PRINCIPLES OF

Environmental Science

Inquiry & Applications

Tenth Edition

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Mc Graw Hill

PRINCIPLES OF ENVIRONMENTAL SCIENCE: INQUIRY AND APPLICATIONS, TENTH EDITION

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About the Authors

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Courtesy Tom Finkle

William P. Cunningham taught at the University of Minnesota for 38 years and wrote about enviromental science for 25 years. He taught a variety of biology courses, including Environmental Science, Conservation Biology, Environmental Health, Environmental Ethics, Plant Physiology, General Biology, and Cell Biology. He was appointed as a member of the Academy of Distinguished Teachers, the highest teaching award granted at the University of Minnesota. He was a member of a number of interdisciplinary programs for international students, teachers, and nontraditional students. He also carried out research or taught in Sweden, Norway, Brazil, New Zealand, China, and Indonesia.

Professor Cunningham participated in a variety of civic organizations, as chair of the Minnesota chapter of the Sierra Club, a member of the Sierra Club national committee on energy policy, vice president of the Friends of the Boundary Waters Canoe Area, chair of the Minnesota governor's task force on energy policy, and a citizen member of the Minnesota Legislative Commission on Energy.

MARY ANN CUNNINGHAM

Courtesy Tom Finkle

Mary Ann Cunningham is a professor of geography at Vassar College, in New York's Hudson Valley. A biogeographer with interests in landscape ecology, geographic information systems (GIS), and land use change, she teaches environmental science, natural resource conservation, and land use planning, as well as GIS and spatial data analysis. Field research methods, statistical methods, and scientific methods in data analysis are regular components of her teaching. As a scientist and educator, she enjoys teaching and conducting research with both science students and non-science liberal arts students. As a geographer, she likes to engage students with the ways their physical surroundings and social context shape their world experience. She has published work on habitat and landcover change, on water quality and urbanization, as well as climate change, its impacts, and carbon mitigation strategies.

CATHERINE M. O'REILLY

Courtesy William Perry

Catherine O'Reilly is a professor in the Department of Geography, Geology, and the Environment at Illinois State University. She has taught courses in natural disasters, environmental geology, and ecology. She is inspired to create opportunities for students to experience science by doing it, through working in the field, the laboratory, or analyzing data to explore environmental concepts. Both her courses and her research highlight how human activities interact with earth processes.

Her research focuses on impacts of human activities on lakes and rivers, focusing on the effects of climate change and land use patterns such as agriculture and urbanization. With her students, she has studied the impacts on climate change and deforestation on Lake Tanganyika in Tanzania and agricultural impacts on water quality in the midwestern USA. She was a member of the 2007 IPCC, which shared the Nobel Peace Prize with Al Gore.

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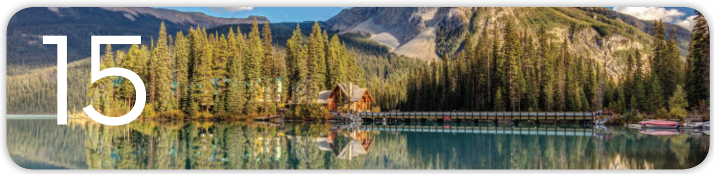

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List of Case Studies

Over 200 additional Case Studies can be found online on the instructor's resource page at www.mcgrawhill-connect.com.

About the Cover

Fireweed (*Epilobium Angustifolium*) springs from the ashes of a fire in the Yukon Territory, Canada. In the full sun and nutrient-enriched soil, these flowers help regenerate a diverse biological community. Fire is a normal part of many ecosystems, including this one, allowing dormant species to flourish and new generations of trees to emerge.

Environmental systems often exhibit surprising renewal following disturbances such as fire, floods, or pest outbreaks. A growing question is, as human impacts increase the frequency and severity of these disturbances, how will ecosystems change? As climate warming increases the intensity and extent of fire, will this northern forest shift to a new type of environment? These are fundamental questions in environmental science.

Environmental science is a field that explores the astonishing and interconnected environmental systems we inhabit. We examine the finely evolved ways in which species have adapted, and the ways we are changing ecosystems and resources. Environmental science also explores solutions—the many ways we can protect, restore, and understand, and enjoy natural diversity in the world around us. Welcome to the journey.

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Preface

UNDERSTANDING CRISIS AND OPPORTUNITY

Welcome to environmental science, a field that applies fundamental principles of science to issues that are current, complex, and often urgent. Studying environmental science involves examining critical challenges of climate change, biodiversity loss, clean water protection, population growth, sustainable food systems, and many other concerns. It introduces foundational principles of science to help organize our understanding of these issues. And it explores the tremendous opportunities we have to address challenges around us. Studying environmental science, then, gives you the opportunity to gain the concepts (the organizing ideas) and the content (background knowledge and examples) to make intelligent choices and address critical questions about the environment, conservation, and sustainability.

As you encounter the many serious issues in this book, from climate change to global hunger, remember that even while we face major challenges, there are good reasons to feel hopeful. Strategies for climate action, biodiversity conservation, transformation of food systems, and other ideas that seemed radical a few years ago are now established policy around the globe. Access to education, health care, information, even political participation and human rights are improving in many areas, around the world and close to home. Creative people are inventing new alternatives for energy, food production, conservation, and pollution abatement that were undreamed of a generation ago. Recognition of Indigenous voices and of people of color in environmental movements has begun to transform and expand protection of the environment and of people who live in it.

Environmental science is also for everyone. Recognizing the importance of equity and access for diverse populations, this book emphasizes the importance of drawing multiple perspectives into discussions—both academic and civic—of environmental science. While this book focuses on science as a way of understanding our world, we also emphasize the importance of countless skills and interest areas—writing, art, policymaking, and more. In addressing the central issue of climate action, for example, we explore the ways food production, and land management, urban planning, and other fields contribute key solutions.

This edition also marks the passing of the first author of this book, Bill Cunningham (1937–2019). He dedicated his life to educating students of all ages, from all backgrounds, on the importance of understanding the natural world around us. Just as important, he taught the value of enjoying the natural world, both on the grand scale and in the fine details. His writing and teaching helped to transform the field to include global perspectives and a concern for social justice and environmental equity. These principles go hand in hand with stewarding natural systems and resources. This book is committed to passing on a love of the environment, and a love of ideas, to new generations (fig. 1). We hope that it continues to foster curiosity and a pleasure in learning. We hope it contributes to the river of ideas that flows through everyone who cares about understanding and protecting our environment, wherever they find it, in whatever way they choose to do so.

▲ **FIGURE 1** Bill Cunningham dedicated his life to sharing his love of learning. Source: Thomas Finkle

WHAT SETS THIS BOOK APART?

Solid science and an emphasis on sustainability: This book reflects the authors' decades of experience in the field and in the classroom, which make it up-to-date in approach, in data, and in applications of critical thinking. The authors have been deeply involved in sustainability, environmental science, and conservation programs at the institutions where they teach. Their experience and courses on these topics have strongly influenced the way ideas in this book are presented and explained.

Demystifying science: We make science accessible by showing how and why data collection is done and by giving examples, practice, and exercises that demonstrate central principles. *Exploring Science* readings empower students by helping them understand how scientists do their work. These readings give examples of technology and methods in environmental science.

Quantitative reasoning: Students can become comfortable with graphs, data, and comparing numbers. We provide focused discussions on why scientists answer questions with numbers, the nature of statistics, of probability, and how to interpret the message in a graph. We give accessible details on population models, GIS (mapping and spatial analysis), remote sensing, and other quantitative techniques. In-text applications and online, testable *Data Analysis* questions give students opportunities to practice with ideas, rather than just reading about them.

Emphasis on inclusion: Reflecting the growing diversity of students today, who bring different socioeconomic and cultural backgrounds to a class, we emphasize throughout the contributions of these diverse perspectives. Students of color, Indigenous groups, first-generation college students, and others have key contributions to make. We emphasize the importance of environmental science for these different groups, and the students' importance to environmental science.

Positive perspective: While fear of impending doom is a powerful motivator, but even better is a belief in progress and an idea of how to make it happen. This book seeks to help empower students to work effectively on the issues they believe in. While we don't shy away from the bad news, we do highlight positive ways in which groups and individuals are working to improve their environment. *What Can You Do?* features in every chapter offer practical examples of things everyone can do to make progress toward sustainability.

Student leadership: Based on decades of experience in the classroom, this book emphasizes how students can engage, by bringing different ideas and skills to the class. We highlight what individuals can do, and how action on campus can have lasting impacts. Students lead the way in reimagining our possible futures. Student ideas are the roots of innovation in technology and science, in sustainability planning, and in environmental governance, both locally and globally. This book gives examples and suggestions to encourage this action.

Critical thinking: We provide a focus on critical thinking, one of the most essential skills for citizens, as well as for students. Starting with a focused discussion of critical thinking in chapter 1, we offer abundant opportunities for students to weigh contrasting evidence and evaluate assumptions and arguments, including *What Do You Think?* readings.

Up-to-date concepts and data: Throughout the text we introduce emerging ideas and issues such as ecosystem services, cooperative ecological relationships, epigenetics, and the economics of air pollution control, in addition to basic principles such as population biology, the nature of systems, and climate processes. Current approaches to climate change mitigation, campus sustainability, sustainable food production, and other issues give students current insights into major issues in environmental science and its applications. We introduce students to current developments such as ecosystem services, coevolution, strategic targeting of Marine Protected Areas, impacts of urbanization, challenges of REDD (reducing emissions through deforestation and degradation), renewable energy development in China and Europe, fertility declines in the developing world, and the impact of global food trade on world hunger.

Active learning: Learning how scientists approach problems can help students develop habits of independent, orderly, and objective thought. But it takes active involvement to master these skills. This book integrates a range of learning opportunities—*Active Learning* exercises, *Critical Thinking and Discussion* questions, and *Data Analysis* exercises—that push students to think for themselves. Data and interpretations are presented not as immutable truths but rather as evidence to be examined and tested, as they should be in the real world. Taking time to look closely at figures, compare information in multiple figures, or apply ideas in text is an important way to solidify and deepen understanding of key ideas.

Synthesis: Students come to environmental science from a multitude of fields and interests. We emphasize that most of our pressing problems, from global hunger or climate change to conservation of biodiversity, draw on sciences and economics and policy. This synthesis shows students that they can be engaged in environmental science, no matter what their interests or career path.

A global perspective: Environmental science is a globally interconnected discipline. Case studies, data, and examples from around the world give opportunities to examine international questions. Nearly half of the opening case studies, and many of the boxed readings, examine international issues of global importance, such as forest conservation in Indonesia, air quality in India, or family planning in Thailand. In addition, Google Earth place marks take students virtually to locations where they can see and learn the context of the issues they read.

Key concepts: In each chapter this section draws together compelling illustrations and succinct text to create a summary "take-home" message. These key concepts draw together the major ideas, questions, and debates in the chapter but give students a central idea on which to focus. These can also serve as starting points for lectures, student projects, or discussions.

Thorough coverage: No other book in the field addresses the multifaceted nature of environmental questions such as climate policy, sustainability, or population change with the thoroughness this book has. We cover not just climate change but also the nature of climate and weather systems that influence our day-to-day experience of climate conditions. We explore both food shortages and the emerging causes of hunger—such as political conflict, biofuels, and global commodity trading—as well as the relationship between food insecurity and the growing pandemic of obesity-related illness. In these and other examples, this book is a leader in in-depth coverage of key topics.

Student empowerment: Our aim is to help students understand that they can make a difference. From campus sustainability assessments (chapter 16) to public activism (chapter 13) we show ways that student actions have led to policy changes on all scales. In all chapters we emphasize ways that students can take action to practice the ideas they learn and to play a role in the policy issues they care about. *What Can You Do?* boxed features give steps students can take to make a difference.

Exceptional online support: Online resources integrated with readings encourage students to pause, review, practice, and explore ideas, as well as to practice quizzing themselves on information presented. McGraw-Hill's ConnectPlus (www.mcgrawhillconnect.com) is a web-based assignment and assessment platform that gives students the means to better connect with their coursework, with their instructors, and with the important concepts that they will need to know for success now and in the future. Valuable assets such as LearnSmart (an adaptive learning system), an interactive ebook, *Data Analysis* exercises, the extensive case study library, and Google Earth exercises are all available in Connect.

WHAT'S NEW IN THIS EDITION?

This edition continues our focus on two major themes, **climate protection and sustainability.** These topics are evolving rapidly, often with student leadership, and they greatly impact the future and the career paths of students. We explore **emerging ideas and examples** to help students consider these dominant issues of our time. The climate chapter (chapter 9), for example, provides up-to-date data from the Paris Accord to the latest Intergovernmental Panel on Climate Change (IPCC) as well as in-depth explanations of climate dynamics, including positive feedbacks and how greenhouse gases capture energy. The energy chapter (chapter 13) explores the rapidly changing landscape of energy production, in which fossil fuels still dominate, but explosive growth of renewables in China, India, and Europe have altered what we think is possible for renewable energy systems.

We also provide a new emphasis on **science and citizenship.** In a world overflowing with conflicting views and arguments, students today need to understand the importance of being able to evaluate evidence, to think about data, to understand environmental systems, and to see linkages among systems we exploit and depend on. And they need to understand their responsibility, as voters and members of civil society, to apply these abilities to decision making and participation in their communities.

Many topics in environmental science are shifting rapidly, and so much of the material in this edition is updated. Nearly two-thirds of the chapters have new opening case studies, and data and figures have been updated throughout the book. Brief **learning objectives** have been added to every A head to help students focus on the most important topics in each major section.

We also recognize that students have a lot to remember from each chapter. As teachers, we have found it is helpful to provide a few key reference ideas, which students can focus on and even compare to other data they encounter. So in this edition, we have provided short lists of **benchmark data,** selected to help students anchor key ideas and to understand the big picture. Specific chapter changes include the following.

Chapter 1, understanding our environment, marks the United Nations Decade of Restoration with a new case study exploring the possibility of restoring the Amazon rainforest. While daunting, the question illustrates the crisis, the opportunity, the urgency, and the multiple benefits of seeking progress in this globally critical region. This chapter emphasizes the centrality of sustainable development goals in environmental science and the point that each person, whatever their interests or background, can contribute to solutions. A new box outlines the foundational influence of environmental justice activism.

Chapter 2, matter, energy, and life, has updated focus on systems and feedbacks, with a focus on nutrients and the Gulf of Mexico dead zone, to illustrate the role of basic chemistry in environmental systems.

Chapter 3, evolution and species interactions, has expanded attention to cooperative relationships and coevolution among species, as well as updated discussion on different forms of competition and key concepts such as keystone species and ecosystem engineers.

Chapter 4, human populations, has fully updated discussions of human population, reflecting dramatic recent changes in birth rates around the world, with profound implications for demographic transitions and population change. A new section explores the question of how slowing growth, a priority for ecologists, might (or might not) influence economic productivity, a concern for policymakers. This question has long put ecologists and economists at odds, but changes in context may alter this relationship. These questions have critical importance for human impacts on environmental systems. A new figure illustrates the historical relationship between fertility rates and population growth.

Chapter 5, biomes and biodiversity, has an expanded discussion of defaunation, or depleted abundance of species, and a new boxed reading on insect declines—an urgent crisis along with the sixth mass extinction question. Updated discussion of the globally important Convention on Biological Diversity and its updated "30 by 30" goals to protect 30 percent of global land and water area by 2030. Updated data report new estimates of the number of species and proportions of threatened species.

Chapter 6, environmental conservation, includes updated trends in forest and grassland extent and conservation. The rising cost of wildfires is updated, as well as changes in Brazil's forest policies. The importance of global wood pellet trade is noted. A new section emphasizes the importance of appreciating biodiversity in local areas, not just exotic places, as local parks are where most people get their start in understanding natural systems.

Chapter 7, food and agriculture, has updated data on food production and consumption, as well as nutrition and diet. Emphasizing the connection to climate impacts, an expanded exploration of eating lower on the food chain includes an essay on meat alternatives. The discussion of the pesticide treadmill is updated, supporting the opening case study on new "pesticide cocktails." Also reflecting climate impacts, an expanded discussion of cover crops and carbon storage in soils reflects ongoing changes in dominant agricultural practices.

Chapter 8, environmental health, opens with a new case study on the COVID-19 pandemic and likely links to wildlife meat trades and other human interactions with wildlife virus reservoirs. A new discussion balances risks of environmental contaminants, diseases, and other factors. New data from the Institute for Health Metrics and Evaluation reflect dramatic improvements in infant health and shifts in health risk factors. The importance of maternal mortality is also added, a tragic, persistent, and preventable global crisis. The discussion of antibiotic resistance and emerging fungal threats is also updated. A new discussion of Toxic Release Inventory (TRI) data presents this important source of environmental health risks. Discussions of toxicity and dose-response curves are updated.

Chapter 9, climate, is a theme that runs through all chapters, but this chapter includes updated data and figures for greenhouse gas emissions, climate change projections. New imaging sensors for detecting methane leaks are discussed. A new section addresses necessary adaptations to climate change. The discussion of climate change costs, and implications for economic growth, are updated, and added emphasis of decoupling climate impacts and economic growth gives a framework for why we continue to debate climate action.

Chapter 10, air pollution, includes updated data for U.S. emissions of major pollutants, which have changed dramatically in magnitudes and sources. New figures show the global distribution of air pollutants and changes in halogen gas emissions.

Chapter 11, water resources, opens with a new case study on non-point source pollution and algae blooms in Lake Erie. This most vulnerable of the Great Lakes exhibits many of the complex issues of land use change, new studies of pollution recirculation, invasive species impacts, and other issues. New discussions and figures highlight issues of point-source and non-point source pollutants.

Chapter 12, environmental geology, includes a new "mineral baby" figure highlighting the earth resources each of us uses in a lifetime. This direct connection between chapter topics and our lives helps underscore the fundamental importance of this topic. We have updated discussions of mining and of geologic hazards, including earthquakes and landslides.

Chapter 13, energy, is a critical chapter in that it answers many of the issues raised in chapter 9, climate. This chapter is thoroughly updated to reflect strategies for climate response, but it also emphasizes the current importance of fossil fuels in our energy mix. A new opening case study examines Germany's approach to energy transition, including accelerating offshore wind power technology. Data on energy consumption and sectors are updated. A new figure compares bird mortality from wind turbines and other risk factors—a question of urgent concern for many students and faculty alike. Emerging technology such as floating offshore wind, floating solar panels, heat pumps, and energy storage (including batteries) is also discussed.

Chapter 14, waste, opens with a discussion of the persistent challenge of plastic waste, along with the question of how to improve and expand recycling. A new figure illustrates the waste management hierarchy, however, which prioritizes waste reduction. Data on waste production and management are updated throughout. A new table shows the evolution of policy for managing hazardous waste.

Chapter 15, economics and cities, opens with a case study on carbon taxes, a much-debated economic policy. A new discussion emphasizes that cities are where many of us live and first learn about our environments. A new figure shows the relative size of the world's largest cities in coming decades. An updated discussion compares challenges of urban growth in low-income and high-income countries. The discussion of common property management regimes is updated. New data on green jobs appear in a new figure.

Chapter 16, environmental policy, starts with an updated discussion of the policy cycle, with a focus on international environmental policy and how it has evolved over time, from the Rio Earth Summit to the Paris Agreement. Sustainable Development Goals, introduced in chapter 1, are revisited as the focus of most environmental policy. We emphasize especially the role of Black voters in U.S. environmental policymaking, as civil rights leaders have struggled simultaneously for environmental progress. A new table describes major international environmental policies.

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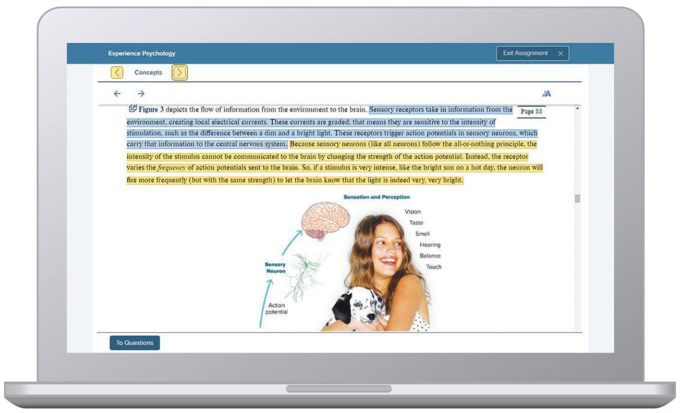

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> ***"I really liked this app—it made it easy to study when you don't have your text-book in front of you."***
>
> - Jordan Cunningham,
> Eastern Washington University

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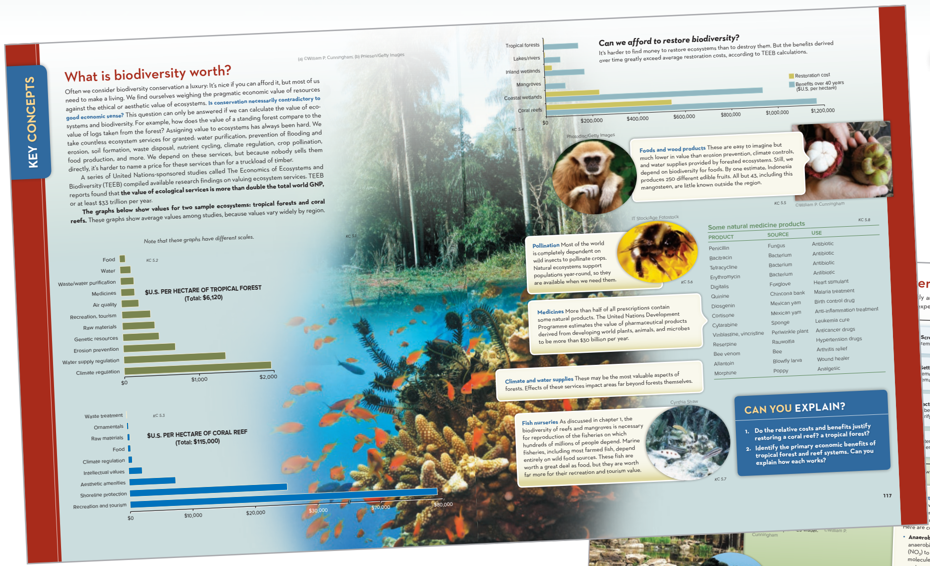
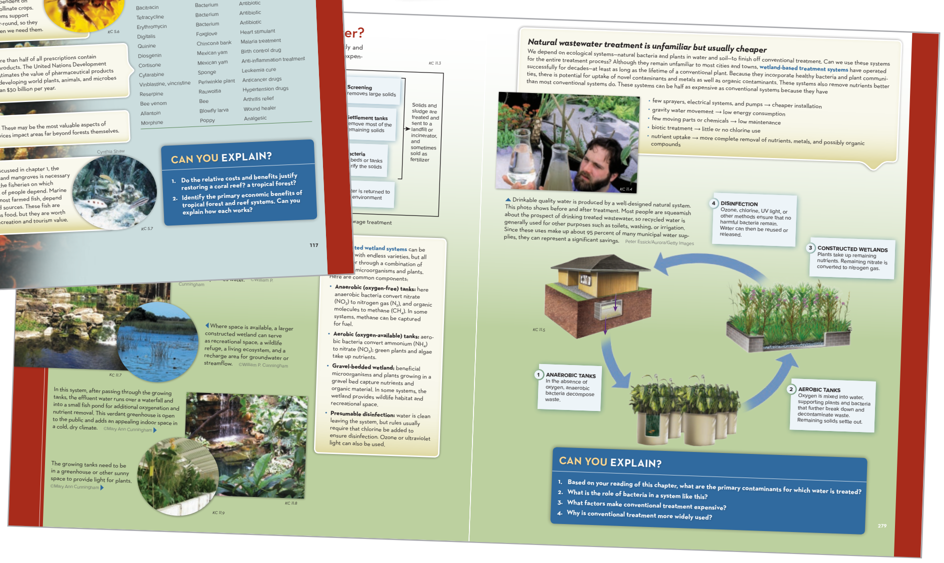
Guided Tour

Application-based learning contributes to engaged scientific investigation.



Key Concepts

Key concepts from each chapter are presented in a beautifully arranged layout to guide the student through the often complex network issues.



Case Studies

All chapters open with a real-world case study to help students appreciate and understand how environmental science impacts lives and how scientists study complex issues.

CASE STUDY

Palm Oil and Endangered Species

Are your donuts, toothpaste, and shampoo killing critically endangered orangutans in Sumatra and Borneo? It seems remote, but they might be. Palm oil, a key ingredient in at least half of the packaged foods, cosmetics, and soaps in the supermarket, is almost entirely sourced from plantations that just 20 years ago were moist tropical forest. In Indonesia and Malaysia these forests were the habitat of orangutans, Sumatran tigers and rhinos, and other endangered species. As palm oil has become the world's most widely used vegetable oil, expanding palm oil plantations have become one of the greatest causes of tropical deforestation.

▲ FIGURE 6.1 Over the past 15 years, palm plantation area in Southeast Asia has grown to more than 14 million hectares (34 million acres), replacing some of the world's richest primary forest. This rapid growth has destroyed habitat and displaced many critically endangered species. KhunJompol/iStock/Getty Images

A 2017 study of orangutan populations in Borneo, an island owned partly by Malaysia and partly by Indonesia, estimated that at least 100,000 of these rare and reclusive forest primates were killed in just 15 years, between 1999 and 2015. This represents over half of the region's orangutans. By 2050 the population is expected to be only around 50,000, many of them in tiny, dispersed, and dwindling populations. The main reasons for this decline are the rapid conversion of primary forest to palm plantations, deforestation for wood products, and the increasing density of human populations as settlements expand to serve these industries. Habitat loss is a driving factor, but actual mortality in this study was attributed mainly to hunting in the forests around plantations, made possible by the expansion of the plantations and logging roads deep into the primary forest.

In Indonesian, *orang utan* means person of the forest. Orangutans are among our closest primate relatives, sharing at least 97 percent of our genes. Traditional cultures in Borneo may recognize this relationship, because taboos have discouraged hunting

composed mainly of ancient, undecomposed plant material, so draining and burning of a hectare of peatland can release 15,000 tons of CO_2. More than 70 percent of the carbon released from Sumatran forests is from burning peat. Indonesia, which has the third largest area of rainforest in the world as well as the highest rate of deforestation, is now the world's third highest emitter of greenhouse gases. Smoke from burning peat often blankets Singapore, Malaysia, and surrounding regions.

At the 2014 UN Climate Summit in New York, 150 companies, including McDonald's, Nestlé, General Mills, Kraft, and Procter & Gamble, promised to stop using palm oil from recently cleared rainforest and to protect human rights in forest regions. It is not clear what these promises have meant, however, and observers continue to report ongoing deforestation for palm oil. Much of the clearing is done by obscure family companies closely tied to the Indonesian government, which market products through networks of subsidiary companies, making sources difficult to trace.

Promises to ban trade with environmental and human rights offenders are easy to sidestep in global commodity trading. Abuses are remote, oversight is rare, and enforcement often nonexistant. Cargill, one of the world's largest palm oil traders, is more transparent than most, providing records of environmental and human rights grievances against companies they work with. Cargill has pledged to stop doing business with some of the worst offenders, such as REPSA, a Guatemalan company implicated in kidnappings and murder of environmental activists, as well as killing millions of fish with effluent from a palm oil operation. Cargill continues to buy from REPSA indirectly, however, and to trade with other offenders.

The death of 100,000 orangutans and uncounted losses of

Martin Kubat/Shutterstock

Active Learning

Students will be encouraged to practice critical thinking skills and apply their understanding of newly learned concepts and to propose possible solutions.

Active LEARNING

Comparing Biome Climates

Look back at the climate graphs for San Diego, California, an arid region, and Belém, Brazil, in the Amazon rainforest (see fig. 5.6). How much colder is San Diego than Belém in January? in July? Which location has the greater range of temperature through the year? How much do the two locations differ in precipitation during their wettest months?

Compare the temperature and precipitation in these two places with those in the other biomes shown in the pages that follow. How wet are the wettest biomes? Which biomes have distinct dry seasons? How do rainfall and length of warm seasons explain vegetation conditions in these biomes?

ANSWERS: San Diego is about 13°C colder in January, about 6°C colder in July; San Diego has the greater range of temperature; there is about 250 mm difference in precipitation in December–February.

What Can YOU DO?

Working Locally for Ecological Diversity

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

- Take walks. The best way to learn about ecological systems in your area is to take walks and practice observing your environment. Go with friends, and try to identify some of the species and trophic relationships in your area.
- Keep your cat indoors. Our lovable domestic cats are also very successful predators. Migratory birds, especially those nesting on the ground, have not evolved defenses against these predators.
- Plant a butterfly garden. Use native plants that support a diverse insect population. Native trees with berries or fruit also support birds. (Be sure to avoid non-native invasive species.) Allow structural diversity (open areas, shrubs, and trees) to support a range of species.
- Join a local environmental organization. Often the best way to be effective is to concentrate your efforts close to home. City parks and neighborhoods support ecological communities, as do farming and rural areas. Join an organization working to maint... stem health: start by looking for environmental clubs at your school, ...ch.

What Can You Do?

Students can employ these practical ideas to make a positive difference in our environment.

EXPLORING *Science* — *Inexpensive Water Purification*

When Ashok Gadgil was a child in Bombay, India, five of his cousins died in infancy from diarrhea spread by contaminated water. Although he didn't understand the implications of those deaths at the time, as an adult he realized how heartbreaking and preventable those deaths were. After earning a degree in physics from the University of Bombay, Gadgil moved to the University of California at Berkeley, where he was awarded a PhD in 1979. He's now senior staff scientist in the Environmental Energy Technology Division, where he works on solar energy and

▲ A woman fills her jug with clean water from the village WaterHealth kiosk. More than 6 million people's lives have been improved by this innovative system of water purification. WaterHealth International

mount the UV source above the water where it couldn't develop mineral deposits. He designed a system in which water flows through a shallow, stainless steel trough. The apparatus can be gravity fed and requires only a car battery as an energy source.

The system can disinfect 15 liters (4 gallons) of water per minute, killing more than 99.9 percent of all bacteria and viruses. This produces enough clean water for a village of 1,000 people. This simple system costs only about 5 cents per ton (950 liter). Of course, removing pathogens doesn't do anything about minerals, such as arsenic,

Exploring Science

Current environmental issues exemplify the principles of scientific observation and data-gathering techniques to promote scientific literacy.

What Do YOU THINK?

Gene Editing

Humans have known for centuries that selective breeding can improve the characteristics of domestic plants and animals. But selective breeding is slow and rather unpredictable. The development of molecular genetics, inserting pieces of DNA from one species into another, dramatically improved our ability to tailor organisms, but this process is difficult and prone to errors. The discovery of a bacterial system for editing genes, however, may unleash a gold rush in genetic engineering.

This gene editing system is called CRISPR, short for "clustered regularly interspaced short palindromic repeats." CRISPR uses short sequences (palindromic repeats) of genetic material to attach to specific sections of DNA in a cell; it then uses an enzyme to cut the DNA in specific places. Bacteria use this

▲ **FIGURE 1** Experiments with CRISPR have modified genes and edited inherited traits in lab mice and other organisms. sidsnapper/E+/Getty Images

In 2017, scientists tried editing a gene inside a living human, in an attempt to permanently cure an inherited metabolic disorder called Hunter syndrome. In this syndrome, cells cannot produce an enzyme needed to break down complex sugars, so these sugar molecules accumulate in cells, blood, and tissues. Consequences can include nerve degeneration and mental impairment. The patient in this experiment received an intravenous transmission of billions of copies of a corrective gene, along with complexes designed to repair the DNA and restore his ability to produce the missing enzyme.

CRISPR has also become the latest question in debates about genetically modified organisms. On one hand, CRISPR makes it easier, quicker, and cheaper to produce

What Do You Think?

Students are presented with challenging environmental studies that offer an opportunity to consider contradictory data, special interest topics, and conflicting interpretations within a real scenario.

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Pedagogical Features Facilitate Student Understanding of Environmental Science

Learning Outcomes

Questions at the beginning of each chapter challenge students to find their own answers.

Practice Quiz

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

CHAPTER

6 Environmental Conservation: Forests, Grasslands, Parks, and Nature Preserves

LEARNING OUTCOMES

After studying this chapter, you should be able to answer the following questions:

- Where do the greatest original forests remains?
- What activities threaten global forests? What steps can be taken to preserve them?
- Why is road construction a challenge to forest conservation?
- Where are the world's most extensive grasslands?
- How do grazing animals coexist with, or damage, grasslands?
- What are the original purposes of parks and nature preserves in North America?
- What is the "Man and Biosphere" program?

Orangutans are among the most critically endangered of all the great apes. Over the past 20 years, about 90 percent of their rainforest habitat in Borneo and Sumatra has been destroyed by logging and conversion to palm oil plantations.

G-miner/iStock/Getty Images

PRACTICE QUIZ

1. What are the two most important nutrients causing eutrophication in the Gulf of Mexico?
2. What are systems, and how do feedback loops regulate them?
3. Your body contains vast numbers of carbon atoms. How is it possible that some of these carbons may have been part of the body of a prehistoric creature?
4. List six unique properties of water. Describe, briefly, how each of these properties makes water essential to life as we know it.
5. What is DNA, and why is it important?
6. The oceans store a vast amount of heat, but this huge reservoir of energy is of little use to humans. Explain the difference between high-quality and low-quality energy.
7. In the biosphere, matter follows circular pathways, while energy flows in a linear fashion. Explain.
8. To which wavelengths do our eyes respond, and why? (Refer to fig. 2.13.) About how long are short ultraviolet wavelengths compared to microwave lengths?
9. Where do extremophiles live? How do they get the energy they need for survival?
10. Ecosystems require energy to function. From where does most of this energy come? Where does it go?
11. How do green plants capture energy, and what do they do with it?
12. Define the terms *species*, *population*, and *biological community*.
13. Why are big, fierce animals rare?
14. Most ecosystems can be visualized as a pyramid with many organisms in the lowest trophic levels and only a few individuals at the top. Give an example of an inverted numbers pyramid.
15. What is the ratio of human-caused carbon releases into the atmosphere shown in figure 2.18 compared to the amount released by terrestrial respiration?

CRITICAL THINKING AND DISCUSSION

Apply the principles you have learned in this chapter to discuss these questions with other students.

1. Ecosystems are often defined as a matter of convenience because we can't study everything at once. How would you describe the characteristics and boundaries of the ecosystem in which you live? In what respects is your ecosystem an open one?
2. Think of some practical examples of increasing entropy in everyday life. Is a messy room really evidence of thermodynamics at work or merely personal preference?
3. Some chemical bonds are weak and have a very short half-life (fractions of a second, in some cases); others are strong and stable, lasting for years or even centuries. What would our world be like if all chemical bonds were either very weak or extremely strong?
4. If you had to design a research project to evaluate the relative biomass of producers and consumers in an ecosystem, what would you measure? (*Note:* This could be a natural system or a human-made one.)
5. Understanding storage compartments is essential to understanding material cycles, such as the carbon cycle. If you look around your backyard, how many carbon storage compartments are there? Which ones are the biggest? Which ones are the longest lasting?

Critical Thinking and Discussion Questions

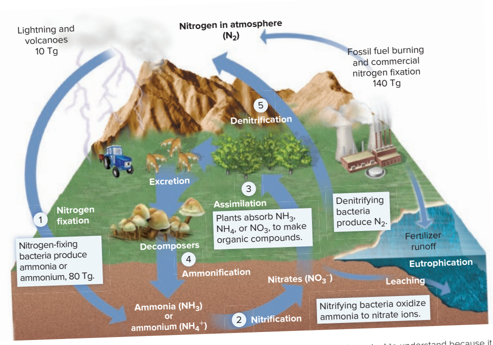
Brief scenarios of everyday occurrences or ideas challenge students to apply what they have learned to their lives.

Data Analysis

At the end of each chapter, these exercises give students further opportunities to apply critical thinking skills and analyze data. These are assigned through Connect in an interactive online environment. Students are asked to analyze data in the form of documents, videos, and animations.

DATA ANALYSIS A Closer Look at Nitrogen Cycling

1. Which forms of N do plants take up? Can they capture N_2 from the air?
2. Refer to section 2.5. How is N_2 captured, or fixed, from the air into the food web?
3. Most of the processes are hard to quantify, but the figure shown here gives approximate amounts for fossil fuel burning and commercial N fixation, and for N fixing by bacteria. What do these terms mean? What is the magnitude of each? What is the difference?
4. If anthropogenic processes introduce increasing amounts of atmospheric N to the biosphere and hydrosphere, where does that N go? (*Hint:* Refer to the opening case study.)
5. Why is N so important for living organisms?
6. In marine systems, N is often a limiting factor. What is a "limiting factor"? What is a consequence of increasing the supply of N in a marine system?



▲ Nitrogen cycles through living and nonliving systems. This biogeochemical cycle is important to understand because it strongly influences how ecosystems function.

CHAPTER

1 Understanding Our Environment

LEARNING OUTCOMES

After studying this chapter, you should be able to answer the following questions:

- List several major themes in environmental science.
- Explain the idea of sustainability and some of its aims.
- Why are scientists cautious about claiming absolute proof of particular theories?
- What is critical thinking, and why is it important in environmental science?
- Why do we use graphs and data to answer questions in science?
- Identify several people who helped shape our ideas of resource conservation and preservation—why did they promote these ideas when they did?
- Outline the steps of the scientific method.

The year 2021 marked the start of a Decade of Restoration for the United Nations. Can this be an opportunity to protect and restore the Amazon rainforest?

Salparadis/Shutterstock

CASE STUDY

Can We Restore the Amazon?

The Amazon rainforest is one of the most important ecosystems on Earth. The vast and dense forest, much of it seasonally flooded by the world's largest river, occupies a river basin that runs from the Peruvian Andes to the Brazilian Atlantic coast. The region harbors some of the world's greatest concentrations of biodiversity. The Amazon basin is the world's most important forest carbon sink, storing about 20 percent of the world's tree biomass, according to Global Forest Watch data, and capturing up to 5 percent of global carbon dioxide emissions (some 2 billion tons of CO_2) each year. The trees transpire moisture back to the atmosphere, recycling over and over the rain that keeps the forest wet—and providing essential rainfall for agriculture. Thousands of indigenous communities also live here, and their struggle for survival has helped give legal protection (though not always real protection) to these ancient forests.

The Amazon rainforest is also under threat. An inexorable process of forest burning has eaten away at the ecosystem, as ranchers and farmers clear the forest to graze cattle and to grow soybeans for sale abroad in China and Europe. Brazilian conservationists, including indigenous activists seeking land rights, have fought the tide of expanding agribusiness for decades, but cattle and soybean interests have been writing the rules for even longer. In recent years, Brazil's President Jair Bolsonaro, with close ties to the agriculture and industry, moved to expand cropping of sugar cane in Amazonia and to allow mining and oil extraction on indigenous lands.

Protecting the Amazon from further destruction is a priority for scientists, conservationists, and human rights advocates around the world. But another question has emerged recently: Can the Amazon be restored? Is the region's natural resilience lost when the land is cleared, or might the forest regrow again, given time?

The year 2021 marked the start of a United Nations Decade of Restoration, which UN agencies and partners hope will promote restoration of biodiversity worldwide. So this is a good time to envision restoration in the Amazon, even though it is hard to imagine restoration on a scale this large. Global Forest Watch has identified the Amazon region as a global restoration hot spot. Under the 2015 Paris Agreement on Climate Change, Brazil promised to restore 120,000 km^2 of forest, as part of its commitment to reducing carbon emissions. As the global focus on climate protection intensifies, pressure will grow to follow through on this promise.

What does restoration mean in an area this vast? Replanting is important, but allowing natural regeneration is also critical. Studies have shown that while original forest is healthier and more diverse than second growth, natural regeneration does proceed in a matter of decades, and the rainforest can be surprisingly resilient, if it is allowed to grow and mature.

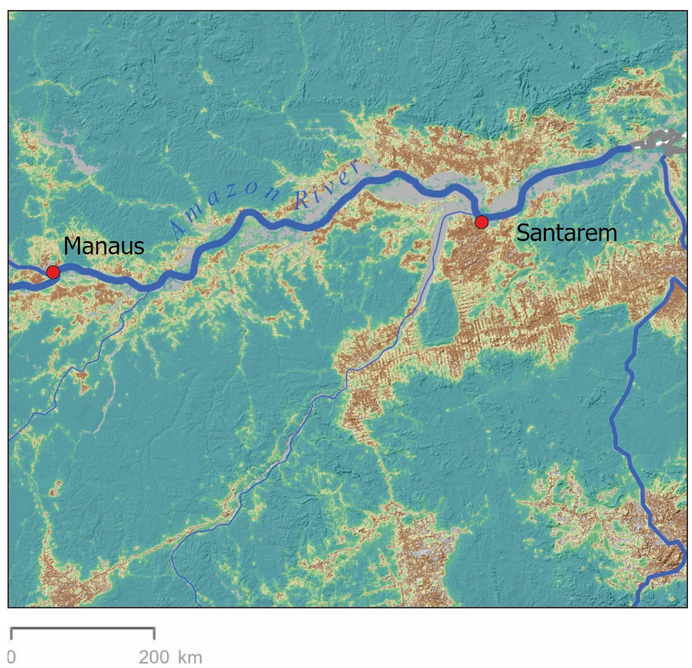
Restoration also includes agroforestry—growing trees that produce fruits, nuts, or other products with sustainable value. Agroforestry can allow economic development for low-income populations while also protecting forest ecosystems. Restoration is also sure to involve some means of paying communities for protecting and rebuilding, rather than destroying, their standing forests.

Restoration certainly means reducing economic incentives that promote deforestation. Globally, banks are rethinking whether they should finance expanding cattle, soy, and mining operations that clearly accelerate global climate change. European and North American bankers and investors, then, can exercise considerable leverage over the future of the Amazon.

Restoration also involves monitoring. Brazilian environmental scientists and satellite remote sensing analysts are doing their best to publicize rates of change (fig. 1.1). When the whole world is watching, it is harder to destroy forests freely.

Restoration also means global support for indigenous land rights. Tribal communities have traditional knowledge for living in the forest and on the river. As they fight to keep miners and ranchers at bay, they also protect the forest.

Can the Amazon rainforest be restored? This might depend on decisions we all make. How we vote, how our policymakers think, how we invest, what we buy, and what we eat can all influence the fate of the Amazon. Educating yourself about what is going on and why it matters is a good place to start. Environmental science is about understanding how our environment functions, and how it is changing. It is about understanding how we know about changes in our surroundings, why they matter, and ultimately how to steward or restore the environments we depend on. As you read this chapter, consider where your interests fit in the field of environmental science, and how you want to make use of your knowledge of the world around you. ■



▲ **FIGURE 1.1** Amazon forests are steadily converting to beef pastures and soy fields, especially around roads and growing cities.
Data Source: Forest Landscape Integrity Index, https://www.pnas.org/content/117/6/3015

> *Today we are faced with a challenge that calls for a shift in our thinking, so that humanity stops threatening its life-support system.*
>
> —WANGARI MAATHAI, WINNER OF 2004 NOBEL PEACE PRIZE

Benchmark Data

Among the ideas and values in this chapter, these are a few worth remembering.

280 ppm	Pre-industrial concentration of CO_2 in the atmosphere, in parts per million
415 ppm	Approximate concentration of CO_2 now
6 billion	Global population 2000
9 billion	Global population in 2050 (projected)
5	Average number of children per woman in 1950
2	Average number by 2050 (projected)

1.1 WHAT IS ENVIRONMENTAL SCIENCE?

- *Environmental science draws on diverse disciplines, skills, and interests.*
- *A global perspective helps us understand environmental systems.*
- *The scientific method makes inquiry orderly.*

Environmental science uses scientific approaches of observation and analysis to understand the natural systems around us. How do we know about changes in the extent or composition of the forests of the Amazon basin? How do we understand the impacts of those changes, for people or for biodiversity? These questions are urgent, but it is exciting to work on such important questions. The challenges are daunting, but understanding of the problems can suggest better ways to restore and protect the environments we live in.

In this chapter, we introduce some central ideas and approaches in environmental science. You will explore these themes in greater depth in later chapters. We focus on issues of sustainability, environmental justice, and the scientific method that underlies our understanding of these ideas. We also examine some key ideas that have influenced our understanding of environmental science.

Environmental science integrates diverse fields and viewpoints

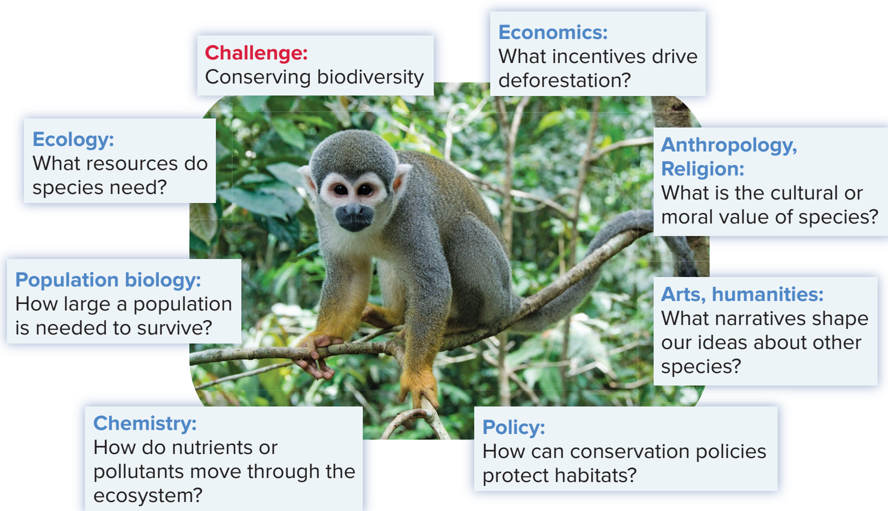
Studying environment systems and environmental challenges often means considering both natural systems—the biodiversity, water resources, or climate systems around us—and cultural systems of knowledge, technology, and ideas that shape the ways we use and occupy our environment. Consequently, the field draws on a wide range of disciplines and worldviews (fig. 1.2). Biology, chemistry, earth science, and geography contribute ideas about our physical environment. Political science, economics, communications, and arts help us understand how people share resources, or compete for them, and communicate about the world around us. As you begin, pause and consider how your interests intersect with the topics of this course (Active Learning, p. 4). Identifying what you most want to learn will help make this course more useful and more interesting for you.

Just as we need a wide diversity of scientific disciplines to fully understand environmental science, so too we need a diversity of perspectives. Whatever your background, class, race, or income, you have useful experiences or observations that tie to issues in this book. Your ideas and experiences can enrich conversations about these topics.

Topics in environmental science, even seemingly abstract ones, are also directly relevant, relating to issues that matter to communities around you. We examine connections of science and citizenship, and we examine what you can do locally to address global problems. Watch for connections to current issues. You may be surprised at how many you find.

Environmental science examines systems

Systems are networks composed of interconnected parts. A forest ecosystem, for instance, includes trees, understory plants, animals, soil bacteria, and fungi, as well as streams, ground water, earth, and other components. Plants capture solar energy and pass it to animals or decomposers. Moisture, nutrients, and pollutants travel through the components of the system. Changes in one part of a



▲ **FIGURE 1.2** Many types of knowledge are needed in environmental science. A few examples are shown here.
National Geographic Image Collection/Alamy Stock Photo

system ripple through and affect other parts, sometimes in surprising ways. Studies in Yellowstone National Park, for example, have found surprising effects after wolves were eliminated from the ecosystem. Elk populations (once held in check by wolves) grew, depleting grazing lands and eroding stream banks. Focusing on systems helps us identify **system drivers**, the factors or processes that cause systems to persist or to change. Often drivers are not immediate or obvious: If stream banks are eroding, is it obvious that the reason is a loss of wolves? Not necessarily. As you read this book, consider system drivers that are not immediately obvious, but that still cause system changes.

Thinking about system interactions and drivers also helps us understand how and why systems transform. **Transformational change**, a shift in fundamental aspects or processes, often occurs when the drivers in a system are altered. Ideas in environmental science can help you contribute to transformation of food systems, climate justice, and other challenges.

Environmental science is global

You are already aware of our global dependence on resources and people in faraway places, from computers built in China to oil extracted in Iraq or Nigeria. These interdependencies become clearer as we learn more about global and regional environmental systems. Often the best way to learn environmental science is to see how principles play out in real places. Familiarity with the world around us will help you understand the problems and their context. Among the learning resources you can find on Connect are Google Earth place marks and questions. These help you see places and environments relating to topics in this book. In Google Earth you can also save your own placemarks and share them with your class.

Active LEARNING

Finding Your Strengths in This Class

A key strategy for doing well in this class is to figure out where your strengths and interests intersect with the subjects you will be reading about. As you have read, environmental science draws on many kinds of knowledge (fig. 1.2). Nobody is good at all of these, but everyone is good at some of them. Form a small group of students; then select one of the topics in section 1.2. Explain how each of the following might contribute to understanding or solving that problem:

artist, writer, politician, negotiator, chemist, mathematician, hunter, angler, truck driver, cook, parent, builder, planner, economist, speaker of multiple languages, musician, businessperson

ANSWERS: All of these provide multiple insights; answers will vary.

▲ **FIGURE 1.3** Earthrise, a view of the bountiful blue planet as seen from Apollo 8, for the first time showed many how precious our Earth is.
Source: National Aeronautics and Space Administration (NASA)

Environmental science helps us understand our remarkable planet

On Christmas Eve, 1968, the astronauts of Apollo 8 chanced to take a snapshot of the Earth rising over the desolate surface of the moon (fig. 1.3). They were astonished to glimpse our bountiful, blue planet, a small, precious oasis in the vast emptiness of space. Alone in our solar system, and in the universe as far as we know, our planet has mild temperatures that support liquid water and life. Plentiful supplies of clean air, fresh water, and fertile soil are regenerated endlessly and spontaneously by biogeochemical cycles and biological communities (discussed in chapters 2 and 3). The value of these ecological services is almost incalculable, although economists estimate that they account for a substantial proportion of global economic activity (see chapter 15).

Perhaps the most amazing feature of our planet is its rich diversity of life. Millions of beautiful and intriguing species populate the Earth and help sustain a habitable environment (fig. 1.4). This vast

▲ **FIGURE 1.4** Perhaps the most amazing feature of our planet is its rich diversity of life. Fuse/Getty Images multitude of life creates complex, interrelated communities where towering trees and huge animals live together with, and depend upon, such tiny life-forms as viruses, bacteria, and fungi. Together, all these organisms make up delightfully diverse, self-sustaining ecosystems, including dense, moist forests; vast, sunny savannas; and richly colorful coral reefs.

From time to time we should pause to remember that, in spite of the challenges of life on Earth, we are incredibly lucky to be here. Because environmental scientists observe this beauty around us, we often ask what we can do, and what we *ought* to do, to ensure that future generations have the same opportunities to enjoy this bounty.

Methods in environmental science

Environmental scientists study fascinating systems and communities. To do so, they rely on orderly collection and analysis of evidence. Ideally, these practices help us understand our world and make reasoned, evidence-based decisions. These are some of the approaches involved.

Observation: A first step in understanding our environment is careful, detailed observation and evaluation of factors involved in pollution, environmental health, conservation, population, resources, and other issues. Knowing about the world we inhabit helps us understand where our resources originate, and why.

The scientific method: Discussed later in this chapter, the scientific method is an orderly approach to asking questions, collecting observations, and interpreting those observations to find an answer to a question. In daily life, many of us have prior expectations when we start an investigation, and it takes discipline to avoid selecting evidence that conveniently supports our prior assumptions. In contrast, the scientific method aims to be cautious, using statistics, blind tests, and careful replication to avoid simply confirming the investigator's biases and expectations.

Quantitative reasoning: How do we know about changes in biodiversity, water quality, or other environmental conditions? We can gain confidence in what we know by examining quantitative evidence, such as the number of species in an area, or the concentration of pollutants. As you read this book, pause to examine data and graphs that provide evidence for ideas.

Uncertainty: Recognizing and understanding the limits of our knowledge is an essential part of science. Science is based on observation and testable hypotheses, but we know that we cannot make all observations in the universe, and we have not asked all possible questions. So knowledge always has limits. Understanding how much we *don't* know, ironically, can improve our confidence in what we *do* know.

Critical and analytical thinking: The practice of stepping back to examine what you think and why you think it, or why someone says or believes a particular idea, is known generally as critical thinking. Acknowledging uncertainty is one part of critical thinking. This is a skill you can practice in all your academic pursuits as you make sense of the complexity of the world we inhabit.

1.2 MAJOR THEMES IN ENVIRONMENTAL SCIENCE

- *Water, air quality, and climate change are key concerns.*
- *Population growth has slowed, as food resources and education have improved.*
- *Natural resource depletion is a major concern.*

In this section we review some of the main themes in this book. All of these are serious problems, but they are also subjects of innovation and progress. Often solutions lie in policy and economics, but environmental scientists provide the evidence on which policy decisions can be made (fig. 1.5).

We often say that crisis and opportunity go hand in hand. Serious problems can drive us to seek better solutions. As you read, ask yourself what factors influence these conditions and what steps might be taken to resolve them.

Environmental quality

Climate Change The atmosphere retains heat near the earth's surface, which is why it is warmer here than in space. But concentrations of heat-trapping "greenhouse gases," especially CO_2, increased dramatically, from 280 parts per million (ppm) 200 years ago to over 415 ppm today. Burning fossil fuels, clearing forests and farmlands, and raising billions of methane burping cattle are some of the main causes. Climate models indicate that by 2100, if current trends continue, global mean temperatures will probably increase by 2° to 6°C compared to 1990 temperatures (3.6° to 12.8°F), far warmer than the earth has been since the beginning of human civilization. For comparison, the last ice age was about 4°C cooler than now. Increasingly severe droughts and heat waves are expected in many areas. Greater storm intensity and flooding

▲ **FIGURE 1.5** Environmental science provides the evidence needed for policy progress, such as the youth-led climate movement. Here, activist Greta Thunberg holds a school strike for the climate outside the Swedish Parliament.
Jasper Chamber/Alamy Stock Photo

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are expected in many regions. Disappearing glaciers and snowfields threaten the water supplies on which cities such as Los Angeles and Delhi depend.

Military experts point out that climate change is among our greatest threats, contributing to refugee crises and terrorism. Already, climate change has forced hundreds of millions of people from farmlands that have become too dry or hot to produce crops. Storms, floods, and rising sea levels threaten villages in many regions. Climate refugees in Syria, Nigeria, Pakistan, and other regions are vulnerable to terrorist activity and sometimes carry it abroad.

These risks are dire, but efforts to find solutions to climate change have already led to unprecedented international cooperation and technical innovation. New strategies for energy production could reduce conflicts over oil and promote economic progress for the world's poorest populations.

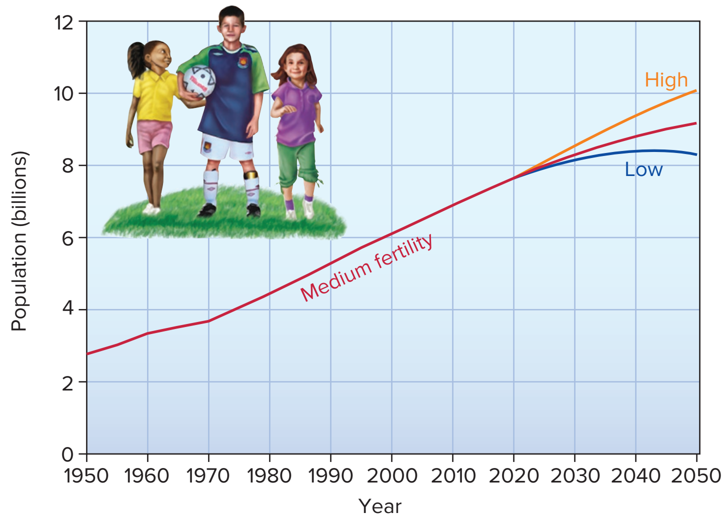
Clean Water Water may be the most critical resource in the twenty-first century. At least 1.1 billion people lack access to safe drinking water, and twice that many don't have adequate sanitation. Polluted water contributes to milions of deaths every year, most of the victims children under age 5. About 40 percent of the world population lives in countries where water demands now exceed supplies, and the United Nations projects that by 2025 as many as three-fourths of us could live under similar conditions. Where we focus attention, though, progress can be dramatic. More than 800 million people have gained access to treated water supplies and modern sanitation since 1990.

Air Quality Air quality has worsened dramatically in newly industrializing areas, especially in much of China and India. In Beijing and Delhi, wealthy residents keep their children indoors on bad days and install air filters in their apartments. Poor residents become ill, and cancer rates are rising in many areas. Millions of early deaths and many more illnesses are triggered by air pollution each year. Worldwide, the United Nations estimates, more than 2 billion metric tons of air pollutants (not including carbon dioxide or windblown soil) are released each year. These air pollutants travel easily around the globe. On some days 75 percent of the smog and airborne particulates in California originate in Asia; mercury, and other industrial pollutants accumulate in arctic ecosystems and in the tissues of native peoples in the far north.

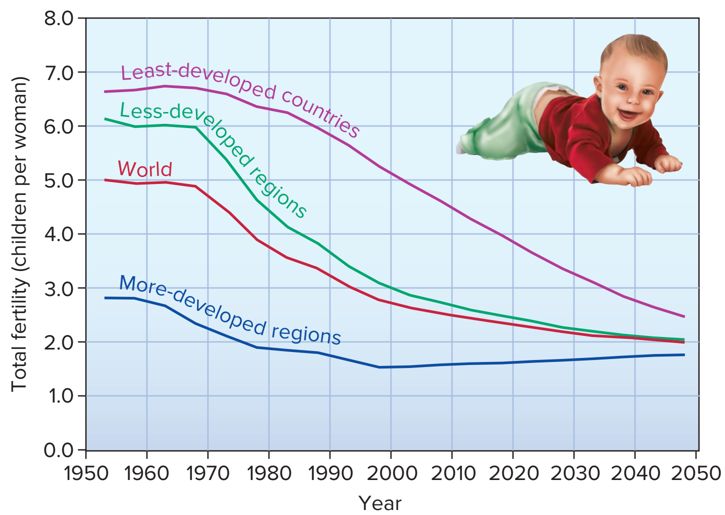
The good news is that we know how to control these pollutants. Cities in Europe and the United States endured deadly air pollution decades ago. Enforcing rules for pollution control, together with newer, safer, and more efficient technology, can rapidly resolve the air pollution and protect public health.

Human population and well-being

Population Growth There are now over 7.8 billion people on Earth, about twice as many as there were 40 years ago. We are adding about 80 million more each year, and trends project a population between 8 and 10 billion by 2050 (fig. 1.6a). Rising populations have often had severe impacts on environmental systems. However, the rate of growth has declined almost everywhere, as fertility rates have dropped (fig. 1.6b).



(a) Possible population trends



(b) Fertility rates

▲ **FIGURE 1.6** Bad news and good news: Globally, populations continue to rise (a), but our rate of growth has plummeted (b). Some countries are below the replacement rate of about two children per woman. Source: United Nations Population Division, *World Population Prospects, 2019.*

Declining birth has resulted mainly from improved education and opportunities for girls, and better health care and child survival. These changes represent tremendous humanitarian progress, as well as demographic stabilization. Even in many low-income regions, the average number of children per woman has dropped from over 5 to just over 2. By 2050, most countries may be below the replacement level of 2.1 children per woman, and the population could stabilize near a moderate estimate of around 9–11 billion.

Safe drinking water has dramatically reduced communicable diseases, leading to longer, healthier lives. Better healthcare access includes oral vaccines. The devastating disease polio, for example, has been eliminated nearly everywhere (fig. 1.7a), and smallpox has been completely eradicated.

More recently, vaccines for the Covid-19 pandemic were developed with astonishing speed, with multiple vaccines developed and distributed in less than a year. Unprecedented levels of global cooperation and communication made this success possible.

Hunger and Food Over the past century, global food production has increased faster than human population growth. We now produce about half again as much food as we need to survive, and consumption of protein has increased worldwide. In most countries weight-related diseases are far more prevalent than hunger-related illnesses. In spite of population growth that added nearly a billion people to the world during the 1990s, the number of people facing food insecurity and chronic hunger during this period actually declined by about 40 million.

Despite this abundance, hunger remains a chronic problem worldwide because food resources are unevenly distributed. In a world of food surpluses, more than 850 million people are chronically undernourished. After decades of progress, hunger has begun increasing, because of war, political oppression, environmental stress. At the same time, soil scientists report that about two-thirds of all agricultural lands show signs of erosion or declining fertility. The biotechnology and intensive farming techniques responsible for much of our recent production gains are too expensive for many poor farmers. How can we produce food sustainably and distribute it fairly? These are key questions in environmental science.

Information and Education Because so many environmental issues can be fixed by new ideas, technologies, and strategies, expanding access to knowledge is essential to progress. The increased speed at which information now moves around the world offers unprecedented opportunities for sharing ideas. At the same time, literacy and access to education are expanding in most regions of the world (fig. 1.7b). Rapid exchange of information on the Internet also makes it easier to quickly raise global awareness of environmental problems, such as deforestation or pollution, that historically would have proceeded unobserved and unhindered. Improved access to education is helping to release much of the world's population from cycles of poverty and vulnerability, especially as girls' education leads to smaller, healthier families.

Natural resources

Biodiversity Loss Biologists report that habitat destruction, overexploitation, pollution, and the introduction of exotic organisms are eliminating species as quickly as the great extinction that marked the end of the age of dinosaurs. The United Nations Environment Programme reports that over the past century more than 800 species have disappeared and at least 10,000 species are now considered threatened (fig. 1.7c). This includes about half of all primates and freshwater fish, together with around 10 percent of all plant species. Top predators, including nearly all the big cats in the world, are particularly rare and endangered. The world's insect populations are also declining. A 2017 study in Germany found that populations of insects, key pollinators and components of the food web, had declined 75 percent since 1990, and bird populations were 15 percent lower. At least half of the forests existing before the introduction of agriculture have been cleared, and many of the ancient forests, which harbor some of the greatest biodiversity, are rapidly being cut for timber, for oil extraction, or for agricultural production of globally traded commodities such as palm oil or soybeans.

Conservation of Forests and Nature Preserves Although exploitation continues, the rate of deforestation has slowed in many regions. The number and extent of protected lands and waters has increased sharply–although protection is sometimes weak. Equally important, conservation efforts increasingly recognize the urgency of protecting rights of indigenous people. In fact, it is increasingly clear that protecting indigenous rights is often the best way to protect biodiversity, forests, fisheries, and other resources we all value. While progress has been slow, indigenous voices are gaining force in defending biodiversity globally.

Marine Resources The ocean provides irreplaceable and imperiled food resources. More than a billion people in developing countries depend on seafood for their main source of animal protein, but most commercial fisheries around the world are in steep decline. According to the World Resources Institute, more than three-quarters of the 441 fish stocks for which information is available are severely depleted or in urgent need of better management. Some marine biologists estimate that 90 percent of all the large predators, including bluefin tuna, marlin, swordfish, sharks, cod, and halibut, have been removed from the ocean.

Despite this ongoing overexploitation, many countries are beginning to acknowledge the problem and find solutions. Marine protected areas and improved monitoring of fisheries provide opportunities for sustainable management. The strategy of protecting fish nurseries is an altogether new approach to sustaining ocean systems and the people who depend on them. Marine reserves have been established in California, Hawaii, New Zealand, Great Britain, and many other areas.

Energy Resources How we obtain and use energy will greatly affect our environmental future. Fossil fuels (oil, coal, and natural gas) presently provide around 80 percent of the energy used in industrialized countries. The costs of extracting and burning these fuels are among our most serious environmental challenges. Costs include air and water pollution, mining damage, and violent conflicts, in addition to climate change.

Transformations in our energy systems are one of the most important and exciting recent developments in environmental science. Renewable energy is an increasingly available and attractive option (fig. 1.7d). The cost of solar power has plummeted, and in many areas solar costs the same as conventional electricity over time. Solar and wind power are now far cheaper, easier, and faster to install than nuclear power or new coal plants.

▲ **FIGURE 1.7** In recent years much of the world has seen dramatic progress in health care (a) and education (b). Major challenges include slowing biodiversity loss, as in this Amazon gold mine (c) and increasing access to renewable energy (d). (a): Dimas Ardian/Getty Images News/Getty Images; (b): Anjo Kan/Shutterstock; (c): kakteen/Shutterstock; (d): DOE Photo/Alamy Stock Photo

1.3 SUSTAINABILITY AND ENVIRONMENTAL SCIENCE

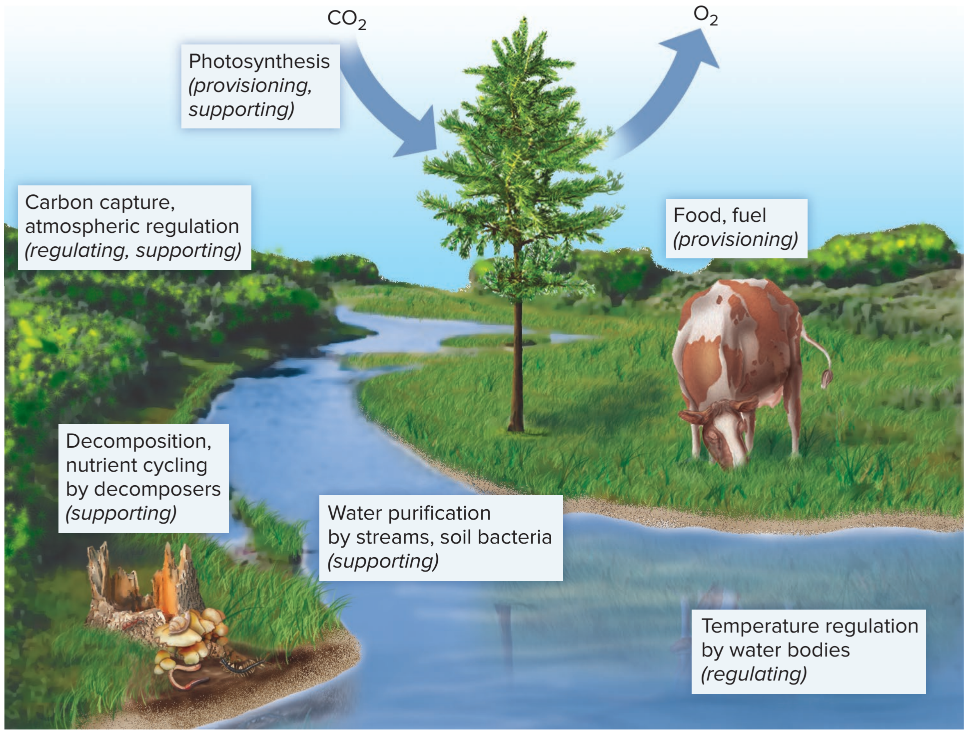
- *Ecosystem services are important in evaluating system values.*
- *Sustainable development goals identify key needs.*
- *Both poverty and wealth produce environmental challenges.*

Aldo Leopold, one of the greatest thinkers on conservation, observed that the great challenges in conservation have less to do with managing resources than with managing people and our demands on resources. Foresters have learned much about how to grow trees, but still we struggle to establish conditions under which villagers in developing countries can manage plantations for themselves. Engineers know how to control pollution but not how to persuade factory owners to install the necessary equipment. City planners know how to design urban areas, but not how to make them affordable for everyone. In this section we'll review some key ideas that guide our understanding of human dimensions of environmental science and resource use. These ideas will be useful throughout the rest of this book.

How do we describe resource use and conservation?

The natural world supplies the water, food, metals, energy, and other resources we use. Some of these resources are finite; some are constantly renewed (see chapter 14). Often, renewable resources can be destroyed by excessive exploitation, as in the case of fisheries or forest resources (see section 1.2). When we consider resource consumption, an important idea is **throughput,** the amount of resources we use and dispose of. A household that consumes abundant consumer goods, foods, and energy brings in a great deal of natural resource–based materials; that household also disposes of a great deal of materials. Conversely a household that consumes very little also produces little waste (see chapter 2).

Ecosystem services, another key idea, refers to services or resources provided by environmental systems (fig. 1.8). *Provisioning* of resources, such as the fuels we burn, may be the most obvious service we require. *Supporting* services are less obvious until you start listing them: These include water purification, production of



▲ FIGURE 1.8 Ecosystem services we depend on are countless and often invisible.

food and atmospheric oxygen by plants, and decomposition of waste by fungi and bacteria. *Regulating* services include maintenance of temperatures suitable for life by the earth's atmosphere and carbon capture by green plants, which maintains a stable atmospheric composition. Cultural services include a diverse range of recreation, aesthetic, and other nonmaterial benefits.

Global ecosystem services amounted to a value of about $124 trillion to $145 trillion per year in 2011, according to ecological economist Robert Costanza, far more than the $65 trillion global economy in that year. These services support most other economic activity, but we tend to forget our reliance on them, and conventional economics has little ability to value them.

Planetary boundaries

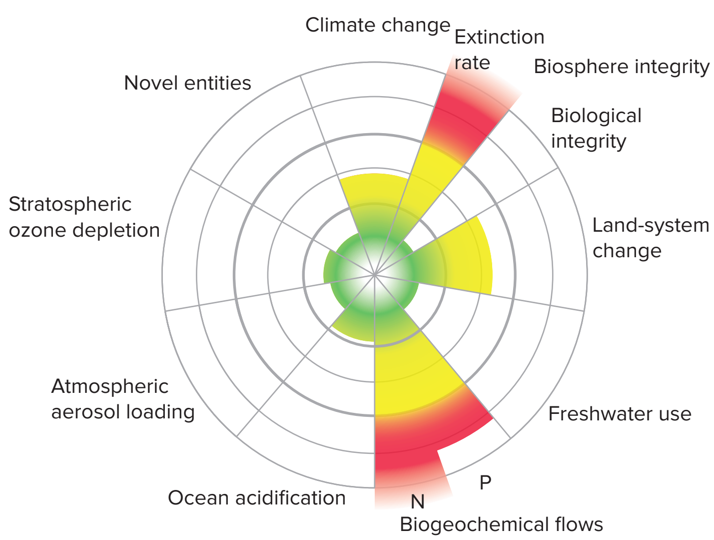
Another way to think about environmental services is planetary boundaries, or thresholds of abrupt or irreversible environmental change. Studies by Johan Rockström and colleagues at the Stockholm Resilience Centre have identified nine major systems with these critical thresholds: climate change, biodiversity, land system change, freshwater use, biogeochemical flows (nitrogen and phosphorus), ocean acidification, atmospheric aerosols, stratospheric ozone loss, and "novel entities," including chemical pollution and other factors (fig. 1.9). Calculations are that we have already passed the planetary boundaries for three of these—climate change, biodiversity loss, and nitrogen cycling. We are approaching the limits for freshwater supplies, land use, ocean acidification, and phosphorus loading.

These ecosystem services are tightly coupled. Destruction of tropical forests in Southeast Asia, for example, can influence heat and drought in North America. Drought and fires in North America enhance climate warming and sea ice loss in the Arctic. A planetary perspective helps us see interconnections in global systems and their effects on human well-being. What it means to pass these boundaries remains uncertain.

Sustainable development involves environmental and social progress

Sustainability is a search for ecological stability and human progress that can last over the long term. Of course, neither ecological systems nor human institutions can continue forever. We can work, however, to protect the best aspects of both realms and to encourage resiliency and adaptability in both of them. World Health Organization director Gro Harlem Brundtland has defined **sustainable development** as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." In these terms, development means bettering people's lives. Sustainable development, then, means progress in human well-being that we can extend or prolong over many generations, rather than just a few years.

In 2016 the United Nations initiated a 15-year program to promote 17 **Sustainable Development Goals** (SDGs). Ambitious and global, the goals include eliminating the most severe poverty and hunger; promoting health, education, and gender equality; providing safe water and clean energy; and preserving biodiversity (fig. 1.10). This global effort seeks to coordinate data gathering and



▲ FIGURE 1.9 Calculated planetary boundaries, or thresholds beyond which irreversible change is likely. Green shading represents safe ranges; yellow represents a zone of increasing risk; red wedges represent factors exceeding boundaries. Source: Will Steffen, Katherine Richardson, Johan Rockström, et al. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 15 Jan 2015: 1259855 DOI: 10.1126/science.1259855.

Sustainable development

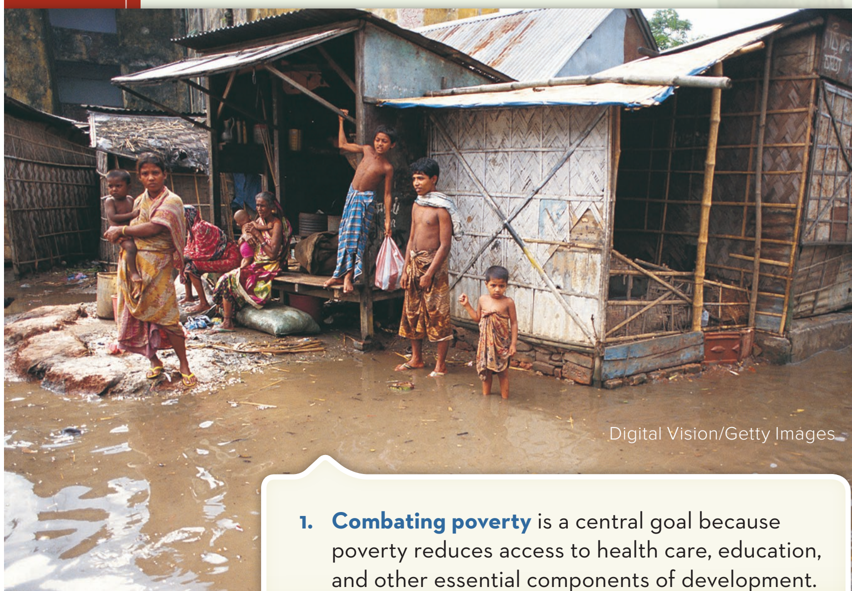
What does it mean? What does it have to do with environmental science?

Sustainable development is a global challenge. The aim is to meet the needs of people today without compromising resources and environmental systems for future generations. In this context, the term *development* refers to improving access to health care, education, and other conditions necessary for a healthy and productive life, especially in regions of extreme poverty. Meeting the needs of people now, while also guarding those resources for their great-great grandchildren, is both a steep challenge and a good idea.

What parts of it are achievable, and how? In general, development means equitable economic growth, which supports better education, housing, and health care. Often development involves accelerated extraction of natural resources, such as more mining, forestry, or conversion of forests and wetlands to farmlands. Sometimes development involves more efficient use of resources or growth in parts of the economy that don't depend on resource extraction, such as education, health care, or knowledge-based economic activities.

Some resources can be enhanced, for example, through reforestation, maintaining fish nurseries, or careful management of soil resources, to use them without depletion for future generations.

Here are ten key factors necessary for sustainable development, according to the United Nations agreement on development, Agenda 21.



Digital Vision/Getty Images

KC 1.1

1. **Combating poverty** is a central goal because poverty reduces access to health care, education, and other essential components of development.

2. **Reducing resource consumption** is a global consideration, but wealthy regions are responsible for most of the world's consumption. For example, the United States and Europe have less than 15 percent of the world's population, but these regions consume about half of the world's metals, food, energy, and other resources.

3. **Population growth** leads to ever-greater resource demands, because all people need some resources. Better family planning, ensuring that all children are wanted, is a matter of justice, resource supply, and economic and social stability for states as well as for families.

KC 1.2 Cynthia Shaw

KC 1.3 Dimas Ardian/Getty Images News/Getty Images

4. **Health care,** especially for children and mothers, is essential for a productive life. Underdeveloped areas such as that shown above can lead to disease, accidents, respiratory and digestive impairments, and other conditions. Without health, economic security is at risk, and poverty can persist through generations.

5. **Sustainable cities** are key because over half of humanity now lives in cities. Sustainable development involves ensuring that cities are healthy places to live and that they cause minimal environmental impact.

KC 1.4

William P. Cunningham

Environmental science is essential to sustainable development because it helps us understand how environmental systems work, how they are degraded, and what factors can help restore them. Studying environmental science can prepare you to aid human development and environmental quality, both at home and abroad, through better policies, resource protection, and planning.

KC 1.7

6. **Environmental policy** needs to guide decision making in local and national governments, to ensure that environmental quality is protected before it gets damaged and to set agreed-upon rules for resource use.
7. **Protection of the atmosphere** is essential for minimizing the rate of climate change and for reducing impacts of air pollution on people, plants, and infrastructure.

Chris Knorr/Design Pics/PunchStock/ Getty Images *KC 1.8*

8. **Combating deforestation and protecting biodiversity** go together because much of the world's biodiversity is in forests. We also depend on forests for water resources, climate regulation, and resources including food, wood, medicines, and building materials. Other key zones of biodiversity include coral reefs, wetlands, and coastal areas.

9. **Combating desertification and drought** through better management of water resources can save farms, ecosystems, and lives. Often removal of vegetation and soil loss make drought worse, and a few bad rainfall years can convert a landscape to desertlike conditions.

Piyaset/Shutterstock *KC 1.6*

10. **Agriculture and rural development** affect the lives of the nearly half of humanity who don't live in cities. Improving conditions for billions of rural people, including more sustainable farming systems, soil stewardship to help stabilize yields, and access to land, can help reduce populations in urban slums.

KC 1.5

Santokh Kochar/Photodisc/Getty Images

These ten ideas and others were described in Agenda 21 of the United Nations Conference on Environment and Development (the "Earth Summit") in Rio de Janeiro, Brazil, in 1992. Laying out priorities for stewardship of resources and equity in development, the document known as Agenda 21 was a statement of principles for guiding development policies. This document has no legal power, but it does represent an agreement in principle by the more than 200 countries participating in that 1992 conference.

CAN YOU EXPLAIN?

1. **What is the relationship between environmental quality and health?**
2. **Why is sustainable development an issue for people in wealthy countries to consider?**
3. **Examine the top left photo carefully. What health risks might affect the people you see? What do you suppose the rate of material consumption is here, compared to your neighborhood? Why?**

William P. Cunningham

FIGURE 1.10 The United Nations Sustainable Development Goals are intended to improve well-being of the world's poorest people while also protecting biodiversity, natural resources, and climate. These goals follow the largely successful Millennium Development Goals. Source: Used with permission of the United Nations, www.un.org/sustainabledevelopment/. The content of this publication has not been approved by the United Nations and does not reflect the views of the United Nations or its officials or Member States.

reporting, so that countries can monitor their progress, and to promote sustainable investment in developing areas.

For each of the 17 goals, organizers identified targets: some quantifiable, some more general. For example, Goal 1, "End poverty," includes targets to eradicate extreme poverty, defined as less than $1.90 per day, and to ensure that all people have rights to basic services, ownership and inheritance of property, and other necessities for economic stability. Goal 7, "Ensure access to affordable, sustainable energy," includes targets of doubling energy efficiency and enhancing international investment in clean energy. Goal 12, "Ensure sustainable consumption and production," calls for cutting food waste in half and phasing out fossil fuel subsidies that encourage wasteful consumption. These goals may not be accomplished by 2030, but having a target to aim for improves the odds of success. And targets allow us to measure how far we have fallen short.

The SDGs also include targets for economic and social equity and for better governance. To most economists and policymakers it seems clear that economic growth is the only way to improve the lot of all people: As former U.S. president John F. Kennedy put it, "a rising tide lifts all boats." But history shows that equity is also essential. Extreme inequality undermines democracy, opportunity, and political stability. Economic and social equality, on the other hand, can promote economic growth by ensuring that extreme poverty and political unrest don't impede progress.

These ambitious goals might appear unrealistic, but they build on the remarkable (though not complete) successes of the **Millennium Development Goals** program, from 2000 to 2015. Targets included an end to poverty and hunger, universal education, gender equity, child health, maternal health, combating of HIV/AIDS, environmental sustainability, and global cooperation in development efforts. While only modest progress was achieved on some goals, UN Secretary General Ban Ki-Moon called that effort "the most successful anti-poverty movement in history." Extreme poverty dropped from nearly half the population of developing countries to just 14 percent in only 15 years. The proportion of undernourished people dropped by almost half, from 23 percent to 13 percent. Primary school enrollment rates climbed from 83 percent to 91 percent in developing countries. Girls gained access to education, employment, and political representation in national parliaments.

The value of having clearly stated goals, especially with quantifiable targets, is that they help people agree on what to work for. With so many simultaneous problems in developing areas, it can be hard for leaders to know where to focus first. Agreed-upon targets, especially when they are shared and monitored by many countries, can strongly motivate action. International agreement on goals can also help motivate financial and planning assistance, both often badly needed in developing areas.

How do we know the state of poverty and wealth?

Policymakers are becoming aware that eliminating poverty and protecting our common environment are inextricably interlinked. The poorest people are often forced to meet short-term survival needs at the cost of long-term sustainability. The good news is that between 1990 and 2015 more than 1 billion people moved out of extreme poverty, mostly in China and India. But the World Bank estimates that at least 760 million people (10 percent of the world population) live below an international poverty line of (U.S.) $1.90 per day. Seventy percent of those poorest people are women and children.

▲ **FIGURE 1.11** The very poor often are forced to live in degraded or unproductive areas, where they have little access to sufficient clean water, diet, medical care, and other essentials for a humane existence. Courtesy of Tom Finkle

TABLE 1.1 Quality-of-Life Indicators

	LEAST-DEVELOPED COUNTRIES	MOST-DEVELOPED COUNTRIES
GDP/person[1]	$615	$40,677
Poverty index[2]	71.8%	0
Life expectancy	59.2 years	82.8 years
Adult literacy	34.8%	99%
Female primary education	10%	95%
Total fertility[3]	6.3	1.3
Infant mortality[4]	74.7	4.3
Improved sanitation	19.8%	100%
Improved water	50.8%	100%
CO_2/capita[5]	0.3 tons	11 tons

[1]ANNUAL gross domestic product (U.S.$).
[2]PERCENT living on less than (U.S.)$2/day.
[3]AVERAGE births/woman.
[4]PER 1,000 live births.
[5]METRIC tons/yr/person.

Source: "Human Development Indices and Indicators." UNDP Human Development Index, 2017. http://hdr.undp.org/sites/default/files/2018_summary_human_development_statistical_update_en.pdf.

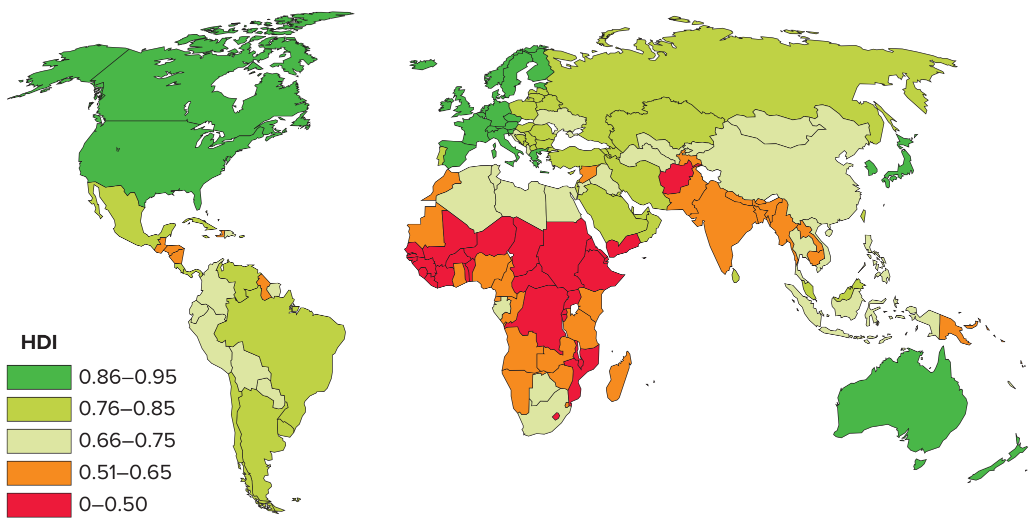
The human suffering engendered by poverty is tragic. The very poor often lack access to an adequate diet, decent housing, basic sanitation, clean water, education, medical care, and other essentials for a humane existence (fig. 1.11). Poverty is both a cause and a consequence of poor health. Every year tens of millions of poor people die from malnutrition and infectious diseases that could be avoided fairly easily. People too ill to work become trapped in a cycle of poverty.

The status of well-being in different countries is reflected in **quality-of-life indicators** monitored by the United Nations (table 1.1). More than 1 billion people have insufficient access to clean water, and 2.6 billion lack basic sanitation. These measures are summarized in the Human Development Index (HDI), calculated each year by the United Nations Development Fund (fig. 1.12). The HDI represents a wide variety of factors, such as life expectancy, years of school, gross national income, and income equity. The bottom 20 HDI rankings are generally in Sub-Saharan Africa, former colonies of European powers. The highest HDI scores aren't usually in the richest countries—these often have repressive monarchies, a few very wealthy citizens, and large populations with few rights. The happiest and healthiest countries have high levels of economic equality, education, and human rights.

Inequality is increasingly recognized as a key concern in economic development. As global incomes have risen, so have disparities in wealth. China, for example, has more billionaires and a larger middle class than any other country, but it also has millions of extremely impoverished people. On a global scale, inequality is even more extreme: The most affluent 1 percent of the world now owns more wealth than the other 99 percent. Even more startling, the richest 62 individuals in the world own more wealth than the poorest half (3.8 billion) of the world's population. Vast differences in wealth and power exist within countries, as well, and these inequities often lead to some of our worst environmental and humanitarian crises (Science and Citizenship, p. 14).

Indigenous peoples safeguard biodiversity

In both rich and poor countries, native, or **indigenous, peoples** are generally the least powerful, most neglected groups. Typically descendants of the original inhabitants of an area taken over by more powerful outsiders, native people often are distinct from their country's dominant language, culture, religion, and racial communities. Of the



▲ **FIGURE 1.12** Human Development Index. Values near 1 represent strong health, education, and quality of life indicators. Data Source: UNEP 2016.

SCIENCE AND Citizenship

Standing up for Change in Cancer Alley

Ideas about environmental justice and environmental racism have shifted our understanding of environment and society in recent decades. These concepts highlight the deep ties between environmental harm and social inequity. They explain how structures of inequality simultaneously produce poverty, generations of illness, and ongoing environmental contamination. Together, these ills weaken society at large, as well as devastating environmental systems. Where do these ideas come from?

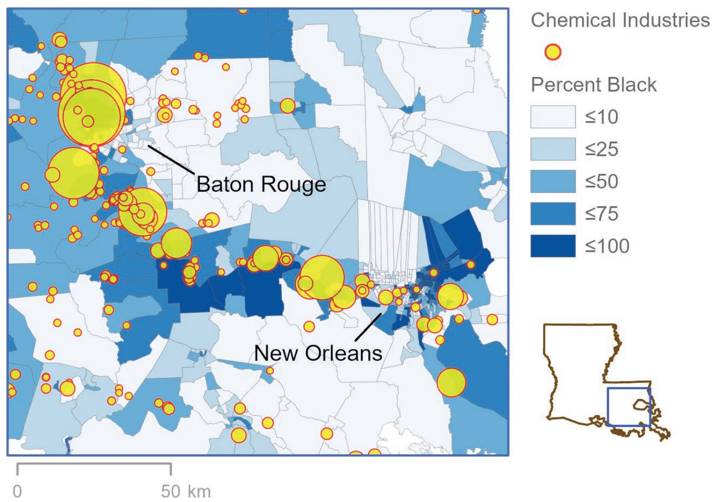
Like many transformative ideas, the concept of environmental racism emerged from the margins, from communities for whom social and environmental injustice are facts of daily life. One of these is the chemical-industry corridor in southern Louisiana known as Cancer Alley. A strip of industrial Mississippi riverfront from the state capitol of Baton Rouge to New Orleans, this corridor holds scores of petrochemical refineries and plastics factories. They process the region's abundant oil and natural gas, producing solvents, vinyl, plastic bags, fertilizers, pesticides, pharmaceutical and cosmetic components, and countless products that you might use regularly. State and federal permits allow these facilities to release clouds of cancer-causing organic compounds, particulate matter, and toxic substances into the air and water (fig. 1). Permitted facilities promise not to release more contaminants than allowed. Evidence suggests these promises often are not kept.

Exposure to pollutants has devastated local communities. Unusually high rates of cancer, kidney diseases, miscarriages, and asthma plague the mostly Black, mostly low-income communities in the corridor. These conditions result from chronic exposure to chloroprene, ethylene oxide, vinyl chloride, ammonia, sulfuric acid, and other compounds in the air and water. Despite decades of protest, policies to control pollutants have been elusive. Industry operators and owners have close friends in government, both in Baton Rouge and in Washington, and billions of dollars in profits tie the state's economy, and lawmakers' fortunes, to these facilities.

In this long struggle, community activists have defined and demonstrated fundamentally important ideas in environmental health. *Environmental justice* and *environmental racism* are both terms popularized in this chemical corridor. Writers such as Dr. Robert Bullard, starting in the 1980s, and more recently, organizers like Ms. Sharon Lavigne, of the organization Rise St. James, have used their writing, speaking, and organizing abilities to publicize the fight against multinational corporations, state government, and federal agencies. The struggle goes on, and the battle is far from won, but these communities have advanced our understanding of environment and social justice. In their work, activists in Cancer Alley invented language and concepts that are now used everywhere to help us see how environmental destruction also destroys communities of color. In doing this, they have led the way for countless other communities struggling against similar obstacles.

Struggles here have also had broad impacts elsewhere. Activists in this area have given evidence that supports national policies on protecting people from hazardous air and water pollutants. This benefits everyone. If you are fortunate enough to live in cleaner, safer neighborhood, you can repay the favor by helping advocate for stronger pollution control policies. You can take some time to learn about environmental justice issues in your area, and what factors have caused them. You can also work on learning about issues that result from products you buy. Where do your fuels, plastics, and solvents come from? How can you use your voice to support policies that make the world safer in those places? These are steps toward making the world healthier for everyone, regardless of race or income.

(a)



(b)

▲ **FIGURE 1** Chemical facilities in Cancer Alley regularly emit air and water pollutants (a). These facilities are concentrated along the Mississippi River corridor, in communities of color (b). Circle sizes represent reported emissions of volatile organic compounds. Data Source: US EPA National Emissions Inventory. (a): TTstudio/Shutterstock world's nearly 6,000 recognized cultures, 5,000 are indigenous, and these account for only about 10 percent of the total world population. In many countries, traditional caste systems, discriminatory laws, economics, and prejudice repress indigenous people. At least half of the world's 6,000 distinct languages are dying because they are no longer taught to children. When the last elders who still speak the language die, so will much of the culture that was its origin. Lost with those cultures will be a rich repertoire of knowledge about nature and a keen understanding of a particular environment and way of life.

Nonetheless, the 500 million indigenous people who remain in traditional homelands still possess valuable ecological wisdom and remain the guardians of little-disturbed habitats that are refuges for rare and endangered species and undamaged ecosystems. The eminent ecologist E. O. Wilson argues that the cheapest and most effective way to preserve species is to protect the natural ecosystems in which they now live. As the Kuna Indians of Panama say, "Where there are forests, there are native people, and where there are native people, there are forests."

Native people also are playing a valuable role in protecting their homelands. From the Amazon jungles, where members of the Suri tribe are using smartphones and computers to track information about illegal logging, to far-northern Alaska, where the Gwich'in tribe is resisting oil drilling in the Arctic National Wildlife Refuge, indigenous people have been effective in environmental protection.

In North America, indigenous groups have led many of the most important recent environmental struggles. Canada's Idle No More movement, one of the largest of these, has mobilized thousands of First Nations, Métis, and Inuit people across the country to protest environmentally destructive projects and land use issues. A particular focus has been the water pollution and destruction of boreal forest and wetlands caused by tar sands mining in Alberta, as well as the dangers of pipeline spills in transporting this dirty fuel to markets (fig. 1.13).

Canada's First Nations have linked with native groups in the United States who share their concerns about the dangers of oil pipelines crossing their territories and threatening natural resources. Protests against the Dakota Access Pipeline in North Dakota, led by indigenous youth, galvanized the movement in 2016. Thousands of people representing hundreds of native tribes gathered where the pipeline route crossed treaty lands beneath the Missouri River, just upstream from the Standing Rock Reservation. Protesting risks of spills to the river, the standoff lasted for months, attracting global attention and support.

Indigenous communities have gained stronger voices in recent years, leading other groups in climate and environmental justice campaigns. The Indigenous Environmental Network (IEN) has helped strengthen many of these efforts. The IEN was a leader in the struggle against Keystone XL pipeline, designed to carry Alberta tar sands across farmlands, grazing lands, and groundwater resources. They finally won this struggle in 2021, when President Joe Biden canceled the pipeline on his first day in office.

1.4 SCIENCE HELPS US UNDERSTAND OUR WORLD

- *The scientific method is an orderly way to ask questions.*
- *Understanding probability reduces uncertainty.*
- *Science is a cumulative process.*

Because environmental questions are complex, we need orderly methods of examining and understanding them. Environmental science provides such an approach. In this section we'll investigate what science is, what the scientific method is, and why that method is important.

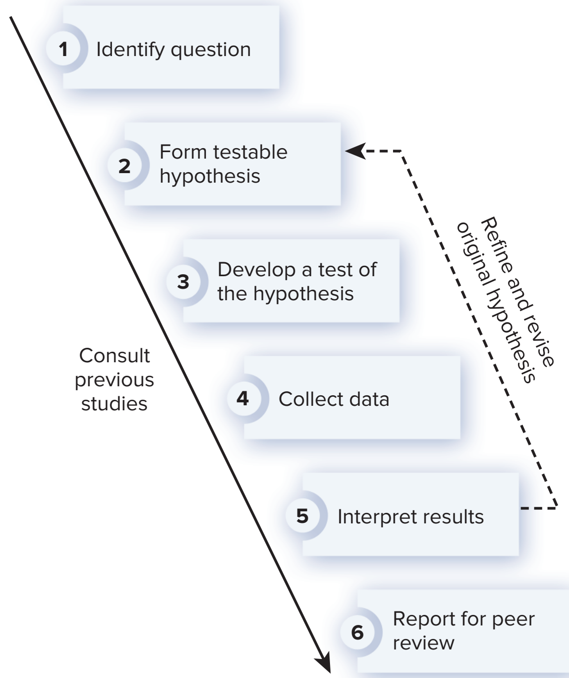
What is science? **Science** (from *scire,* Latin, to know) is a process for producing knowledge based on observations (fig. 1.14). We develop or test theories (proposed explanations of how a process works) using these observations. *Science* also refers to the cumulative body of knowledge produced by many scientists. Science is valuable because it

▲ **FIGURE 1.13** Indigenous and First Nations activists march to protest tar sands pipelines. William P. Cunningham

▲ **FIGURE 1.14** Scientific studies rely on repeated, careful observations to establish confidence in their findings. Source: Dave Partee, Alaska Sea Grant, University of Alaska Fairbanks

TABLE 1.2 | **Basic Principles of Science**

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



▲ **FIGURE 1.15** Ideally, scientific investigation follows a series of logical, orderly steps to formulate and test hypotheses.

helps us understand the world and meet practical needs, such as finding new medicines, new energy sources, or new foods. In this section we'll investigate how and why science follows standard methods.

Science rests on the assumption that the world is knowable and that we can learn about it by careful observation and logical reasoning (table 1.2). For early philosophers of science, this assumption was a radical departure from religious and philosophical approaches. In the Middle Ages the ultimate sources of knowledge about matters such as how crops grow, how diseases spread, or how the stars move were religious authorities or cultural traditions. Although these sources provided many useful insights, there was no way to test their explanations independently and objectively. The benefit of scientific thinking is that it searches for testable evidence. As evidence improves, we can seek better answers to important questions.

Science depends on skepticism and reproducibility

Ideally scientists are skeptical. They are cautious about accepting a proposed explanation until there is substantial evidence to support it. Even then, every explanation is considered only provisionally true, because there is always a possibility that some additional evidence will appear to disprove it. Scientists also aim to be methodical and unbiased. Because bias and methodical errors are hard to avoid, scientific tests are subject to review by informed peers, who can evaluate results and conclusions (fig. 1.15). The peer review process is an essential part of ensuring that scientists maintain good standards in study design, data collection, and interpretation of results.

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

We use both deductive and inductive reasoning

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

Insight, creativity, and experience can also be essential in science. Often discoveries are made by investigators who are passionately interested in their subjects and who pursue hunches that appear unreasonable to other scientists. For example, some of our most basic understanding of plant genetics comes from the intuitive guesses of Barbara McClintock, a geneticist who discovered that genes in corn can move and recombine spontaneously. Where other corn geneticists saw random patterns of color and kernel size, McClintock's years of experience in corn breeding and her uncanny ability to recognize patterns led her to guess that genes can recombine in ways that no one had previously imagined. This intuition helped to transform our understanding of genetics.

The scientific method is an orderly way to examine problems

You may use the scientific method even if you don't think about it. Suppose you have a flashlight that doesn't work. The flashlight has several components (switch, bulb, batteries) that could be faulty. If you change all the components at once, your flashlight might work, but a more methodical series of tests will tell you more about what was wrong with the system—knowledge that may be useful next time you have a faulty flashlight. So you decide to follow the standard scientific steps:

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

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

As you'll read in later chapters, the elusiveness of absolute proof is a persistent problem in environmental policy and law. Rarely can you absolutely prove that the toxic waste dump up the street is making you sick. You could collect evidence to show that it is very probable that the waste has made you and your neighbors sick (fig. 1.16). But scientific uncertainty is often used as an excuse to avoid environmental protection.

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

▲ **FIGURE 1.16** Careful, repeated measurements, and well-formed hypotheses are essential for good science. Chris Sattlberger/Photodisc/Getty Images

Understanding probability reduces uncertainty

One strategy to improve confidence in the face of uncertainty is to focus on probability. **Probability** is a measure of how likely something is to occur. Usually probability estimates are based on a set of previous observations or on standard statistical measures. Probability does not tell you what *will* happen, but it tells you what *is likely* to happen. If you hear on the news that you have a 20 percent chance of catching a cold this winter, that means that 20 of every 100 people are likely to catch a cold. This doesn't mean that *you* will catch one. In fact, it's more likely, an 80 percent chance, that you *won't* catch a cold. If you hear that 80 out of every 100 people will catch a cold, you still don't know whether you'll get sick, but there's a much higher chance that you will.

Science often involves probability, so it is important to be familiar with the idea. Sometimes probability has to do with random chance: If you flip a coin, you have a random chance of getting heads or tails. Every time you flip, you have the same 50 percent probability of getting heads. The chance of getting ten heads in a row is small (in fact, the chance is 1 in 2^{10}, or 1 in 1,024), but on any individual flip, you have exactly the same 50 percent chance, since this is a random test. Sometimes probability is weighted by circumstances: Suppose that about 10 percent of the students in your class earn an A each semester. Your likelihood of being in that 10 percent depends a great deal on how much time you spend studying, how many questions you ask in class, and other factors. Sometimes there is a combination of chance and circumstances: The probability that you will catch a cold this winter depends partly on whether you encounter someone who is sick (largely random chance) and on whether you take steps to stay healthy (get enough rest, wash your hands frequently, eat a healthy diet, and so on).

Probability is often a more useful idea than proof. This is because absolute proof is hard to achieve, but we can frequently demonstrate a strong trend or relationship, one that is unlikely to be achieved by chance. For example, suppose you flipped a coin and got heads 20 times in a row. That could happen by chance, but it would be pretty unlikely. You might consider it very likely that there was a causal explanation, such as that the coin was weighted toward heads. Often we consider a causal explanation reliable (or "significant") if there is less than 5 percent probability that it happened by random chance.

Experimental design can reduce bias

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

Other scientists can use **manipulative experiments,** in which conditions are deliberately altered and all other variables are held constant. Most manipulative experiments are done in the laboratory, where conditions can be carefully controlled. Suppose you are interested in studying whether lawn chemicals contribute to deformities in tadpoles. You might keep two groups of tadpoles in fish tanks and expose one to chemicals. In the lab you can ensure that both tanks have identical temperatures, light, food, and oxygen. By comparing a treatment (exposed) group and a control (unexposed) group, you also make this a **controlled study.**

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

In each of these studies there is one **dependent variable** and one, or perhaps more, **independent variables.** The dependent variable, also known as a response variable, is affected by the independent variables. In a graph, the dependent variable is on the vertical (Y) axis, by convention. Independent variables are rarely really independent (they may be affected by the same environmental conditions as the dependent variable, for example). Often we call them **explanatory variables** because we hope they will explain differences in a dependent variable (Exploring Science, p. 19).

Science is a cumulative process

The scientific method outlined in figure 1.14 is the process used to carry out individual studies. Larger-scale accumulation of scientific knowledge involves cooperation and contributions from countless people. Good science is rarely carried out by a single individual working in isolation. Instead, a community of scientists collaborates in a cumulative, self-correcting process. You often hear about big breakthroughs and dramatic discoveries that change our understanding overnight, but in reality these changes are usually the culmination of the labor of many people, each working on different aspects of a common problem, each adding small insights to solve a problem. Ideas and information are exchanged, debated, tested, and retested to arrive at **scientific consensus,** or general agreement among informed scholars.

The idea of consensus is important. For those not deeply involved in a subject, the multitude of contradictory results can be bewildering: Are coral reefs declining, and does it matter? Is climate changing, and how much? Among those who have done many studies and read many reports, there tends to emerge a general agreement about the state of a problem. Scientific consensus now holds that many coral reefs are in danger, as a result of pollution, physical damage, and warming seas. Consensus is that global climate conditions are changing, though models differ somewhat on how rapidly they will change in different regions.

Sometimes new ideas emerge that cause major shifts in scientific consensus. These great changes in explanatory frameworks were termed **paradigm shifts** by Thomas Kuhn (1967), who studied revolutions in scientific thought. According to Kuhn, paradigm shifts occur when a majority of scientists accept that the old explanation no longer describes new observations very well. For example, two centuries ago geologists explained many of the earth's features in terms of Noah's flood. The best scientists held that the flood created beaches well above modern sea level, scattered boulders erratically across the landscape, and gouged enormous valleys where there is no water now (fig. 1.17). Then the Swiss glaciologist Louis Agassiz and others suggested that the earth had once been much colder and that glaciers had covered large areas. Periodic ice ages proved to be a more durable explanation for geologic features than did a flood, and

Active LEARNING

Calculating Probability

An understanding of probability (the likelihood of an event) is fundamental in most areas of modern science. Working with these concepts is critical to your ability to comprehend scientific information.

Every time you flip a coin, the chance that heads will end up on top is 1 in 2 (50 percent, assuming you have a normal coin). The odds of getting heads two times in a row is $1/2 \times 1/2$, or 1/4.

1. What are the odds of getting heads five times in a row?
2. As you start the fifth flip, what are the odds of getting heads?
3. If there are 100 students in your class and everybody flips a coin five times, how many people are likely to get five heads in a row?

ANSWERS: 1. $1/2 \times 1/2 \times 1/2 \times 1/2 \times 1/2 = 1/32$; 2. 1 in 2; 3. 100 students $\times$ 1/32 = about 3.

EXPLORING Science — Understanding sustainable development with statistics

In environmental science, we know sustainable development is important, but how do we evaluate it? Mainly with statistics. Distilling complex problems to a few numbers can allow you to see the state of a group, compare groups, and see change over time. One key statistic for understanding poverty is the Human Development Index (HDI), a measure that combines national scores for income, education, health care, and other measures (Key Concepts, p. 10).

Suppose you want to know how India is doing on human development and environmental conditions. You might recall that India has a growing population—soon to be the world's largest—and that poverty remains a persistent problem there. If you look up India's HDI score on the website of the United Nations Development Programme (UNDP), you can find that India's HDI is 0.59, on a scale from 0 to 1.0. Does this mean India is doing well? Or not?

Finding the center and distribution of a data set Many statistics mean little without context. To understand an HDI of 0.59, you can compare it to those of other countries. To start, you can compare India's HDI to the mid-point of the group. One common measure of the mid-point is the mean (or average): Add up all the HDI values for the 182 countries with reported scores; then divide the sum by the number of countries (182). It turns out that the mean HDI among these countries is 0.69. Evidently India is slightly below average in development.

Many of us understand visual patterns more readily than numbers. A **histogram,** for example, is a graph that shows the distribution of a data set at a glance. To make a histogram, we first specify ranges of HDI values—say, 0.3 to 0.4, 0.4 to 0.5, and so on. Then we count up the number of countries that fall in each value range. The resulting distribution appears in figure 1.

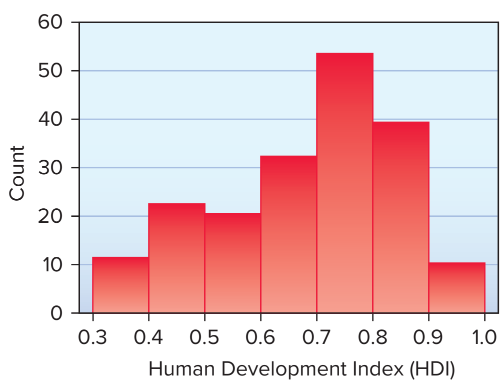


FIGURE 1 A histogram shows a distribution.

Plotting relationships among variables You may recall from earlier in this chapter that many developing areas lack access to safe drinking water and that young children, especially, are vulnerable to waterborne illness. How strong is the relationship between pollution-related deaths and HDI? The UNDP keeps data on estimated numbers of children under 5 years old who die each year from unsafe water. You can use a scatterplot to show the relationship between this variable and HDI (fig. 2). Each point represents a country.

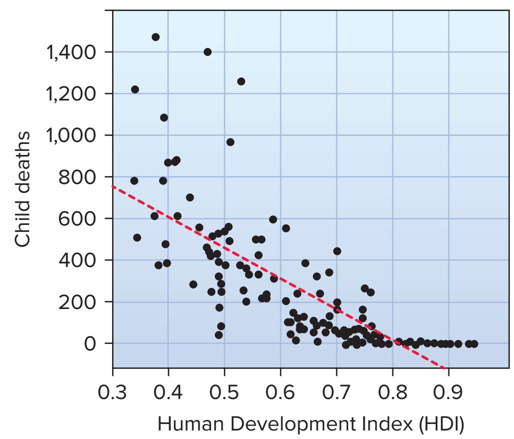


FIGURE 2 A scatter plot shows the relationship.

The scatterplot shows a pattern that generally declines from left to right. Look carefully at the axis labels: Number of deaths generally *decreases* (vertical axis) as HDI *increases* (horizontal axis). This is a **negative relationship.** A straight line shows the approximate trend in the data.

The points don't fit the straight line very tightly, though. Countries with low HDI, around 0.3 to 0.5, have a very wide range of infant deaths, from about 400 to 1,400. Some countries clearly have better success than others in controlling this risk factor. Almost every country with an HDI above about 0.75 has near zero infant deaths from unsafe water. It appears that while there is a negative relationship, countries don't need perfect HDI scores to see much improved infant health.

Error bars improve confidence When you calculate a mean of a *sample* (a portion of all possible observations), your calculated mean is properly considered an approximation of the universal *population* mean. In our case, we have HDI numbers for most countries but not all, and the data set excludes dozens of regions that were once independent states. So we basically have a sample of a larger population. To be confident that we have a reasonable approximation of the population mean from our sample, it is best to estimate the range of *likely* values for the actual (universal) population mean. One approach is *standard error bars*, which use sample size (were there many observations or few?) and variation in the data (all similar? widely different?) to calculate the likely range of the population mean.

This becomes important if you are comparing groups. Suppose you are concerned that affluence is associated with environmental harm, such as climate-changing greenhouse gas emissions. You could compare the average emissions and see if the high-HDI countries also tend to have high CO_2 emissions.

Continued

Continued

Figure 3 shows that your hunch was correct. Not only is the mean higher for high-HDI countries, the standard error bars (the likely range of means) don't overlap. You can say with confidence that these groups are really different in their climate impacts.

Statistics give useful insights into problems we care about. Like any source of knowledge, they are often just part of the story, but they can provide good confidence about what we know, and what we don't know, about an issue.

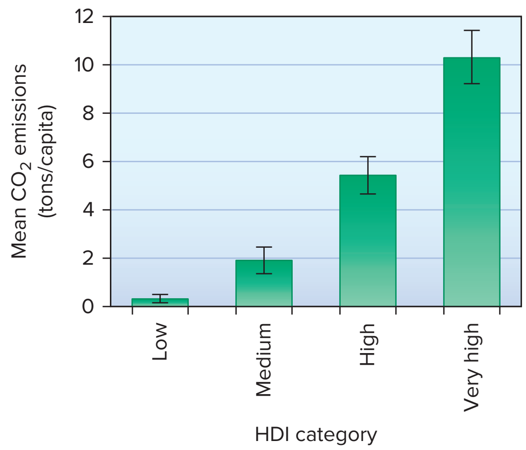


FIGURE 3 Standard error bars show whether groups differ meaningfully.

FIGURE 1.17 Paradigm shifts change the ways we explain our world. Geologists now attribute Yosemite's valleys to glaciers, where once they believed catastrophes like Noah's flood were responsible for geological features like these. John A. Karachewski/McGraw Hill

this new idea completely altered the way geologists explained their subject. Similarly, the idea of tectonic plate movement, in which continents shift slowly around the earth's surface (see chapter 11), revolutionized the ways geologists, biogeographers, ecologists, and others explained the development of the earth and its life-forms.

How do you evaluate your sources?

Environmental science often deals with questions that are emotionally or politically charged. Scientific studies of climate change may be threatening to companies that sell coal and oil; studies of the health costs of pesticides worry companies that use or sell these chemicals. In a world where "fake news" abounds, how can you separate truth from fiction?

When you hear arguments about whose science is valid, remember the basic principles of science: Are the disputed studies reproducible? Are conclusions drawn with caution and skepticism? Is evidence selected to support just one view? Are conclusions supported by a majority of scholars who have studied the problem? Do any of the experts have an economic interest in the outcome?

Often media figures on television or radio will take a position contrary to the scientific majority. A contrarian position gains them publicity and political allies (and sometimes money). This strategy has been especially popular around large issues such as climate change. For decades now, almost all climate scientists have agreed that human activities, such as fossil fuel burning and land clearing, are causing climate change. But it is always possible to find a contrarian scientist who is happy to contradict the majority of evidence for a fee or favors. There are always "expert" witnesses who will testify on opposite sides of any case.

One defense against "fake" news is to be wary of people who claim to have some special knowledge that experts don't know about. (This is a popular strategy in conspiracy theories.) Pause and think: how likely is it, really, that this source knows more than others who study the topic? Have they provided clear evidence or simply repeated inuendo? Another defense is to check well-reputed sources. Major news organizations follow standard rules about transparency, checking alternative opinions, and documenting sources. Avoid sources that don't do so. Still another defense is critical thinking. Astronomer Carl Sagan summarized these ideas in what he called a "Baloney Detection Kit" (table 1.3).

Uncertainty, proof, and group identity

Scientific uncertainty is frequently invoked as a reason to postpone actions that a vast majority of informed scientists consider to be prudent. In questions of chemical safety, energy conservation, climate change, or air pollution control, opponents of change may charge that the evidence doesn't constitute absolute proof, so that no action needs to be taken. You will see examples of this in later chapters on environmental health, climate, air and water pollution, and other topics.

TABLE 1.3 Questions for Baloney Detection

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

Source: Sagan, Carl. *The Demon Haunted World: Science as a Candle in the Dark*. 1997. https://www.google.com/books/edition/_/WGCiHAAACAAJ?sa=X&ved=2ahUKEwiYpoyd9LnvAhVOEVkFHQK7DeEQ8fIDMBl6BAgrEGA.

Similarly, disputes over evolution often hinge on the concept of uncertainty and proof in science. Opponents of teaching evolution in public schools often charge that because scientists call evolution a "theory," evolution is just a matter of conjecture. This is a confused use of terminology. The theory of evolution is supported by overwhelming evidence, but we still call it a theory because scientists prefer to be precise about the idea of proof.

In recent years sociologists have pointed out that our decisions to accept or dispute scientific evidence often depend on group identity. We like to associate with like-minded people, so we tend to adhere to a group viewpoint. Subconsciously we may ask, "Does the community I belong to agree with evolution? Does it accept the evidence for climate change?" Our urge to be agreeable to our group can be surprisingly strong, compared to our interest in critically analyzing evidence. Expectations of group behavior can shift over time, though. In decades past, you might have asked, "Am I the kind of person who recycles?" Today recycling is normal for most people, and few people probably decline to recycle just because their friends don't. Resolving differences on environmental policy sometimes requires recognition of group identity in our attitudes toward science, as well as our attitudes toward policies and issues beyond science. In these ways, you are often integrating your education in environmental science with your actions as a member of society.

1.5 CRITICAL THINKING

- *Critical thinking helps us analyze information.*
- *There are many aspects of critical thinking.*

In science we frequently ask, "How do I know that what you just said is true?" Part of the way we evaluate arguments in science has to do with observable evidence, or data. Logical reasoning from evidence is also essential. And part of the answer lies in critical evaluation of evidence.

An ability to think critically, clearly, and analytically about a problem may be the most valuable skill you can learn in any of your classes. As you know by now, many issues in environmental science are hotly disputed, with firm opinions and plenty of evidence on both sides. How do you evaluate contradictory evidence and viewpoints? **Critical thinking** is a term we use to describe logical, orderly, analytical assessment of ideas, evidence, and arguments. Developing this skill is essential for the course you are taking now. Critical thinking is also an extremely important skill for your life in general. You can use it when you evaluate the claims of a car salesman, a credit card offer, or the campaign rhetoric of a political candidate.

Critical thinking helps us understand why prominent authorities can vehemently disagree about a topic. Disagreements may be based on contradictory data, on different interpretations of the same data, or on different priorities. One expert might consider economic health the overriding priority; another might prioritize environmental quality. A third might worry only about company stock prices, which might depend on the outcome of an environmental policy debate. You can examine the validity of contradictory claims by practicing critical thinking.

Critical thinking is part of science and of citizenship

We evaluate many claims every day, in class, in TV advertising, in understanding public affairs and polices, in reading or watching the news. It is worth pausing to think about what critical thinking means. In general, it means examining sources and considering how a source influences statements or ideas. In general, critical thinking involves breaking an argument down into its component parts, considering sources, and then putting an argument in context to ask, "What does it all mean?"

These processes are often self-reflective and self-correcting. They encourage you to ask, "How do I know that what I just said is true?" Developing habits of critical thinking can help you identify unspoken assumptions, biases, beliefs, priorities, or motives (table 1.4). These habits will also help you do well in class, and they can help you be an informed, thoughtful reader of the world around you.

TABLE 1.4 Steps in Critical Thinking

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

Source: Paul, R. *Critical Thinking*. Foundation for Critical Thinking, 1993. https://www.google.com/books/edition/_/5HhEAQAAIAAJ?sa=X&ved=2ahUKEwjUkYKP9bnvAhXvGFkFHR7qDzIQ7_IDMBd6BAgnEBo.

Here are some steps to practice in critical thinking:

1. *Identify and evaluate premises and conclusions in an argument.* What is the basis for the claims made? What evidence is presented to support these claims, and what conclusions are drawn from this evidence? If premises and evidence are reasonable, do the conclusions truly follow from them?
2. *Acknowledge and clarify uncertainties, vagueness, equivocation, and contradictions.* Are terms used in vague or ambiguous ways? Are all participants in an argument using the same meanings? Is ambiguity or equivocation deliberate?
3. *Distinguish between facts and values.* Can claims be tested, or are statements based on untestable assumptions and beliefs? Are claims made about the worth or lack of worth of something? (If so, these are value statements or opinions and probably cannot be verified objectively.)
4. *Recognize and assess assumptions.* Consider the backgrounds and views behind an argument: What underlying reasons might there be for the premises, evidence, or conclusions presented? Does anyone have a personal agenda in this issue? What does he or she think you know, need, want, or believe? Do hidden biases based on race, gender, ethnicity, economics, or belief systems distort arguments?
5. *Distinguish source reliability from unreliability.* What qualifies the experts on this issue? Is that qualification sufficient for you to believe them? Why or why not?
6. *Recognize and understand conceptual frameworks.* What basic beliefs, attitudes, and values underlie an argument or action? How do these beliefs and values affect the way people view themselves and the world around them?

In this book you will have many opportunities to practice critical thinking skills. Every chapter includes facts, figures, opinions, and theories. Are all of them true? Probably not. They were the best information available when this text was written, but new evidence is always emerging. Data change constantly, as does our interpretation of data.

1.6 WHERE DO OUR IDEAS ABOUT THE ENVIRONMENT COME FROM?

- *Utilitarian conservation focuses on usable resources.*
- *Preservation of nature recognizes the rights of other species.*
- *Modern environmentalism focuses on health and social justice.*

Historically, many societies have degraded the resources on which they depended, while others have lived in relative harmony with their surroundings. Today our burgeoning population and our technologies that accelerate resource exploitation have given the problems of environmental degradation increased urgency.

Many of our current responses to these changes are rooted in the writings of relatively recent environmental thinkers. For simplicity, their work can be grouped into four distinct stages: (1) resource conservation for optimal use, (2) nature preservation for moral and aesthetic reasons, (3) concern over health and ecological consequences of pollution, and (4) environmental justice and citizenship. These stages are not mutually exclusive. You might embrace them all simultaneously. As you read this section, consider why you agree with those you find most appealing.

Environmental protection has historic roots

While many traditional societies have lived in harmony with their environments, many societies have also degraded the water, land, and ecosystems they occupied. Plato complained in the fourth century B.C. that Greece once was blessed with fertile soil and clothed with abundant forests of fine trees. After the trees were cut to build houses and ships, however, heavy rains washed the soil into the sea, leaving only a rocky "skeleton of a body wasted by disease." Springs and rivers dried up, and farming became all but impossible.

Expansion of European colonies, which brought educated scientists into contact with rapid environmental (and human) devastation, led to early writings on environmental costs of human activities. Some of the earliest recorded scientific studies of environmental damage were carried out in the eighteenth century by French or British colonial administrators, many of whom were trained scientists and who observed the impacts of rapid deforestation in colonies. Caribbean sugar plantations, in particular, cleared forests and rapidly eroded soils. With forests gone, rainfall patterns changed, runoff increased, and streams and wells ran dry. Changing rainfall and water resources threatened viability of plantations. Observing this, the pioneering British plant physiologist Stephen Hales, suggested that conserving forest cover preserves rainfall. His ideas were put into practice in 1764 on the Caribbean island of Tobago, where about 20 percent of the land was marked as "reserved in wood for rains."

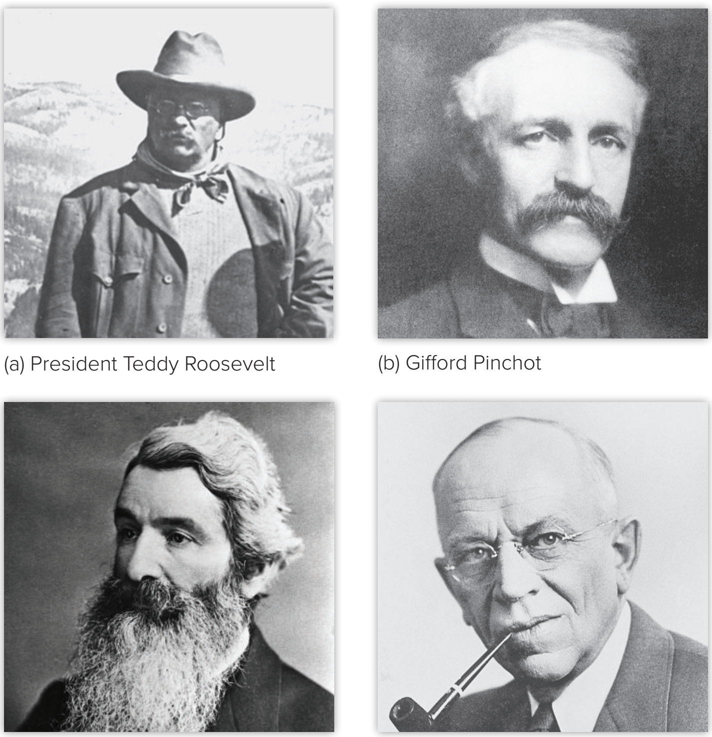
Pierre Poivre, an early French governor of Mauritius, an island in the Indian Ocean, was appalled at the environmental and social devastation caused by the destruction of wildlife (such as the flightless dodo) and the felling of ebony forests on the island by early European settlers. In 1769 Poivre ordered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

Resource waste triggered pragmatic resource conservation (stage 1)

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

Among those influenced by Marsh's warnings were U.S. President Theodore Roosevelt and his chief conservation adviser, Gifford Pinchot (fig. 1.18a,b). In 1905 Roosevelt, who was the leader of the populist Progressive movement, moved forest management out of the corruption-filled Interior Department into the Department of Agriculture. Pinchot, who was the first American-born professional forester, became the first chief of the new Forest Service. He put resource management on an honest, rational, and scientific basis for the first time in American history. Together with naturalists and activists such as John Muir, Roosevelt and Pinchot established the framework of the national forest, park, and wildlife refuge system. They passed game protection laws and tried to stop some of the most flagrant abuses of the public domain. In 1908 Pinchot organized and chaired the White House Conference on Natural Resources, perhaps the most prestigious and influential environmental meeting ever held in the United States. Pinchot also was governor of Pennsylvania and founding head of the Tennessee Valley Authority, which provided inexpensive power to the southeastern United States.

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



(a) President Teddy Roosevelt

(b) Gifford Pinchot

(c) John Muir

(d) Aldo Leopold

▲ **FIGURE 1.18** Some early pioneers of the American conservation movement. (a) President Teddy Roosevelt and his main adviser, (b) Gifford Pinchot, emphasized pragmatic resource conservation, whereas (c) John Muir and (d) Aldo Leopold focused on ethical and aesthetic relationships.

(a): Source: Underwood & Underwood, Library of Congress Prints and Photographs Division [LC-USZC4-4698]; (b): Courtesy of Grey Towers National Historic Landmark; (c): Bettmann/Getty Images; (d): AP Images

Ethical and aesthetic concerns inspired the preservation movement (stage 2)

John Muir (fig. 1.18c), amateur geologist, popular author, and first president of the Sierra Club, strenuously opposed Pinchot's utilitarian policies. Muir struggled to protect California's wild lands, including rapidly dwindling giant sequoia forests, from loggers and from dam-builders. Logging and dams had clear utilitarian value, but Muir argued that forests and wild rivers also had value, even if they weren't "useful" for making money and building houses. He argued that nature deserves to exist for its own sake, regardless of its usefulness to us. Aesthetic and spiritual values formed the core of his philosophy of nature protection. This outlook prioritizes **preservation** because it emphasizes the fundamental right of other organisms—and nature as a whole—to exist and to pursue their own interests (fig. 1.19). Muir wrote, "The world, we are told, was made for man. A presumption that is totally unsupported by the facts. . . . Nature's object in making animals and plants might possibly be first of all the happiness of each one of them. . . . Why ought man to value himself as more than an infinitely small unit of the one great unit of creation?"

Muir, who was an early explorer and interpreter of California's Sierra Nevada range, fought long and hard for establishment of Yosemite and Kings Canyon national parks. The National Park Service, established in 1916, was first headed by Muir's disciple, Stephen Mather, and has always been oriented toward preservation of nature rather than consumptive uses. Muir's preservationist ideas have often been at odds with Pinchot's utilitarian approach. One of Muir and Pinchot's biggest battles was over the damming of Hetch Hetchy Valley in Yosemite. Muir regarded flooding the valley a sacrilege against nature. Pinchot, who championed publicly owned utilities, viewed the dam as a way to free San Francisco residents from the clutches of greedy water and power monopolies.

In 1935, pioneering wildlife ecologist Aldo Leopold (fig. 1.18d) bought a small, worn-out farm in central Wisconsin. A dilapidated chicken shack, the only remaining building, was remodeled into a rustic cabin. Working together with his children, Leopold planted thousands of trees in a practical experiment in restoring the health and beauty of the land. "Conservation," he wrote, "is the positive exercise of skill and insight, not merely a negative exercise of abstinence or caution." The shack became a writing refuge and the main focus of *A Sand County Almanac,* a much beloved collection of essays about our relation with nature. In it, Leopold wrote, "We abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to

▲ **FIGURE 1.19** A conservationist might say this forest is valuable as a supplier of useful resources, including timber and fresh water. A preservationist might argue that this ecosystem is important for its own sake. Many people are sympathetic with both outlooks. Altrendo Nature/Getty Images

use it with love and respect." Together with Bob Marshall and two others, Leopold was a founder of the Wilderness Society.

Rising pollution levels led to the modern environmental movement (stage 3)

The undesirable effects of pollution probably have been recognized as long as people have been building smoky fires. In 1723 the acrid coal smoke in London was so severe that King Edward I threatened to hang anyone who burned coal in the city. In 1661 the English diarist John Evelyn complained about the noxious air pollution caused by coal fires and factories and suggested that sweet-smelling trees be planted to purify city air. Increasingly dangerous smog attacks in Britain led, in 1880, to formation of a national Fog and Smoke Committee to combat this problem. But nearly a century later, London's air (like that of many cities) was still bad. In 1952 an especially bad episode turned midday skies dark and may have caused 12,000 deaths (see chapter 10). This event was extreme, but noxious air was common in many large cities.

The tremendous expansion of chemical industries during and after World War II added a new set of concerns to the environmental agenda. *Silent Spring,* written by Rachel Carson (fig. 1.20a) and published in 1962, awakened the public to the threats of pollution and toxic chemicals to humans as well as other species. The movement she engendered might be called **modern environmentalism** because its concerns extended to include both natural resources and environmental pollution.

Under the leadership of a number of other brilliant and dedicated activists and scientists, the environmental agenda was expanded in the 1970s to most of the issues addressed in this textbook, such as human population growth, atomic weapons testing and atomic power, fossil fuel extraction and use, recycling, air and water pollution, and wilderness protection. Environmentalism has become well established in the public agenda since the first national Earth Day in 1970.

As environmental concerns have expanded to climate action, one of the new leaders has been Bill McKibben (fig. 1.20b), an author, educator, and environmentalist who has written extensively about climate change and has led campaigns to demand political action on this existential threat. As a scholar in residence at Middlebury College, he worked with a group of students to create 350.org, an organization that has sponsored thousands of demonstrations in 181 countries to raise public awareness about climate change and has sparked actions for fossil fuel divestment on many campuses.

Environmental quality is tied to social progress (stage 4)

In recent decades, the intersection between environmental quality and social progress has emerged as a strong theme in conservation. Struggles against pollution and climate change are now understood to be deeply integrated with struggles for human rights and climate justice. This has not always been the case. Eighteenth-century British colonial administrators protected portions of Tobago's forests, to prevent loss of rainfall, but they also witnessed and accepted brutality toward laborers on sugar plantations. With their nineteenth-century views, John Muir and Teddy Roosevelt sought to protect public lands, but they often disregarded the rights of indigenous people who had lived on them.

At the same time, views on the intersection of social and environmental equity have deep roots. Gifford Pinchot, Teddy Roosevelt,

(a) Rachel Carson (b) Bill McKibben

(c) Van Jones (d) Wangari Maathai

▲ **FIGURE 1.20** Among many distinguished environmental leaders in modern times, (a) Rachel Carson, (b) Bill McKibben, (c) Van Jones, and (d) Wangari Maathai stand out for their dedication, innovation, and bravery. (a): RHS/AP Images; (b): Cindy Ord/Getty Images; (c): Ryan Rodrick Beiler/Shutterstock; (d): s_bukley/Shutterstock and John Muir all strove to keep nature accessible to the public at a time when public lands, forests, and waterways were increasingly controlled by a few wealthy individuals and private corporations. The idea of national parks, one of our principal strategies for nature conservation, is to provide public access to natural beauty and outdoor recreation. Aldo Leopold, a founder of the Wilderness Society, promoted ideas of land stewardship among farmers, fishers, and hunters. Robert Marshall, also a founder of the Wilderness Society, campaigned all his life for social and economic justice for working classes.

Increasingly, environmental activists are making explicit the links between environmental quality and social progress on a global scale (fig. 1.21), and issues of sustainable development are recognized across economic divides in wealthy countries. Anthony Kapel "Van" Jones (fig. 1.20c) is one of those who has been a powerful voice for social and environmental progress, and he has helped bring visibility to the role of people of color in environmental action. As both a social justice and environmental activist, Jones has fought poverty and racial injustice by creating hundreds of thousands of "green-collar" jobs installing solar systems and upgrading the energy efficiency of millions of American homes. He served as President Barack Obama's Special Advisor for Green Jobs and has worked to build a "green economy for everyone." He has also brought artists, athletes, and local leaders into national dialogues and engagement around social and environmental issues.

Some of today's leading environmental thinkers come from developing nations, where poverty and environmental degradation together plague hundreds of millions of people. Dr. Wangari Maathai of Kenya (1940–2011) was a notable example. In 1977 Dr. Maathai (see fig. 1.20d) founded the Green Belt Movement in her native Kenya as a way to both organize poor rural women and restore their environment. Beginning at a small, local scale, this organization has grown to more than 600 grassroots networks across Kenya. They have planted more than 30 million trees while mobilizing communities for self-determination, justice, equity, poverty reduction, and environmental conservation. Dr. Maathai was elected to the Kenyan Parliament and served as Assistant Minister for Environment and Natural Resources. Her leadership helped bring democracy and good government to her country. In 2004 she received the Nobel Peace Prize for her work, the first time a Nobel has been awarded for environmental action. In her acceptance speech she said, "Working together, we have proven that sustainable development is possible; that reforestation of degraded land is possible; and that exemplary governance is possible when ordinary citizens are informed, sensitized, mobilized and involved in direct action for their environment."

▲ **FIGURE 1.21** Environmental scientists increasingly try to address both public health and environmental quality. The poorest populations often suffer most from environmental degradation. kaetana/Shutterstock

Photographs of the earth from space (see fig. 1.3) provide powerful icons for the fourth wave of ecological concern, which might be called **global environmentalism.** Such photos remind us how small, fragile, beautiful, and rare our home planet is. We all share an environment at this global scale. As Ambassador Adlai Stevenson noted in his 1965 farewell address to the United Nations, we now need to worry about the life-support systems of the planet as a whole: "We cannot maintain it half fortunate, half miserable, half confident, half despairing, half slave to the ancient enemies of mankind and half free in a liberation of resources undreamed of until this day. No craft, no crew, can travel with such vast contradictions. On their resolution depends the security of us all."

TAKE-AWAY POINTS

Environmental science gives us useful tools and ideas for understanding environmental problems and for finding new solutions to those problems. Environmental science draws on many disciplines, and on people with diverse interests, to understand the persistent problems we face, including human population growth, contaminated water and air, climate change, and biodiversity losses. There are also encouraging examples of progress. Population growth has slowed, the extent of habitat preserves has expanded greatly in recent years, we have promising new energy options, and in many regions we have made improvements in air and water quality.

The scientific method provides an orderly way to examine these issues. Ideally, scientists are skeptical about evidence and cautious about conclusions. These practices are much like critical thinking, which is also emphasized in environmental science.

Environmental science also is concerned with sustainable development because both poverty and affluence contribute to environmental degradation. Impoverished populations often overexploit land and water supplies, while wealthy populations consume or degrade extraordinary amounts of energy, water, forest products, food, and other resources. Differences in wealth lead to contrasts in life expectancy, infant mortality, and other measures of well-being. Resolving these multiple problems together is the challenge for sustainability.

Our ideas about conservation and environment have evolved in response to environmental conditions, from a focus on conservation of usable resources to preservation of nature for its own sake. Throughout these ideas has been a concern for social equity, for the rights of low-income people to have access to resources and to a healthy environment. In recent years these twin concerns have expanded to recognize the possibilities of change in developing countries and the global interconnections of environmental and social concerns.

PRACTICE QUIZ

1. Describe how global fertility rates and populations are changing (see fig. 1.6).
2. What is the idea of "ecological services"? Give an example.
3. Distinguish between a hypothesis and a theory.
4. Describe the steps in the scientific method.
5. What is probability? Give an example.
6. Why are scientists generally skeptical? Why do tests require replication?
7. What is the first step in critical thinking, according to table 1.4?
8. Distinguish between utilitarian conservation and preservation. Name two environmental leaders associated with each of these philosophies.
9. Why do some experts regard water as the most critical natural resource for the twenty-first century?
10. Where in figure 1.5 does the most dramatic warming occur?
11. What are the HDI ranges for the United States, India, and China (see fig. 1.11)?
12. What is the link between poverty and environmental quality?
13. Define *sustainability* and *sustainable development*.

CRITICAL THINKING AND DISCUSSION

Apply the principles you have learned in this chapter to discuss these questions with other students.

1. Changing fertility rates are often explained in terms of better education for girls and women. What might be some reasons for this association?
2. The analytical approaches of science are suitable for answering many questions. Are there some questions that science cannot answer? Why or why not?
3. Often opinions diverge sharply in controversial topics, such as the allowable size of fish catches or the balance of environmental and economic priorities in land management. Think of a controversial topic with which you are familiar. What steps can you take to maintain objectivity and impartiality in evaluating the issue?
4. Environmental activists often focus on questions of social justice and environmental justice. Consider an issue such as air or water quality. Why does it affect different groups unequally?
5. Suppose you wanted to study the environmental impacts of a rich versus a poor country. What factors would you examine, and how would you compare them?

DATA ANALYSIS Working with Graphs

To understand trends and compare values in environmental science, we need to examine a great many numbers. Most people find it hard to quickly assess large amounts of data in a table. Graphing a set of data makes it easier to see patterns, trends, and relationships. For example, scatter plots show relationships between two variables, while bar graphs show the range of values in a set (figs. 1 and 2). Reading graphs takes practice, but it is an essential skill that will serve you well in this course and others.

You will encounter several common types of graphs in this book. Go to the Data Analysis exercise on Connect to practice these skills and demonstrate your knowledge of how to read and use graphs.

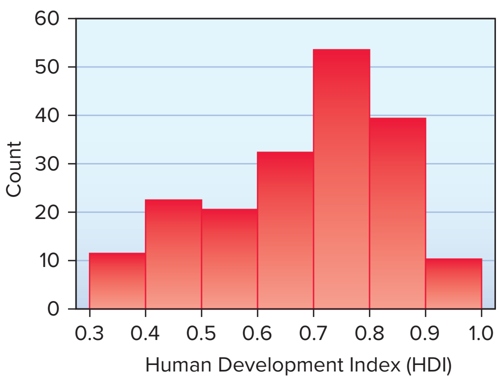


FIGURE 1 A histogram shows a distribution.

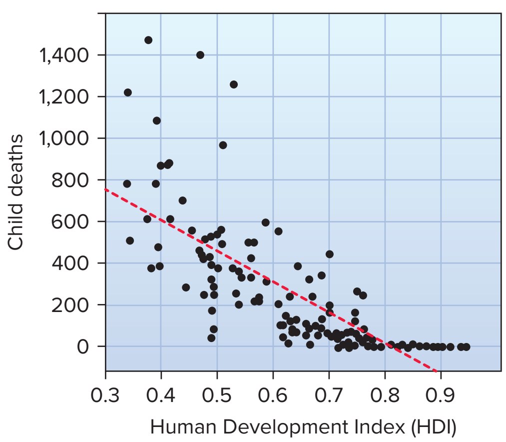


FIGURE 2 A scatter plot shows the relationship.

Design Elements: Active Learning (Toad): Gaertner/Alamy Stock Photo; Case Study (Globe): McGraw Hill; Abstract Background: Martin Kubat/Shutterstock; What do you think (Students using tablets): Richard Hutchings/McGraw Hill; What can you do (Hand holding Globe): deepblue4you/istock/Getty Images

CHAPTER

2 Environmental Systems: Matter, Energy, and Life

LEARNING OUTCOMES

After studying this chapter, you should be able to answer the following questions:

- What are systems, and how do feedback loops affect them?
- Explain the first and second laws of thermodynamics.
- Ecologists say there is no "away" to throw things to, and that everything in the universe tends to slow down and fall apart. What do they mean?
- Explain the processes of photosynthesis and respiration.
- What qualities make water so unique and essential for life as we know it?
- Why are big, fierce animals rare?
- How and why do elements such as carbon, nitrogen, phosphate and sulfur cycle through ecosystems?

Fishing crews come home with empty nets along much of the Louisiana coast in recent years, as low oxygen levels are killing or driving away marine life.

earl_of_omaha/iStock/Getty Images

CASE STUDY

Death by Fertilizer: Hypoxia in the Gulf of Mexico

In the 1980s, fishing crews began observing large areas in the Gulf of Mexico, near the Mississippi River mouth, that were nearly devoid of aquatic life in early summer (fig. 2.1). This region supports shrimp, fish, and oyster fisheries worth $250 to $450 million per year, so this "dead zone" was an economic disaster, as well as an ecological one. Marine biologists suspected that the Gulf ecosystem was collapsing because of oxygen deprivation.

To evaluate the problem, marine scientist Nancy Rabelais began mapping areas of low oxygen concentrations along the Louisiana coast in 1985. Every summer since then, she has found vast areas with oxygen concentration below 2 parts per million (ppm). At 2 ppm, nearly all aquatic life, other than microorganisms and primitive worms, is eliminated. The extent of the Gulf's hypoxic (oxygen-starved) area varies from year to year, but in 2017, the largest year on record, it reached 22,730 km^2 (8,776 mi^2), an area the size of New Jersey.

What causes this huge dead zone? The familiar process of eutrophication, visible in golf course ponds and city parks, is responsible. Eutrophication is the explosive growth of algae and phytoplankton (tiny, floating plants) that occurs when scarce nutrients become available. Normally, scarcity of key nutrients limits plants and algae, but a flush of nutrients allows explosive growth. The overabundance of plants then dies and decays, and decomposers use up nearly all the available oxygen, especially near the sea bed where dead matter falls and collects.

Rabelais and her team observed that each year, 7 to 10 days after large spring rains in the farmlands of the upper Mississippi watershed, oxygen concentrations in the Gulf would drop from 5 ppm to less than 2 ppm. Spring rains are known to wash nutrient-rich soil, organic debris, and fertilizers from farm fields. Pulses of agricultural runoff into the Gulf are followed by a profuse growth of algae and phytoplankton, which drifts to the sea bed. Normally, shrimp, clams, oysters, and other filter feeders consume this debris, but they can't keep up with the sudden flood of material. Instead, decomposing bacteria in the sediment multiply and consume the dead material, using up most of the dissolved oxygen in the process. Putrefying sediments also produce hydrogen sulfide, which further poisons the water near the seafloor.

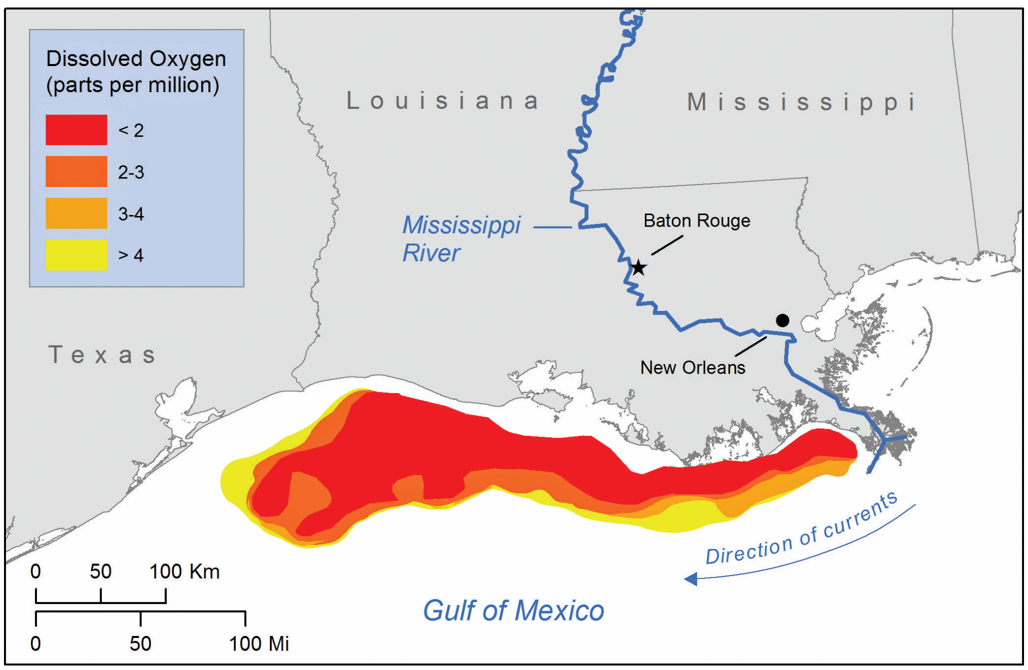
In well-mixed water bodies, such as the open ocean, oxygen from the surface mixes down into lower layers. But warm, protected water bodies like the Gulf are often stratified: Abundant sunlight keeps the upper layers warmer and less dense than lower layers; cold, dense layers lie stable at depth, and fresh oxygen from the surface can't mix downward. Fish may be able to swim away from the hypoxic zone, but bottom dwellers often simply die. Widespread fish kills are also associated with hypoxia in enclosed waters.

First observed in the 1970s, dead zones now occur along the coast of nearly every major populated region. The number increases almost every year, and nearly 700 are now known. They occur mainly in enclosed coastal waters, which tend to be stratified and are vulnerable to nutrient influxes, such as Chesapeake Bay, Long Island Sound, the Mediterranean Sea, the Black Sea, and China's Bohai Bay. But they have also been observed on open coastlines.

Can dead zones recover? Yes. If the influx of nitrogen stops, the system can return to normal. In 1996 in the Black Sea region, farmers in collapsing communist economies were forced to cut nitrogen fertilizer use in half, as fertilizer subsidies collapsed. The Black Sea dead zone disappeared, while farmers saw little decline in their crop yields. But in the Mississippi River watershed, farmers upstream are far from the Gulf and its fisheries. Midwestern policymakers have shown little interest in what happens to fisheries in Louisiana.

The flow of nitrogen reaching U.S. coastal waters has grown by eightfold since the 1950s. Phosphorus, another key nutrient, has tripled. Despite decades of efforts to control nutrients upstream, the dead zone has continued to grow, as intensification of agriculture upstream continues.

The movement of nutrients and energy determines how ecosystems function and how organisms and biological communities flourish or collapse. These topics set the stage for much of the rest of our study of environmental science. In this chapter we examine terms of matter and energy, key elements in living systems, and how they contribute to ecosystems and communities. ■



▲ **FIGURE 2.1** A hypoxic "dead zone" about the size of New Jersey forms in the Gulf of Mexico each summer, the result of nutrients from the Mississippi River. Source: N. Rabalais, LSU/LUMCON, http://www.noaa.gov/media-release/gulf-of-mexico-dead-zone-is-largest-ever-measured

Most institutions demand unqualified faith; but the institution of science makes skepticism a virtue.
—ROBERT KING MERTON

2.1 SYSTEMS DESCRIBE INTERACTIONS

- *Matter and energy move through ecosystems.*
- *Throughput is the amount of matter or energy entering and leaving a system.*
- *Positive feedbacks enhance a process; negative feedbacks diminish it.*

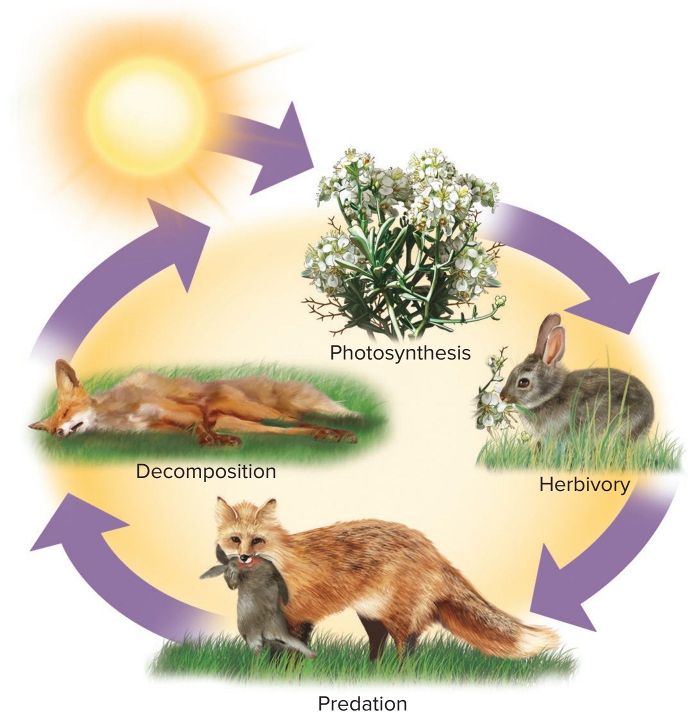
Managing nutrients in the Gulf of Mexico is an effort to restore a stable system, one with equal amounts of inputs and outputs and with balanced populations of plants, animals, and microorganisms. In general, a **system** is a network of interdependent components and processes, with materials and energy flowing from one component of the system to another. The term *ecosystem* is probably familiar to you. This simple word represents complex assemblages of animals, plants, and their environment, through which materials and energy move. In a sense, *you* are a system consisting of trillions of cells and thousands of species that live in or on your body, as well as the energy and matter that move through you.

The idea of systems is useful because it helps us organize our thoughts about the inconceivably complex and interwoven phenomena around us. For example, an ecosystem might consist of countless animals, plants, and their physical surroundings. Keeping track of all the elements and relationships in an ecosystem would probably be an impossible task. But if we step back and think about components in terms of their roles—plants, herbivores, carnivores, and decomposers—and the relationships among them, then we can start to comprehend how the system works (fig. 2.2).

We can use some general terms to describe the components of a system. A simple system consists of compartments (also called state variables), which store resources such as energy or matter, and the flows, or pathways, by which those resources move from one compartment to another. In figure 2.2, the plants and animals represent elements in this cycle of life. We can describe the flows in terms of photosynthesis, herbivory, predation, and decomposition. The plants use photosynthesis to create carbohydrates from carbon, water, and sunlight. The rabbit is an herbivore that consumes plants and uses the energy and chemicals stored there for its own life functions. The fox, in turn, is a carnivore that eats other animals, while the decomposers recycle wastes from all previous compartments.

It may seem cold and analytical to describe a rabbit or a flower as a state variable, but it is also helpful to do so. The energy and matter in the flower or rabbit are really the same; they just change their physical location (or state) when moving from one organism to another.

Understanding the characteristics of ecological systems can help us diagnose disturbances or changes in those systems: For example, if rabbits become too numerous, herbivory can become too rapid for plants to sustain. This could lead to collapse of the system. Similarly, in the Gulf of Mexico, excess nitrogen and phosphorus have led to excess algal growth—this results in reduced oxygen levels in the water, which kills fish and other aquatic organisms. Let's examine some of the common characteristics we can find in systems.



▲ **FIGURE 2.2** A system can be described in very simple terms.

Systems can be described in terms of their characteristics

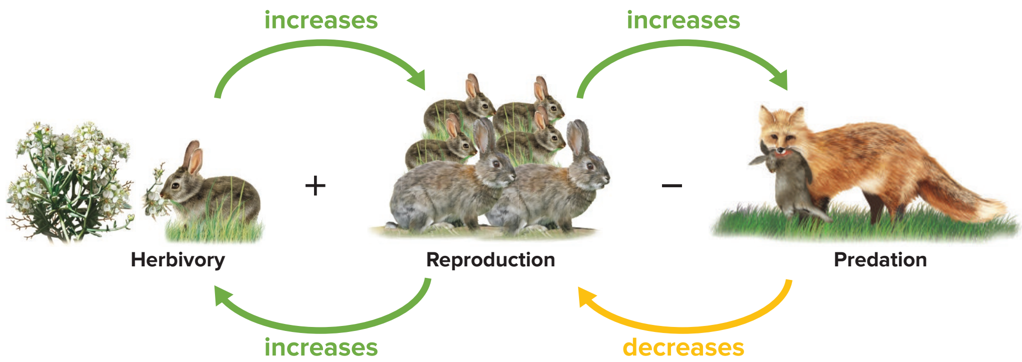
Open systems are those that receive inputs from their surroundings and produce outputs that leave the system. The Gulf of Mexico is an open system. Fresh water, nutrients, and some organisms flow into the Gulf from rivers, while energy comes from the sun. In general, all natural systems are open to some extent.

Benchmark Data

Among the ideas and values in this chapter, the following are a few worth remembering.

2 ppm	Dissolved oxygen minimum for most aquatic life
1:10	Ratio of H^+ ions at successive pH values
1:10	Rule of thumb: energy retained at successive trophic levels
1,372 W/m^2	Solar energy at the top of the atmosphere, the energy for nearly all ecosystems and biogeochemical cycles
80 Tg	Amount of N fixed by natural processes per year
140 Tg	Amount of N released by agriculture and industry per year
7 GT	Amount of C released by land clearing and fossil fuel combustion

In theory, a **closed system** exchanges no energy or matter with its surroundings, but these are rare. Some biological communities may appear to be closed. For example, a carefully balanced aquarium with just a few plants, fish, and decomposers or detritus-eaters may exist for a long time without any input of external materials, but plants need light to survive, and excess heat must be dissipated into the surrounding environment. So although closed to material flow, the aquarium is still open with respect to energy.



▲ **FIGURE 2.3** Positive feedbacks amplify a process, such as reproduction (and population growth) in rabbits: When rabbits feed abundantly, they can produce many young, which feed more and produce more young. Negative feedbacks dampen a process. As rabbits become abundant, predation increases, preventing some from reproducing. Removing foxes from the system could lead to a runaway positive feedback loop, which accelerates until the ecosystem is destabilized—as vegetation is depleted and the landscape erodes.

Throughput is the flow of energy and matter into, through, and out of a system. In a stable system, the amount of matter or energy entering equals the amount leaving: If 100 kg of nitrogen enters a system, ultimately 100 kg should be exported.

Throughput is a useful idea in many systems. Compare the throughputs in houses, for example. An uninsulated house might consume and emit millions of calories of heat in a winter month as the furnace struggles to keep a steady temperature inside. An efficiently insulated house might consume (and lose) a small fraction of that heat. Households also vary in throughput of material goods, water, food, and other resources.

Ideally, systems tend to be stable over time. If the Gulf's nitrogen inputs equal outputs, then the amount of phytoplankton, algae, and other organisms should remain relatively constant. When a system is in a stable balance, we say it is in **equilibrium.** Systems can change, though, sometimes suddenly. Often there are **thresholds,** or "tipping points," where rapid change suddenly occurs if you pass certain limits. The Gulf's oxygen levels may decrease gradually without much visible effect until they reach a level at which organisms can't survive. Then suddenly, decaying organic material releases toxins and uses up even more oxygen, which throws the whole system into a downward spiral from which it's difficult to recover.

Feedback loops help stabilize systems

Systems function in cycles, with each component eventually feeding back to influence the size or rate of itself. A **positive feedback loop** tends to increase a process or component, whereas a **negative feedback loop** diminishes it. Feedbacks occur in countless familiar systems. Think of a sound system, when a microphone picks up the sound coming from speakers. The microphone amplifies the sound and sends it back to the speakers, which get louder and louder (a positive feedback) until the speakers blow out or someone cuts the power. Your body has feedback loops that regulate everything from growth and development to internal temperature. When you exercise and get hot, you sweat, and evaporation cools your skin (a negative feedback) to maintain a stable temperature. When you are cold, you shiver, and that activity helps return your temperature to normal.

Positive and negative feedbacks are a fundamental part of ecosystems. Consider the simple system in figure 2.3. A pair of rabbits produces several baby rabbits, and reproduction can lead to greater and greater numbers of rabbits (a positive feedback). If there were an unlimited food supply, the rabbit population would increase indefinitely. Usually, though, predators capture some rabbits, reducing the number that can reproduce and stabilizing the population (a negative feedback). Another negative feedback would occur if rabbits overgrazed their food resources. Starvation would then reduce their reproductive rate and their population.

Multiple loops interact in ecosystems. As the number of rabbits rises, the fox in figure 2.3 has more to eat and will raise more healthy fox kits. A growing fox population reduces the number of rabbits, which in turn allows plants to increase. In general, the number of plants, rabbits, and foxes should oscillate, or vary, around an average that remains stable over time. Often we call this variation around a stable average a "dynamic equilibrium." It's not quite equilibrium because numbers vary, but the overall trend is relatively stable.

One of the more important global feedback systems now being disrupted is Arctic sea ice. As you can read in chapter 9, over the past 200 years, we have greatly increased the amount of heat-trapping greenhouse gases in the atmosphere, and the resulting warming is melting much of the ice in the Arctic Ocean. Normally Arctic sea ice reflects most sunlight back to space, but open water is warmed by absorbed sunlight. Melting thus leads to more warming, which leads to more melting, in a positive feedback loop that is affecting temperatures globally.

Disturbances, events such as fire, flooding, climate change, invasion by new species, or destructive human activities, also interrupt normal feedback loops. Sometimes systems are resilient, so that they return to something like their previous states after a disturbance. Sometimes disturbances cause a system to shift to a new state, so that conditions become permanently altered.

Emergent properties are another interesting aspect of systems, in which the characteristics of a whole system are greater than the sum of its parts. Consider mangrove forests, which grow along coastlines throughout the tropical world (fig. 2.4). Because their direct economic value can be modest, thousands of kilometers of mangrove-lined coasts have been cleared to make room for shrimp ponds or beach resorts. But the mangrove forest provides countless indirect economic

▲ **FIGURE 2.4** Mangrove forests, like many complex ecosystems, have emergent properties beyond being mere collections of trees. They provide many valuable ecosystem services, such as stabilizing shorelines, providing habitat, and protecting the land from tidal waves and storms.
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values. Prop-roots trap sediment and stabilize mudflats, improving water clarity and protecting offshore coral reefs from silt. Mangroves also protect small fish and other marine species. Many commercial ocean fish and shrimp species spend juvenile stages hiding among the mangrove roots. And the forest protects the shoreline from damaging storms and tsunamis. Collectively these services can be worth hundreds of times the value of a shrimp farm, but they exist only when the many parts of the system function together.

2.2 ELEMENTS OF LIFE

- *Matter is recycled but doesn't disappear.*
- *The elements O, C, H, and N account for most mass of living organisms.*
- *Water has unique properties that make life possible.*

What exactly are the materials that flow through a system like the Gulf of Mexico? If a principal concern is the control of nutrients, such as NO_3 and PO_4, as well as the maintenance of O_2 levels, just what exactly are these elements, and why are they important? What does "O_2" or "NO_3" mean? In this section we will examine matter and the elements and compounds on which all life depends. In the sections that follow, we'll consider how organisms use those elements and compounds to capture and store solar energy, and how materials cycle through global systems as well as ecosystems.

To understand how these compounds form and move, we need to begin with some of the fundamental properties of matter and energy.

Matter is recycled but not destroyed

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

Matter also behaves according to the principle of **conservation of matter:** Under ordinary circumstances, matter is neither created nor destroyed but rather is recycled over and over again. It can be transformed or recombined, but it doesn't disappear; everything goes somewhere. Some of the molecules that make up your body probably contain atoms that once were part of the body of a dinosaur and most certainly were part of many smaller prehistoric organisms, as chemical elements have been used and reused by living organisms.

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

Elements have predictable characteristics

Matter consists of **elements** such as P (phosphorus) or N (nitrogen), which are substances that cannot be broken down into simpler forms by ordinary chemical reactions. Each of the 118 accepted elements (92 natural, plus 26 created under special conditions) has distinct chemical characteristics.

Just four elements—oxygen, carbon, hydrogen, and nitrogen (symbolized as O, C, H, and N)—make up more than 96 percent of the mass of most living organisms. Water is composed of two H atoms and one O atom (written H_2O). All the elements are listed in the periodic table of the elements, which you can find at the end of this book. To start with, it's enough to pay attention to just a few (table 2.1).

Atoms are the smallest particles that exhibit the characteristics of an element. As difficult as it may be to imagine when you look at a solid object, all matter is composed of tiny, moving particles, separated by space and held together by energy. Atoms are composed of a nucleus, made of positively charged protons and electrically neutral neutrons, circled constantly by negatively charged

TABLE 2.1 Functions of Some Common Elements

FUNCTION	ELEMENTS	COMMENTS
Fertilizers	N nitrogen P phosphorus K potassium	Essential components of proteins, cells, other biological compounds; crucial fertilizers for plants
Organic compounds	C carbon O oxygen H hydrogen	Form the basic structure of cells and other components of living things, in combination with many other elements
Metals	Fe iron Al aluminum Au gold	Generally malleable; most (not all) react readily with other elements
Toxic elements	Pb lead Hg mercury As arsenic	Many are metals that can interfere with processes in nervous systems