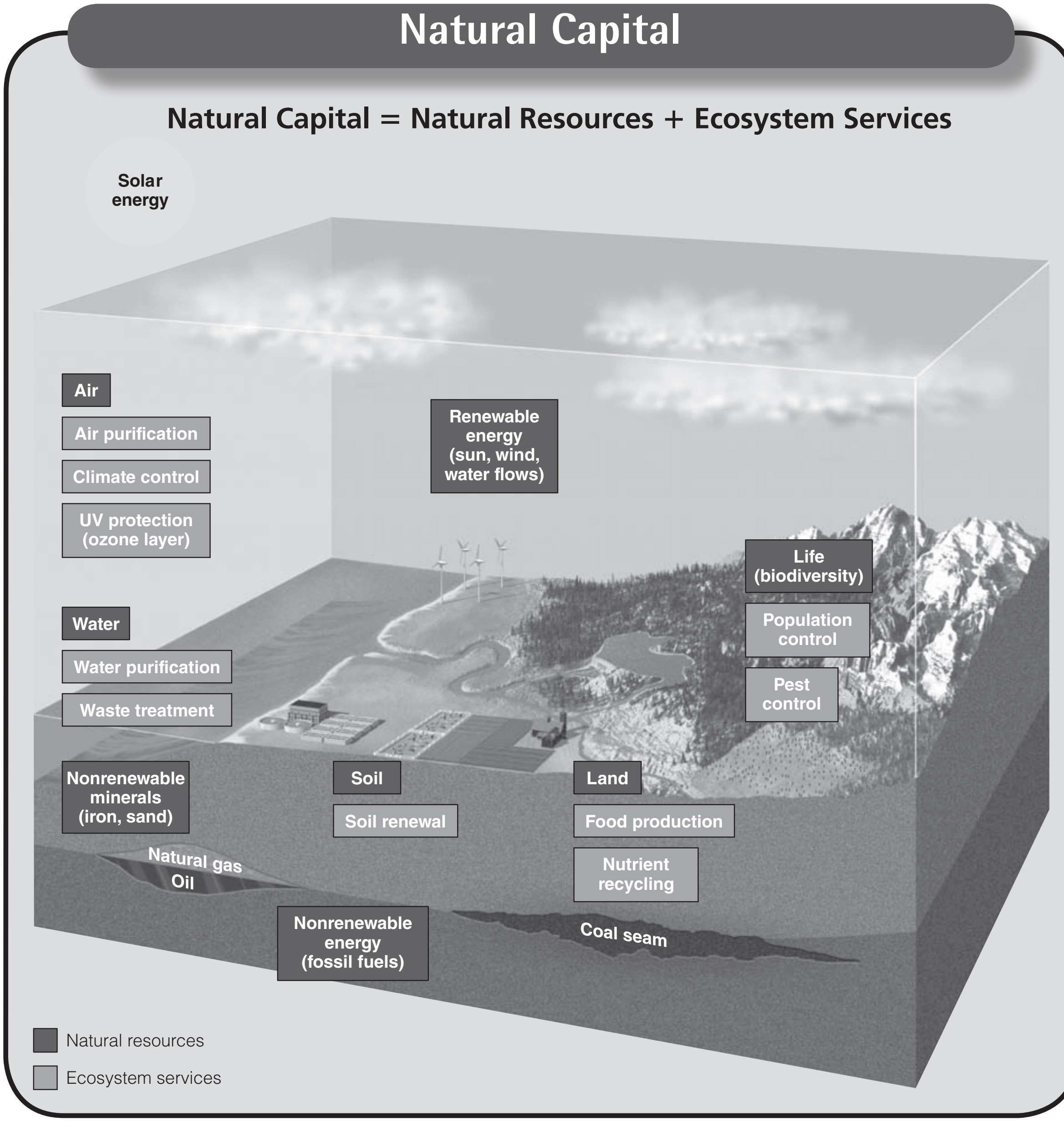


Figure 1-2
Natural capital: These key *natural resources* (darker shaded boxes) and *ecosystem services* (lighter shaded boxes) support and sustain the earth's life and human economies (**Concept 1-1A**).

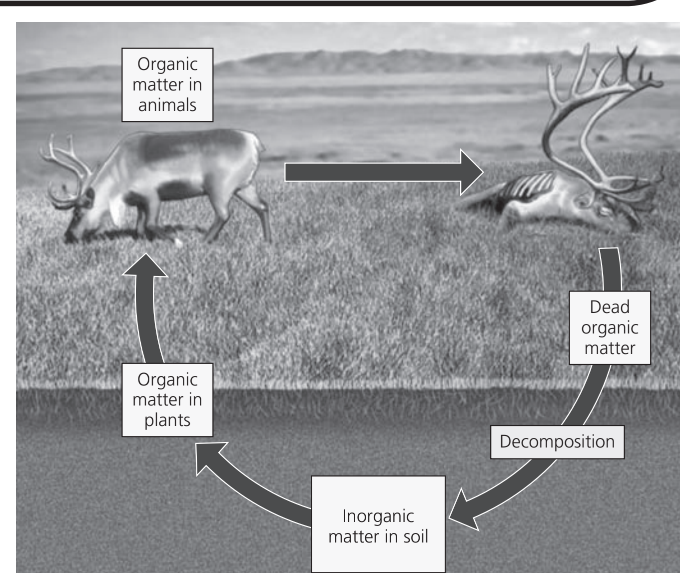


Figure 1-3 *Nutrient cycling:* This important ecosystem service recycles chemicals needed by organisms from the environment (mostly from soil and water) through those organisms and back to the environment.

degradation of forests and other forms of natural capital, their work is limited to finding the *scientific* solutions; the political solutions are left to political processes. For example, a scientific solution to the problem of depletion of forests might be to stop burning or cutting down biologically diverse, mature forests and to allow nature to replenish them. But to implement such solutions, governments would probably have to enact and enforce environmental laws and regulations.

The search for solutions often involves conflicts. For example, when a scientist argues for protecting a natural forest to help preserve its important diversity of plants and animals, the timber company that had planned to harvest the trees in that forest might protest. Dealing with such conflicts often involves making *trade-offs*, or compromises—a fourth component of sustainability. For example, the timber company might be persuaded to plant a tree farm in an area that had already been cleared or degraded, instead of clearing the trees in an undisturbed diverse natural forest. In return, the government might give the company a *subsidy*, or financial support, to meet some of the costs for planting the trees.

In making a shift toward environmental sustainability, the daily actions of each and every individual are important. In other words, *individuals matter*. This is another subtheme of this book. History shows that almost all of the significant changes in human systems have come from the bottom up, through the collective actions of individuals and from individuals inventing more sustainable ways of doing things. Thus, *sustainability begins at personal and local levels*.

Other Principles of Sustainability Come from the Social Sciences

Our search for solutions and trade-offs to the environmental problems has led us to propose three **social science principles of sustainability** (Figure 1-4), derived from studies of economics, political science, and ethics. We believe that these principles (**Concept 1-1B**), along with our three *scientific principles of sustainability* (Figure 1-1), can serve as general guidelines for living more sustainably.

These social science principles of sustainability are:

- **Full-cost pricing** (from economics): Many economists urge us to find ways to include the harmful environmental and health costs of producing and using goods and services in their market prices—a practice called **full-cost pricing**. This would give

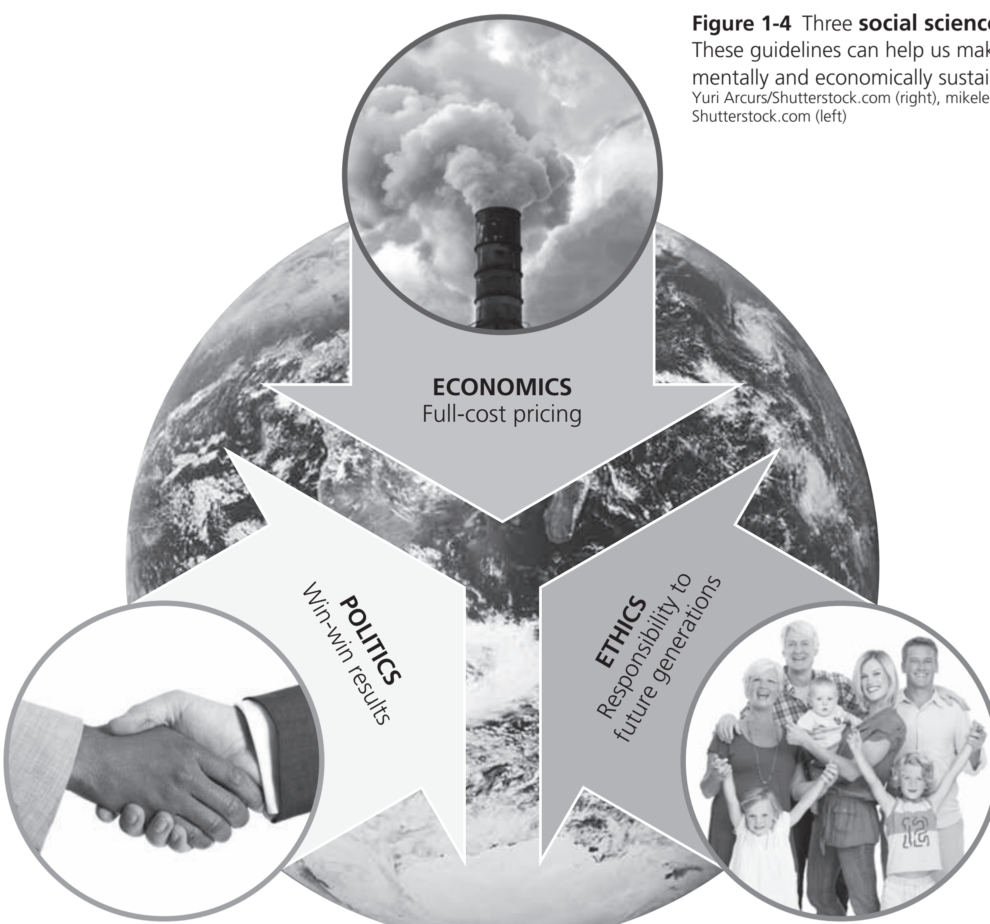


Figure 1-4 Three **social science principles of sustainability:** These guidelines can help us make a transition to a more environmentally and economically sustainable future (**Concept 1-1B**).
Yuri Arcurs/Shutterstock.com (right), mikeledray/Shutterstock.com (center), Minerva Studio/Shutterstock.com (left)

consumers better information about the environmental impacts of their lifestyles, and it would allow them to make more informed choices about the goods and services they use.

- **Win-win solutions** (from political science): We can learn to work together in dealing with environmental problems by focusing on solutions that will benefit the largest possible number of people. This means shifting from an *I win, you lose* approach to a *we both win* approach (*win-win* solutions), and to an *I win, you win, and the earth wins* approach (*win-win-win* solutions).
- **A responsibility to future generations** (from ethics): We should accept our responsibility to leave the planet's life-support systems in at least as good a condition as what we now enjoy, for future generations.

We will explore these principles further in this chapter and apply them throughout this textbook. For quick reference, you can find all six principles of sustainability on the back cover of this book.

Some Resources Are Renewable and Some Are Not

From a human standpoint, a **resource** is anything obtained from the environment to meet our needs and wants. Some resources, such as solar energy, fresh air, fertile topsoil, and edible wild plants, are directly available for use. Other resources, such as petroleum, iron, water stored underground, and cultivated crops, become useful to us only with some effort and technological ingenuity.

Resources vary in terms of how quickly we can use them up and how well nature can replenish them after we use them. Solar energy is called an **inexhaustible resource** because its continuous supply is expected to last at least 6 billion years, until the sun dies. A **renewable resource** is one that can be replenished by natural processes within hours to centuries, as long as we do not use it up faster than nature can renew it. Examples include forests, grasslands, fish populations, and fertile topsoil. The highest rate at which we can use a renewable resource indefinitely without reducing its available supply is called its **sustainable yield**.

Nonrenewable resources are those that exist in a fixed quantity, or *stock*, in the earth's crust. On a time scale of millions to billions of years, geologic processes can renew such resources. But on the much shorter human time scale of hundreds to thousands of years, we can deplete these resources much faster than nature can form them. Such exhaustible stocks include *energy resources* (such as coal and oil), *metallic mineral resources* (such as copper and aluminum), and *nonmetallic mineral resources* (such as salt and sand).

As we deplete such resources, human ingenuity often can find substitutes. For example, a mix of renewable energy resources, such as wind, the sun, flowing water, and the heat in the earth's interior, could reduce our dependence on nonrenewable oil and coal during this century. However, for many nonrenewable resources, we have yet to find acceptable and affordable substitutes.

We can recycle or reuse some nonrenewable resources, such as copper and aluminum, to extend their supplies. **Reuse** involves using a resource over and over in the same form. For example, we can collect, wash, and refill glass bottles many times. **Recycling** involves collecting waste materials and processing them into new materials. We can crush and melt discarded aluminum to make new aluminum cans or other aluminum products, for example.

Many scientists argue that our priorities for more sustainable use of nonrenewable resources should be, in order: **R**educe (use less), **R**euse, and **R**ecycle. Recycling nonrenewable metallic resources uses much less energy, water, and other resources and produces much less pollution and environmental degradation than exploiting virgin metallic resources. Reusing such resources requires even less energy, water, and other resources and produces less pollution and environmental degradation than recycling.

Countries Differ in Their Resource Use and Environmental Impact

As the human population grows, more and more people seek to satisfy their needs and wants. Governmental and societal leaders are charged with making this possible by maintaining and expanding their national economies, which can lead to growing environmental problems.

Economic growth is an increase in a nation's output of goods and services. It is usually measured by the percentage of change in a country's **gross domestic product** (**GDP**), the annual market value of all goods and services produced by all businesses, foreign and domestic, operating within a country. Changes in a country's economic growth per person are measured by **per capita GDP**, the GDP divided by the total population at midyear.

Whereas economic growth provides people with more goods and services, **economic development** has the goal of using economic growth to improve living standards. The United Nations (UN) classifies the world's countries as economically more developed or less developed based primarily on their average income per person (per capita GDP). In using these classifications in this textbook, we do not mean to imply that either type of country is superior to the other. We are simply distinguishing between countries in terms of their economic activity, because this measure is highly useful for studying the resource use and environmental impacts of nations and regions.

The **more-developed countries** include the United States, Canada, Japan, Australia, New Zealand, and most European countries. According to UN and World Bank data, the more-developed countries, with only 17% of the world's population, use about 88% of the world's resources and produce about 75% of the world's pollution and waste.

All other nations, in which 83% of the world's people live, are classified as **less-developed countries**, most of them in Africa, Asia, and Latin America. Some are *middle-income, moderately developed countries* such as China, India, Brazil, Turkey, Thailand, and Mexico. Others are *low-income, least-developed countries* such as Haiti, Nigeria, and Nicaragua.

1-2 How Are Our Ecological Footprints Affecting the Earth?

CONCEPT 1-2 As our ecological footprints grow, we are depleting and degrading more of the earth's natural capital.

We Are Living Unsustainably

A large and growing body of scientific evidence indicates that we are living unsustainably by wasting, depleting, and degrading the earth's natural capital at an accelerating rate—a process known as **environmental degradation**, or **natural capital degradation** (Figure 1-5).

In many parts of the world, potentially renewable forests are shrinking, deserts are expanding, soils are eroding, and suburbs are replacing croplands. In addition, the lower atmosphere is warming; polar sea ice and glaciers are melting at unexpected rates; sea levels are rising; ocean acidity is increasing; and floods, droughts, severe weather, and forest fires are more frequent in some areas. In certain areas, rivers are running dry; harvests of many species of fish are dropping sharply; and coral reefs are disappearing. Species are becoming extinct at least 100 times faster than in prehuman times, and extinction rates are expected to rise by at least another 100-fold during this century.

In 2005, the UN released its *Millennium Ecosystem Assessment*. According to this 4-year study by 1,360 experts from 95 countries, human activities have degraded about 60% of the earth's natural or ecosystem

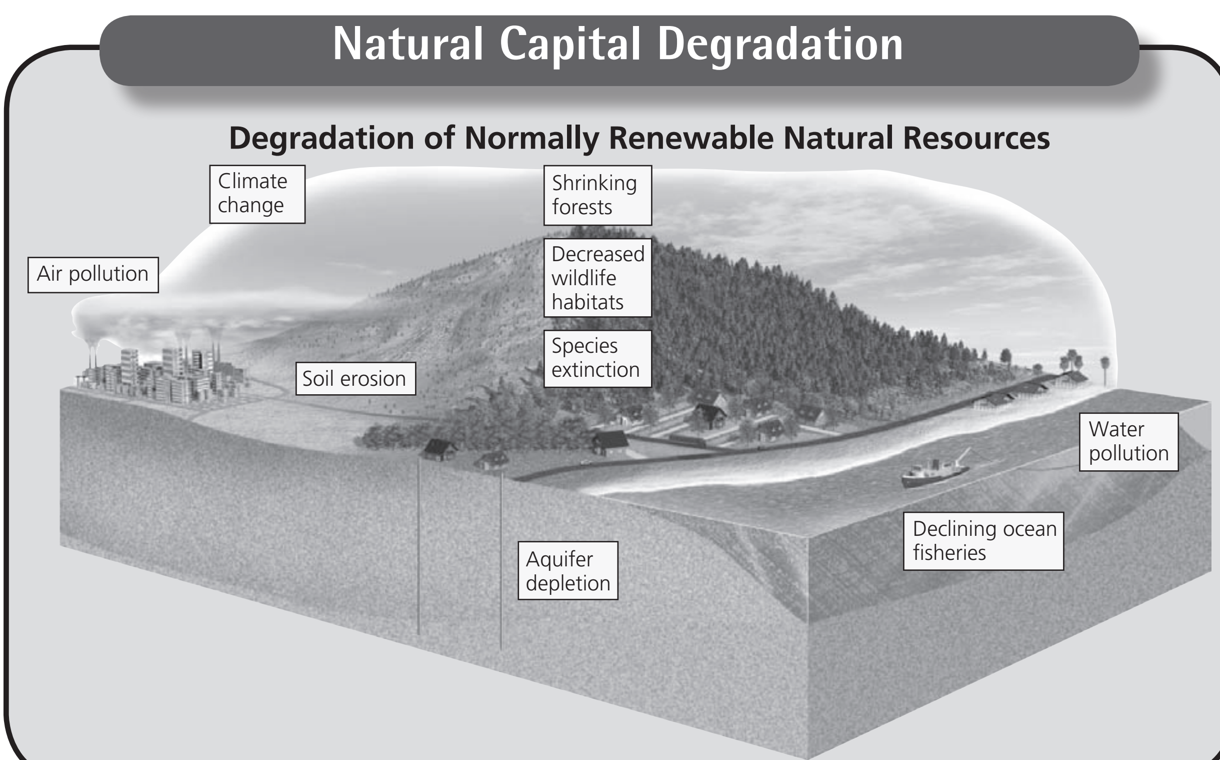


Figure 1-5 Natural capital degradation: Examples of the degradation of normally renewable natural resources and services in parts of the world, mostly as a result of rising populations and resource use per person.

services (Figure 1-2), mostly since 1950. In its summary statement, the report warned that "human activity is putting such a strain on the natural functions of Earth that the ability of the planet's ecosystems to sustain future generations can no longer be taken for granted." However, as the UN report also noted, we have the knowledge and tools to conserve rather than degrade or destroy the planet's natural capital, and there are a number of common-sense strategies for doing so.

Pollution Comes from a Number of Sources

One of the earliest problems that environmental scientists addressed, and one that is basic to many other environmental issues, is **pollution**—any presence within the environment of a chemical or other agent (such as noise or heat) at a level that is harmful to the health, survival, or activities of humans or other organisms. Polluting substances, or *pollutants*, can enter the environment naturally, such as from volcanic eruptions, or through human activities, such as the burning of coal and gasoline and the dumping of chemicals into rivers, lakes, and oceans.

The pollutants we produce come from two types of sources. **Point sources** are single, identifiable sources. Examples are the smokestack of a coal-burning power or industrial plant and the drainpipe of a factory. **Nonpoint sources** are dispersed and often difficult to identify. Examples are pesticides blown from the land into the air and the runoff of fertilizers from the land into streams and lakes. It is much easier and less costly to identify and control pollution from point sources than from nonpoint sources.

There are two main types of pollutants. **Biodegradable pollutants** are materials that natural processes can break down over time. Examples are human sewage and newspapers. **Nondegradable pollutants** are substances and chemicals that natural processes cannot break down. Examples are some types of plastic and toxic chemical elements such as lead, mercury, and arsenic.

We have tried to deal with pollution in two very different ways. One method is **pollution cleanup**, which involves cleaning up or diluting pollutants after we have produced them. The other method is **pollution prevention**, or efforts focused on greatly reducing or eliminating the production of pollutants. We need both pollution prevention (front-of-the-pipe) and pollution cleanup (end-of-the-pipe) solutions. But environmental scientists urge us to put more emphasis on prevention, because it works better and in the long run is cheaper than cleanup, as we discuss further in later chapters.

The Tragedy of the Commons: Degrading Commonly Shared Renewable Resources

Some renewable resources, known as *open-access renewable resources*, are owned by no one and available for use by everyone at little or no charge. Examples include the atmosphere, water stored underground (groundwater), the open ocean, and its fishes. Other examples of less open, but often *shared resources*, are grasslands and forests. Many of these commonly held resources have been environmentally degraded. In 1968, biologist Garrett Hardin (1915–2003) called such degradation the *tragedy of the commons*.

Degradation of a shared or open-access resource occurs because most users of an open-access resource believe that their actions will have little impact on the resource. When the number of users is small, this logic works. Eventually, however, the cumulative effect of many people using a shared resource can degrade it and gradually exhaust or ruin it. Then no one can benefit from it, and that is a tragedy.

There are two major ways to deal with this difficult problem. One is to use a shared renewable resource at a rate well below its estimated sustainable yield by using less of the resource, regulating access to it, or doing both. For example, governments can establish laws and regulations limiting the annual harvests of various types of ocean fishes or regulating the amounts of pollutants we add to the atmosphere or to surface waters.

The other way is to convert open-access renewable resources to private ownership. The reasoning is that if you own something, you are more likely to protect your investment. However, history shows that shared renewable resources (such as forests and soils) can be quickly degraded once they are privately owned. Also, this approach is not practical for global open-access resources such as the atmosphere and the oceans, which cannot be divided up and sold as private property.

Ecological Footprints: Our Environmental Impacts

Many people in less-developed countries struggle to survive. Their individual use of resources and the resulting environmental impact is low and is devoted mostly to meeting their basic needs. However, collectively, their impact is high. People in some extremely poor countries, for example, clear virtually all available trees to get enough wood to use for heating and cooking. In such cases, short-term survival is a more urgent priority than long-term sustainability. By contrast, many individuals in more affluent nations consume large amounts of resources far beyond their basic needs. Their environmental impact is more a product of their *rates of resource use* per person.

When people use renewable resources, it can result in natural capital degradation (Figure 1-5), pollution, and wastes. We can think of it as an **ecological footprint**—the amount of biologically productive land and water needed to provide the people in a particular country or area with an indefinite supply of renewable resources and to absorb and recycle the wastes and pollution produced by such resource use. The **per capita ecological footprint** is the average ecological footprint of an individual in a given country or area. Figure 1-6 compares the total and per capita ecological footprints for selected countries.

If a country's (or the world's) total ecological footprint is larger than its *biological capacity* to replenish its renewable resources and absorb the resulting wastes and pollution, it is said to have an *ecological deficit*. In other words, it is living unsustainably by depleting its natural capital. The World Wildlife Fund (WWF) and the Global Footprint Network have estimated that humanity's global ecological footprint now exceeds the *earth's* ecological capacity to support humans and other forms of life indefinitely by 30% to 50% and is projected to grow.

In other words, humanity is living unsustainably. According to the WWF, we need at least the equivalent of almost 1.5 earths to provide an endless supply of renewable resources at their current average use per person and to dispose of the resulting pollution and wastes indefinitely (Figure 1-7, left). If the number of people and the average use of renewable resources per person continue growing as projected, by around 2030, we will need the equivalent of two planet Earths (Figure 1-7, center) to supply such resources indefinitely (**Concept 1-2**).

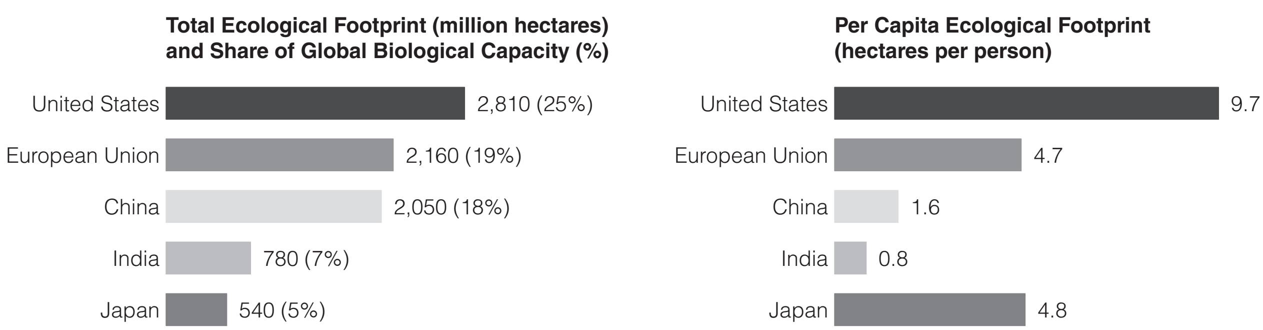


Figure 1-6 Natural capital use and degradation: Total and per capita ecological footprints of selected countries. (Compiled by the authors using data from World Wildlife Fund, *Living Planet Report 2012*, and Global Footprint Network).

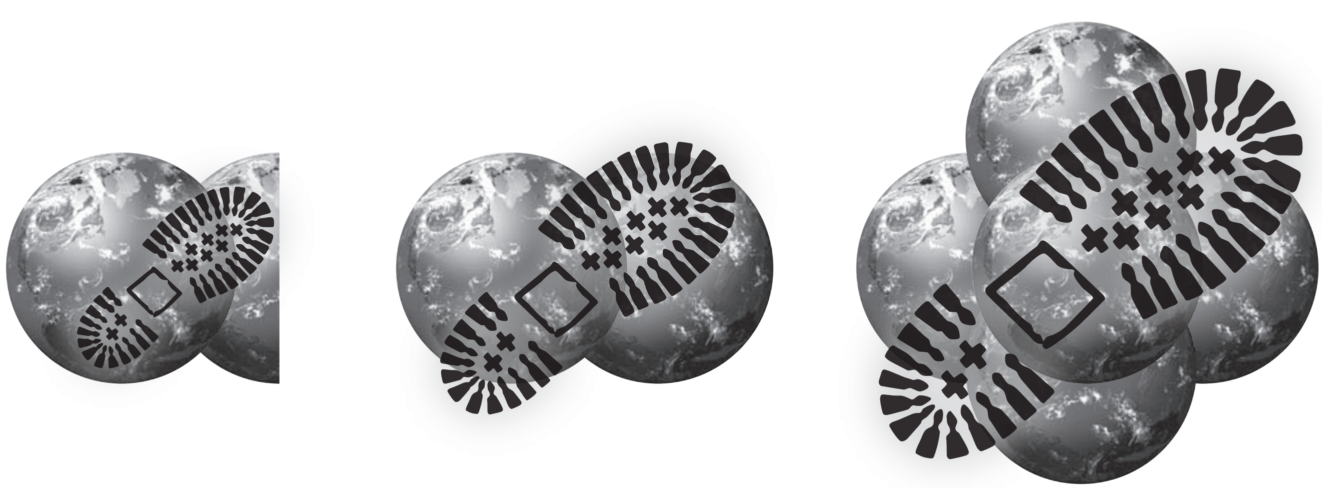


Figure 1-7 Natural capital use and degradation: Estimated number of planet Earths needed to indefinitely support our ecological footprints today (left), in 2030 (center), and today if everyone were to have the same per capita ecological footprint as the average American now has (right). **Question:** If we are living beyond the earth's renewable biological capacity, why do you think the human population and per capita resource consumption are still growing rapidly? (Compiled by the authors using data from World Wildlife Fund, *Living Planet Report 2012*, and Global Footprint Network)

The per capita ecological footprint is an estimate of how much of the earth's renewable resources an individual consumes. The United States has the world's fifth largest per capita ecological footprint. The Global Footprint Network has estimated that the U.S. per capita ecological footprint in 2012 was about twice as large as that of the European Union and 12 times larger than India's per capita footprint (Figure 1-6).

According to William Rees and Mathis Wackernagel, the developers of the ecological footprint concept, assuming the use of current technology, it would take the land area of about *five* planet Earths for the rest of the world to reach current U.S. levels of renewable per capita resource consumption (Figure 1-7, right). Put another way, if everyone consumed as much as the average American does today, the earth could indefinitely support only about 1.3 billion people—less than one-fifth of today's global population.

Some scientists worry that we are headed in this direction. As countries with large populations, such as China (see the Case Study that follows) and India, become more developed, it appears that their per capita resource use is growing toward the per capita levels of more-developed countries such as the United States. Throughout this book, we discuss ways to shrink our ecological footprints.

■ **CASE STUDY**

China's New Affluent Consumers

About 1.4 billion affluent consumers put immense pressure on the earth's renewable and nonrenewable natural capital. Most of these middle-class consumers live in more-developed countries, but an estimated 300 million of them—a number almost the size of the U.S. population—live in China, and this number may double by 2020.

China has the world's largest population and second-largest economy. It is the world's leading consumer of wheat, rice, meat, coal, fertilizer, steel, cement, and oil. China also leads the world in the production of goods such as televisions, cell phones, and refrigerators. It has also produced more wind turbines than any other country and will soon become the world's largest producer of solar cells and fuel-efficient cars. Between 2010 and 2025, China expects to build 10 cities the size of New York City.

Now, after 20 years of industrialization, China contains two-thirds of the world's most polluted cities. Some of its major rivers are choked with waste and pollution, and some areas of its coastline are basically devoid of fishes and other ocean life. A massive cloud of air pollution, largely generated in China, affects other Asian countries, areas of the Pacific Ocean, and even parts of the West Coast of North America.

Suppose that China's economy continues to grow at a rapid rate and its population size reaches 1.5 billion by around 2025, as projected by UN population experts. Environmental policy expert Lester R. Brown estimates that, if such projections are accurate, China will need two-thirds of the world's current grain harvest, twice the amount of paper consumed in the world, and more than all the oil currently produced in the world.

Cultural Changes Can Grow or Shrink Our Ecological Footprints

Until about 10,000 to 12,000 years ago, we were mostly *hunter–gatherers* who obtained food by hunting wild animals or scavenging their remains and gathering wild plants. Early hunter–gatherers lived in small groups, consumed few resources, had few possessions, and moved as needed to find enough food for their survival.

Since then, three major cultural changes have occurred. *First* was the *agricultural revolution*, which began 10,000–12,000 years ago when humans learned how to grow and breed plants and animals for food, clothing, and other purposes. *Second* was the *industrial–medical revolution*, beginning about 275 years ago when people invented machines for the large-scale production of goods in factories. This involved learning how to get energy from fossil fuels (such as coal and oil) and how to grow large quantities of food in an efficient manner. It also included medical advances that have allowed a growing number of people to live longer and healthier lives. Finally, the *information–globalization revolution* began about 50 years ago, when we developed new technologies for gaining rapid access to much more information and resources on a global scale.

Each of these three cultural changes gave us more energy and new technologies with which to alter and control more of the planet's resources to meet our basic needs and increasing wants. They also allowed expansion of the human population, mostly because of larger food supplies and longer life spans. In addition, they each resulted in greater resource use, pollution, and environmental degradation as they allowed us to dominate the planet and expand our ecological footprints.

On the other hand, some technological leaps have enabled us to begin shrinking our ecological footprints by reducing our use of energy and matter resources and our production of wastes and pollution. For example, use of the energy-efficient compact fluorescent and LED light bulbs and energy-efficient cars and buildings are on the rise. GOOD NEWS Many environmental scientists and other analysts see such developments as evidence of an emerging fourth major cultural change in the form of a **sustainability revolution**, in which we could learn to live more sustainably with smaller ecological footprints, during this century.

1-3 Why Do We Have Environmental Problems?

▶ **CONCEPT 1-3 Major causes of environmental problems are population growth, unsustainable resource use, poverty, avoidance of full-cost pricing, and increasing isolation from nature.**

Experts Have Identified Five Basic Causes of Environmental Problems

According to a number of environmental and social scientists, the major causes of pollution, environmental degradation, and other environmental problems are population growth, unsustainable resource use, poverty, failure to include in market prices the harmful environmental costs of goods and services, and increasing isolation from nature among a growing number of people (Figure 1-8) (**Concept 1-3**).

We discuss all of these causes in detail in later chapters of this book. But let us begin with a brief overview of them.

The Human Population Is Growing Exponentially at a Rapid Rate

Exponential growth occurs when a quantity (such as the human population) increases at a fixed percentage per unit of time, such as 1% or 2% per year. Exponential growth starts off slowly, but eventually it causes the quantity to double again and again. After only a few doublings, it grows to enormous numbers, because each doubling is twice the total of all earlier growth.

Here is an example of the immense power of exponential growth: Fold a piece of paper in half to double its thickness. If you could continue doubling the thickness of the paper 50 times, it would be thick enough to almost reach the sun—149 million kilometers (93 million miles) away!

Because of exponential growth in the human population (Figure 1-9), in 2012, there were about 7.1 billion people on the planet. Each year we add about 83 million people to the earth's population. Unless death rates rise sharply, there will probably be 9.6 billion of us by 2050. This projected addition of 2.5 billion people within your lifetime is equivalent to about 8 times the current U.S. population and more than twice that of China, the world's most populous nation.

The exponential rate of global population growth has declined some since 1963. Even so, in 2010, we added about 83 million more people to the earth—an average of about 227,000 people per day. This is roughly equivalent to adding a new U.S. city of Los Angeles, California, every 2 weeks, a new France every 9 months, and a new United States every 4 years.

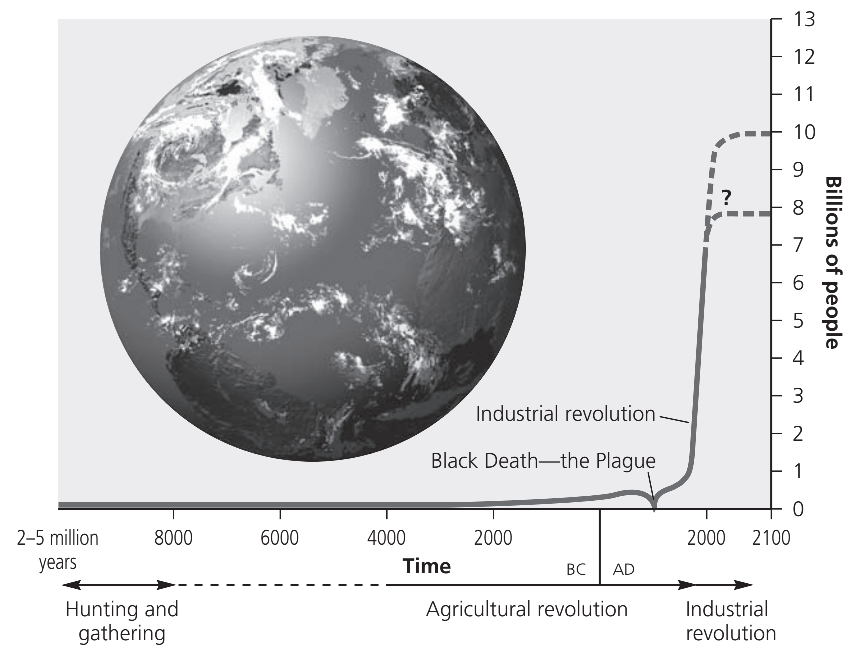
We can slow population growth with the goal of having it level off at around 8 billion by 2040. Some ways to do this include reducing poverty through economic development, promoting family planning, and elevating the status of women, as we discuss in Chapter 4.

Affluence Has Harmful and Beneficial Environmental Effects

The lifestyles of many consumers in more-developed countries and in less-developed countries, such as India and China (see Case Study, p. 10), are built upon growing **affluence**, or wealth, that results in high levels of

Figure 1-8 Environmental and social scientists have identified five basic causes of the environmental problems we face (**Concept 1-3**). **Question:** For each of these causes, what are two environmental problems that result?

Figure 1-9 *Exponential growth:* The J-shaped curve represents past exponential world population growth, with projections to 2100 showing possible population stabilization as the J-shaped curve of growth changes to an S-shaped curve. (This figure is not to scale.) (Compiled by the authors using data from the World Bank and United Nations; photo L. Yong/UNEP/Peter Arnold, Inc.)



resource use along with the resulting environmental degradation, wastes, and pollution.

The harmful environmental effects of affluence can be dramatic. In its 2012 *Living Planet Report,* the WWF estimated that the United States is responsible for almost half of the global ecological footprint. The average American consumes about 30 times as much as the average Indian and 100 times as much as the average person in the world's poorest countries. According to some ecological footprint estimates, it takes about 27 tractor-trailer loads of resources per year to support one American or 8.5 billion truckloads per year to support the entire U.S. population.

The problem is that providing each of these tractor-trailer loads represents environmental degradation—air pollution and water pollution from factories and motor vehicles and land degradation from the mining of raw materials used to make the products we consume. This is why higher levels of consumption expand a person's ecological footprint. Another downside to wealth is that it allows affluent consumers to obtain their resources from almost anywhere in the world without seeing the harmful environmental and health impacts of their high-consumption lifestyles.

On the other hand, affluence can allow for better education, which can lead people to become more concerned about environmental quality. It also provides money for developing technologies to reduce pollution, environmental degradation, and resource waste. As a result, in the United States and most other affluent countries, the air is clearer, drinking water is purer, and most rivers and lakes are cleaner than they were in the 1970s. In addition, the food supply is more abundant and safer; the incidence of life-threatening infectious diseases has been greatly reduced; and life spans are longer.

GOOD NEWS

Poverty Has Harmful Environmental and Health Effects

Poverty is a condition in which people are unable to fulfill their basic needs for adequate food, water, shelter, health, and education. According to the World Bank, about 900 million people—almost three times the U.S. population—live in *extreme poverty*, struggling to live on the equivalent of less than $1.25 a day. This is less than what many people spend for a bottle of water or a cup of coffee. About one of every three persons (or 2.6 billion of the world's people) struggles to live on less than $2.25 a day.

Poverty causes a number of harmful environmental and health effects (Figure 1-10). The daily lives of the world's poorest people are focused on getting enough food, water, and fuel for cooking and heating to survive. Desperate for short-term survival, some of these individuals degrade potentially renewable forests, grasslands, and wildlife at an ever-increasing rate. They do not have the luxury of worrying about long-term environmental quality or sustainability. Even though the poor in less-developed countries have no choice but to use very few resources per person, their large population size leads to a high overall environmental impact.

Poverty is also connected to population growth. To many poor people, especially in less-developed countries, having more children is a matter of survival. Their children help them gather fuel (mostly wood and ani-

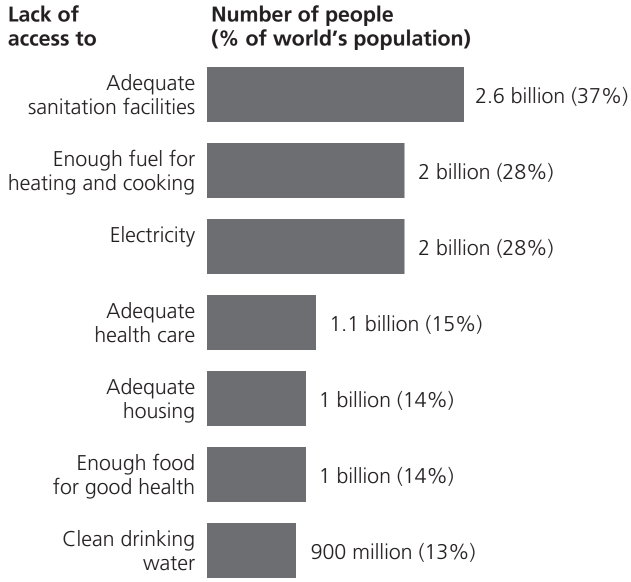


Figure 1-10 Some of the harmful effects of poverty. **Questions:** Which two of these effects do you think are the most harmful? Why? (Compiled by the authors using data from United Nations, World Bank, and World Health Organization)

mal dung), haul drinking water, and tend crops and livestock. The children also help to care for their parents in their old age (their 40s or 50s in the poorest countries), because they do not have social security, health care, and retirement funds. This is largely why populations in some of the poorest, less-developed countries continue to grow at high rates.

However, poverty does not necessarily lead to environmental degradation. Some of the world's poor people have learned how to take care of their environment as a part of their long-term survival strategy. For example, many small-scale farmers in African countries plant and nurture trees and work to conserve the soils that they depend on.

Although poverty can increase some types of environmental degradation, the reverse is also true. Pollution and environmental degradation have a severe impact on the poor and can increase their poverty. Consequently, many of the world's poor people die prematurely from several preventable health problems. One such problem is *malnutrition* caused by a lack of protein and other nutrients needed for good health. The resulting weakened condition can increase an individual's chances of death from normally nonfatal ailments such as diarrhea and measles.

A second health problem is limited access to adequate sanitation facilities and clean drinking water. More than one-third of the world's people have no real bathroom facilities and are forced to use backyards, alleys, ditches, and streams. As a result, about one of every eight of the world's people get their water for drinking, washing, and cooking from sources polluted by human and animal feces. A third health problem is severe respiratory disease that people get from breathing the smoke of open fires or poorly vented stoves used for heating and cooking inside their dwellings. This indoor air pollution kills about 2.4 million people a year, according to the World Health Organization (WHO).

In 2010, the WHO estimated that one or more of these factors, mostly related to poverty, cause premature death for about 7 million children under the age of 5 each year. Some hopeful news is that this number of annual deaths is down from about 10 million in 1990. Even so, every day an average of at least 19,000 young children die prematurely from these causes. This is equivalent to *95 fully loaded 200-passenger airliners crashing every day with no survivors.* The daily news rarely covers this ongoing human tragedy.

THINKING ABOUT ✓

Poverty, Affluence, and Population Growth

Some see the rapid population growth in less-developed countries as the primary cause of our environmental problems. Others say that the much higher resource use per person in more-developed countries is a more important factor. Which factor do you think is more important? Why?

Market Prices of Goods and Services Do Not Include Environmental Costs

Another basic cause of environmental problems has to do with how goods and services are priced in the marketplace. Companies using resources to provide goods for consumers generally are not required to pay for the harmful environmental costs of supplying such goods. For example, timber companies pay the cost of clear-cutting forests but do not pay for the resulting environmental degradation and loss of wildlife habitat. The primary goal of these companies is to maximize profits for their owners or stockholders. As a result, the prices of goods and services do not include their harmful environmental costs.

Because of this, consumers have no effective way to evaluate the harmful effects, on their own health and on the earth's life-support system, of producing and using these goods and services. For example, producing and using gasoline results in air pollution and other problems that damage the environment and people's health. Scientists and economists have estimated that the real cost of gasoline to U.S. consumers would be about $3.70 per liter ($14 per gallon) if the estimated short- and long-term harmful environmental and health costs were included in its pump price.

Partly because of this inadequate pricing system, many people do not understand the importance and truly high value of the natural resources and ecosystem services that make up the earth's natural capital (Figure 1-2). This lack of information is a major reason for why we are degrading these key components of our life-support system (Figure 1-7).

Another problem arises when governments (taxpayers) give companies *subsidies*, such as tax breaks and payments, to assist them with using resources to run their businesses. This helps to create jobs and stimulate economies, but some subsidies are environmentally harmful, because they encourage the depletion and degradation of natural capital.

We could live more sustainably by finding ways to include in market prices the harmful environmental and health costs of the goods and services that we use. Implementing such full-cost pricing would be a way to apply one of the three **social science principles of sustainability** (Figure 1-4). We discuss the problem of harmful subsidies and some possible solutions in Chapter 14.

We Are Increasingly Isolated from Nature

Today, three out of four people in the more-developed countries and one of every two people in the world live in urban areas, and this shift from rural to urban living is continuing at a rapid pace. Our artificial urban environments and our increasing use of cell phones, computers, and other electronic devices isolate us from the natural world that provides the food, water, and most of the raw materials used to produce the consumer goods that we depend on.

Thus, it is not surprising that many people do not know the full story of where their food, water, and other goods come from. Similarly, many people are unaware of the amounts of wastes and pollutants they produce and how these wastes and pollutants affect the environment. Many do not understand that life on earth has been sustained largely by the recycling of wastes—one of the **scientific principles of sustainability** (Figure 1-1).

According to some analysts, many of us are increasingly suffering from *nature deficit disorder*. They suggest that, because of infrequent contacts with the natural world, some people are more likely to suffer from stress, have health problems, show unwarranted irritability or aggression, and be less adaptable to changes in life. These analysts also argue that this disorder helps to explain why we are rapidly degrading our life-support system. They ask: How will we shrink our ecological footprints and live more sustainably if we do not experience and understand our utter dependence on the earth's natural systems and the natural capital they provide for us?

People Have Different Views about Environmental Problems and Their Solutions

Another challenge we face is that people disagree about the seriousness of the world's environmental problems and what we should do to help solve them. This can delay our dealing with these problems, which can make them harder to solve.

Differing opinions about environmental problems arise mostly out of differing environmental worldviews. Your **environmental worldview** is your set of assumptions and values that reflect how you think the world works and what you think your role in the world should be. An important element in any environmental worldview is one's sense of **environmental ethics**, or one's beliefs about what is right and wrong with how we treat the environment. Here are some important *ethical questions* relating to the environment:

- Why should we care about the environment?
- Are we the most important beings on the planet, or are we just one of the earth's millions of different forms of life?
- Do we have an obligation to see that our activities do not cause the extinction of other species? Should we try to protect all species or only some? How do we decide which to protect?
- Do we have an ethical obligation to pass the natural world on to future generations in a condition that is at least as good as what we inherited?
- Should every person be entitled to equal protection from environmental hazards regardless of race, gender, age, national origin, income, social class, or any other factor? This is the central ethical and political issue for what is known as the *environmental justice* movement.

THINKING ABOUT

Our Responsibilities

How would you answer each of the questions above? Compare your answers with those of your classmates. Record your answers and, at the end of this course, return to these questions to see if your answers have changed.

People with widely differing environmental worldviews can take the same data, be logically consistent with it, and arrive at quite different conclusions, because they start with different assumptions and moral, ethical, or religious beliefs. Environmental worldviews are discussed in detail in Chapter 14, but here is a brief introduction.

The **planetary management worldview** holds that we are separate from and in charge of nature, that nature exists mainly to meet our needs and increasing wants, and that we can use our ingenuity and technology to manage the earth's life-support systems, mostly for our benefit, into the distant future.

The **stewardship worldview** holds that we can and should manage the earth for our benefit, but we have an ethical responsibility to be caring and responsible managers, or *stewards*, of the earth. It says we should encourage only environmentally beneficial forms of economic growth and development and discourage environmentally harmful forms.

The **environmental wisdom worldview** holds that we are part of and dependent on nature and that the earth's life-support system exists for all species, not just for us. According to this view, our success depends on learning how life on earth sustains itself and on integrating such *environmental wisdom* into the ways we think and act.

1-4 What Is an Environmentally Sustainable Society?

CONCEPT 1-4 Living sustainably means living off the earth's natural income without depleting or degrading the natural capital that supplies it.

Environmentally Sustainable Societies Protect Natural Capital and Live Off Its Income

According to most environmental scientists, our ultimate goal should be to achieve an **environmentally sustainable society**—one that meets the current and future basic resource needs of its people in a just and equitable manner without compromising the ability of future generations to meet their basic needs.

Imagine you win $1 million in a lottery. Suppose you invest this money (your capital) and earn 10% interest per year. If you live on just the interest, or the income made by your capital, you will have a sustainable annual income of at least $100,000 that you can spend each year indefinitely without depleting your capital. However, if you spend $200,000 per year, while still allowing interest to accumulate, your capital of $1 million will be gone early in the seventh year. Even if you spend only $110,000 per year and allow the interest to accumulate, you will be bankrupt early in the eighteenth year.

The lesson here is an old one: *Protect your capital and live on the income it provides.* Deplete or waste your capital and your lifestyle will become unsustainable.

The same lesson applies to our use of the earth's natural capital (Figure 1-2)—the global trust fund that nature has provided for us, future generations, and the earth's other species. *Living sustainably* means living on **natural income**, the renewable resources (such as plants, animals, soil, and clean air and water) provided by the earth's natural capital. It also means not depleting or degrading the earth's natural capital, which supplies this income, and providing the human population with adequate and equitable access to the earth's natural income for the foreseeable future (**Concept 1-4**).

Individuals Matter

Making a shift toward a more sustainable future will involve some tough challenges. However, research by social scientists suggests that it takes only 5% to 10% of the population of a community, a country, or the world to bring about major change. Such research also shows that significant beneficial changes can occur in a much shorter time than most people think. Anthropologist Margaret Mead summarized our potential for change: "Never doubt that a small group of thoughtful, committed citizens can change the world. Indeed, it is the only thing that ever has."

GOOD NEWS

Evidence from the physical sciences and the social sciences indicates that we have perhaps 50 years and no more than 100 years to make a new cultural shift from unsustainable living to more sustainable living, if we start now. Many analysts argue that, because such a shift will likely take several decades to be complete, we now face a critical fork in the road and must choose a path toward sustainability or continue on our current unsustainable course. One of the goals of this book is to provide a realistic vision of a more environmentally sustainable future. Instead of immobilizing you with fear, gloom, and doom, we hope to energize you by inspiring realistic hope as you play your role in deciding which path to follow.

Based on the six **principles of sustainability**, some strategies for reducing our ecological footprints, helping to sustain the earth's natural capital, and making a transition to more sustainable lifestyles and economies are summarized in the *three big ideas* of this chapter.

SUSTAINABILITY

- A more sustainable future will require that we rely more on energy from the sun and other renewable energy sources, stop disrupting the earth's vitally important chemical cycles, and protect biodiversity through the preservation of natural capital.

- A major goal for becoming more sustainable is full-cost pricing—the inclusion of harmful environmental and health costs in the market prices of goods and services.
- We will benefit ourselves and future generations if we commit to finding win-win-win solutions to our problems and to leaving the planet's life-support system in at least as good a condition as that which we now enjoy.

What's the use of a house if you don't have a decent planet to put it on?

HENRY DAVID THOREAU

REVIEW

1. Review the Key Questions and Concepts for this chapter on p. 1. Define **environment**. Distinguish among **environmental science, ecology,** and **environmentalism.** Distinguish between an **organism** and a **species**. What is an **ecosystem**? What are three **scientific principles of sustainability** derived from a study of how nature has sustained itself for at least 3.5 billion years?
2. Define **nutrient** and **nutrient cycling** and explain why they are important. Define **natural capital**, **natural resources**, and **ecosystem services** and give an example of each. Describe how we can degrade natural capital and how finding solutions to environmental problems involves making trade-offs. Explain why individuals matter in dealing with the environmental problems we face. What are three **social science principles of sustainability**? Define **full-cost pricing** and give an example of it.
3. What is a **resource**? Distinguish between an **inexhaustible resource** and a **renewable resource** and give an example of each. What is **sustainable yield**? Define and give two examples of a **nonrenewable resource**. Distinguish between **recycling** and **reuse** and give an example of each. What do some scientists say our priorities for more sustainable use of nonrenewable resources should be? Distinguish between **economic growth** and **economic development**. Distinguish between **gross domestic product** (**GDP**) and **per capita GDP**. Distinguish between **more-developed countries** and **less-developed countries** and give an example of a high-income, middle-income, and low-income country.
4. Define and give three examples of **environmental degradation** (**natural capital degradation**). About what percentage of the earth's ecosystem services have been degraded by human activities? Define **pollution**. Distinguish between **point sources** and **nonpoint sources** of pollution. Distinguish between **biodegradable pollutants** and **nondegradable pollutants** and give an example of each. Distinguish between **pollution cleanup** and **pollution prevention** and give an example of each. What is the *tragedy of the commons*?
5. What is an **ecological footprint**? What is a **per capita ecological footprint**? Compare the total and per capita ecological footprints of the United States and India. Use the ecological footprint concept to explain how we are living unsustainably. Describe the environmental impacts of China's new affluent consumers.
6. Describe three major cultural changes that have occurred since humans were hunter–gatherers. What would a **sustainability revolution** involve?
7. List five basic causes of the environmental problems that have been identified by scientists. What is **exponential growth**? Describe the past, current, and projected exponential growth of the human population. What is **affluence**? How do Americans, Indians, and the average people in the poorest countries compare in terms of consumption? How can growing affluence damage the environment? How can affluence help us to solve environmental problems? What is **poverty**, and what are three of its harmful environmental and health effects? Describe the connection between poverty and population growth.
8. Explain how excluding the environmental costs of producing goods and services from their market prices can cause environmental problems. What are subsidies, and what effect can they have on natural capital? What is nature deficit disorder, and how can it contribute to environmental problems? What is an **environmental worldview**? What are **environmental ethics**? Distinguish among the **planetary management**, **stewardship**, and **environmental wisdom worldviews**.
9. What is the definition of an **environmentally sustainable society** according to most environmental scientists? What is **natural income**, and how is it related to natural capital? Why is it that each individual's choices and actions will have a great effect on whether and how we can make the shift toward living more sustainably?
10. What are three strategies for reducing our ecological footprints, as summarized in this chapter's *three big ideas*?

Note: Key terms are in **bold** type.

CRITICAL THINKING

1. Do you think you are living unsustainably? Explain. If so, what are the three most environmentally unsustainable components of your lifestyle? List two ways in which you could apply each of the **principles of sustainability** (Figures 1-1 and 1-4) to making your lifestyle more environmentally sustainable.

2. For each of the following actions, state one or more of the six **principles of sustainability** (Figures 1-1 and 1-4) that are involved: **(a)** recycling aluminum cans; **(b)** using a rake instead of a leaf blower; **(c)** walking or bicycling to class instead of driving a car or a motor scooter; **(d)** taking your own reusable bags to the grocery store to carry your purchases home; **(e)** buying the more expensive of two products because it was produced in a more sustainable fashion; and **(f)** volunteering to help restore a prairie.

3. Suppose you are a landowner and your land holdings include a large section of old-growth forest and another large area of abandoned cropland that is becoming filled with weeds. Now suppose that a timber company proposes to you that you sell them the forest land so that they can log it and plant a new tree farm. Assuming you were willing to sell some part of your land, what would be a counterproposal that you could make that would be an application of the win-win **principle of sustainability**? Would you accept their proposal, or would you make the counterproposal? Explain.

4. What do you think when you read that **(a)** the average American consumes 30 times more resources than the average citizen of India, and **(b)** human activities are projected to make the earth's climate warmer? Are you skeptical, indifferent, sad, helpless, guilty, concerned, or outraged? Which of these feelings can help to perpetuate such problems, and which can help to solve them?

5. What do you think when you read that, on average, at least 19,000 children age five and younger die every day (13 per minute) from preventable malnutrition and infectious disease? Can you think of something that you and others could do to address this problem? What might that be?

6. Explain why you agree or disagree with each of the following statements: **(a)** humans are superior to other forms of life; **(b)** humans are in charge of the earth; **(c)** the value of other forms of life depends only on whether they are useful to humans; **(d)** all forms of life have an inherent right to exist; **(e)** all economic growth is good; **(f)** technology can solve our environmental problems; **(g)** I do not believe I have any obligation to future generations; and **(h)** I do not believe I have any obligation to other forms of life.

7. What are the basic beliefs within your environmental worldview? (Record your answer, so that when you've finished this course, you can return to your answer to see if your worldview has changed.) Are the beliefs included in your environmental worldview consistent with your answers to question six? Are your actions that affect the environment consistent with your environmental worldview? Explain.

DOING ENVIRONMENTAL SCIENCE

Estimate your own ecological footprint by using one of the many estimator tools available on the Internet. Is your ecological footprint larger or smaller than you thought it would be according to this estimate? Why do you think this is so? List three ways in which you could reduce your ecological footprint. try one of them for a week, and write a report on this change.

2 Science, Matter, Energy, and Systems

Key Questions and Concepts

2-1 What do scientists do?

CONCEPT 2-1 Scientists collect data and develop theories, models, and laws about how nature works.

2-2 What is matter, and what happens when it undergoes change?

CONCEPT 2-2A Matter consists of elements and compounds that are in turn made up of atoms, ions, or molecules.

CONCEPT 2-2B When matter undergoes a physical or chemical change, no atoms are created or destroyed (the law of conservation of matter).

2-3 What is energy, and what happens when it undergoes change?

CONCEPT 2-3A When energy is converted from one form to another in a physical or chemical change, no energy is created or destroyed (first law of thermodynamics).

CONCEPT 2-3B When energy is converted from one form to another in a physical or chemical change, we end up with lower-quality or less usable energy than we started with (second law of thermodynamics).

2-4 What keeps us and other organisms alive?

CONCEPT 2-4 Life is sustained by the flow of energy from the sun through the biosphere, the cycling of nutrients within the biosphere, and gravity.

2-5 What are the major components of an ecosystem?

CONCEPT 2-5 Ecosystems contain nonliving and living components, including organisms that produce the nutrients they need, organisms that get the nutrients they need by consuming other organisms, and organisms that recycle nutrients by decomposing the wastes and remains of other organisms.

2-6 What happens to energy in an ecosystem?

CONCEPT 2-6 As energy flows through ecosystems in food chains and webs, the amount of chemical energy available to organisms at each succeeding feeding level decreases.

2-7 What happens to matter in an ecosystem?

CONCEPT 2-7 Matter, in the form of nutrients, cycles within and among ecosystems throughout the biosphere, and human activities are altering these chemical cycles.

Science is built up of facts, as a house is built of stones;
but an accumulation of facts is no more a science
than a heap of stones is a house.

HENRI POINCARÉ

Links: SUSTAINABILITY refers to the book's sustainability theme. GOOD NEWS refers to good news about the environmental challenges we face.

2-1 What Do Scientists Do?

CONCEPT 2-1 Scientists collect data and develop theories, models, and laws about how nature works.

Science Is a Search for Order in Nature

Science is a human effort to discover how the physical world works by making observations and measurements and carrying out experiments. It is based on the assumption that events in the physical world follow orderly cause-and-effect patterns that we can understand.

You may have heard that scientists follow a specific set of steps called the *scientific method* to learn about how the physical world works. In fact, they use a variety of methods to study nature, although these methods tend to fall within a general process, described in Figure 2-1.

There is nothing mysterious about this process. You use it all the time in making decisions. Here is an example of how you might apply the scientific process in an everyday situation.

Observation: My cell phone is not charged after being plugged into an electrical outlet.

Question: Why is the cell phone not charged?

Hypothesis: Maybe the outlet is not working.

Test the hypothesis with an experiment: Plug the charger into another outlet.

Result: The cell phone still is not charged.

New hypothesis: Maybe the charger is not working.

Experiment: Obtain and try using a new charging cord.

Result: The cell phone is charged.

Conclusion: New hypothesis is verified.

Here is a more formal outline of the steps scientists often take in trying to understand the natural world, although they do not always follow the steps in the order listed.

- *Identify a problem.*
- *Find out what is known about the problem.*
- *Ask a question to investigate.*
- *Collect data to answer the question.* To collect **data**—information needed to answer a question—scientists make observations in the subject area they are studying. Scientific observations involve gathering information by using the human senses of sight, smell, hearing, and touch and enhancing those senses by using tools such as rulers, microscopes, and satellites. Often scientists conduct **experiments**, or procedures carried out under controlled conditions, to gather information and test ideas.

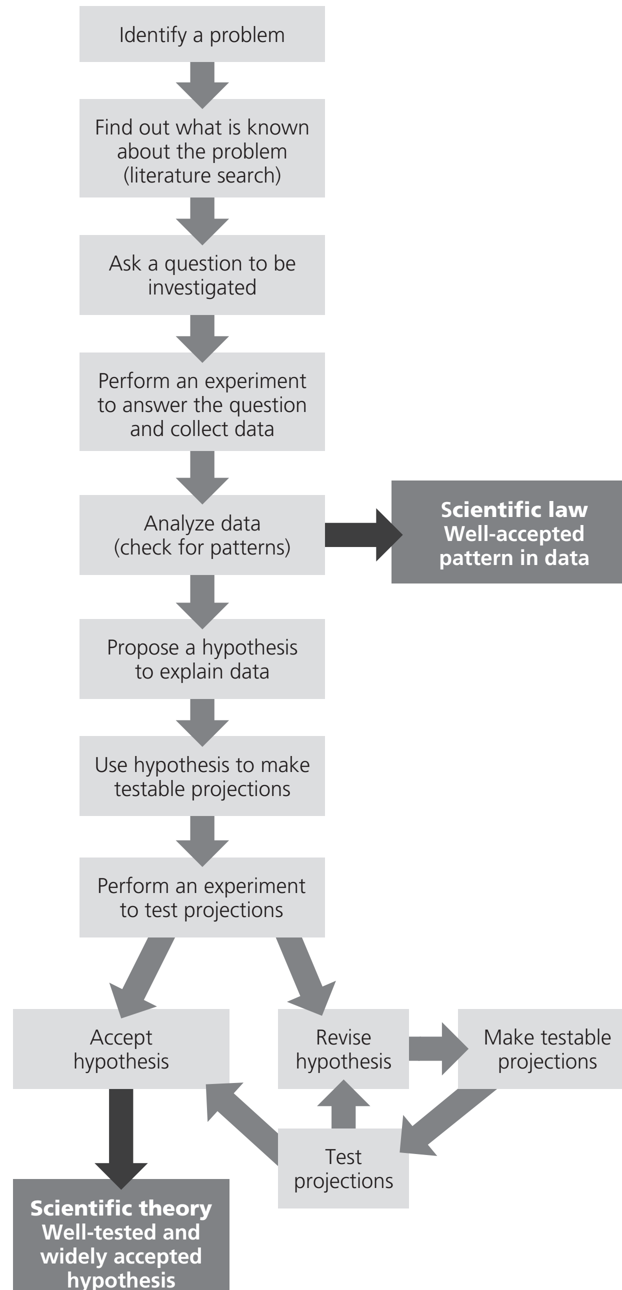


Figure 2-1 The general process that scientists use for discovering and testing ideas about how the natural world works.

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- *Propose a hypothesis to explain the data.* Scientists suggest a **scientific hypothesis**—a possible explanation of what they observe, in nature or in the results of their experiments, that they can test.
- *Make testable projections*. Scientists make projections about what should happen if their hypothesis is valid, and then they run experiments to test the projections.
- *Test the projections with further experiments, models, or observations*. Scientists often repeat their experiments, but another way to test predictions is to develop a **model**, an approximate representation or simulation of a system being studied. Data from experiments can be fed into such models and used to project outcomes. These projections can be compared with the actual measured outcomes from experiments.
- *Accept or reject the hypothesis*. If their new data do not support their hypothesis, scientists come up with other testable explanations. This process of proposing and testing various hypotheses goes on until there is general agreement among the scientists in this field of study that a particular hypothesis is the best explanation of the data. A well-tested and widely accepted scientific hypothesis or a group of related hypotheses is called a **scientific theory**.

Scientists do not always follow the order of steps described here. For example, sometimes a scientist might start by coming up with a hypothesis to answer the initial question and then run experiments to test the hypothesis.

Four important features of the scientific process are *curiosity, skepticism*, *reproducibility*, and *peer review*. Good scientists are extremely curious about how nature works. But they tend to be highly skeptical of new data, hypotheses, and models until they can be tested and verified. Scientists also require that any evidence gathered must be reproducible. In other words, other scientists should be able to get the same results when they run the same experiments.

Science is a community effort, and an important part of the scientific process is **peer review**. Peer review involves scientists openly publishing details of the methods and models they used, the results of their experiments, and the reasoning behind their hypotheses for other scientists working in the same field (their peers) to evaluate.

Scientific knowledge advances in this self-correcting way, with scientists continually questioning measurements and data, making new measurements, and sometimes coming up with new and better hypotheses. Skepticism and debate among peers in the scientific community is essential to the scientific process.

Scientific Theories and Laws Are the Most Important Results of Science

When an overwhelming body of observations and measurements supports a scientific hypothesis, it becomes a scientific theory. *We should never take a scientific theory lightly*. A scientific theory has been tested widely, is supported by extensive evidence, and is accepted by most scientists in a particular field or related fields of study. People often use the word *theory* incorrectly when they actually mean *scientific hypothesis*, a tentative explanation that needs further evaluation.

Another important and reliable outcome of science is a **scientific law**, or **law of nature**—a well-tested and widely accepted description of what we find happening repeatedly in nature in the same way. An example is the *law of gravity*. After making many thousands of observations and measurements of objects falling from different heights, scientists developed the following scientific law: all objects fall to the earth's surface at predictable speeds.

A scientific law is no better than the accuracy of the observations or measurements upon which it is based. But if the data are accurate, a scientific law cannot be broken, unless and until we get contradictory new data.

Scientific Results Can Be Tentative, Reliable, or Unreliable

A fundamental part of science is *testing*. Scientists insist on testing their hypotheses, models, methods, and results over and over again to establish the reliability of these scientific tools and the resulting conclusions.

Sometimes, preliminary scientific results that capture news headlines are controversial because they have not been widely tested and accepted by peer review. They are not yet considered reliable, and can be thought of as **tentative science** or **frontier science**. Some of these results will be validated and classified as reliable and some will be discredited and classified as unreliable. At the frontier stage, it is normal for scientists to disagree about the meaning and accuracy of data and the validity of hypotheses and results.

By contrast, **reliable science** consists of data, hypotheses, models, theories, and laws that are widely accepted by all or most of the scientists who are considered experts in the field under study, in what is referred to as a *scientific consensus*. The results of reliable science are based on the self-correcting process of testing, open peer review, reproducibility, and debate. New evidence and better hypotheses may discredit or alter accepted views. But until that happens, those views are considered to be the results of reliable science.

Scientific hypotheses and results that are presented as reliable without having undergone the rigors of widespread peer review, or that have been discarded as a result of peer review, are considered to be **unreliable science**. Here are some critical thinking questions you can use to uncover unreliable science:

- Was the experiment well designed? Did it involve enough testing?
- Does the proposed hypothesis explain the data? Are there no other, more reasonable explanations for the data?
- Are the investigators unbiased in their interpretations of the results? Were the investigators funded by an unbiased source?
- Have the data and conclusions been subjected to peer review?
- Have other scientists reproduced the results?
- Are the conclusions of the research widely accepted by other experts in the field?

If the answer to each of these questions is "yes," then you can classify the results as reliable science. Otherwise, the results may represent tentative science that needs further testing and evaluation, or you can classify them as unreliable science.

Science Has Some Limitations

Environmental science and science in general have four important limitations. *First*, scientists cannot prove or disprove anything absolutely, because there is always some degree of uncertainty in scientific measurements, observations, and models. Instead, scientists try to establish that a particular scientific theory or law has a very high *probability* or *degree of certainty* (at least 90%) of being true and thus is classified as reliable science.

Second, scientists are human and thus not totally free of bias about their own results and hypotheses. However, the high standards of evidence required through peer review can usually uncover or greatly reduce personal bias and expose occasional cheating by scientists who falsify their results.

A *third* limitation—especially important to environmental science—is that many systems in the natural world involve a huge number of variables with complex interactions. This makes it difficult and too costly to run experiments in order to test each variable. To try to deal with this problem, scientists develop *mathematical models* that can take into account the interactions of many variables. Running such models on high-speed computers can sometimes overcome the limitations of testing each variable individually, saving both time and

SCIENCE FOCUS

Statistics and Probability

Statistics is a field of study involving the use of mathematical tools to collect, organize, and interpret numerical data. For example, suppose we make measurements of the weight of each individual in a population of 15 rabbits. We can use statistics to calculate the average weight of the population. To do this, we add up the combined weight of the 15 rabbits and divide the total by 15.

Scientists also use the statistical concept of probability to evaluate their results. A **probability** is the chance that a given event will occur or that a given projection will be valid. For example, if you toss a nickel, what is the chance that it will come up heads? If your answer is 50%, you are correct. The probability of the nickel coming up heads is 1/2, which can also be expressed as 50% or 0.5. Probability is often expressed as a number between 0 and 1 written as a decimal (such as 0.5).

Now suppose you toss the coin ten times and it comes up heads six times. Does this mean that the probability of it coming up heads is 0.6 or 60%? The answer is no because the *sample size*—the number of events studied—was too small to yield a statistically accurate result. If you increase your sample size to 1,000 by tossing the coin 1,000 times, you are almost certain to get heads 50% of the time and tails 50% of the time.

In addition to having a large enough sample size, it is important when doing scientific research in a physical area to take samples from different places, in order to get a reasonable evaluation of the variable you are studying. For example, if you wanted to study the effects of a certain air pollutant on the needles of a pine tree species, you would need to locate different stands of the species that are exposed to the pollutant over a certain period of time. At each location, you would have to take measurements of the atmospheric levels of the pollutant at different times and average the results. You would also need to take measurements of the damage (such as needle loss) from a large enough number of trees in each location over the same time period. Then you would average the results in each location and compare the results among all locations.

If the average results were consistent in different locations, you could then say that there is a certain probability, say 60% (or 0.6), that this type of pine tree suffered a certain percentage loss of its needles when exposed to a specified average level of the pollutant over a given time.

Critical Thinking

Could there be other factors, such as natural needle loss, insects, plant diseases, and drought, that might have caused some of the needle loss you observed? How would you go about determining the effects of these other factors?

money. In addition, scientists can use computer models to simulate global experiments on phenomena like climate change that are impossible to do in a controlled physical experiment.

A *fourth* limitation involves the use of statistical tools, which are necessary in many situations. For example, there is no way to measure accurately how many metric tons of soil are eroded annually worldwide. Instead, scientists use statistical sampling and other mathematical methods to estimate such numbers. However, such results should not be dismissed as "only estimates," because they can indicate important trends.

Despite these limitations, science is the most useful way we have for learning about how nature works and projecting how it might behave in the future. With this important set of tools, we have made significant progress, but we still know too little about how the earth works, its present state of environmental health, and the current and future environmental impacts of our activities. These knowledge gaps point to important research frontiers, many of which will provide career opportunities in the future.

2-2 What Is Matter, and What Happens When It Undergoes Change?

▶ **CONCEPT 2-2A Matter consists of elements and compounds that are in turn made up of atoms, ions, or molecules.**

▶ **CONCEPT 2-2B When matter undergoes a physical or chemical change, no atoms are created or destroyed (the law of conservation of matter).**

Matter Consists of Elements and Compounds

To begin our study of environmental science, we look at matter—the stuff that makes up life and its environment. **Matter** is anything that has mass and takes up space. It can exist in three *physical states*—solid, liquid, and gas. Water, for example, exists as solid ice, liquid water, or water vapor depending mostly on its temperature.

Matter also exists in two *chemical forms*—elements and compounds. An **element** is a fundamental type of matter that has a unique set of properties and cannot be broken down into simpler substances by chemical means. For example, gold is an element. It cannot be broken down chemically into any other substance.

Some matter is composed of one element, such as gold. But most matter consists of **compounds**, combinations of two or more different elements held together in fixed proportions. For example, water is a compound made of the elements hydrogen and oxygen that can combine chemically with one another.

To simplify things, chemists represent each element by a one- or two-letter symbol. Examples used in this book are hydrogen (H), carbon (C), oxygen (O), nitrogen (N), phosphorus (P), sulfur (S), chlorine (Cl), fluorine (F), bromine (Br), sodium (Na), calcium (Ca), lead (Pb), mercury (Hg), arsenic (As), and uranium (U). Just four elements—oxygen, carbon, hydrogen, and nitrogen—make up about 96% of your body weight and that of most other living things.

Atoms, Molecules, and Ions Are the Building Blocks of Matter

The most basic building block of matter is an **atom**, the smallest unit of matter into which an element can be divided and still have its characteristic chemical properties (**Concept 2-2A**). The idea that all elements are made up of atoms is called the **atomic theory**, and it is the most widely accepted scientific theory in chemistry.

Atoms are incredibly small. In fact, more than 3 million hydrogen atoms could sit side by side on the period at the end of this sentence. If you could view them with a supermicroscope, you would find that each different type of atom contains a certain number of three types of *subatomic particles*: **neutrons (n)** with no electrical charge, **protons (p)** with a positive electrical charge (+), and **electrons (e)** with a negative electrical charge (–).

Each atom consists of an extremely small center called the **nucleus**—containing one or more protons and, in most cases, one or more neutrons—and one or more electrons in rapid motion somewhere around the nucleus (Figure 2-2). We cannot determine the exact location of the electrons. Instead, we can estimate the *probability* that they will be found at various locations outside the nucleus—sometimes called an *electron probability cloud*. This is somewhat like saying that there are six airplanes flying around inside a cloud. We do not know their exact location, but the cloud represents an area in which we can probably find them.

Each atom in its basic form has equal numbers of positively charged protons and negatively charged electrons. Because these electrical charges cancel one

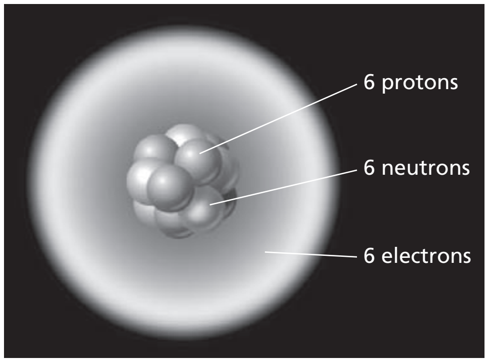


Figure 2-2 Greatly simplified model of a carbon-12 atom. It consists of a nucleus containing six positively charged protons and six neutrons with no electrical charge. Six negatively charged electrons are found outside its nucleus.

another, *an atom in its basic form has no net electrical charge*.

Each element has a unique **atomic number** equal to the number of protons in the nucleus of its atom. Carbon (C), with six protons in its nucleus (Figure 2-2), has an atomic number of six, whereas uranium (U), a much larger atom, has 92 protons in its nucleus and an atomic number of 92.

Because electrons have so little mass compared to protons and neutrons, *most of an atom's mass is concentrated in its nucleus.* The mass of an atom is described by its **mass number**, the total number of neutrons and protons in its nucleus. For example, a carbon atom with six protons and six neutrons in its nucleus has a mass number of 12, and a uranium atom with 92 protons and 143 neutrons in its nucleus has a mass number of 235 (92 + 143 = 235).

Each atom of a particular element has the same number of protons in its nucleus. But the nuclei of atoms of a particular element can vary in the number of neutrons they contain and, therefore, in their mass numbers. The forms of an element having the same atomic number but different mass numbers are called **isotopes** of that element. Scientists identify isotopes by attaching their mass numbers to the name or symbol of the element. For example, the three most common isotopes of carbon are carbon-12 (Figure 2-2, with six protons and six neutrons), carbon-13 (with six protons and seven neutrons), and carbon-14 (with six protons and eight neutrons). Carbon-12 makes up about 98.9% of all naturally occurring carbon.

A second building block of matter is a **molecule**, a combination of two or more atoms of the same or different elements held together by forces called *chemical bonds*. Molecules are the basic units of some compounds, called *molecular compounds* (**Concept 2-2A**). Chemists use a **chemical formula** to show the number of each type of atom or ion in a compound. This shorthand contains the symbol for each element present and uses subscripts to represent the number of atoms or ions of each element in the compound's basic structural unit. Examples of compounds and their formulas encountered in this book are water (H_2O, read as "H-two-O"), oxygen (O_2), ozone (O_3), nitrogen (N_2), nitrous oxide (N_2O), nitric oxide (NO), hydrogen sulfide (H_2S), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), sodium chloride (NaCl), ammonia (NH_3), sulfuric acid (H_2SO_4), nitric acid (HNO_3), methane (CH_4), and glucose ($C_6H_{12}O_6$).

A third building block of matter is an **ion**—an atom or a group of atoms with one or more net positive or negative electrical charges. Like atoms, ions are made up of protons, neutrons, and electrons. A positive ion forms when an atom loses one or more of its negatively charged electrons, and a negative ion forms when an atom gains one or more negatively charged electrons.

Chemists use a superscript after the symbol of an ion to indicate how many positive or negative electrical charges it has. (One positive or negative charge is designated by a plus sign or a minus sign, respectively.) Examples encountered in this book include *positive* hydrogen ions (H^+), sodium ions (Na^+), calcium ions (Ca^{2+}), and ammonium ions (NH_4^+) and *negative* chloride ions (Cl^-), nitrate ions (NO_2^-), sulfate ions (SO_4^{2-}), and phosphate ions (PO_4^{3-}). Ions are the building blocks of some compounds, called *ionic compounds* (**Concept 2-2A**).

Ions are also important for measuring a substance's **acidity** in a water solution, a chemical characteristic that helps determine how a substance dissolved in water will interact with and affect its environment. The acidity of a water solution is based on the comparative amounts of hydrogen ions (H^+) and hydroxide ions (OH^-) contained in a particular volume of the solution. Scientists use a numerical scale of **pH** values to compare the acidity and alkalinity in water solutions (Figure 2-3). The pH of a soil influences the uptake of natural chemicals in the soil by plants.

Organic Compounds Are the Chemicals of Life

Plastics, as well as table sugar, vitamins, aspirin, penicillin, and most of the chemicals in your body are called **organic compounds**, because their molecules contain at least two carbon atoms combined with atoms of one or more other elements. All other compounds are called **inorganic compounds**, except for methane (CH_4), which has only one carbon atom but is considered an organic compound.

The millions of known organic (carbon-based) compounds include the following:

- *Hydrocarbons*: compounds of carbon and hydrogen atoms. One example is methane (CH_4), the main component of natural gas and the simplest organic compound. Another is octane (C_8H_{18}), a major component of gasoline.

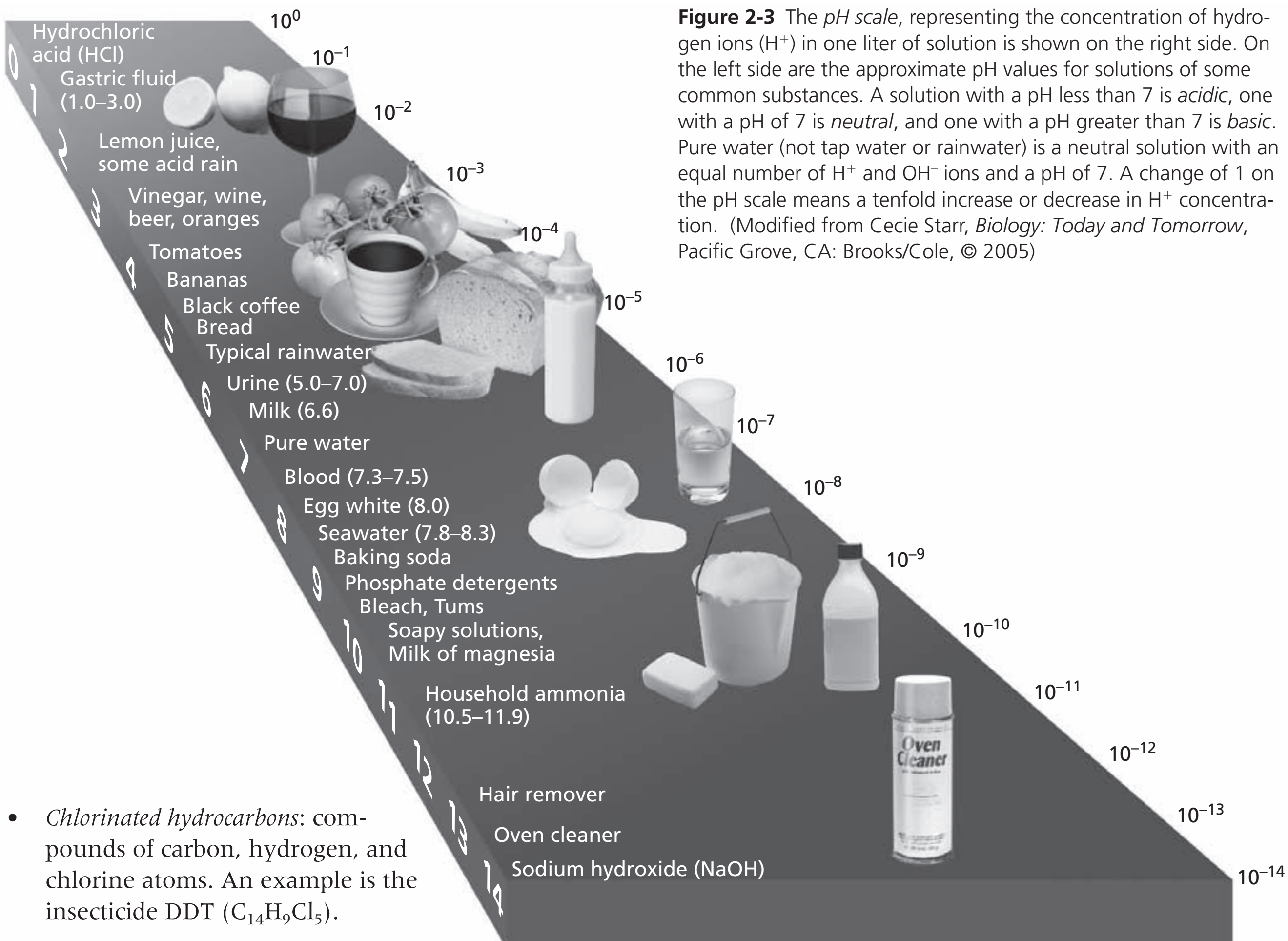


Figure 2-3 The *pH scale*, representing the concentration of hydrogen ions (H^+) in one liter of solution is shown on the right side. On the left side are the approximate pH values for solutions of some common substances. A solution with a pH less than 7 is *acidic*, one with a pH of 7 is *neutral*, and one with a pH greater than 7 is *basic*. Pure water (not tap water or rainwater) is a neutral solution with an equal number of H^+ and OH^- ions and a pH of 7. A change of 1 on the pH scale means a tenfold increase or decrease in H^+ concentration. (Modified from Cecie Starr, *Biology: Today and Tomorrow*, Pacific Grove, CA: Brooks/Cole, © 2005)

- *Chlorinated hydrocarbons*: compounds of carbon, hydrogen, and chlorine atoms. An example is the insecticide DDT ($C_{14}H_9Cl_5$).
- *Simple carbohydrates (simple sugars)*: certain types of compounds of carbon, hydrogen, and oxygen atoms. An example is glucose ($C_6H_{12}O_6$), which most plants and animals break down in their cells to obtain energy.

Larger and more complex organic compounds, essential to life, are composed of *macromolecules*. Some of these molecules are called *polymers*, formed when a number of simple organic molecules (*monomers*) are linked together by chemical bonds—somewhat like rail cars linked in a freight train. The three major types of organic polymers are:

- *Complex carbohydrates*, such as cellulose and starch, used by plants to store energy and by the animals that eat the plants; they consist of two or more monomers of simple sugars such as glucose.
- *Proteins*, formed by monomers called *amino acids,* that are linked together; important to living life forms for storing energy, maintaining immune systems, building body tissues, and creating hormones.
- *Nucleic acids* (DNA and RNA), formed by monomers called *nucleotides,* that are linked together.

Lipids, which include fats and waxes, are not made of monomers but are a fourth type of macromolecule essential to some life forms for storing energy and building tissues.

Matter Comes to Life through Genes, Chromosomes, and Cells

Within some DNA molecules are certain sequences of nucleotides called **genes**. Each of these coded units of genetic information concerns a specific **trait**, or characteristic, passed on from parents to offspring during reproduction in an animal or plant.

Thousands of genes, in turn, make up a single **chromosome**, a special DNA molecule wrapped around a number of proteins. Genetic information coded in your chromosomal DNA is what makes you different from an oak leaf, an alligator, or a flea and from your parents. In other words, it makes you human, but it also makes you unique.

Finally, these building blocks combine to form the fundamental unit of all living things—the **cell**: a minute compartment containing chemicals necessary for life and within which most of the processes of life take place. Living things may consist of a single cell (bacteria, for instance) or huge numbers of cells as is the case for most plants and animals. The relationships among these genetic materials and cells are shown in Figure 2-4.

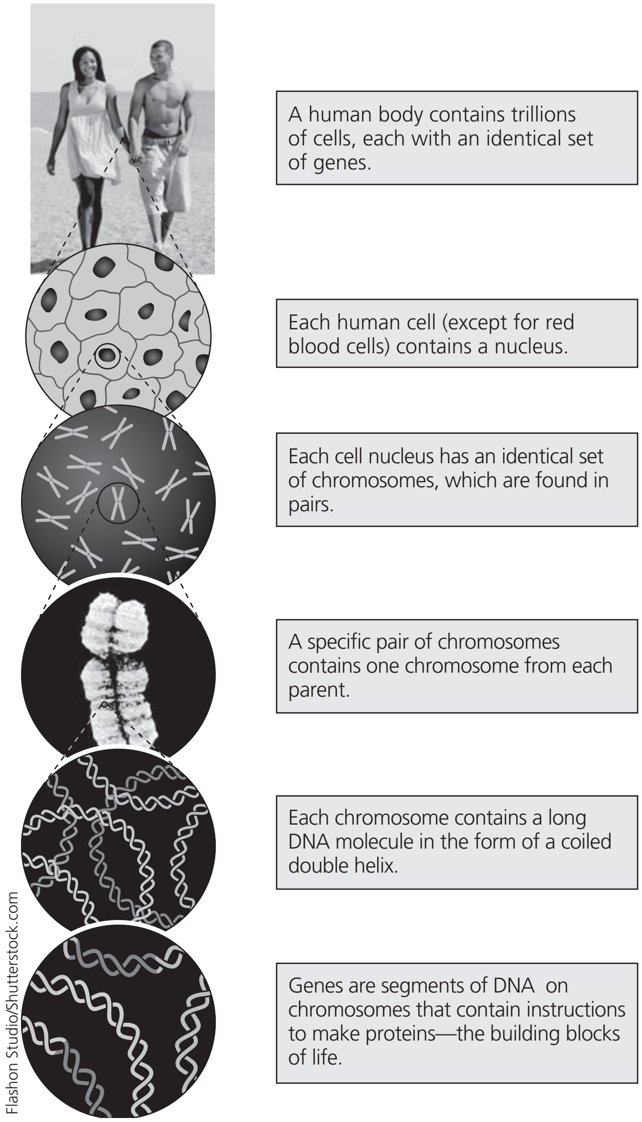


Figure 2-4 The relationships among cells, nuclei, chromosomes, DNA, and genes.

Figure 2-5 Differences in matter quality. *High-quality matter* (left column) is fairly easy to extract and is highly concentrated; *low-quality matter* (right column) is not highly concentrated and is more difficult to extract than high-quality matter.

Some Forms of Matter Are More Useful Than Others

Matter quality is a measure of how useful a form of matter is to humans as a resource, based on its availability and *concentration*—the amount of it that is contained in a given area or volume (Figure 2-5). **High-quality matter** is highly concentrated, is typically found near the earth's surface, and has great potential for use as a resource. **Low-quality matter** is not highly concentrated, is often located deep underground or dispersed in the oceans or the atmosphere, and usually has little potential for use as a resource.

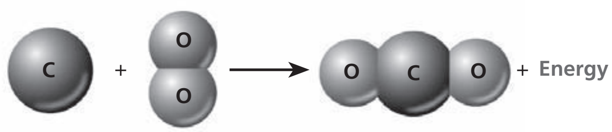
In summary, matter consists of elements and compounds that in turn are made up of atoms, ions, or molecules (**Concept 2-2A**). Some forms of matter are more useful as resources than others because of their availability and concentrations.

Matter Can Undergo Change but Cannot Be Created or Destroyed

When a sample of matter undergoes a **physical change**, there is no change in its *chemical composition*, or the arrangement of its atoms or ions within its molecules. A piece of aluminum foil cut into small pieces is still aluminum foil. When solid water (ice) melts and when liquid water boils, the resulting liquid water and water vapor are still made up of H_2O molecules.

When a **chemical change**, or **chemical reaction**, takes place, there is a change in the chemical composition of the substances involved. Chemists use a *chemical* *equation* to show how atoms and ions are rearranged in a chemical reaction. For example, when coal is burned completely, the solid carbon (C) in the coal combines with oxygen gas (O_2) from the atmosphere to form the gaseous compound carbon dioxide (CO_2). We represent this reaction with the following equation:

Reactant(s)			→	Product(s)		
Carbon	+	Oxygen	→	Carbon dioxide	+	**Energy**
C	+	O_2	→	CO_2	+	**Energy**



Black solid *Colorless gas* *Colorless gas*

We can change elements and compounds from one physical or chemical form to another, but we can never create or destroy any of the atoms involved in any physical or chemical change. All we can do is rearrange the atoms, ions, or molecules into different spatial patterns (physical changes) or chemical combinations (chemical changes). These observations, based on many thousands of measurements, describe a scientific law known as the **law of conservation of matter**: when matter undergoes a physical or chemical change, no atoms are created or destroyed (**Concept 2-2B**).

CONNECTIONS ✓

Waste and the Law of Conservation of Matter

The law of conservation of matter means we can never really throw anything away, because the atoms in any form of matter cannot be destroyed as the matter undergoes physical or chemical changes. We can put trash into a landfill, but we have not really thrown it away because the atoms in this waste material will always be around in one form or another. We can burn trash, but we then end up with ash that must be put somewhere and with gases emitted by the burning that can pollute the air. The law of conservation of matter means we will always face the problem of what to do with some quantity of the wastes and pollutants we produce, because their atoms cannot be destroyed.

2-3 What Is Energy, and What Happens When It Undergoes Change?

▶ **CONCEPT 2-3A When energy is converted from one form to another in a physical or chemical change, no energy is created or destroyed (first law of thermodynamics).**

▶ **CONCEPT 2-3B When energy is converted from one form to another in a physical or chemical change, we end up with lower-quality or less usable energy than we started with (second law of thermodynamics).**

Energy Comes in Many Forms and Some Are More Useful Than Others

Energy is the capacity to do work or to transfer heat. Work is done when something is moved. Work is performed when an object (such as this book) is moved over some distance. Heat is transferred when natural gas, for example, is burned to heat a house.

There are two major types of energy: *moving energy* (called kinetic energy) and *stored energy* (called potential energy). Matter in motion has **kinetic energy**, which is energy associated with motion. Examples are flowing water, wind (a mass of moving air), and electricity (electrons flowing through a wire or other conducting material).

Another form of kinetic energy is **heat**, the total kinetic energy of all moving atoms, ions, or molecules within a given substance. When two objects at different temperatures contact one another, heat flows from the warmer object to the cooler object. You learned this the first time you touched a hot stove.

Another form of kinetic energy is called **electromagnetic radiation**, in which energy travels in the form of a *wave* as a result of changes in electrical and magnetic fields. There are many different forms of electromagnetic radiation (Figure 2-6), each having a different *wavelength* (the distance between successive peaks or troughs in the wave) and *energy content*. Forms of electromagnetic radiation with short wavelengths, such as gamma rays, X rays, and ultraviolet (UV) radiation, have more energy than do forms with longer wavelengths, such as visible light and infrared (IR) radiation. Visible light makes up most of the spectrum of electromagnetic radiation emitted by the sun.

The other major type of energy is **potential energy**, which is stored and potentially available for use. Examples of this type of energy include a rock held in your hand, the water in a reservoir behind a dam,

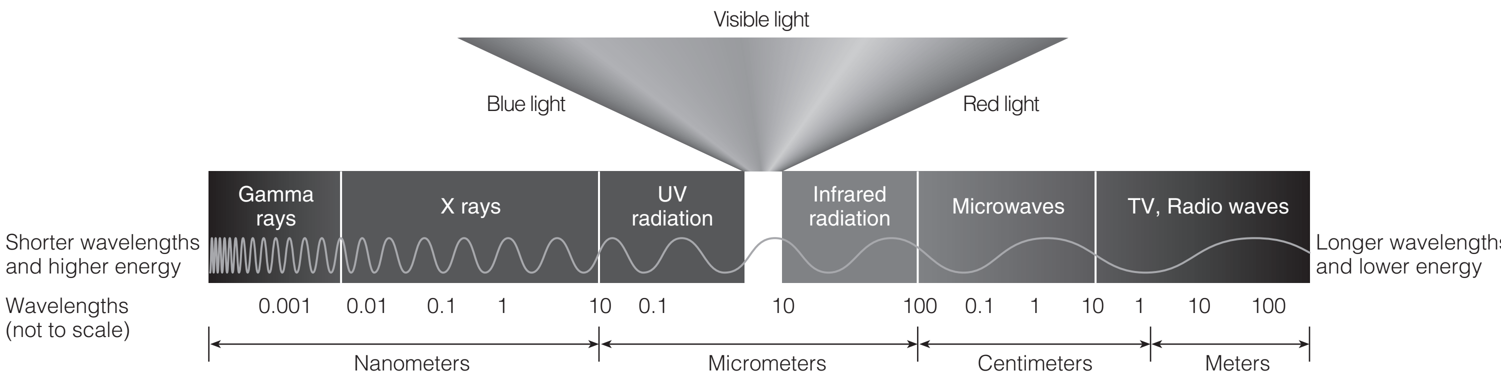


Figure 2-6 The *electromagnetic spectrum* consists of a range of electromagnetic waves, which differ in wavelength (the distance between successive peaks or troughs) and energy content.

and the chemical energy stored in the carbon atoms of coal or in molecules of food that you eat.

We can change potential energy to kinetic energy. If you hold this book in your hand, it has potential energy. However, if you drop it on your foot, the book's potential energy changes to kinetic energy. Potential energy stored in the molecules of foods you eat becomes kinetic energy when your body uses it to move and do other forms of work.

About 99% of the energy that heats the earth and our buildings, supports plants (through a process called *photosynthesis*), and provides us and other animals with food comes from the sun at no cost to us. This is in keeping with the solar energy **principle of sustainability** (see back cover). This *direct* input of solar energy produces several other *indirect* forms of renewable solar energy. Examples are *wind* (moving air driven by heat from the sun), *hydropower* (falling and flowing water kept fluid by solar energy), and *biomass* (solar energy converted to chemical energy and stored in the chemical bonds of organic compounds in trees and other plants).

Energy quality is a measure of the capacity of a type of energy to do useful work. **High-quality energy** has a great capacity to do useful work, because it is concentrated. Examples are very-high-temperature heat, concentrated sunlight, high-speed wind, and the energy released when we burn gasoline or coal.

By contrast, **low-quality energy** is so dispersed that it has little capacity to do useful work. An example is heat dispersed in the moving molecules of a large amount of matter (such as the atmosphere or an ocean) so that its temperature is low.

Energy Changes Are Governed by Two Scientific Laws

Thermodynamics is the study of energy transformations. After observing and measuring energy being changed from one form to another in millions of physical and chemical changes, scientists have summarized their results in the **first law of thermodynamics**, also known as the **law of conservation of energy**. According to this scientific law, *whenever energy is converted from one form to another in a physical or chemical change, no energy is created or destroyed* (**Concept 2-3A**).

This scientific law tells us that, no matter how hard we try or how clever we are, we cannot get more energy out of a physical or chemical change than we put in. This is one of nature's basic rules that has never been violated.

Because the first law of thermodynamics states that energy cannot be created or destroyed, but only converted from one form to another, you may be tempted to think we will never have to worry about running out of energy. Yet if you fill a car's tank with gasoline and drive around or use a flashlight battery until it is dead, something has been lost. What is it? The answer is *energy quality,* the amount of energy available for performing useful work.

Thousands of experiments have shown that *whenever energy is converted from one form to another in a physical or chemical change, we end up with lower-quality or less useable energy than we started with* (**Concept 2-3B**). This is a statement of the **second law of thermodynamics**. The resulting low-quality energy usually takes the form of heat that flows into the environment where it is dispersed by the random motion of air or water molecules and becomes even less useful as a resource.

In other words, *when energy is changed from one form to another, it always goes from a more useful to a less useful form*. No one has ever found a violation of this fundamental scientific law.

Consider three examples of the second law of thermodynamics in action. *First*, when you drive a car, an average of about 87% of the high-quality energy available in its gasoline fuel is degraded to low-quality heat that is released into the environment. That is, about 87% of the money we spend on gasoline is not used to transport us anywhere.

Second, when electrical energy in the form of moving electrons flows through filament wires in an

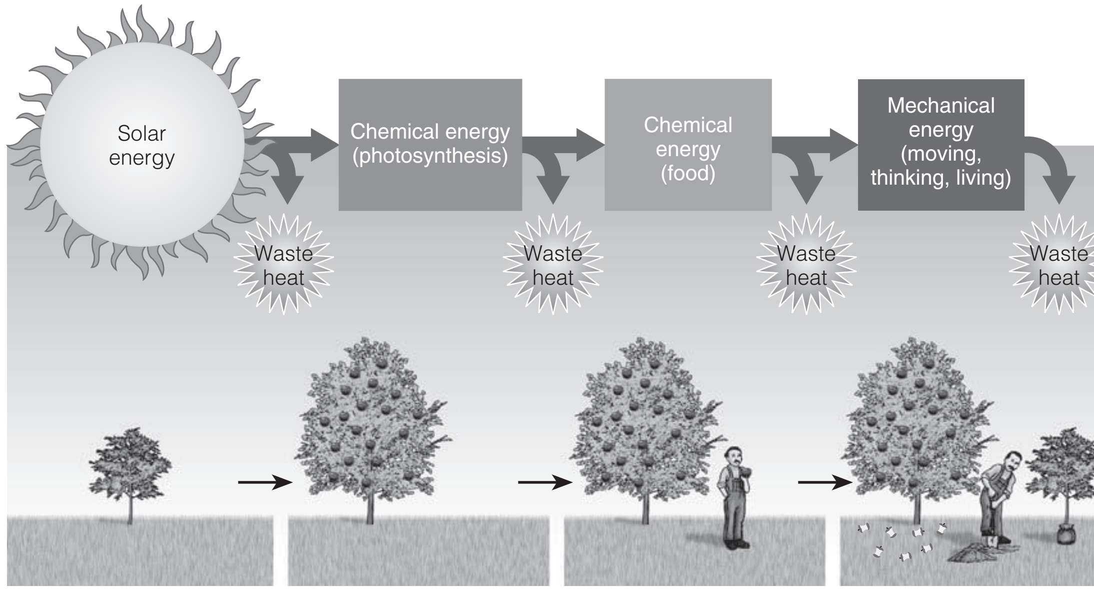


Figure 2-7 The second law of thermodynamics in action in living systems. Each time energy changes from one form to another, some of the initial input of high-quality energy is degraded, usually to low-quality heat that is dispersed into the environment.

incandescent light bulb, about 5% to 10% of it is converted into useful light, and 90% to 95% flows into the environment as low-quality heat. By comparison, in a compact fluorescent bulb with the same brightness, about 80% of the energy input becomes heat. In other words, the *incandescent light bulb* is really an energy-wasting *heat bulb*.

Third, in living systems, solar energy is converted into chemical energy (food molecules) and then into mechanical energy (used for moving, thinking, and living). During each conversion, high-quality energy is degraded and flows into the environment as low-quality heat. Trace the flows and energy conversions in Figure 2-7 to see how this happens.

The second law of thermodynamics also means *we can never recycle or reuse high-quality energy to perform useful work*. Once the concentrated energy in a serving of food, a liter of gasoline, or a chunk of uranium is released, it is degraded to low-quality heat that is dispersed into the environment.

2-4 What Keeps Us and Other Organisms Alive?

▶ **CONCEPT 2-4 Life is sustained by the flow of energy from the sun through the biosphere, the cycling of nutrients within the biosphere, and gravity.**

Ecology Is the Study of Connections in Nature

Ecology (from the Greek words *oikos*, "house" or "place to live," and *logos*, "study of") is the study of how living things interact with one another and with their nonliving environment. In effect, it is a study of *connections in nature*—the house for the earth's life.

To enhance their understanding of nature, scientists classify matter into levels of organization from atoms to cells to the biosphere. Ecologists focus on trying to understand the interactions among organisms, populations, communities, ecosystems, and the biosphere (Figure 2-8).

An **organism** is any form of life. It is the most fundamental unit of ecology. Organisms may consist of a single cell (bacteria, for instance) or many cells. Look in the mirror. What you see is about 10 trillion cells divided into about 200 different types.

Every organism is a member of a certain **species**: a set of organisms that resemble one another in appearance, behavior, chemistry, and genetic makeup. Organisms that reproduce sexually (combining cells from both parents to produce offspring) must be able to produce live, fertile offspring in order to be considered members of the same species.

We do not know how many species are on the earth. Estimates range from 4 million to 100 million, with recent estimates ranging between 7 million and 14 million. So far, biologists have identified about 2 million species, most of them insects (Science Focus, p. 30).

Life Is Organized Within Populations, Communities, and Ecosystems

A **population** is a group of individuals of the same species that live in the same place at the same time. Examples include a school of sunfish in a pond, the field mice living in a cornfield, and the people who live in a country. In most natural populations, individuals vary slightly in their genetic makeup, which is why they do not all look or act alike. This variation in a population is called **genetic diversity**.

The place where a population or an individual organism normally lives is its **habitat**. It may be as large as an ocean or as small as the intestine of a termite. Each habitat contains certain resources, such as water, and environmental conditions, such as temperature and light, that favor the organisms living there.

A **biological community**, or **community**, consists of all the populations of different species that live in a particular place. For example, a catfish species in a pond usually shares the pond with other fishes, and with plants, insects, ducks, and many other species. Many of these organisms interact with one another during feeding and other activities.

An **ecosystem** is a community of different species interacting with one another and with their nonliving environment of soil, water, other forms of matter, and energy, mostly from the sun. Ecosystems can range in size from a puddle of water to an ocean or from a patch of woods to a forest. Ecosystems can be natural or artificial (human created). Examples of artificial ecosystems are crop fields and reservoirs.

The **biosphere** consists of the parts of the earth's air, water, and soil where life is found. In effect, it is the global ecosystem in which all ecosystems and living organisms exist and can interact with one another. In the biosphere, *everything is linked to everything else*.

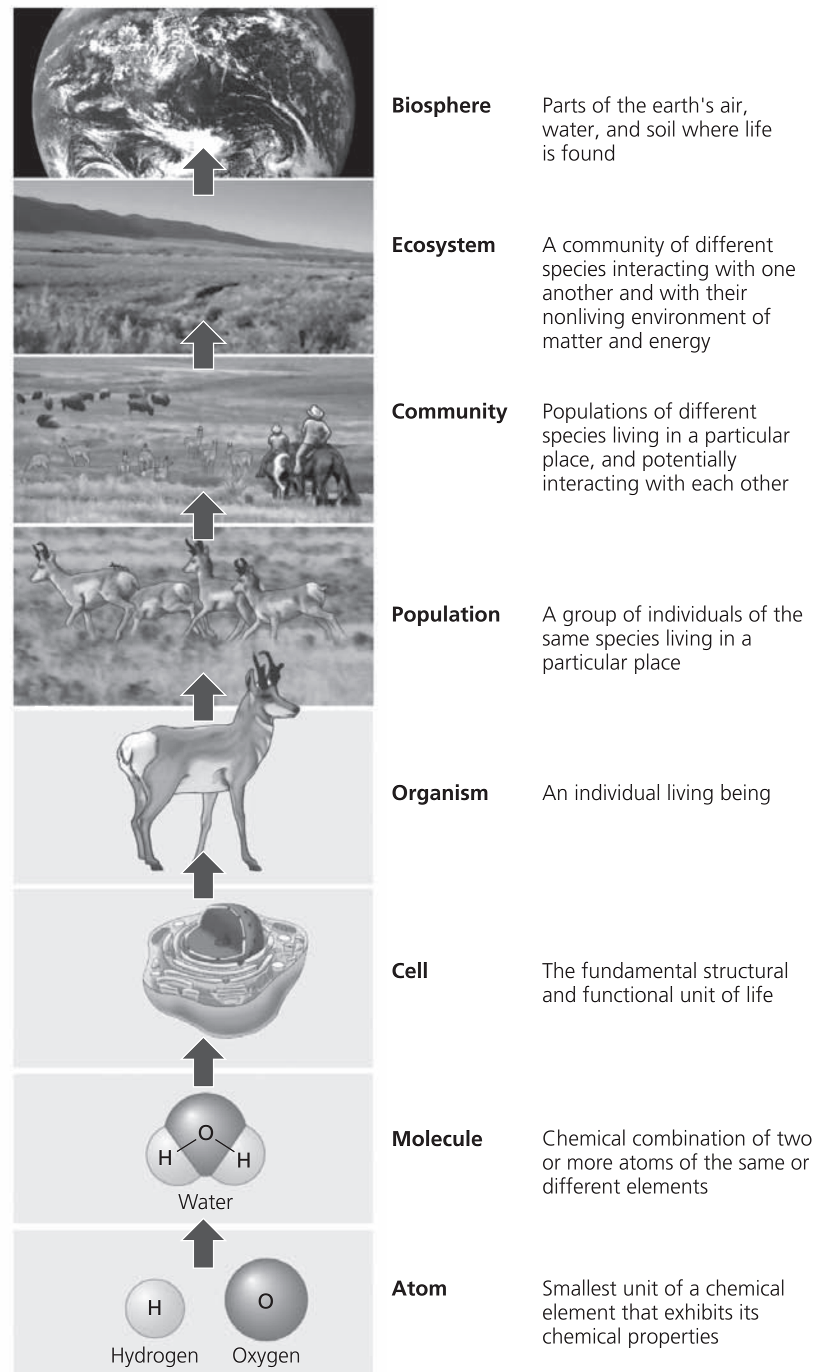


Figure 2-8 Some levels of organization of matter in nature are shown here. Ecology focuses on the top five of these levels.

Earth's Life-Support System Has Four Major Components

The earth's life-support system consists of four main spherical systems that interact with one another (Figure 2-9). The **atmosphere** is a thin spherical envelope of gases surrounding the earth's surface. Its inner layer, the **troposphere**, extends only about 17 kilometers (11 miles) above sea level at the tropics and about 7 kilometers (4 miles) above the earth's north and south poles. It contains air that we breathe, consisting mostly of nitrogen (78% of the total volume) and oxygen (21%). The remaining 1% of the air includes water vapor, carbon dioxide, and methane, all of which are called **greenhouse gases**, which absorb and release energy that warms the lower atmosphere. Without

SCIENCE FOCUS

Have You Thanked the Insects Today?

Although insects generally have a bad reputation, they are an important part of the earth's natural capital. We classify many insect species as *pests*, because they compete with us for food, spread human diseases such as malaria, bite or sting us, and invade our lawns, gardens, and houses.

Some people fear insects and think the only good bug is a dead bug. They fail to recognize the vital roles insects play in helping to sustain life on earth. For example, pollination is a natural service that allows plants to reproduce sexually when pollen grains are transferred from one plant to a receptive part of another plant. A great many of the earth's plant species depend on insects to pollinate their flowers.

Insects that eat other insects help control the populations of at least half the species of insects we call pests. Some insects also play a key role in loosening and renewing the soil that supports terrestrial plant life.

Insects have been around for at least 400 million years—about 2,000 times longer than the latest version of our own human species. Some insects reproduce at an astounding rate and can rapidly develop new genetic traits, such as resistance to pesticides. They also have an exceptional ability to evolve into new species when faced with changing environmental conditions, and they are very resistant to extinction. This is fortunate because, according to ant specialist and biodiversity expert E. O. Wilson, if all insects disappeared, parts of the life-support systems that keep us and other species alive would be greatly disrupted.

The environmental lesson: although insects do not need newcomer species such as humans, we and most other land organisms need them.

Critical Thinking

Identify three insect species that benefit your life. How do they do so?

these gases, the earth would be too cold for the existence of life as we know it. Almost all of the earth's weather occurs within this layer.

The next layer, stretching 17–50 kilometers (11–31 miles) above the earth's surface, is called the **stratosphere**. Its lower portion holds enough ozone (O_3) gas to filter out about 95% of the sun's harmful *UV radiation*. This global sunscreen allows life to exist on land and in the surface layers of bodies of water.

The **hydrosphere** consists of all the water on or near the earth's surface. It is found as *water vapor* in the atmosphere, *liquid water* on the surface and underground, and *ice*—polar ice, icebergs, glaciers, and ice in frozen soil layers called *permafrost*.

The **geosphere** consists of the earth's intensely hot *core*, a thick *mantle* composed mostly of rock, and a thin outer *crust*. Most of the geosphere is located in the earth's interior. Its upper portion contains nonrenewable *fossil fuels*, such as coal, oil, and natural gas, and minerals that we use as well as renewable soil chemicals that organisms need to live, grow, and reproduce.

As noted above, the biosphere consists of the parts of the atmosphere, hydrosphere, and geosphere where life is found. Biologists have classified the terrestrial (land) portion of the biosphere into **biomes**—large regions such as forests, deserts, and grasslands, with distinct climates and certain species (especially vegetation) adapted to them. Scientists divide the watery parts of the biosphere into **aquatic life zones**, each containing numerous ecosystems. There are *freshwater life zones* (such as lakes and streams) and *ocean* or *marine life zones* (such as coral reefs, coastal estuaries, and the deep ocean).

The biosphere extends from about 9 kilometers (6 miles) above the earth's surface down to the bottom of the ocean and includes the lower part of the atmosphere, most of the hydrosphere, and the uppermost part of the geosphere. If the earth were an apple, the biosphere would be no thicker than the apple's skin. *One important goal of environmental science is to understand the interactions that occur within this thin layer of air, water, soil, and organisms.*

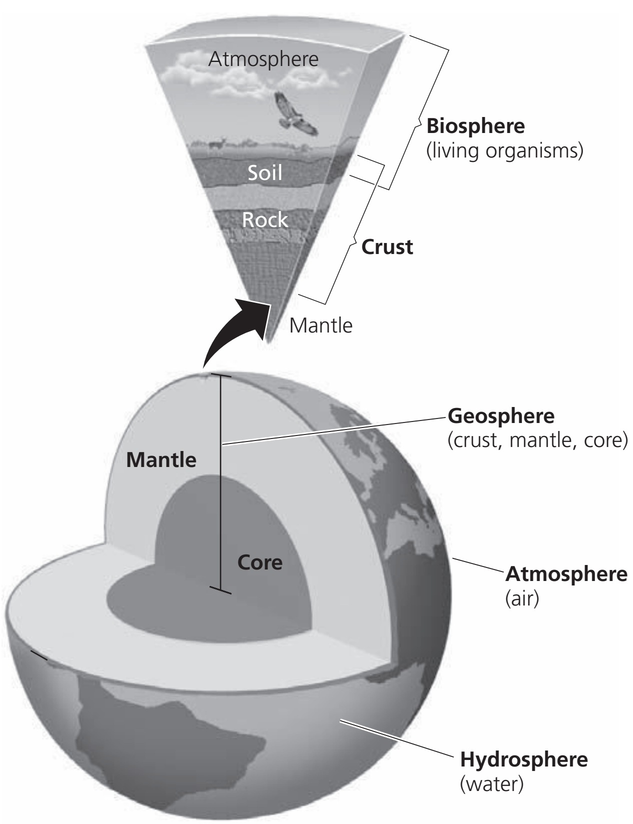


Figure 2-9 Natural capital: General structure of the earth, showing that it consists of a land sphere, an air sphere, a water sphere, and a life sphere.

Three Factors Sustain the Earth's Life

Life on the earth depends on three interconnected factors (**Concept 2-4**):

1. The *one-way flow of high-quality energy* from the sun, through living things in their feeding interactions, into the environment as low-quality energy (mostly heat dispersed into air or water at a low temperature), and eventually back into space as heat. No round-trips are allowed because high-quality energy cannot be recycled. The two laws of thermodynamics (**Concepts 2-3A** and **2-3B**) govern this energy flow.
2. The *cycling of nutrients* through parts of the biosphere. Because the earth is closed to significant inputs of matter from space, its essentially fixed supply of **nutrients**—the elements and compounds that organisms need to live, grow, and reproduce—must be continually recycled to support life (see Figure 1-4, p. 5). Nutrient cycles in ecosystems and in the biosphere are round-trips, which can take from seconds to centuries to complete. The law of conservation of matter (**Concept 2-2B**) governs this nutrient cycling process.
3. *Gravity,* which allows the planet to hold onto its atmosphere and helps to enable the movement and cycling of chemicals through air, water, soil, and organisms.

Sun, Earth, Life, and Climate

Only a very small amount of the sun's tremendous output of energy reaches the earth—a tiny sphere in the vastness of space. This energy reaches the earth in the form of electromagnetic waves, composed mostly of visible light, UV radiation, and heat (infrared radiation) (Figure 2-6). Much of this energy is absorbed or reflected back into space by the earth's atmosphere and surface (Figure 2-10).

About half of the total solar radiation intercepted by the earth reaches the planet's surface, and most of it is then reflected back up toward space as longer-wavelength infrared radiation. In the lower atmosphere, it encounters *greenhouse gases* such as water vapor, carbon dioxide, methane, nitrous oxide, and ozone. It causes these gaseous molecules to vibrate and release infrared radiation with even longer wavelengths. The vibrating gaseous molecules then have higher kinetic energy, which helps to warm the lower atmosphere and the earth's surface. Without this **natural greenhouse effect**, the earth would be too cold to support the forms of life we find here today.

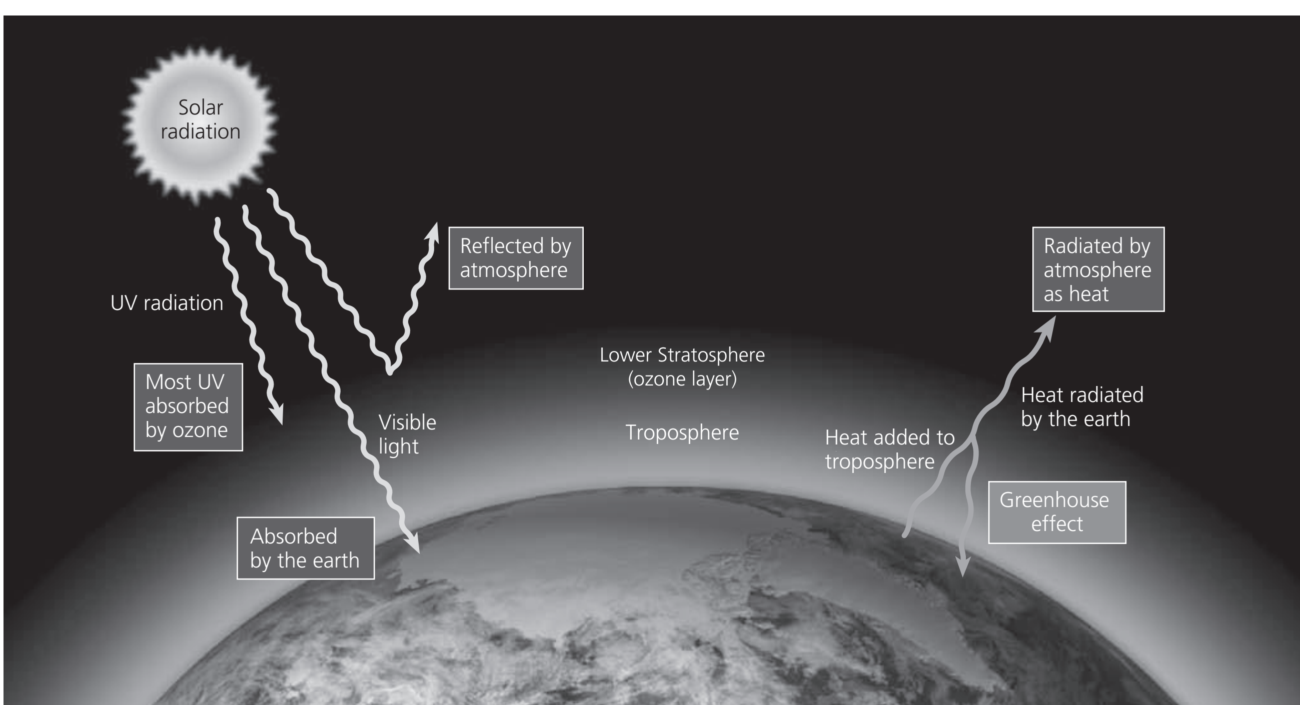


Figure 2-10 High-quality energy flows from the sun to the earth. As it interacts with the earth's air, water, soil, and life, it is degraded into lower-quality energy (heat), some of which flows back into space.

2-5 What Are the Major Components of an Ecosystem?

▶ **CONCEPT 2-5 Ecosystems contain nonliving and living components, including organisms that produce the nutrients they need, organisms that get the nutrients they need by consuming other organisms, and organisms that recycle nutrients by decomposing the wastes and remains of other organisms.**

Ecosystems Have Living and Nonliving Components

The biosphere and its ecosystems are made up of **biotic**, or living components, and **abiotic**, or nonliving components. Examples of nonliving components are water, air, nutrients, rocks, heat, and solar energy. Living components include plants, animals, and microbes. Figure 2-11 is a greatly simplified diagram of some of the living and nonliving components of a terrestrial ecosystem.

Each population in an ecosystem has a **range of tolerance** to variations in its physical and chemical environment (Figure 2-12). Individuals within a population may also have slightly different tolerance ranges for temperature or other factors because of small differences in genetic makeup, health, and age. For example, a trout population may do best within a narrow band of temperatures (*optimum level* or *range*), but a few individuals can survive above and below that band. Of course, if the water becomes much too hot or too cold, none of the trout can survive.

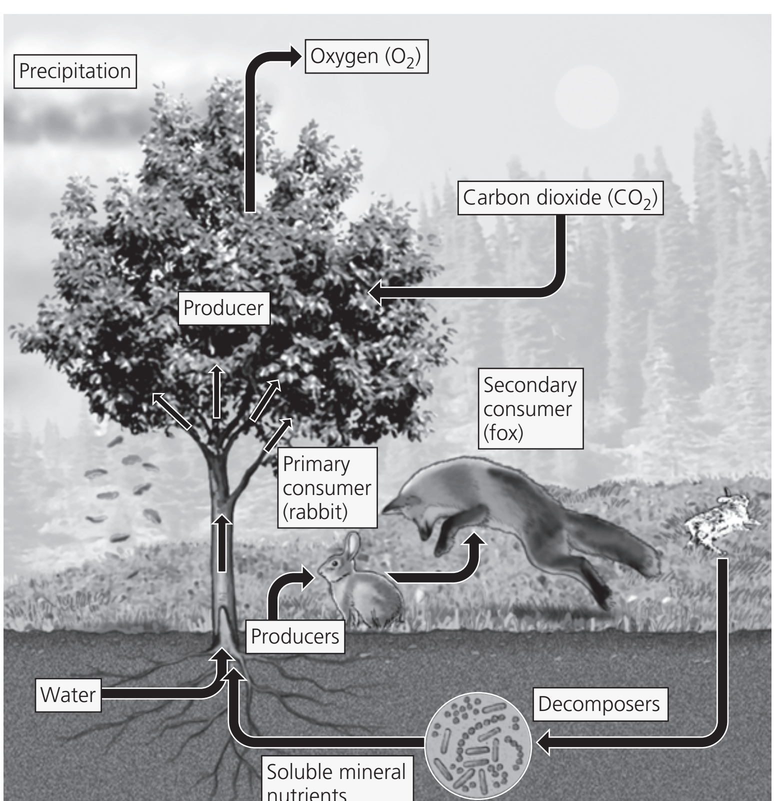


Figure 2-11 Key living and nonliving components of an ecosystem in a field.

A variety of abiotic factors can affect the number of organisms in a population. Sometimes one or more factors, known as **limiting factors**, are more important in regulating population growth than are other factors. This ecological principle is called the **limiting factor principle**: *too much or too little of any abiotic factor can limit or prevent growth of a population, even if all other factors are at or near the optimal range of tolerance.* This principle describes one way in which natural population control takes place.

On land, precipitation often is the limiting abiotic factor. Lack of water in a desert limits plant growth. Soil nutrients also can act as a limiting factor on land. Suppose a farmer plants corn in phosphorus-poor soil. Even if water, nitrogen, potassium, and other nutrients are at optimal levels, the corn will stop growing when it uses up the available phosphorus. Too much of an abiotic factor can also be limiting. For example, too much water or fertilizer can kill plants.

Important limiting abiotic factors in aquatic life zones include temperature, sunlight, nutrient availability, and *dissolved oxygen content*—the amount of oxygen gas dissolved in a given volume of water at a particular temperature and pressure. Another such factor is *salinity*—the amounts of various inorganic minerals or salts dissolved in a given volume of water.

Producers and Consumers Are the Living Components of Ecosystems

Ecologists assign every type of organism in an ecosystem to a *feeding level*, or **trophic level**, depending on its source of food or nutrients. We can broadly classify the living organisms that transfer energy and nutrients from one trophic level to another in an ecosystem as producers and consumers.

Producers, sometimes called **autotrophs** (self-feeders), make the nutrients they need from compounds and energy obtained from their environment (**Concept 2-5**). On land, most producers are green plants. In aquatic ecosystems, algae and aquatic plants growing near shorelines are the major producers. In open water, the dominant producers are *phytoplankton*—mostly microscopic organisms that float or drift in the water.

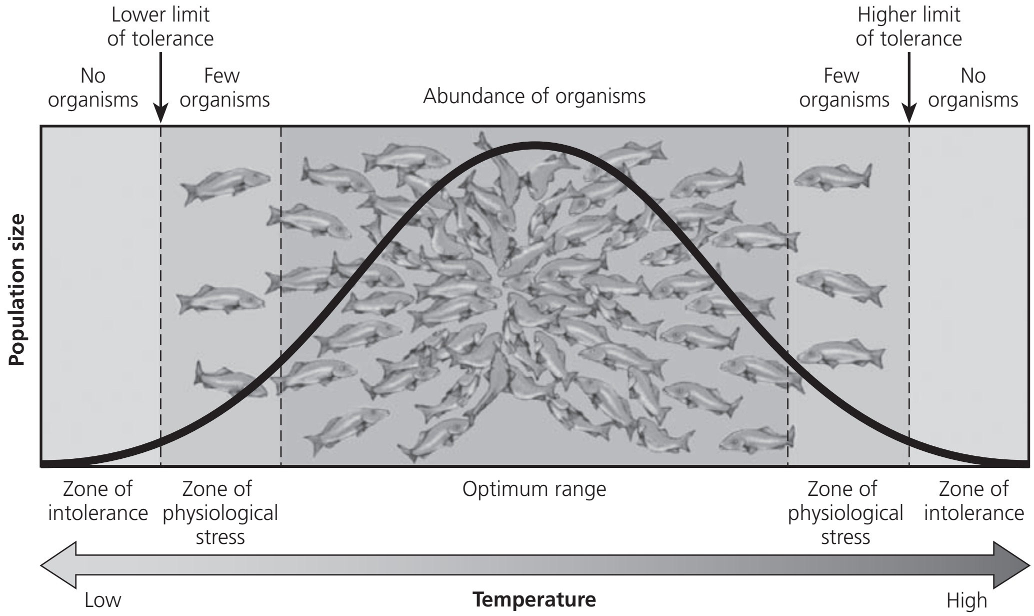


Figure 2-12 Range of tolerance for a population of organisms, such as fishes, to an abiotic environmental factor—in this case, temperature. These restrictions keep particular species from taking over an ecosystem by keeping their population size in check.

In a process called **photosynthesis**, plants typically capture about 1% of the solar energy that falls on their leaves and combine it with carbon dioxide and water to form organic molecules, including energy-rich carbohydrates (such as glucose, $C_6H_{12}O_6$), which store the chemical energy they need. Although hundreds of chemical changes take place during photosynthesis, we can summarize the overall reaction as follows:

carbon dioxide + water + **solar energy** → glucose + oxygen

All other organisms in an ecosystem are **consumers**, or **heterotrophs** ("other-feeders"), that cannot produce their own nutrients and must obtain them by feeding on other organisms (producers or other consumers) or their remains. In other words, all consumers (including humans) depend on producers for their nutrients.

There are several types of consumers. **Primary consumers**, or **herbivores** (plant eaters), are animals, such as caterpillars and giraffes, that eat producers. **Carnivore**s (meat eaters) are animals that feed on the flesh of other animals. Some carnivores (such as spiders, lions, and most small fishes) are **secondary consumers** that feed on the flesh of herbivores. Other carnivores (such as tigers and killer whales) are **tertiary** (or higher) **consumers** that feed on the flesh of other carnivores. **Omnivores** such as pigs, rats, and humans eat plants and other animals.

Decomposers are consumers that, in the process of obtaining their own nutrients, release nutrients from the wastes or remains of plants and animals that then go back to the soil, water, and air for reuse as nutrients by producers (**Concept 2-5)**. Most decomposers are bacteria and fungi. Other consumers, called **detritus feeders** or **detritivores**, feed on the wastes or dead bodies of other organisms; these wastes are called *detritus* (dih-TRI-tus), which means debris. Examples are earthworms, some insects, and vultures.

Hordes of detritus feeders and decomposers can transform a fallen tree trunk into wood particles and, finally, into simple inorganic molecules that plants can absorb as nutrients (Figure 2-13). Thus, in natural ecosystems the wastes and dead bodies of organisms serve as resources for other organisms, as the nutrients that make life possible are continuously recycled, in keeping with one of the three **principles of sustainability** (see back cover). As a result, *there is very little waste of nutrients in nature*.

Decomposers and detritus feeders, many of which are microscopic organisms (Science Focus, p. 34), are the key to nutrient cycling. Without them, the planet would be overwhelmed with plant litter, animal wastes, dead animal bodies, and garbage.

Producers, consumers, and decomposers use the chemical energy stored in glucose and other organic compounds to fuel their life processes. In most cells, this energy is released by **aerobic respiration**, which uses oxygen to convert organic nutrients back into carbon dioxide and water. The net effect of the hundreds of steps in this complex process is represented by the following chemical reaction:

glucose + oxygen → carbon dioxide + water + **energy**

Although the detailed steps differ, the net chemical change for aerobic respiration is the opposite of that for photosynthesis.

To summarize, ecosystems and the biosphere are sustained through a combination of *one-way energy flow* from the sun through these systems and the *nutrient cycling* of key materials within them (**Concept 2-4**)—in keeping with two of the **principles of sustainability** (Figure 2-14).