OUR CHANGING CLIMATE

SCIENCE

An Introduction to Environmental Science

Resource Guide

2024–2025

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Introduction

Environmental science is the study of the impacts that human activities have on the environment, including the pollution impact of turning on your lights, the loss of biodiversity from deforestation and the overfishing of the oceans, and the many global impacts of adding billions of tons of greenhouse gases to the atmosphere. However, environmental science is also a tool for developing ways to manage those impacts so that humans, and the other species with whom we share the Earth, can have a sustainable future.

To study these impacts requires an **interdisciplinary** approach, relying on many aspects of biology, earth and atmospheric sciences, fundamental principles of chemistry and physics, and human population dynamics. Section I starts with an overview of how environmental science is conducted—what types of scientific approaches are used and what unique issues environmental science has to deal with. We then explore how the Earth is made up of interconnected systems—living (humans and other species) and nonliving components (e.g., air, water, minerals) joined together by the flow of energy and matter. Environmental science deals with natural systems like lakes and forests and also domesticated systems like cities and farms.

Section II deals with biodiversity, from genes to ecosystems. You will learn the basics of ecosystem ecology—the study of the different ways that living and nonliving components are organized together in nature. We will then focus on nonhuman species—how they have evolved, what controls their distribution and abundance, how they interact with each other, and how human activities impact them. You will also learn some of the ways that environmental scientists develop strategies to protect species and their ecosystems.

In Section III we will turn to the natural resources on which human society depends—how we impact them and how we can use science to sustainably manage them. Natural resources include minerals that provide the raw materials for many of our modern products, as well as the soils in which we grow our food. They also include water resources—critical for drinking and for agriculture—and the natural resources we harvest from ecosystems, such as timber from forests and fish from the ocean. Unfortunately, we have depleted many of these resources through poor management. Environmental scientists are working to develop new, science-based management strategies that will allow for the sustainable use of natural resources.

In Section IV, we deal with four related topics: 1) atmospheric science and air pollution; 2) our various energy sources and how their use causes pollution and other environmental impacts; 3) human health impacts from pollution and other human activities; and 4) how economic **development** and increased energy use has impacted our atmosphere and the global environment—global change in general and global climate change in particular. The human act of adding greenhouse gases to the atmosphere is impacting us today and will likely impact people in the future even more. We will explore what environmental science can add to the work of maintaining a sustainable Earth.

NOTE TO STUDENTS: Throughout this resource guide, you will notice that some terms have been bold-faced. Boldface indicates a key term, and these terms are defined in the glossary of terms at the end of the resource guide.

Section I

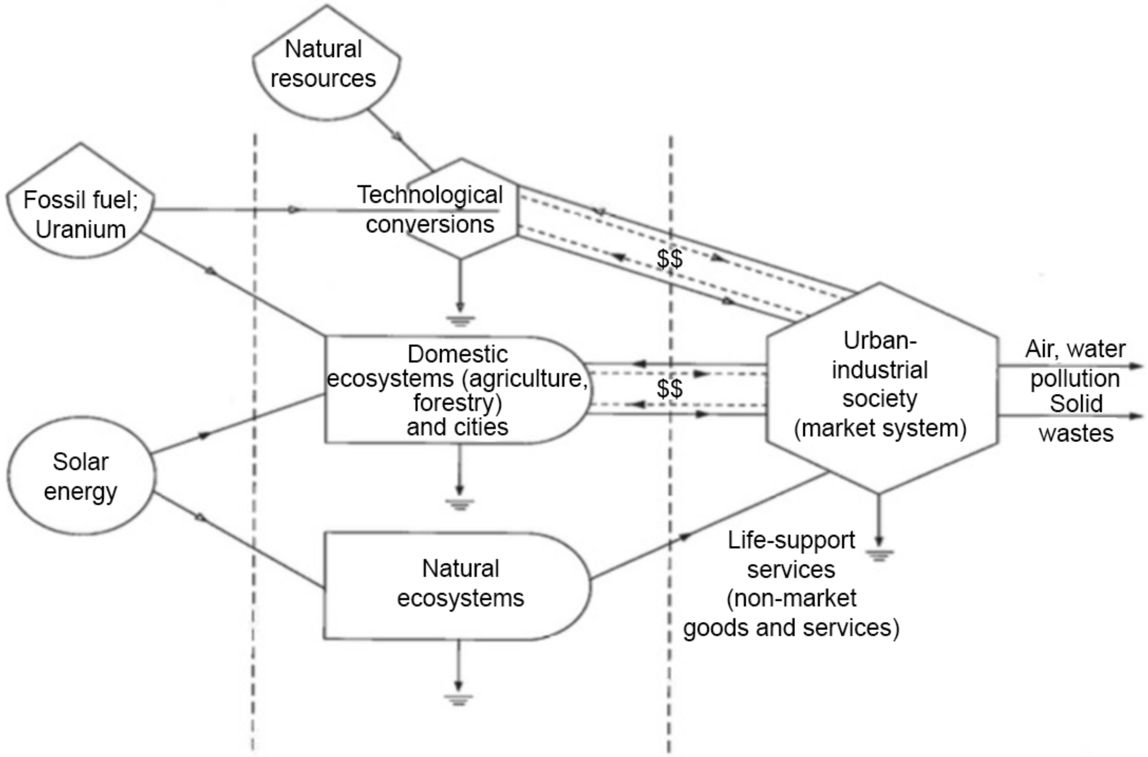
Foundations of Environmental Science

WHAT IS ENVIRONMENTAL SCIENCE?

Environmental science is the study of the impacts of human activities on environmental systems. These human activities include large-scale actions, such as clearing land for agriculture, fishing the oceans for food, mining the land for minerals and fuels, and changing our planet's **climate** through the emissions of decades worth of greenhouse gases. These activities also include everyday individual actions, like driving a car to the store, turning on your lights, and choosing whether to use plastic, paper, or reusable containers.

The **environment** is the sum total of all the conditions and living and nonliving factors that surround an organism, including the others of its kind, its food sources (prey), any predators that may feed on it, the **weather**, the landscape, and any other aspect of the world in which it lives. A local environment is the area immediately surrounding an organism or person; an environment, however, can encompass an area of greater scale. An environment can be as small as a pond or as large as a complete mountain range or an ocean. The immensely complicated global environment is the sum of all the aspects of the Earth.

FIGURE 1



Environmental science is the study of how human activities impact environmental systems.

Source: Odum, E.P., *Ecology: A Bridge Between Science and Society*, 3rd Ed. Sinauer, 1997.

The amount of new growth on trees can be used as an indicator of the health of a forest.

Image Source: Smithsonian Environmental Research Center

Environmental science is interdisciplinary, covering many aspects of biology, earth and atmospheric sciences, fundamental principles of chemistry and physics, human population dynamics, and biological and **natural resources**. Environmental science is a science-based discipline, meaning it is based on the scientific method that includes observations, **hypothesis** testing, field and laboratory research, and other practices, which we will discuss later in this section.

One way of studying the environment is to study its different systems and the ways they interact. A **system** is a set of living and/or nonliving components connected in such a way that changes in one part of the system affect other parts. A particular system can usually be isolated and studied apart from other systems. The Earth is a system and so is an ant colony, a lake ecosystem, and a farm. Because systems are so important to an understanding of the environment, we will devote much of Section I to looking at environmental systems in detail. But first, we will explore how environmental scientists monitor human impacts on environmental systems.

ENVIRONMENTAL INDICATORS

If we wanted to determine whether a person is healthy, we might measure body temperature, heart rate, blood pressure, and respiration rate. If something is amiss with one or more of these indicators, it is usually a reliable signal that something is wrong in the human body. What indicators can we use to determine the vitality of the planet? Evaluating the health of the Earth, or even a specific environment, is much more complex, and we cannot measure every single component. However, as with individuals, assessing certain key aspects of the environment gives us an indication of its health.

An **environmental indicator** is a measure that reflects the environmental health of a system. For example, the amount of new growth on trees might be used to indicate the state of a forest. Unfortunately, at present, there is no single indicator that effectively assesses the whole planet. In addition, the same environmental indicator can tell a very different story depending on when or where the measurement is taken. Measuring new growth on trees over the summer will yield very different data than the same measurements taken over the winter. Likewise, some parts of the world are experiencing declines in annual **precipitation**, while others are seeing increases. Rates of change are also important when considering environmental indicators. This is analogous to taking a person's temperature multiple times during a day to see if it is stable and, if not, how fast it is changing. The importance of a measurement may be best understood in the context of a pattern of measurements: Is growth increasing? Decreasing? Are the changes global? Or regional?

The table below lists a number of commonly used environmental indicators; some are appropriate for studying small-scale situations, while others are global. On a global scale, some of the most common indicators are the size of the human population, food production, species diversity, global temperature, and the concentration of atmospheric CO_2. Each has advantages and limitations. The differing opinions about the status of the planet that you might observe among scientists, the media, and the general public depend in part on what indicators and which time periods are used to make the assessment.

Some Common Environmental Indicators

Environmental Indicator	**Unit of Measure**
Human population	individuals
Ecological footprint	hectares of land

Per capita food production	kg of grain/person
Total food production	kg of grain/hectare of land
Carbon dioxide	concentration in air (ppm)
Global temperature	degrees Centigrade
Sea level change	mm
Annual precipitation	mm
Species diversity	number of species per functional group
Fish consumption advisories	present or absent; or number of fish allowed per week
Ambient water quality (toxics)	concentration
Ambient water quality (conventional)	concentration; presence or absence of bacteria
Atmospheric deposition rates	quantity per unit area per time
Fish catch or harvest	weight of fish per annum or weight of fish per effort expended
Extinction rate	Number of mammal species per 10,000 species per 100 years
Habitat loss rate	land cleared or "lost" per year
Infant mortality rate	Number of deaths of infants under age 1 per 1,000 live births
Life expectancy	Average number of years a newborn infant can be expected to live under current conditions.

This long list of indicators can be grouped into the six indicators on which we will focus:

- Biological diversity
- Human population growth
- Food Production
- Resource consumption
- Global temperature and atmospheric greenhouse gas levels
- Pollution levels

Biological Diversity

Overall **biological diversity** describes the diversity of genes, species, **habitats**, and ecosystems on Earth. The number of species on Earth, and whether that number is increasing or decreasing, can help us measure the biological status of the planet. A **species** is defined as a group of organisms that is distinct from other groups in morphology (body type), physiology, or biochemical properties. Individuals within a species can breed and produce viable offspring. There are approximately 1.8 million "known"—that is, identified and catalogued—species on Earth today. The actual number of species, while highly debated, is likely to be more than ten times that number because most species, especially microbial species, have not yet been identified or catalogued.

Species extinction is a natural part of the process of life on Earth. Roughly 99.9 percent of the species that have ever lived on Earth are now extinct. Though it is difficult to determine what the "background" rate of extinction was before people played a role, estimates have been made using "quiet" periods in the geologic record (that is, time periods with no massive environmental or biological upheaval). "Background" extinction rates are now estimated to be two mammal extinctions per 10,000 species per one hundred years.[1]

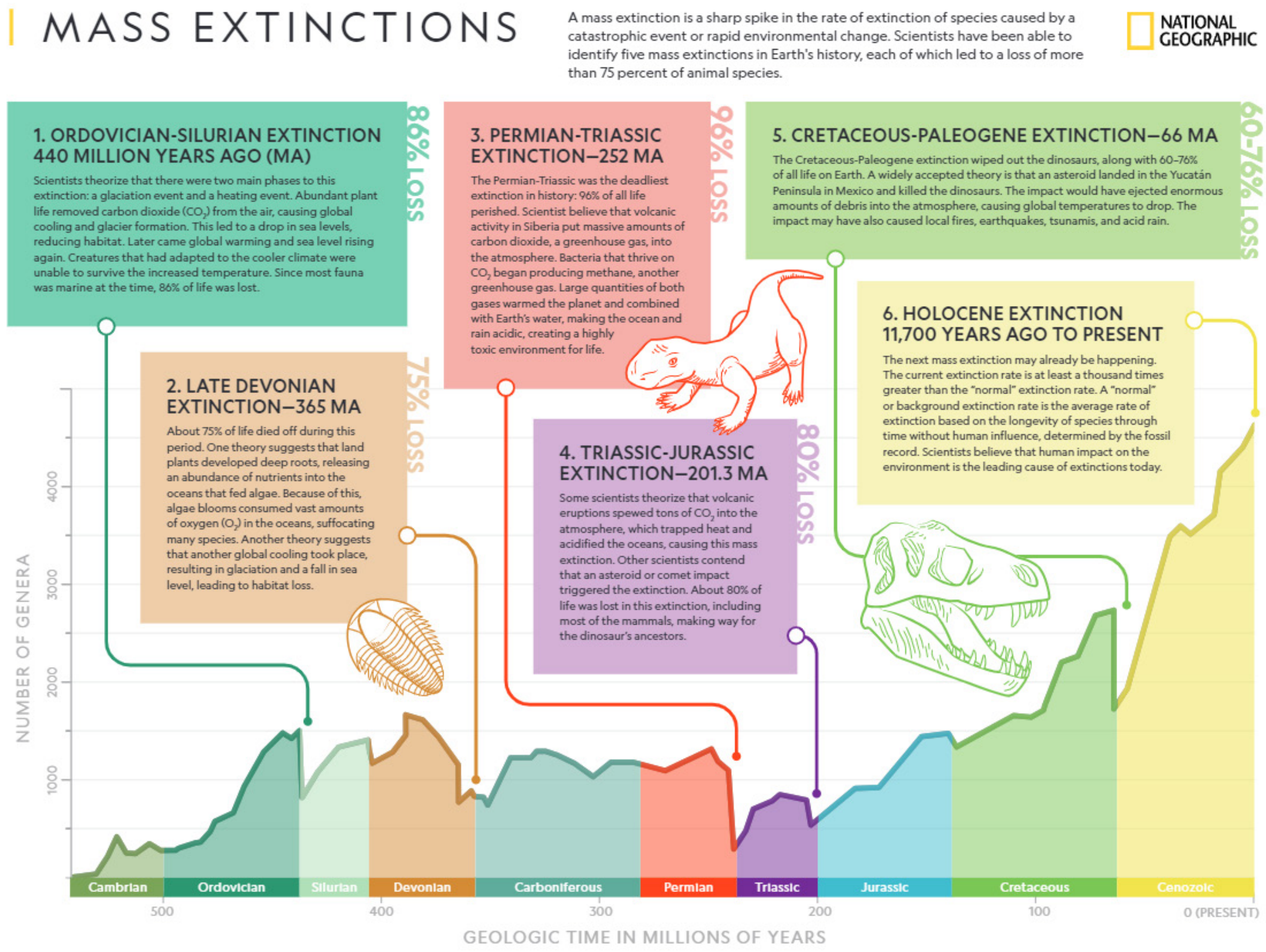
From recent studies, it is clear that human beings have greatly accelerated species extinction rates to up to a hundred times higher than background. The loss and degradation of habitat by human beings is considered the major cause of species extinction today. Attempts to estimate species loss by relating it to the area of land that has been altered by human activity suggest that as many as 40,000 species per year may be going extinct. Gains have

Snow leopards are endangered and may go extinct if present trends are not reversed.

been made in saving certain species, particularly those that attract the attention of people, such as the American bison, peregrine falcon, bald eagle, and California condor, but overall, the number of species on Earth is declining at a rate to rival past **mass extinction** events, such as the extinction of the dinosaurs. (See Figure 2.)

Species such as the Bengal tiger, the snow leopard, and the West Indian Manatee are **endangered** and may go extinct if present trends are not reversed. And the loss of species of particular importance within an ecosystem—**keystone species**—can cause a cascade of extinction of species dependent on them, resulting in harm to or loss of entire ecosystems. The overall rate at which species go extinct on Earth not only tells us how biological diversity on Earth is decreasing but is an important indicator of the state of land, water, and air on the planet. If we use species diversity as an indicator of **environmental quality**, we must conclude that the situation is getting worse and is not sustainable.

FIGURE 2



MASS EXTINCTIONS

A mass extinction is a sharp spike in the rate of extinction of species caused by a catastrophic event or rapid environmental change. Scientists have been able to identify five mass extinctions in Earth's history, each of which led to a loss of more than 75 percent of animal species.

1. ORDOVICIAN-SILURIAN EXTINCTION 440 MILLION YEARS AGO (MA)

Scientists theorize that there were two main phases to this extinction: a glaciation event and a heating event. Abundant plant life removed carbon dioxide (CO_2) from the air, causing global cooling and glacier formation. This led to a drop in sea levels, reducing habitat. Later came global warming and sea level rising again. Creatures that had adapted to the cooler climate were unable to survive the increased temperature. Since most fauna was marine at the time, 86% of life was lost.

2. LATE DEVONIAN EXTINCTION—365 MA

About 75% of life died off during this period. One theory suggests that land plants developed deep roots, releasing an abundance of nutrients into the oceans that fed algae. Because of this, algae blooms consumed vast amounts of oxygen (O_2) in the oceans, suffocating many species. Another theory suggests that another global cooling took place, resulting in glaciation and a fall in sea level, leading to habitat loss.

3. PERMIAN-TRIASSIC EXTINCTION—252 MA

The Permian-Triassic was the deadliest extinction in history: 96% of all life perished. Scientist believe that volcanic activity in Siberia put massive amounts of carbon dioxide, a greenhouse gas, into the atmosphere. Bacteria that thrive on CO_2 began producing methane, another greenhouse gas. Large quantities of both gases warmed the planet and combined with Earth's water, making the ocean and rain acidic, creating a highly toxic environment for life.

4. TRIASSIC-JURASSIC EXTINCTION—201.3 MA

Some scientists theorize that volcanic eruptions spewed tons of CO_2 into the atmosphere, which trapped heat and acidified the oceans, causing this mass extinction. Other scientists contend that an asteroid or comet impact triggered the extinction. About 80% of life was lost in this extinction, including most of the mammals, making way for the dinosaur's ancestors.

5. CRETACEOUS-PALEOGENE EXTINCTION—66 MA

The Cretaceous-Paleogene extinction wiped out the dinosaurs, along with 60–76% of all life on Earth. A widely accepted theory is that an asteroid landed in the Yucatán Peninsula in Mexico and killed the dinosaurs. The impact would have ejected enormous amounts of debris into the atmosphere, causing global temperatures to drop. The impact may have also caused local fires, earthquakes, tsunamis, and acid rain.

6. HOLOCENE EXTINCTION 11,700 YEARS AGO TO PRESENT

The next mass extinction may already be happening. The current extinction rate is at least a thousand times greater than the "normal" extinction rate. A "normal" or background extinction rate is the average rate of extinction based on the longevity of species through time without human influence, determined by the fossil record. Scientists believe that human impact on the environment is the leading cause of extinctions today.

The five past mass extinctions events. Current human impacts may be causing another such extinction event.

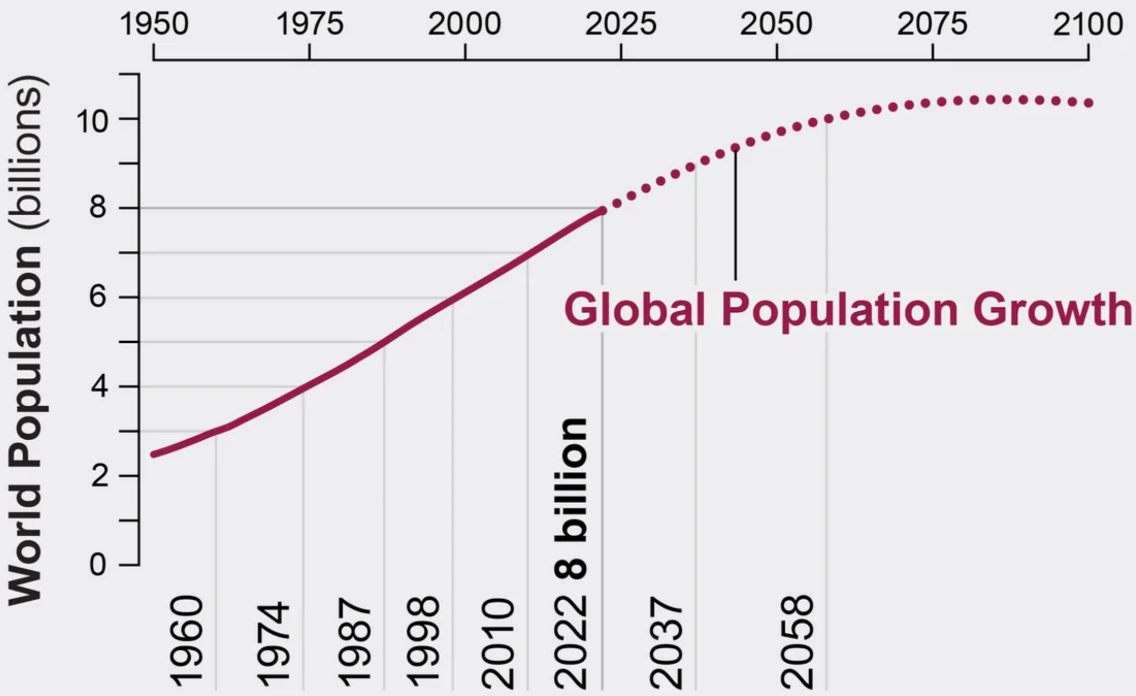
Source: National Geographic

World Human Population

According to the United Nations, the global human population reached eight billion people in November 2022. Roughly 378,000 infants are born and 148,000 people die each day resulting in 230,000 new inhabitants on Earth each day, or almost a million new people on Earth every four days. Until the 1960s, the world population was undergoing *exponential growth*, which is growth that increases as a percentage of the numbers already in the population. While human population growth has slowed and is no longer exponential, world population size will nonetheless continue to increase for at least fifty to a hundred years. The United Nations projects that world population will level off somewhere between 8 and 12 billion people by the year 2150.

The growing human population on the Earth creates a greater demand on Earth's finite resources.

FIGURE 3



Human population size estimates from 1960 to today and a projection to 2100.

Credit: Katie Peek; Data Source: World Population Prospects 2022, United Nations Population Division. Image Source: Scientific American

Can the Earth sustain so many people? If we use the human population on Earth as an environmental indicator, it is encouraging that the *rate* of population growth has slowed, but we still should be concerned that the total population will continue to increase for at least the next fifty years and possibly longer. The additional people on Earth will create a greater demand on Earth's finite resources, including energy, food, water, and land and—unless we dramatically change our industrial society—will produce more **pollution** and **waste** for the foreseeable future.

Combustion of fossil fuel is the primary human activity that produces carbon dioxide.

Food Production

Food grains such as wheat, corn and rice provide more than half the **calories** eaten by humans. Worldwide grain production is a result of the quality of **soils**, climatic conditions, land area under cultivation, human labor, energy, and water expended on growing food, and other influences. Therefore, an increase or decrease in the amount of grain grown worldwide for human consumption is an environmental indicator.

The term "intensity" in the context of agriculture refers to how much food is grown per hectare or acre of land. The agricultural practices used to produce food vary widely from high-intensity monoculture (one crop) to low-intensity polyculture (many crops). The yield (tons of grain per unit area of land) from a given area can indicate both the intensity of agricultural methods and the quality of the land. High-intensity agricultural practices often lead to soil erosion, runoff of fertilizers and animal wastes into waterways, and buildup of pesticides, all of which reduce the quality of the land. As land becomes more degraded, its yield begins to decline.

Resource Consumption

Sustainable use occurs when present-day consumption of resources allows an adequate supply to remain for future generations. Although there is no single way to determine the sustainability of a given society, the rapid depletion of a resource is a clear indication that its use is not sustainable. The human consumption of resources, energy, and land all contribute to a decrease in the sustainability of not only human activities, but of the natural ecosystem on which all species, including humans, depend. However, many of the same human activities that cause adverse impacts can improve the overall quality of life among human beings. Somehow, there must be a balance between utilizing resources to improve life today, saving them for future generations, and protecting the natural environment.

Obviously, the larger the population, the greater the consumption of resources. So, more people, regardless of their lifestyle or where they live, means a greater environmental impact. But resource use per person, which varies from region to region and by type of economy and country, is also critical. Patterns of resource consumption differ vastly in different parts of the world. For example, a country where most people live in relatively small houses will have less impact than a country where most people live in large houses, all other factors being equal. And the way people heat and light their homes (with kerosene, candles, or electricity, for example), will produce different environmental impacts.

For some resources, a very small portion of the world's population may be responsible for most of the consumption. The United Nations Development Program reports that the twenty percent of the people in the world who live in **developed countries** consume forty-five percent of all meat and fish, fifty-eight percent of total energy, and eighty-four percent of all paper, and own eighty-seven percent of the world's automobiles and trucks. The poorest twenty percent of the people in the world consume or use five percent or less of each of these items. Thus, while it is true that a larger population translates to more consumption, more pollution, and more environmental impact, the way people live is also an important predictor of environmental impact.

Global Temperatures and Greenhouse Gases

The temperature of the Earth is regulated by many factors, including incoming solar radiation, absorbed solar heat emanating from the Earth, the surface area of ice caps and ocean, and the concentration of certain gases that surround the Earth. These gases trap heat around the Earth, warming the **atmosphere**—much like the glass around a greenhouse traps heat—so they are sometimes called greenhouse gases. Carbon dioxide and methane are two greenhouse gases that are present in the atmosphere due to both natural processes and human activities. Combustion of fossil fuel is the primary human activity that produces carbon dioxide.

For the past 130 years, global temperatures have fluctuated but show an overall increase. (See Figure 4.) During the same period, atmospheric carbon dioxide and methane concentrations also increased steadily. (See Figure 5.) Virtually all scientists agree that the increase in carbon dioxide during the last two centuries is **anthropogenic** (a result of human activity), coming especially from the combustion of fossil fuels and destruction of forests.

FIGURE 4

Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

Changes in global surface temperature relative to 1850–1900

(a) Change in global surface temperature (decadal average) as reconstructed (1–2000) and **observed** (1850–2020)

(b) Change in global surface temperature (annual average) as **observed** and simulated using human & natural and only natural factors (both 1850–2020)

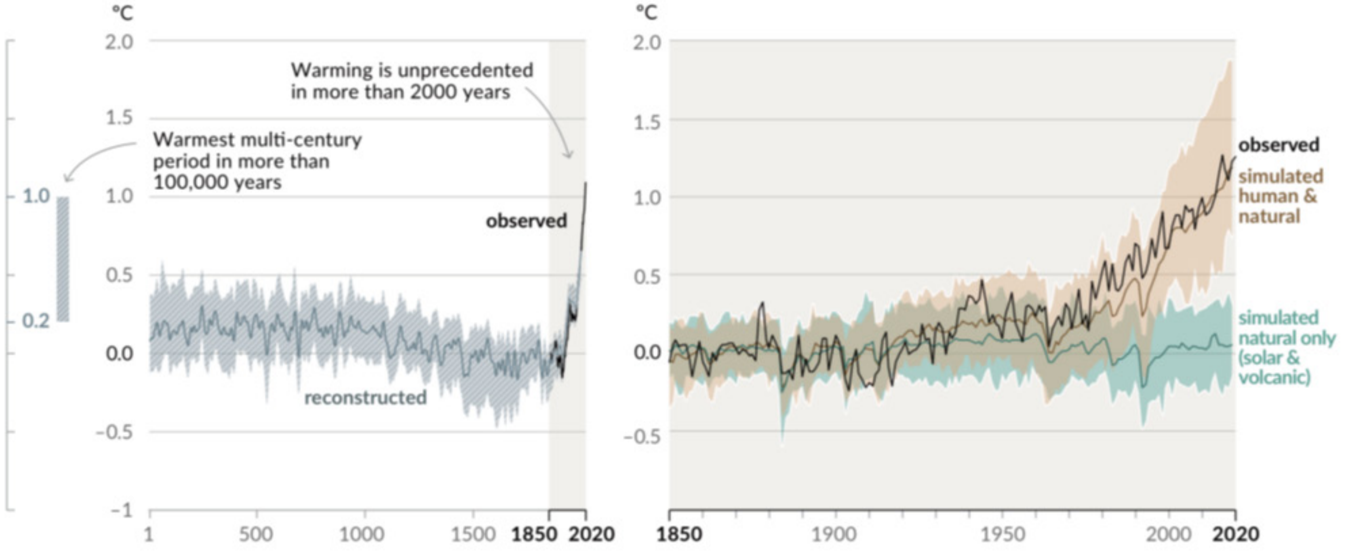


Figure SPM.1 | History of global temperature change and causes of recent warming

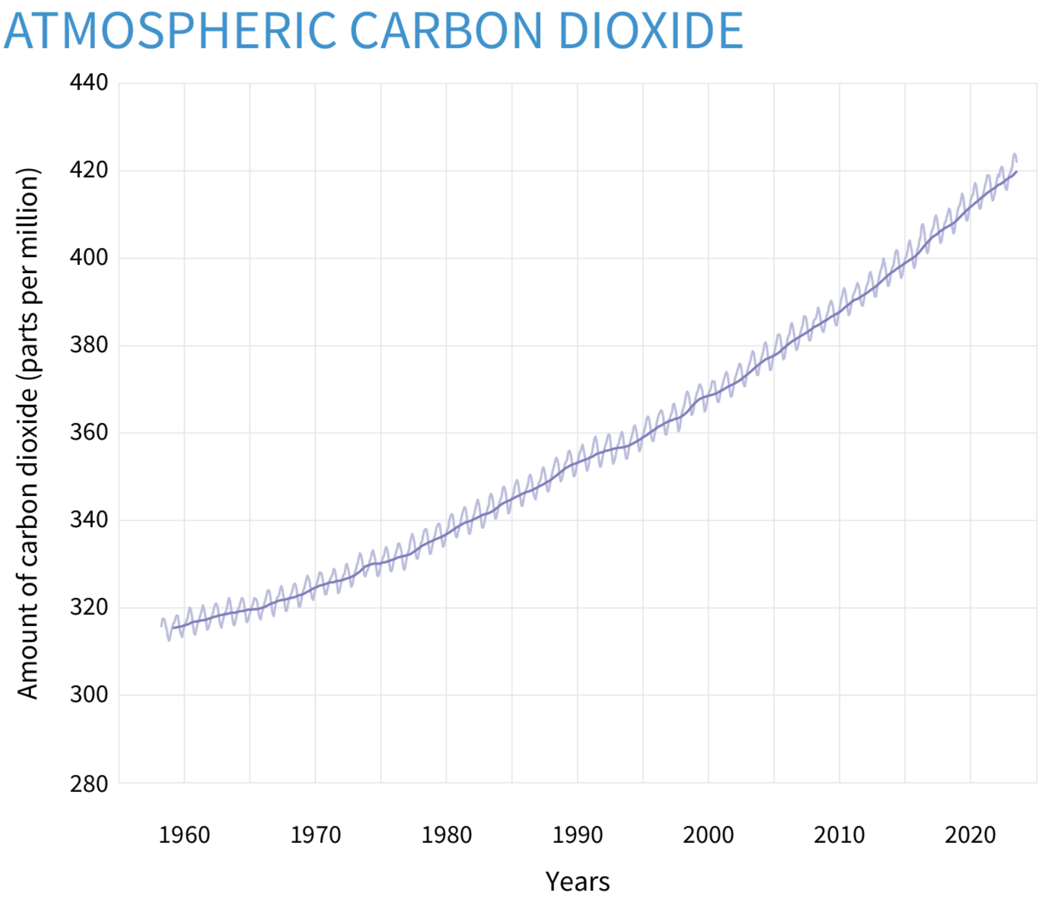
Panel (a) Changes in global surface temperature reconstructed from paleoclimate archives (solid grey line, years 1–2000) **and from direct observations** (solid black line, 1850–2020), both relative to 1850–1900 and decadally averaged. The vertical bar on the left shows the estimated temperature (*very likely* range) during the warmest multi-century period in at least the last 100,000 years, which occurred around 6500 years ago during the current interglacial period (Holocene). The Last Interglacial, around 125,000 years ago, is the next most recent candidate for a period of higher temperature. These past warm periods were caused by slow (multi-millennial) orbital variations. The grey shading with white diagonal lines shows the *very likely* ranges for the temperature reconstructions.

Panel (b) Changes in global surface temperature over the past 170 years (black line) relative to 1850–1900 and annually averaged, compared to Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model simulations of the temperature response to both human and natural drivers (brown) and to only natural drivers (solar and volcanic activity, green). Solid coloured lines show the multi-model average, and coloured shades show the *very likely* range of simulations.

History of global temperature change and causes of recent warming.

Source: IPCC

FIGURE 5



Atmospheric carbon dioxide.

Source: NOAA

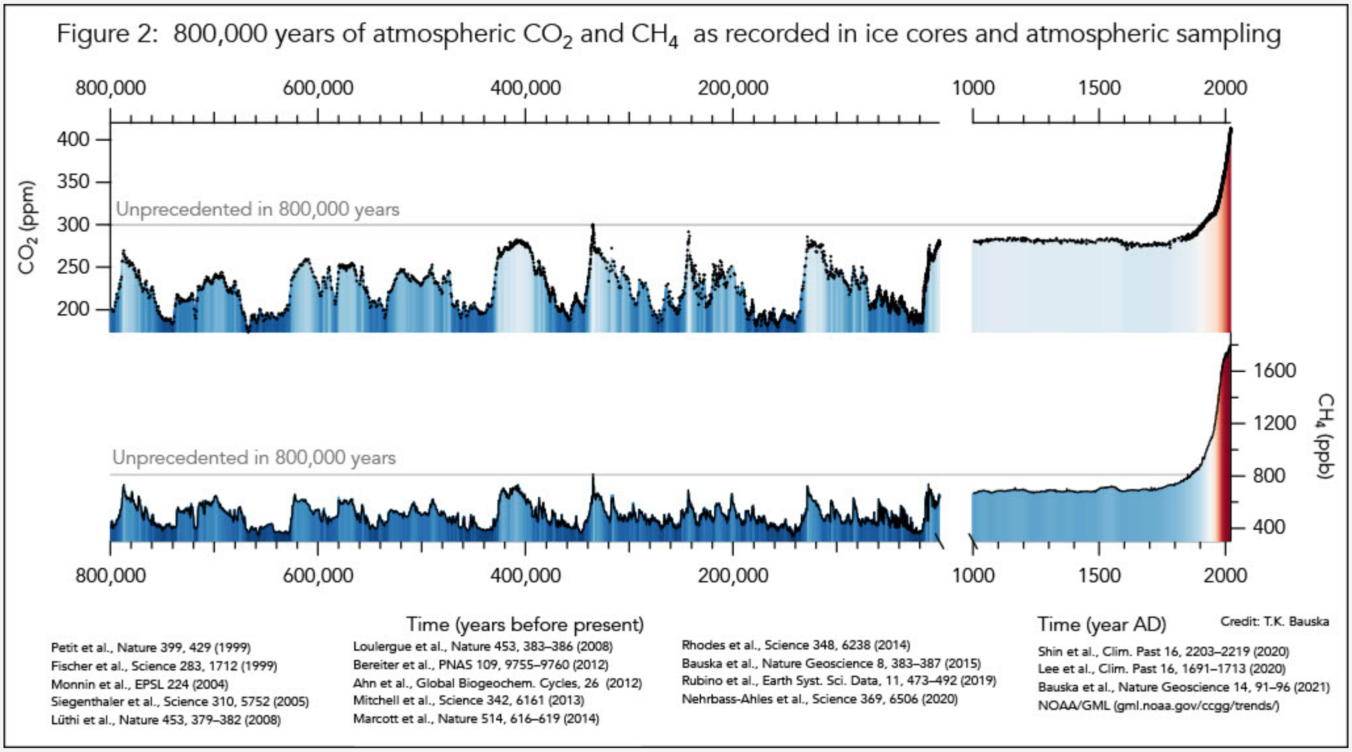
ENVIRONMENTAL SCIENCE CASE STUDY: Measuring Greenhouse Gases in Ice

As we have seen, tracking changes in the concentration of gases over time helps us assess the state of Earth's atmosphere. However, one of the biggest challenges in environmental science is determining the concentration of chemical elements that existed on Earth in ancient times. For example, scientists report that over the past 160,000 years, global temperatures and atmospheric concentrations of carbon dioxide and methane have fluctuated frequently. (See Figure 6.) But how do we know it? Ice gives us the answer.

Ice sheets and **glaciers** in Greenland and Antarctica contain layers of snow and ice. As new snow falls, the old snow is buried and slowly turns to ice. Annual layers of snow/ice, which are sometimes visible to the naked eye like the annual rings in trees, can accumulate to thousands of meters in thickness. Each layer contains bubbles of trapped gases (including human-produced air pollutants in more recent layers) in concentrations that reflect their atmospheric concentrations at the time the layer was sealed off from the atmosphere.

Researchers interested in estimating atmospheric concentrations of elements and gases from thousands of years ago must drill into the layers of buried ice and carefully remove an ice core. The ice core is kept frozen

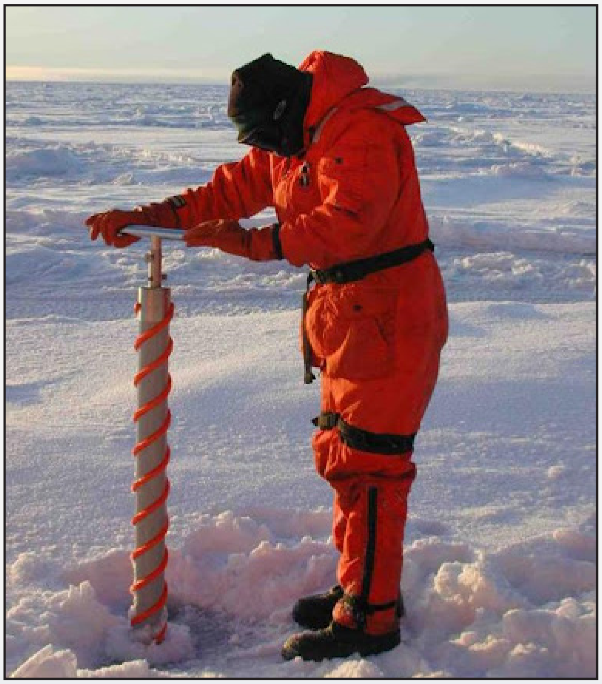
FIGURE 6



800,000 years of ice core records for atmospheric carbon dioxide and temperature change in Antarctica. The last 160,000 years (right side of graph) show variation but an overall decline in both, until recently.

Source: British Antarctic Survey

and brought to a laboratory, where a researcher assigns a date to each annual layer corresponding to the year when it was deposited on the surface as snowfall. The ice for a given year is then removed in a slice, and air bubbles in the ice are analyzed for their chemical content. Carbon dioxide concentrations can be measured directly from the air released as the ice melts. Relative temperature (e.g., warmer or cooler than today) can be inferred by the ratios of different oxygen atoms of varying masses (oxygen isotopes) that are released from the air bubbles.



Researchers interested in estimating atmospheric concentrations of elements and gases from thousands of years ago can drill into the layers of buried ice and carefully remove an ice core.

Air and Water Pollution

The metal lead (chemical symbol Pb) is very useful because it is soft, malleable (can be shaped with just a hammer), and resists corrosion, but it also impairs human central nervous system function and is toxic to most plants and animals. Developing brains (in fetuses and children) are particularly sensitive to lead. The amount of lead in the atmosphere, water, soils, and plants and animals is an indicator of the amount of pollution that has been introduced into the natural environment and an indirect indicator of the amount of harm that may have occurred from human manipulation of the natural environment.

The major source of lead contamination in the U.S. is drinking water.

From five thousand years ago until fairly recently, the global production, or mining, of lead has increased. In the early years of lead production, relatively small amounts of the metal were liberated to the atmosphere during separation and refinement of the lead from other metals. Changes in refining techniques that came with the Industrial Revolution led to greater releases into the atmosphere. In addition, **coal** and oil contain small amounts of lead, and as more of these fuels were burned, more lead was released to the atmosphere. Lead was also used as an additive to gasoline to improve engine performance of the automobile engine. As the automobile became more widely used throughout the world, the use of lead increased as well, and much of the lead production and emissions in the twentieth century were a result of this use.

Beginning in 1975, clean air legislation required that new cars sold in the United States use gasoline without lead, and gradually the same requirements were imposed in many other parts of the world. This switch from leaded to unleaded gasoline is primarily responsible for the decreases in lead emissions. While there is still a great deal of toxic lead produced and emitted throughout the world, the substantial decline in lead emissions is certainly a positive step. If we use global lead emissions as an environmental indicator, we should conclude that the situation is improving. However, this "easy fix" simply stopped adding a harmful element to gasoline. There are still significant quantities of lead emitted in coal, oil and even gasoline that we call "unleaded."

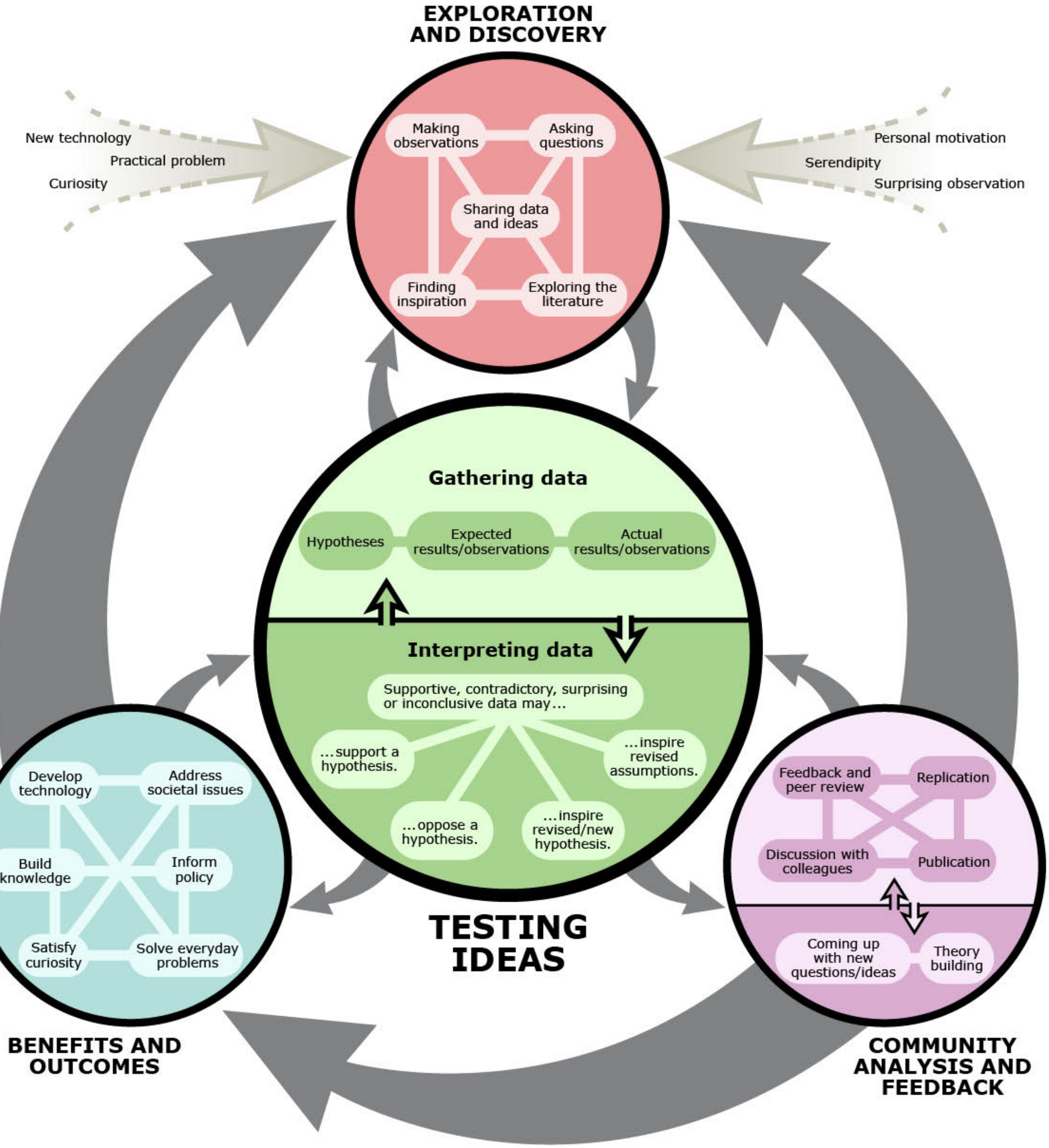
Lead was also a major ingredient in paint. Although houses built after 1960 tend to have much lower concentrations of lead in paint, there are many houses built before 1960 that are covered with peeling paint that can be composed of 50 percent lead. This paint can add to the indoor air concentration of lead, and when it peels, it is sometimes ingested by young children. While not part of the atmospheric measurement of lead, this is another important pathway of lead pollution to human beings.

However, the major source of lead **contamination** in the U.S. today is our drinking water—particularly from lead pipes and other plumbing material that will corrode over time, especially if the water is highly acidic. While many of these lead pipes have been replaced with safer materials, lead plumbing fixtures are still prevalent, especially in lower income communities. Lead is but one example of how human activities contaminate our air, water, and land.

THE SCIENTIFIC METHOD

The scientific information that we will cover—including the information just presented on environmental indicators—has been collected, analyzed, and synthesized through a process called the **scientific method**. The scientific method is an objective way to explore the natural world, draw inferences from it, and predict the outcome of certain events, processes, or alterations. This method is used by scientists in many parts of the world and is the generally accepted way to conduct science. A simple **experiment** conducted by a first-year college student follows the same principles as a large, multi-million-dollar experiment conducted by a group of investigators at a research institution.

FIGURE 7



The process of scientific inquiry.

Source: University of California Berkeley, Understanding Science 101

Let's look at each of the major steps in the scientific method.

- *Observe* the natural world, with or without human interference, and ask questions about those observations.
- *Generate a hypothesis*. Make a general statement about the organisms or processes under observation that could answer the questions posed. The hypothesis must be testable and falsifiable—that is, the researcher must be able to determine whether it is incorrect.
- *Based on existing information, make a preliminary determination of whether the hypothesis is true or false*. Based on the hypothesis, the observations, and questions, it is possible to make an informed projection about the hypothesis.
- *Test the hypothesis with an experiment*. Hypotheses should make predictions about the world. Determine whether the hypothesis is false using an observational experiment or a manipulation experiment, testing these predictions.

An *observational experiment* is conducted by observing phenomena in the natural world without any interference by the researcher. When a wildlife biologist observes hundreds of interactions between moose and wolves, they are conducting an observational experiment. A *manipulation experiment* is conducted by changing some aspect—the experimental **variable**—of a natural or controlled environment. The elements being studied are divided into two groups: the experimental and the control. The experimental group is the one that is manipulated; the **control** group is left undisturbed for comparison. These two groups should be treated identically in every way, with the exception of the one variable that is being tested in the experimental group.

It is important to have a large enough *sample size*—the number of individuals tested or samples collected—so that the data gathered are representative of the entire population. For example, if you are testing the effect of a pollutant on the growth rate of a plant species, you would want to test the effect on ten or a hundred plants, not just one or two.

- *Accept, revise, or reject the hypothesis. Reconcile any differences between the predictions and the results*. If findings differ from the hypothesis, the hypothesis is modified and retested. This may continue until there is general agreement between the hypothesis and the experiment.
- *Report findings to others*. An essential part of the scientific method is to inform others of what has been done. Reporting to others can take place through peer-reviewed written communications in publications or formal presentations of the results at conferences and scientific meetings.
- *Replicate the experiment*. For any given hypothesis, the process described above is generally repeated over and over by different scientists. When a given hypothesis is tested and accepted by many investigators, it may become a scientific finding. If a hypothesis is widely accepted, it becomes a **theory**. If a theory is widely accepted and appears to apply universally without any exceptions, it is called a *universal law*. An example of a universal law is the **First Law of Thermodynamics**, which says that energy cannot be created or destroyed, it simply changes form. Even though we use the term "law," no scientific finding is considered definitively proven, because there is always the possibility of new information that would change the conclusions. Therefore, scientific laws are considered *not disproven*.

An Illustration of the Scientific Method

Let's consider a hypothetical example to see how the scientific method is applied. Scientists have observed that species diversity, one of our environmental indicators, is affected by the alteration of habitat.

An environmental scientist in an area of Southern California that is being developed for housing poses the question, "What will happen to the diversity of species of small mammals and shrubs if the size of a natural area is reduced from ten hectares to one hectare?" (1 hectare = 2.47 acres). The scientist phrases this question as a hypothesis: "Reducing the size of the natural area will result in a significant loss in small mammal and shrub species" and predicts that the hypothesis is correct. (Alternatively, they could predict that it is incorrect.)

The researcher then uses the following situation as an experiment to test their hypothesis:

> *Five housing developments are to be constructed in the suburbs of a major city in Southern California, each on a ten-hectare plot of land with one hectare in the middle left as a "natural area." Before the developments begin, the investigator conducts inventories of all the species on all five ten-hectare areas destined to become housing developments, and five similar ten-hectare areas that will remain undisturbed and act as controls. The survey determines an average number of species per hectare.*

In this example, the experimental variable is the reduction of habitat size from ten hectares to one hectare.

The scientific method is an ongoing discussion among researchers.

Ten years after the housing developments have been completed, the investigator returns to the survey sites and inventories the species again. If the one hectare "natural areas" in the housing developments have fewer species than the undisturbed areas, the investigator could conclude that their hypothesis was not falsified—reducing the size of the natural area did decrease species diversity—and report their findings to the scientific community. Not all scientific studies have a clear experimental variable or manipulation. Sometimes, an observation is made after an event has occurred, and an environmental scientist must determine what has happened without having data from before the event. This kind of analysis is a little bit like detective work, but certain aspects of the scientific method still apply.

The Role of Repetition in Science

The scientific method is an ongoing discussion among researchers. Scientists frequently disagree about hypotheses, experimental conditions, results, and the interpretation of results. Two investigators may even obtain different results from similar experiments, or two interpretations may explain the same set of observations. Any single finding has limited significance. It is when the same finding is repeated over and over by different investigators that we can begin to trust that the observed phenomenon is real and significant. In the meantime, the disagreements and the discussion about contradictory findings are not only normal, but are a valuable part of the scientific process.

While reporting on two studies that reached opposite conclusions, the popular press often assumes the discrepancy is the result of bad science or confusion on the part of scientists. Particularly when a scientific issue is of great popular interest or concerns policy—questions such as global warming, toxicity of pollutants, or species extinction, for example—individual preliminary results may be reported to the general public before scientists have had a chance to reconcile apparent or actual differences.

Understanding How to Interpret Scientific Studies

If it is important to view scientific findings critically, how can we judge whether a report is based on good science? Sometimes scientific investigators do not differentiate between the control group of subjects and the experimental group. Other times, there is not a large enough sample size to draw general conclusions. Alternatively, the conclusions may be made about one group (for instance, mature trees) when the experiment was done on a different group (seedlings). In order to conduct a scientifically sound study, the investigators must use a large enough sample size and have a distinct difference between the experimental group and the control group. Further, they must demonstrate a cause-and-effect relationship between a manipulation and a result and be able to identify a mechanism that would give rise to the observed result. A simple correlation between one event and another—that is, the two occurring together—does not constitute scientific evidence that one caused the other.

THE LIMITATIONS OF ENVIRONMENTAL SCIENCE

Because of the nature of what is studied and the way the research is conducted, applying the traditional scientific method to environmental science presents a number of challenges and limitations that are not usually found in other scientific fields.

When it is difficult or impossible to decide which of two alternative actions, such as using a paper bag or a plastic bag, is better or worse for the environment overall, our assessments and our choices ultimately involve value judgments and personal decisions.

The One Earth Problem

The greatest challenge is the fact that there is no undisturbed baseline with which to compare the contemporary Earth. Virtually every part of the planet has been altered by human beings in some way. Though some remote parts of the Earth appear to be undisturbed, we can find quantities of lead—produced by smelters during the time of the Roman Empire—in the Greenland ice sheet, traces of the organic compound PCB in the fatty tissue of penguins, and species carried by ship to remote tropical islands from other parts of the world. This situation makes it difficult to know the “original” levels of lead or species diversity before humans began to alter the Earth and, consequently, how the current situation deviates from those unknown levels.

Inconsistent Units of Measure for Energy

Although the sources may differ, all energy is essentially the same. However, we use it in many different forms, and our society describes virtually every form in a different way. For example, we purchase gasoline in gallons and electricity in kilowatt hours. When we buy an air conditioner, its energy use is reported in watts or amps, but the amount of work it does in the form of extracting heat from the air is measured in British thermal units per hour, and we measure its effect on our home environment in degrees Fahrenheit or Celsius, depending on where we live. Scientists, on the other hand, measure energy in **joules** or calories. The lack of consistent values makes it very hard to see how much energy we are using overall.

Subjectivity

Paper or plastic? When choosing between two alternative actions, such as using a paper bag or a plastic bag, we often try to compare their environmental impacts. How can we know for sure which is best? There are techniques for determining what harm may come from using benzene to make a plastic bag and techniques for determining what environmental or human damage may come from using chlorine to make a paper bag. However, different substances tend to affect the environment differently: benzene may pose more of a risk to people while chlorine might pose a greater risk to organisms in a stream. It is difficult, if not impossible, to decide which is better or worse for the environment overall. Ultimately, our assessments and our choices involve value judgments and personal decisions.

Unpredictable Consequences of Preferences and Policies

Understanding natural science is the major focus of this resource guide, but it is not the sole answer to our environmental problems. An advancement in scientific understanding or a development in technology may appear capable of achieving fabulous environmental gains. But human action and cooperation are necessary, and they are not always forthcoming. A recent example is the changes that have occurred in passenger vehicle fuel efficiency in the United States. Since 1975, technological improvements have increased the fuel efficiency of most cars in the United States from an average of thirteen miles per gallon to more than thirty miles per gallon by 2021.[2]

We might assume that the overall average miles per gallon of all vehicles in the U.S. should have steadily increased during this time period. Unfortunately, that's not what happened. Due to consumer preferences and personal choice, more and more people have purchased sport utility vehicles, light trucks, and minivans, which often get less than twenty miles to the gallon, which brought the overall average vehicle fuel efficiency down in the 1990s. However, new polices promoting the use of electric and hybrid vehicles along with the popularity of smaller SUVs, has changed this trajectory for the better. It is vital to remember that no matter how great the scientific or technological gains may be, human choices, opinions, action, or lack of action are equally important in the ultimate effect on the environment.

Although we have identified a number of limitations in environmental science, the conclusions reached by environmental scientists are based on data from many areas of the physical and natural sciences, gathered according to the scientific method. Environmental science can help us understand the world we live in.

ENVIRONMENTAL SYSTEMS

System Dynamics

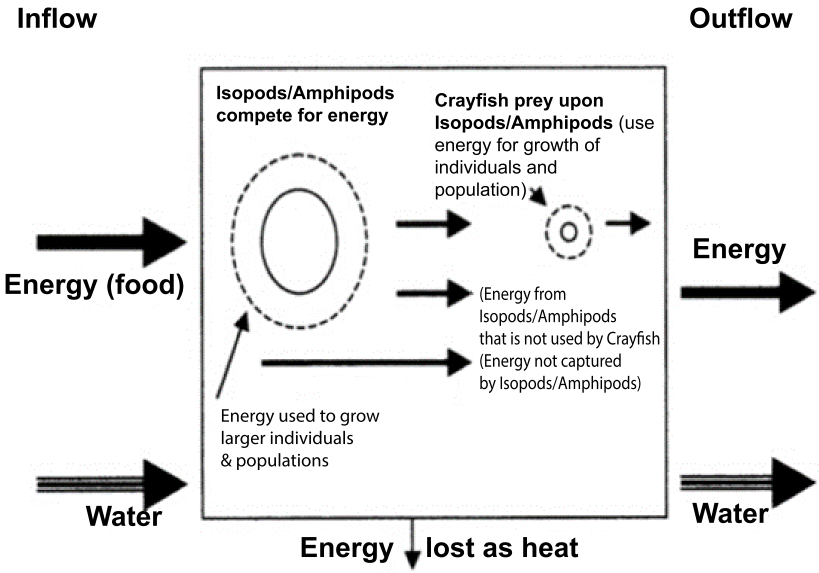
A butterfly stirring the air in Beijing can affect weather patterns in New York a month later. This often-paraphrased statement is a poetic way of describing the interconnectedness of systems on Earth. The study of the environment is the study of systems. Recall that a system is a set of living and/or nonliving components connected in such a way that changes in one part of the system affect other parts. In practice, systems are defined by the person looking at them. For example, one scientist may spend an entire career studying the physiological and anatomical systems of individual humpback whales to learn how they can dive so deep, swim so far, and survive in such a range of marine environments. In contrast, the population biologist will focus on gathering data on **population** changes over time, while the community ecologist will be interested in the whale's interaction with other species, such as their prey. And the conservation biologist will likely be most concerned with the adverse impacts of human fisheries—and the gear used in those fisheries—on the whale population. While all these systems are connected, it is this final one—where human activity has it most serious impacts—where environmental science will interact with fishery policies, law, and economics.

Throughout this resource guide, we will define systems in terms of the particular environmental issue we are studying. The largest system studied by environmental scientists, and the one of which all others are part, is our global system—the Earth. The interactions of systems and components within systems are known as *system dynamics*.

Matter and Energy Exchange

Environmental systems, whether small or large, involve the exchange of matter (materials) or **energy**. One of the most important materials involved in environmental systems is water; some others are fuels (oil, coal, etc.), chemicals, and gases (e.g., oxygen). For other environmental systems, the exchange of energy is the important process. This includes the energy (food) intake of a single animal, the energy flows through an ecosystem, the fossil fuel energy used to drive modern human society, and the energy on which all environmental systems ultimately depend: the energy from the Sun.

FIGURE 8

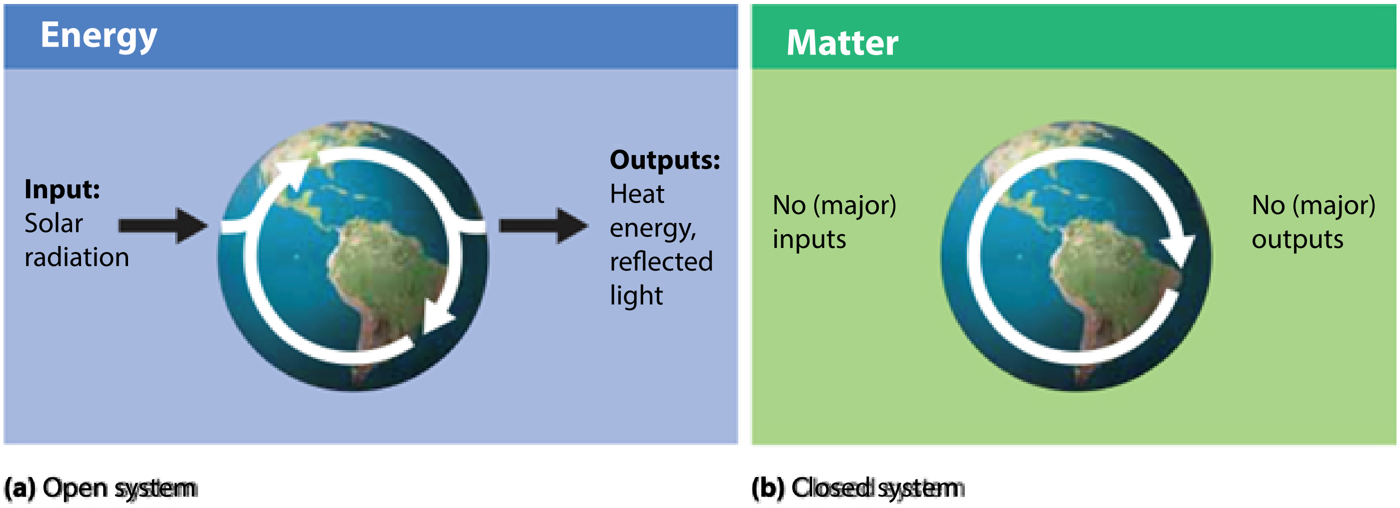


A diagram of a simple cave system showing the flow of water and energy through a system. The study of all systems starts with a similar modeling of the inputs and outputs.

Open and Closed Systems

Systems can be either open or closed. An *open system* is one where the exchange of matter or energy between it and other systems occurs. In a *closed system*, exchange does not occur. The Earth system is open with respect to energy. **Solar energy** enters the Earth's atmosphere, and heat energy escapes from the Earth's atmosphere. However, the Earth system is closed with respect to matter, such as chemical elements. Except for the occasional meteorite or space shuttle, no material enters or leaves the Earth system. The ocean is a system that is open to both energy and matter. Energy from the Sun enters the ocean, and energy from the ocean is easily transferred to other systems such as the atmosphere. And matter, such as sediment and nutrients, enters the ocean via rivers and streams.

FIGURE 9



Open and closed systems. (a) Earth is an open system with respect to energy. Solar radiation enters the Earth system, and energy leaves it in the form of heat and reflected light. (b) However, Earth is essentially a closed system with respect to matter because very little matter enters or leaves the Earth system. The white arrows indicate the cycling of energy and matter.

Source: Friedland, Andrew and Rick Relyea, *Essentials of Environmental Science* 2nd ed. W.H. Freeman, New York (2016).

The Human Component of Environmental Systems

Because environmental systems almost invariably include people or run up against human influence in one form or another, many areas of human endeavor, some of which are not scientific at all, are important to a systems-based understanding of the environment. Some of the most important areas that we will touch on are:

- Economics
- Social structures and institutions, including various levels of government
- Law
- Policy
- Environmental advocacy and action

For example, new scientific data on global warming will affect new policies or laws related to greenhouse gas production, as well as ways to adapt to a changing climate.

SYSTEM ANALYSIS: DETERMINING HOW MATTER AND ENERGY FLOW IN THE ENVIRONMENT

Inputs, Outputs, and Flux

People who examine systems often conduct a *system analysis* to determine what goes in, what comes out, and what has changed within a given system. This type of analysis is very similar to the kind of analysis you might perform on your personal checking account to learn your financial status. In your checking account, you start with a sum of money called your balance. Systems analysts call that balance a *pool*. If you deposit money into your checking account, you are adding an *input*. You also have expenditures—you write checks against your checking account balance or withdraw money from your account. Systems analysts call this an *output*.

In order to determine your financial status, you start with your balance at the beginning of a month, add inputs (deposits), and subtract outputs (checks and withdrawals). This gives you your checkbook balance at the end of the month, or the change in the pool of money. Systems analysts call that change a **flux**. If you quantify your income in terms of so many dollars per month, you are describing a *flux rate*, a flow per unit of time.

FIGURE 10

INPUTS – OUTPUTS = TOTAL FLUX

If inputs are greater than outputs, then flux is positive.

The same kind of analysis can be done for water in a bucket, pollutants in the atmosphere, or nutrients in the ocean. It tells an environmental scientist if the size of the pool is increasing, decreasing, or staying the same. Because it was designed to be done for materials that have mass, it is often called a *mass balance analysis*—an accounting of the inputs and outputs to determine the fluxes in a given system. All types of balance analyses, whether they be mass, energy, or monetary, can be represented as:

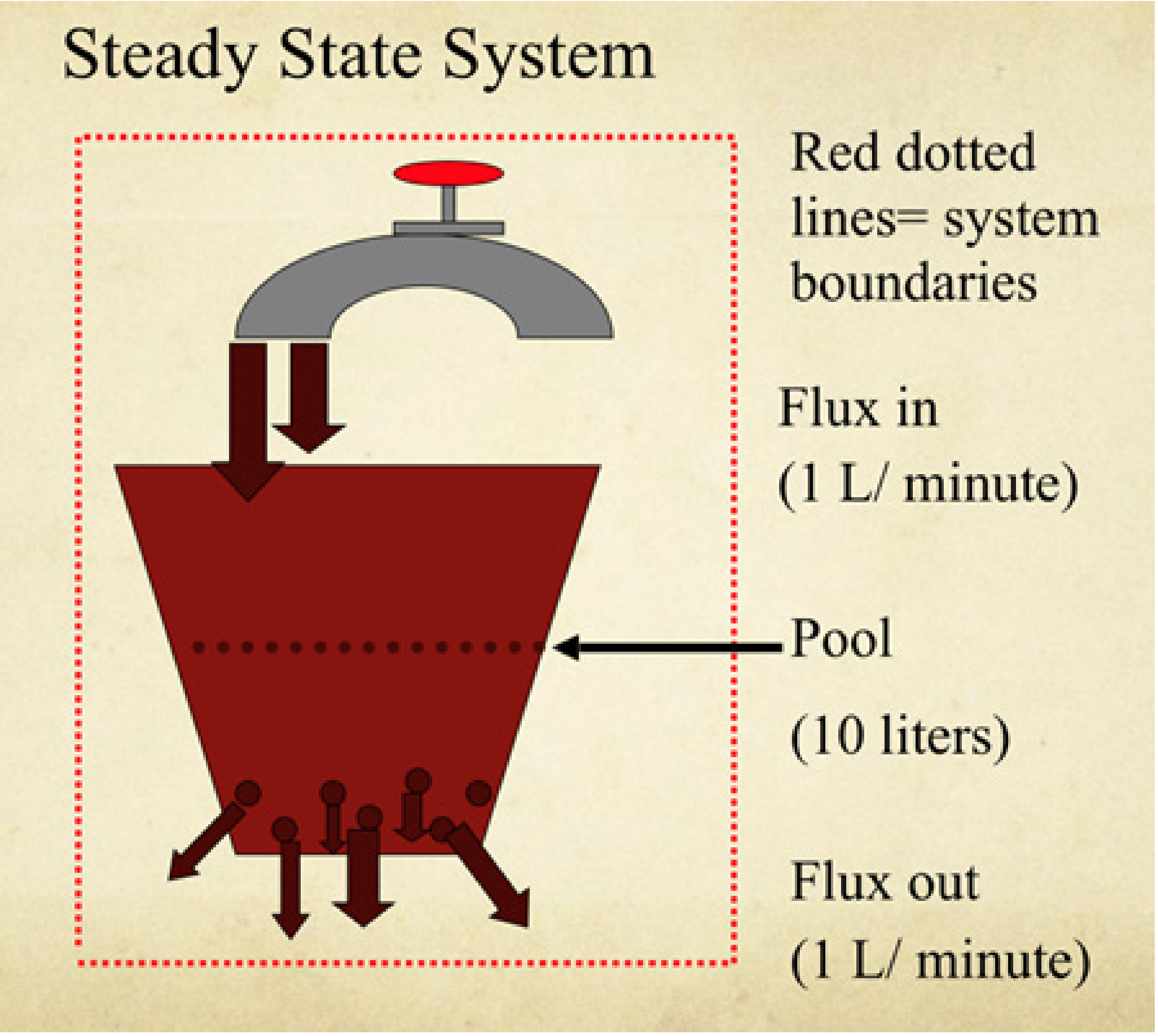
Net Flux = Inputs – Outputs

Steady State

The most important aspect of conducting a mass, energy, or monetary balance analysis is learning if your system is in *steady state*—that is, if input equals output and the size of the pool does not change over time. The first step is to determine the size of the pool. Sometimes we can measure the pool directly. With a bucket of water, for example, we could empty the bucket into a measured container to determine the size of our pool. If we are trying to determine the size of a large or immobile pool, such as a flock of birds or an ocean, we have to calculate or estimate the pool size.

Next, we want to measure, estimate, or calculate the net flux into and out of the system (input and output). For example, imagine that someone has punched holes in the bottom of our bucket, so the water is leaking out, and at the same time we are running water into it from a faucet. We can measure input from the faucet and output from the holes. As Figure 11 shows, the bucket has a pool of 10 liters, a flux in of 1 liter per minute, and a flux out of 1 liter per minute. Since the input equals the output, net flux = 0, and over time there will be no change in this system. The pool will remain at 10 liters until someone changes one of the fluxes, perhaps by turning off the faucet or plugging up the holes in the bottom of the bucket. This system is in steady state.

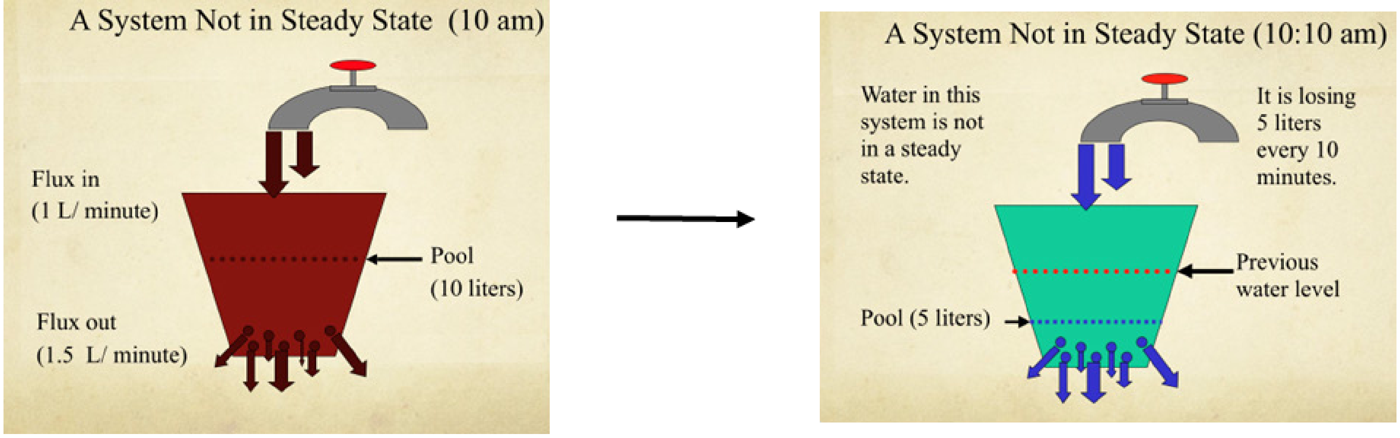
FIGURE 11



A steady state system does not change over time.

Many pools in the natural world are at steady state; the water in the atmosphere is an example. The amount of water that enters the atmosphere from **evaporation** in any given time period is roughly equal to the amount that leaves the atmosphere as precipitation over the same time. The oceans are also at steady state; the water that enters from rivers and streams is roughly equal to the water that evaporates. When a community bans watering lawns and washing cars and declares a drought emergency during a dry summer, it is because their water supply is no longer at steady state; more water is being lost from the reservoir than is replenished by precipitation and streams. If a resource, such as a water supply, is decreasing in size, it means that the system is not being utilized in a sustainable way.

FIGURE 12



A system that is not in a steady state changes over time.

It is important to realize that one part of a system can be in steady state while another part is not. For example, though water in the atmosphere is in a steady state, carbon dioxide in the atmosphere is not; it is slowly increasing, as we will discuss later.

ENVIRONMENTAL SCIENCE CASE STUDY: Mono Lake—An Input–Output System Analysis

Mono Lake is a large, deep, and old lake—one of the oldest lakes in North America, estimated to be between 1 and 3 million years old.[3] It is located about three hundred miles northeast of Los Angeles on the border between the Sierra Nevada Mountain range and the Great Basin Desert. Four interconnected environmental systems are critical to the Mono Lake story.

Mono Lake, one of the oldest lakes in North America, is estimated to be between 1 and 3 million years old.

Source: Cal Matters

The Natural Water System

The first system we'll consider is the natural water system that, analogous to the simplified bucket examples just discussed, involves the inflow (input) and outflow (output) of water. Mono Lake is called a terminal lake because under "normal conditions" water flows into the lake (from tributaries bringing water from snowmelt in the Sierra Nevada Mountains), but since it is the lowest point in the landscape, no water flows out into streams or rivers. Although the water level of the lake fluctuates over the years, for any given time period the water flux in from precipitation and river input is roughly equal to the water flux out through evaporation. This is similar to a bucket of water in which evaporation is balanced by the slow drip of a faucet.

The Salt-Balance System

The second Mono Lake system involves the changing concentrations of salts in the lake. This system is dependent upon the water system since small concentrations of salts such as sodium and magnesium enter the lake via streams (even fresh water contains small concentrations of salts). The salt concentration increases over time because the evaporation process leaves salts behind while new salts continue to enter the lake. Therefore, Mono Lake, like other saline lakes, is slowly becoming saltier. We can calculate a mass balance to see quantitatively how this happens.

We would have to use some very large numbers to do a mass balance for salt in Mono Lake, but we can use a hypothetical model lake, and one element, sodium (Na), to illustrate how salt water accumulates in a terminal lake. Since small concentrations of sodium enter the lake but none leaves, the mass balance for sodium in our lake involves a small, steady input and virtually no output. Remember the mass balance equation we introduced earlier? We can use that to estimate the change in salinity (concentration of salt in a liquid) over time (mg = milligrams):

Net Flux = Inputs – Outputs

Input (from tributaries) = (1,000 liters water/day) x (5mg Na/liter) = 5,000 mg Na/day

Output (from evaporation) = (1,000 liters water/day) x 0 mg Na/liter = 0mg Na/day

Net Flux = + 5,000 mg Na/day

This mass balance indicates that although the amount of water in our hypothetical lake remains roughly constant, the salt content steadily increases by 5,000 mg per day. Over time, our lake becomes saltier and saltier. This calculation explains why lakes like Mono Lake, Great Salt Lake, and the Dead Sea have such high salt contents.

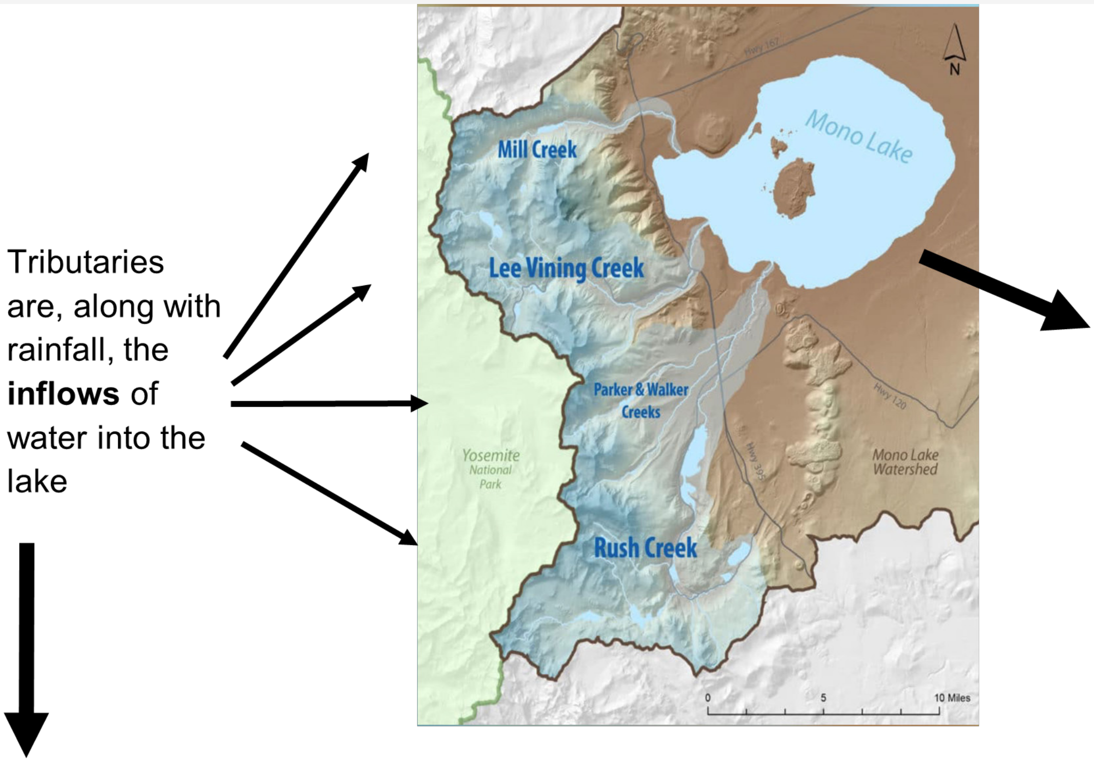
The Ecological System

The third critical environmental system is the ecological system (ecosystem) of populations interacting with each other and with the physical environment of Mono Lake. We will discuss just one part of this ecosystem, the relatively simple **food chain** going from photosynthetic algae at the bottom of the food chain to gulls at the top. The algae, being green photosynthesizers, receive most of their energy from the Sun’s light. Brine shrimp and flies eat the algae and are eaten by gulls. The algae obtain most of their important nutrients (such as nitrogen) that they need to carry out photosynthesis from the excretions and **decay** of flies, shrimp, and birds.

The Water-Use System

The use of Mono Lake’s waters by the population of Los Angeles is the final key environmental system affecting the overall lake system. Los Angeles began withdrawing water from the non-salty Mono Lake tributaries in 1941 at a rate of approximately 80.4 million gallons/day. The effect of this water withdrawal on the total pool was exactly what we would expect from a bucket in which the in-flow is decreased (with water being to diverted to Los Angeles) without any compensatory decrease in evaporation (the outflow); the lake level dropped—forty feet in forty years. Given this significant change, what were some impacts of this change in the human water use system on the other three environmental systems of Mono Lake?

FIGURE 13



Tributaries are, along with rainfall, the **inflows** of water into the lake

Evaporation is the only **outflow** of water from the lake

Diversion of inflow from tributaries to Los Angeles started in 1941

Mono Lake's input/output water system.

Source: Modified image from Mono Lake Committee

The lowering of Mono Lake's water level had two very noticeable effects. One was the **exposure** of the previously water-covered tufa towers, which are the main habitat for the flies and shrimp on which the gulls depend for food. Exposure of these habitats did not directly lead to the death of the flies and shrimp, but it did make it easier for birds to prey upon them. This resulted in an initial glut of food for the birds but an ultimate decline in the prey population from over-predation, which was followed in turn by a decline in the bird population. Secondly, as the lake level went down, alkaline dust was exposed, leading to vast dust storms affecting bird and other nearby wildlife populations.

Lowered water levels had another, less obvious, but even more critical effect on Mono Lake's environmental system. The salts that were once diluted by the lake's original large volume were now concentrated in a smaller volume of water, leading to a dramatic increase in salinity. The algae, shrimp, and other Mono Lake residents could survive with the natural salt concentrations, but this drastic and rapid increase in salts proved difficult for them. The most significant effect was on algae, which are the base of the food chain. Higher salinity slows the uptake of nitrogen from the decayed animals and their excretions. Since nitrogen is a critical element for growth, slower nitrogen uptake led to slower growth of the algae population and less food for the flies and shrimp and thus eventually for the birds. By the early 1980s, Mono Lake and the populations that depended upon it were dying.

The Mono Lake story up to this point is a real-world example of input, output, and steady state in a mass balance system. Before 1941, the water system of Mono Lake was in an approximate steady state with the outflow of water from evaporation more or less matching the inflow from streams. The salt-balance system was not in a steady state and was slowly moving toward increased salt concentrations. The food chain had been able to compensate (at least over recent ecological history) for the increasing salinity but was not able to adapt to the rapid changes resulting from the addition of the new, human water use system.

Since the early 1980s, the history of Mono Lake is an example of the interaction of environmental science with other human components mentioned earlier—environmental policy, environmental law, and environmental advocacy. The effects of Los Angeles's water use on the Mono Lake environmental systems was first noticed by ecologists and environmental scientists, who provided information to environmental advocates and lawyers to bring a series of lawsuits and legislative proposals seeking to stop water withdrawals.

At the same time, environmental advocates attempted to change the water-use policy through a public campaign advertising both the beauty and the fragility of Mono Lake. These early attempts to use environmental science and advocacy to inform environmental law and policy failed. However, in 1983, the California Supreme Court ruled that it was the duty of the California government to protect the environment of Mono Lake. This court decision led to new laws requiring federal and state agencies to better manage Mono Lake. The result is the current reduction in water withdrawals and increase in the lake's water level. In 2023, the water level further increased from snowmelt in the Sierra Nevada mountains and the resulting increase in in-flows from tributaries. The final answer to preventing the death of Mono Lake proved simple: increase inflow and decrease the diversion of water to Los Angeles until the bucket filled back up.

Mean Residence Time

The Mono Lake example demonstrates that even a basic understanding of input–output system dynamics can be useful in solving some environmental problems. However, in many situations, for example if we want to determine how long it will take for a pollutant to be flushed from a lake, it is valuable to know the rate at which a pool turns over—that is, how long it takes for the contents of the pool to change.

If a pool is in steady state, we can calculate a mean **residence time** (MRT), which is the average time that a portion of the pool remains in the system. The mean residence time is the pool divided by the input or the output:

$$\text{MRT} = (\text{pool})/(\text{flux in or out})$$

Note that we can calculate the mean residence time using either the flux in or the flux out. Because the system is in steady state, the flux in and out are equal, and so either flux will give the same answer. For example, consider the bucket discussed earlier, with a pool of ten liters, a flux in of one liter per minute, and a flux out of one liter per minute:

$$\text{MRT} = (10\ \cancel{\text{liters}}\ ) / (1\ \cancel{\text{liter}}/\ \text{minute})$$
$$\text{MRT} = 10\ \text{minutes}$$

The MRT value tells you that an average quantity of water—say, a milliliter—will remain in the bucket for ten minutes before being flushed out. In fact, some water may remain for a longer time, and some may remain for a shorter time, but the mean residence time is an average.

Though we determined the mean residence time for water, if we have information on the pool and flux of something dissolved in water, such as a particular pollutant, we can determine the mean residence time for that substance as well. We can also calculate residence times for air pollutants. In that case, MRT is usually defined as the period that an average molecule will remain chemically active in the atmosphere. Residence times (also referred to as atmospheric lifetime) have been estimated for several gases known to be involved in the greenhouse effect and in the depletion of the ozone layer:

Gas	**Residence Time (years)[4]**
Carbon dioxide	100*
Methane	11.8
Nitrous oxides	109
Chlorofluorocarbons	100
Hydrofluorocarbons	222

It is important to note that the estimated residence time for carbon dioxide is a particularly rough estimate since this gas is not destroyed in the atmosphere but is cycled through different parts of the global carbon cycle at different rates—ranging from a few years to thousands of years. (We will learn more about the global carbon cycle in Sections II and IV of this resource guide.) As we discuss the impacts of human activities on global climate change in later sections, these values will take on important significance.

Warmer temperatures at the Earth's surface lead to greater evaporation from oceans and lakes. The additional moisture in the atmosphere from evaporation enhances the layer of heat-trapping gases, including water vapor, that cover the Earth, which makes the Earth warmer, which leads to greater evaporation, and more warming, creating a positive feedback loop.

Accumulation and Depletion

It is important to remember that mean residence time is valid only if the system is in steady state. If a system is not in steady state, we may want to determine the rate at which it is accumulating or losing material. For example, if a pollutant is accumulating in a drinking water reservoir, it may be valuable to know the time when pollutant concentrations will become toxic to organisms in the reservoir or to humans drinking the water in the reservoir. We can calculate accumulation or depletion rates by using the formula for net flux:

$$\text{Net Flux} = \text{Inputs} - \text{Outputs}$$

For example, assume that a pollutant is slowly decreasing in concentration in the water because it is interacting with the sediment that lines the bottom of the reservoir. A calculation of the change in the system can indicate when that water will be safe to drink. Suppose the reservoir holds 1,000,000 liters of water, and the pollutant is at a concentration of 10 mg/L. Assume no additional pollutant is entering the reservoir, and that 1,000 mg/day interacts with the sediment. We can calculate:

$$\text{Flux} = 0 - 1{,}000 \text{ mg/day}$$
$$\text{Flux} = -\,1{,}000 \text{ mg/day}$$

At the start, the reservoir holds 10 mg/L X 1,000,000 liters = 10,000,000 mg of the pollutant.

Losing 1,000 mg/day, the reservoir will contain no pollutant in 10,000 days. In other words, it will take 10,000 /365 days/yr = 27.4 years before the pollutant is totally gone from the reservoir.

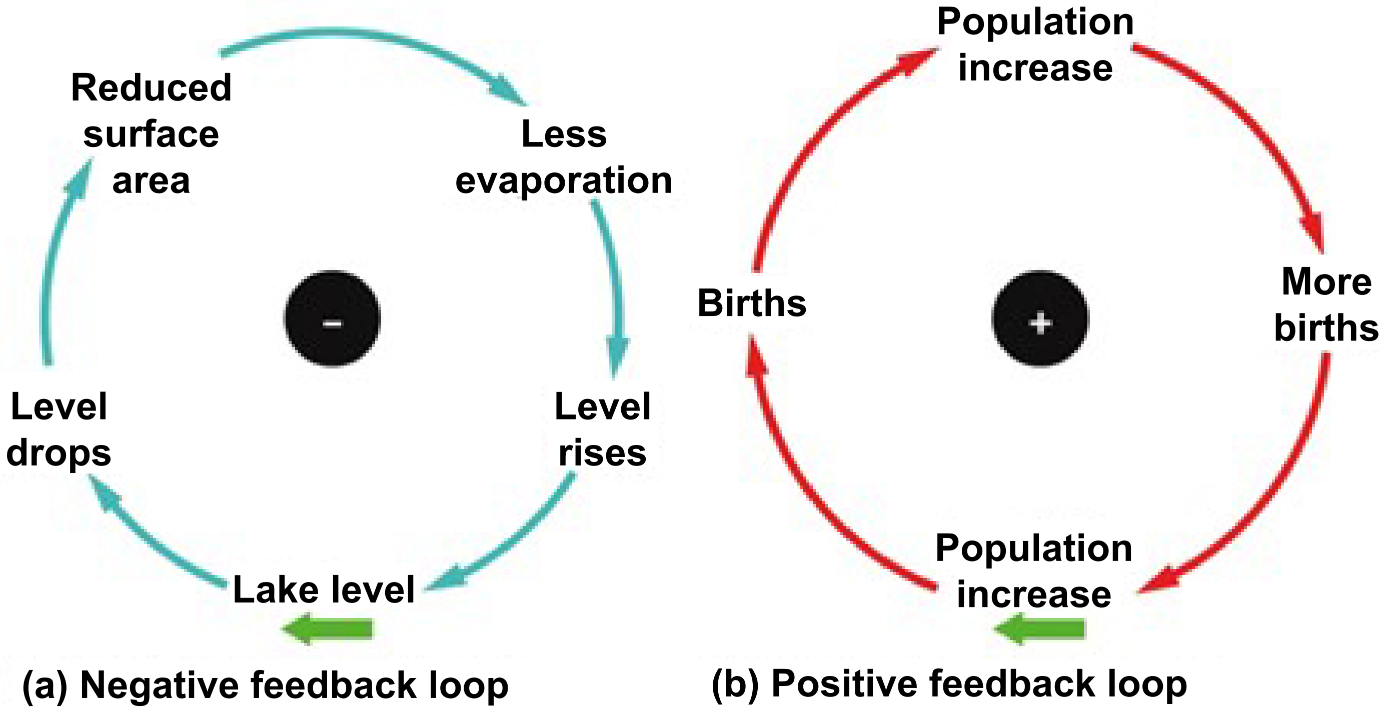
Feedbacks

So far, we have presented fairly simple systems with easily defined inputs and outputs. Any change in the system involves simply increasing or decreasing the inputs or outputs. Even Mono Lake, a major environmental system, could be described as a simple input/output system. For other environmental systems, the important factors are not the input and output themselves, but the mechanisms that control, or regulate, these flows. In these regulatory mechanisms, a change in the system either leads to further change or returns the system to its original state.

Consider your own or your parents' behavior with respect to a bank account. If you notice that your pool of money (your checkbook balance) is decreasing, you may spend less money to reduce the flux of dollars out of your checkbook, or you may work more hours to increase the flux of dollars into your checkbook. Essentially, you alter your behavior in one or more ways in order to change your cash flow situation. These changes in behaviors, called *feedbacks*, are adjustments made by a system in response to behavior or events.

Balancing your checkbook is an example of a *negative feedback loop*, in which the behavior always brings the *system variable*—in this case, your money—back to a starting point. By contrast, a gambler, who bets more and more money as they begin losing, will not return to the starting point—the loss of money will cause increased betting and more losses, until all the money is gone. This is an example of a *positive feedback loop*, in which the system variable is continuously moved away from the stable point—what we often call a vicious cycle.

FIGURE 14



Negative and positive feedback loops.

Source: Friedland, Andrew and Rick Relyea, *Essentials of Environmental Science*, 2nd ed. W.H. Freeman, New York (2016).

Feedback systems are found throughout the environment. One major feedback system that is of great importance to environmental scientists, policy makers, and citizens is the Earth's heating system feedback loop. In general, warmer temperatures at the Earth's surface lead to greater evaporation from oceans and lakes. The additional moisture in the atmosphere from evaporation enhances the layer of heat-trapping gases, including water vapor, that cover the Earth. This helps to make the Earth warmer, which leads to greater evaporation, and more warming, and the cycle continues.

In the absence of other factors that compensate for or balance the warming, this positive feedback loop could continue making temperatures warmer and warmer, driving the system away from the starting point. However, more evaporation also leads to more cloud cover, which would reflect more incident sunlight and possibly lower temperatures, resulting in a negative feedback loop. It is unknown whether or not the sum of these loops would lead to an increase or decrease in temperature.

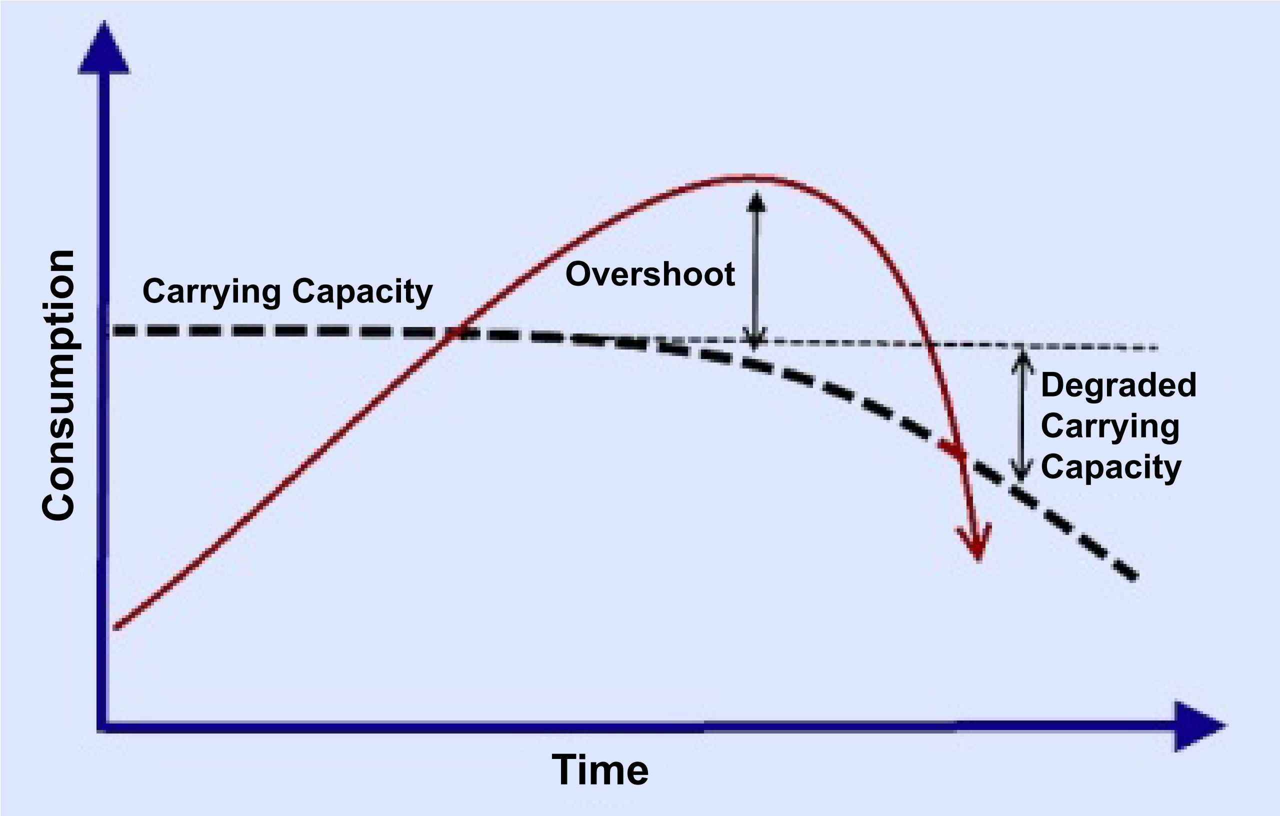
The balance in many environmental systems is dependent on the smooth operation of feedback loops. Sometimes conflicting factors lead to a breakdown in the negative feedback loop and send the environmental system away from its *set point*, the stable value for the **parameter** under examination. This is particularly true when the system involves a conflict between ecological control factors regulating a natural resource, such as a commercial fish or an energy source, and economic and social factors driving human use of such resources. As you study the exploitation of natural resources, both living and nonliving, try to determine what factors may be disrupting the negative feedback loop of those systems.

Overshoot

One last system dynamics concept to consider in both positive and negative feedback systems is the time between when a signal is generated and when it is received and responded to. Consider the bank account example. As soon as you notice that your balance is steadily decreasing, you might alter your spending habits or try to make some more money. But what if you don't have an app that provides you with a continuous update of your account? This delay in receiving the signal might mean that you would keep overspending and exceed your intended balance.

Exceeding the stable set point of a system is known as *overshoot*. In the natural world, many systems experience delays in the transmittance of information that lead to overshoot. Overshoot is an important part of human and nonhuman population systems. When a population's birth rate is high, the factors controlling population growth (disease, reduced fertility, etc.) cannot compensate fast enough, and the population will grow past the maximum number of individuals that can be supported by its environment, known as the **carrying capacity**. The result of such an overshoot will usually be a dramatic population crash from disease or starvation.

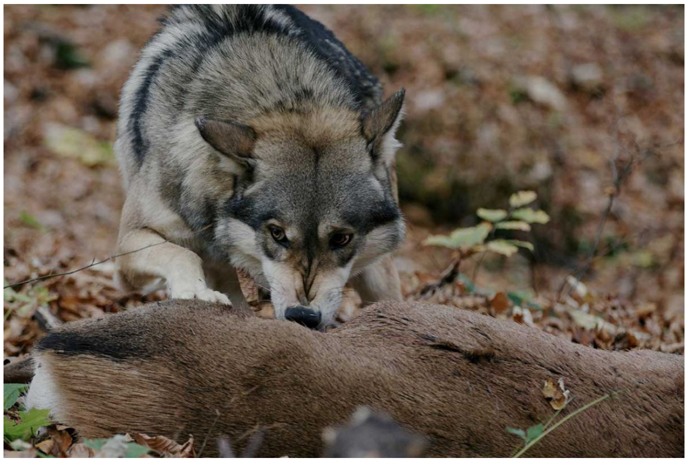
FIGURE 15



Because of a slow response to a signal, an action continues long after it should. This is known as overshoot.

Source: Paul Chefurka, "Population: The Elephant in the Room."

Regulating Population Systems



In most predator-prey systems, such as wolf-deer systems, the amount of predation will increase as the number of prey increases. This negative feedback cycle will drive the prey population back to its starting point.

Environmental scientists define a population as a group of individuals of a single species. We will discuss populations in detail in Section II, but for the purpose of illustrating feedback systems, we need to introduce some basic population concepts here.

The size of any population is controlled by two inputs—the number of births and the amount of immigration—and two outputs—the number of deaths and the amount of emigration (individuals leaving the population).

Net Population Change = Input (Births + Immigration) – Output (Deaths + Emigration)

For most—though not all—populations, births and deaths greatly outnumber immigration and emigration, so it is the former two "flows" that we will concentrate on. Environmental scientists usually find it easy to estimate birth rates and death rates. What is more difficult, and more interesting, is determining how these two flows are regulated.

Environmental scientists study both single population systems and systems of interacting populations. In both cases, the size of any one population can be regulated, through various feedbacks, by abiotic (nonliving) components of the environment and by populations of other organisms (the biotic components of the environment). For example, as a deer population increases in size, the amount of food available for each individual will probably decrease. Less food means less energy for females to put into reproduction, resulting in fewer births, or less food for newly born fawns—a negative feedback.

In more complex systems containing many interacting populations, one population may be regulated by the size of another. A deer population may have enough food to fuel an increase in population size, but it may live in an area with many wolves, which prey upon the deer. In most predator-prey systems, such as wolf-deer systems, the amount of predation will increase as the number of prey increases (they become easier to find and to hunt). This negative feedback cycle will drive the deer population back to its starting point.

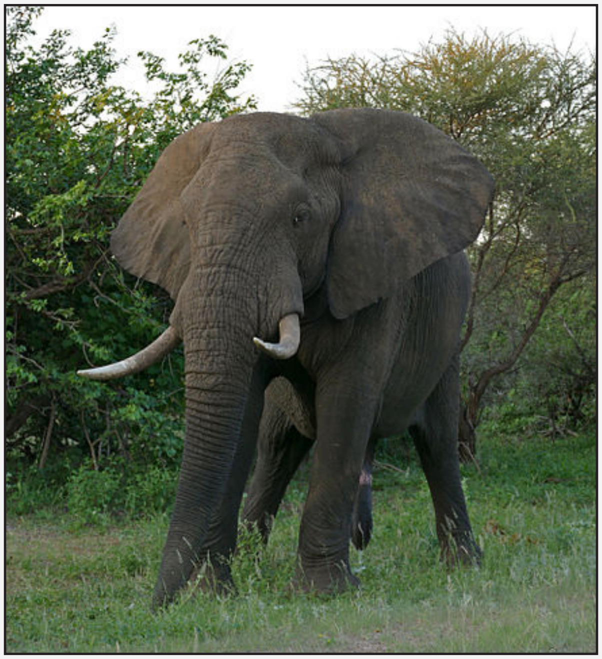
Let's now look in more detail at three different real-world examples of environmental systems that are impacted by human activity and studied by environmental scientists.

ENVIRONMENTAL SCIENCE CASE STUDY: Humans and Elephants in Africa—Feedback and Regulation in Interacting Population Systems

Elephants are found throughout most of central and southern Africa. Overall, the African elephant population is declining, most notably in East Africa where few elephants are found outside of protected nature reserves. There are two main reasons for this decline: the loss of habitat resulting from the conversion of land to agricultural use and the **poaching** of elephants for their ivory. Both factors are related to the rapid growth of the human population in Africa—a growing, mostly poor, population that needs food and money (from the sale of ivory) to survive. The decline of the elephant population was the main motivation for the 1989 CITES (Convention on International Trade in Endangered Species) ban on the ivory trade. However, the illegal trade in ivory continues, as does the use of former elephant habitat for farming.

Habitat loss regulates the elephant population size by changing both inputs and outputs. First, diminished habitat results in fewer food resources. This will result in fewer young being born or surviving (decreased input). Second, by decreasing the amount of food and space available for elephants to survive, habitat loss also increases death rates (increased output). Both of these effects are examples of positive feedbacks; decline in habitat causes the elephant population to move further and further from its starting point.

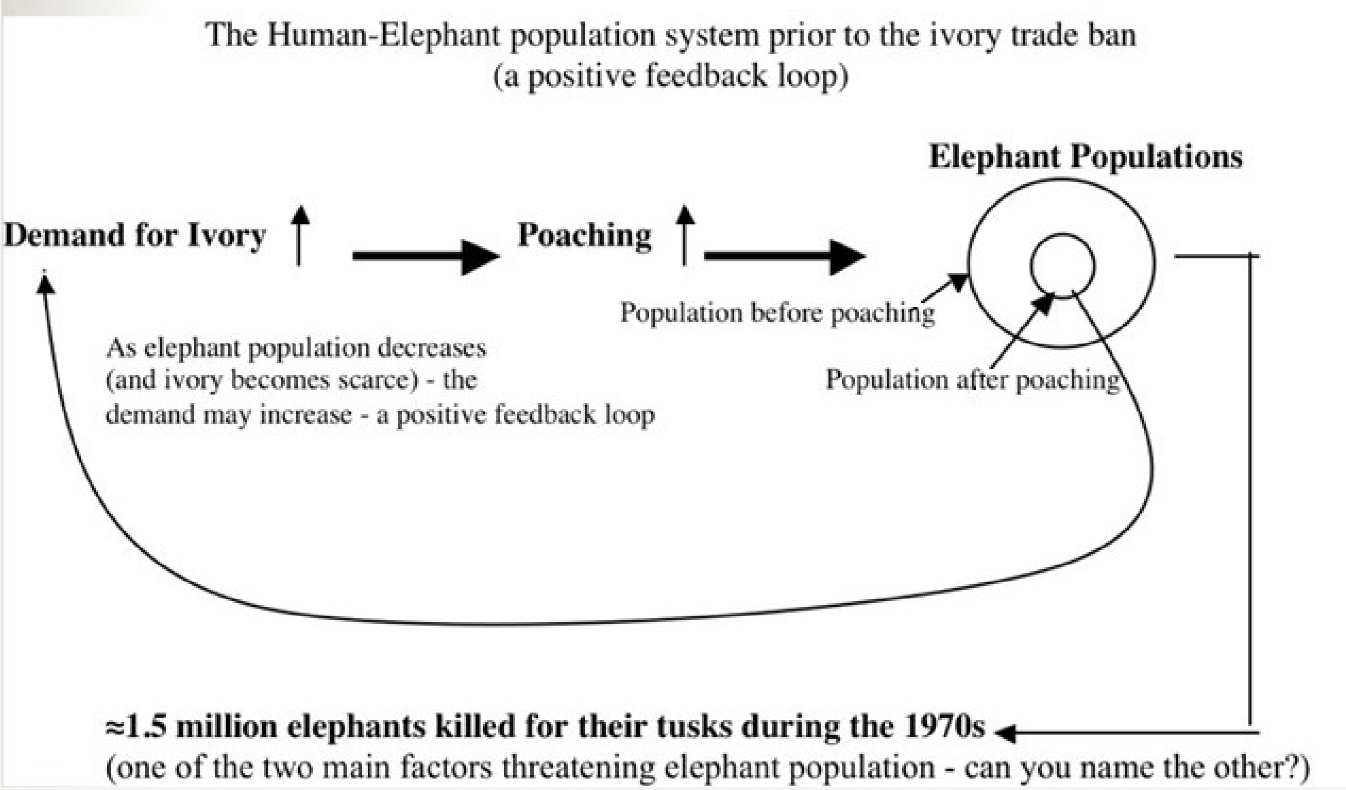
Poaching is a severe problem for all elephant populations, particularly in Kenya and the rest of East Africa. Like water use in Mono Lake, the effects of poaching arise from the interaction of several ecological and nonecological systems. Most importantly, the increased death rate due to hunting is coupled with an increased demand (and value) for the elephants' ivory as the populations decrease. Again, this is an example of a positive feedback system, where the poaching pressure increases as the population decreases, driving the elephants away from a stable point and toward extinction.



The African elephant population is declining largely due to habitat loss and poaching.

Photo by Bernard DUPONT from FRANCE - African Elephant (Loxodonta africana) male, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=40724295

FIGURE 16



An elephant economic/ecological system.

Various negative feedback loops are also involved in regulating elephant populations. Most of these feedbacks are *density-dependent*—that is, they change as the population density (i.e., the number of animals per km^2) changes. Three general types of density-dependent feedback loops will affect any population:

- Increase in death rates or decrease in birth rates due to a shortage of food
- Increase in death rates due to increases in predation, **parasitism**, or disease
- Increase in death rates or decrease in birth rates due to the increased intensity of social interactions within a population

Food availability is the simplest feedback system. In Kenya, the food resources for elephants are being reduced through the conversion of natural savannas to farmland or to **deserts**. In southeastern Kenya, much of the elephant population is located at Tsavo National Park, a semi-arid habitat that gets less than 500 mm of rain a year and, as a result, does not have dense vegetation on which the elephants can feed. A recent study by environmental scientists suggested that a viable elephant population in Tsavo, or habitats like it, would require 1,000 miles^2 of habitat. Only seven of the twenty major nature reserves in central and southern Africa approach this size.

Environmental scientists have found that the two other density-dependent factors we listed also contribute to the regulation of the elephant population. For example, elephants have few predators, but in densely packed populations, death rates have increased due to higher rates of disease; this effect is similar to what is found among humans living in high-density/low-resource areas. Although elephants are normally very social within their group, they exhibit an increase in fighting in overcrowded situations. This behavior leads to an increase in death rates, emigration rates, and even a reduction in birth rates due to the interference with normal mating behavior.

Although the interactions between elephants and the human population are complex, the inputs, outputs, and feedback are reasonably apparent to a trained observer. Sometimes, however, an environmental system contains so many interacting components and/or components that are difficult to uncover, that even scientists who are familiar with the system will find it difficult to determine the various inputs, outputs, and feedback loops. This was the case with the unexplained decline of red spruce trees in the northeastern United States, which we will consider next.

ENVIRONMENTAL SCIENCE CASE STUDY: Red Spruce in the Northeastern United States—an Environmental System Impacted by the Interaction of Natural and Human-Caused Factors

Forest ecosystems are complex systems that simultaneously experience all sorts of inputs and outputs. In a forest, there are births (inputs) and deaths (outputs) of plants and other organisms and also inputs and outputs of water, nutrients, and pollutants.

Red spruce is a tree species that grows in some of the forests of the eastern United States. It is a needle-bearing tree that can live for more than three hundred years and is tolerant of shade. It is used primarily for making pulp and paper. Red spruce grows throughout the eastern United States along the Appalachian Mountain chain from New England to Georgia. It is an important component of the low-elevation conifer forests of Maine and eastern Canada and also exists in high-elevation northeastern forests, such as those in the Adirondack Mountains of New York, although it rarely comprises more than 40 percent of the latter. Understanding the red spruce system in the northeastern United States became very important in the 1980s when the trees started to undergo an unexplained decline in number and health.

There had been occasional reports of unexplained red spruce death in North America since 1870. But in the early 1980s, multiple reports of damage to red spruce, combined with a knowledge of the relatively recent phenomenon of pollution from **acid rain**, led environmental scientists to suspect that there was a link: perhaps recent air pollution severity was causing red spruce to die in unusually large numbers. The concern was that red spruce might be a "canary in the coal mine," a sensitive indicator species revealing that air pollution was reaching harmful levels.

A red spruce forest. In the early 1980s, multiple reports of damage to red spruce, combined with a knowledge of the relatively recent phenomenon of pollution from acid rain, led environmental scientists to suspect that there was a link between acid rain and the demise of the red spruces.

By Kenneth P. James - iPhone 3G Camera, CC BY 3.0 us, https://commons.wikimedia.org/w/index.php?curid=12100560

A number of researchers conducted studies of the forest to determine if there was a systematic decline in the species rather than isolated tree deaths or deaths that could be easily explained by a pathogen or insect **pest**, and if so, whether air pollution might be a factor. The researchers came up with several preliminary findings and possible explanations for the tree deaths:

- Surveys taken in 1964 and 1982 at Whiteface Mountain, a 1,483 m peak in the Adirondacks of New York, revealed that red spruce had decreased by almost 70 percent in eighteen years. There were no natural factors, such as disease or drought, that could explain the decrease.
- In the northeastern states surveyed (New York, Vermont, New Hampshire), the percentage of standing dead red spruce trees was positively correlated with elevation—in other words, there were more dead red spruce trees at higher elevations than at lower elevations. Many stressful conditions increase with elevation, including colder temperatures, higher winds, thinner soils, and fewer nutrients in soils. Air pollution also increases with elevation.
- A survey of nineteen mountains along a west-to-east area from New York to Maine showed that there were more dead red spruce trees standing in New York and Vermont (the western part of the region) than in New Hampshire and Maine (the eastern part of the region). The western part of the region is closer to the Midwest, which is the primary source of acid rain. There is more acid rain in New York than in Maine, for example. So again, air pollution correlated with the pattern of tree death.
- Experimental work conducted in the laboratory and field showed that the unexplained red spruce decline was caused by freezing injury to needles. This was puzzling because red spruce is a species that exists in cold temperatures—why should it succumb to freezing injury? This led to the suspicion that some other factor, perhaps a component of air pollution, was making the species more sensitive to injury.

To put all the factors together and explain exactly what was happening to the red spruce, environmental scientists conducted a system analysis of the red spruce ecosystem. The system was defined as the trees as well as the plants, soils, and rocks that occur where red spruce grows. Inputs of water and nutrients came from the atmosphere; outputs left via streams.

Researchers first constructed a diagram showing the number and size of red spruce trees, which comprises the *basal area* of the trees. Over the course of a year, detailed analysis of the basal area's net gains—the growth of individual trees—and losses—the death of individual trees—confirmed that red spruce basal area had decreased.

Additional mass balance analyses of trees and chemical elements suggested that a number of factors together contributed to red spruce decline. First, the analyses showed significant inputs of sulfate, a component of acid rain. The analyses also showed that calcium had been lost both from the soils and from specific locations within spruce needles. Experimental work in the laboratory confirmed that calcium deficiencies adversely affect the ability of many trees, including red spruce, to withstand cold.

At the same time as red spruce death was increasing (1960–90), the combustion of oil and coal released large amounts of sulfur dioxide into the atmosphere, leading to the formation of sulfuric acid, a component of acid rain. This acid is composed of hydrogen and sulfate. This pattern was consistent with the hypothesis that sulfate promoted freezing injury to red spruce, but it did not prove that this was occurring.

When investigators examined the flux of various chemical elements in the red spruce ecosystem, they found that the input of sulfate to the forest during the 1960–90 time period was much, much greater than in previous decades. Therefore, they concluded that pollution was the factor making the trees susceptible to freezing. A system analysis led to the answer that the combination of a natural factor—cold temperatures—and a pollutant—sulfate—was the cause of red spruce decline.

ENVIRONMENTAL SCIENCE CASE STUDY: Managing Environmental Systems in the Florida Everglades

The Florida Everglades wetland is one part of a larger watershed that covers most of southern Florida.

Source: University of Florida Museum

The Florida Everglades **wetland** is one part of a larger **watershed** that covers most of southern Florida and is divided into three connected basins. The entire watershed extends over more than 50,000 km^2.

The Everglades is made up of several interacting subsystems: water-flow systems similar to Mono Lake; energy and nutrient systems similar to the red spruce forest; and population systems similar to the elephant-human system we examined earlier in this section. One example of a small subsystem is the “alligator hole,” which consists of small pools (e.g., two to four meters^2) surrounded by **marsh** plants. The pools themselves are kept plant-free by the activity of alligators. Alligator holes throughout the Everglades are permanent homes to many small aquatic animals and plant species that receive their entire input of energy from resources within the pools themselves. However, the alligators, with their greater food and space requirements, depend upon the entire Everglade system for survival.

During the twentieth century, human population growth and development, and the resulting need for water and farmland, have had an impact on all the environmental subsystems in the Everglades. What was once a subtropical wetland of over one million acres, and home to several bird, mammal, reptile, and plant species found nowhere else in the U.S., is now half its original size. The Everglades has been managed throughout the last century by state and federal agencies, but the particular management strategy has varied in response to large-scale and unpredictable regional changes in the weather that has resulted in periods of floods or droughts.

In 1999, after years of work by several agencies (led by the U.S. Army Corps of Engineers and the South Florida Water Management District, or SFWMD), a **restoration** plan for the Florida Everglades watershed was adopted by Congress as part of the Water Resource Development Act of 2000. The Comprehensive Everglades Restoration Plan is really a collection of several plans ranging from water management to endangered species protection, each designed to manage a particular subsystem within the Everglades. As part of the implementation of the plan, the SFWMD developed an "Everglades Landscape Model," which integrates information from all levels of systems in the Everglades—from the alligator hole to large-scale water flow through the three water basins.

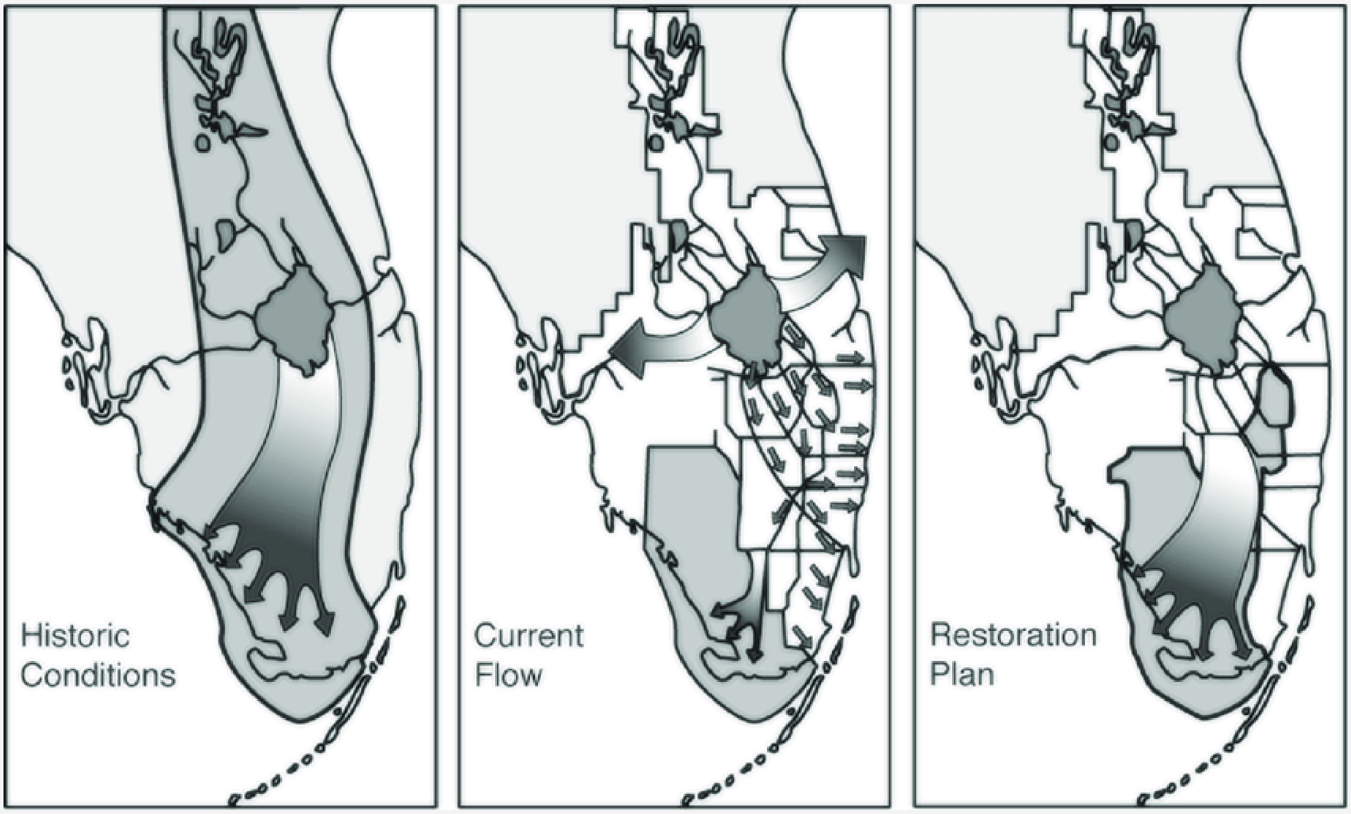
This multi-system management plan, while complex in its details, is based upon a few principles. First, there needs to be an increased flow of water through the watershed in order to counteract the effects of decades of drainage and to provide enough water for the aquatic and marsh organisms normally found in this type of environment. Second, because water pollution has toxic effects on plants and animals and adversely affects the normal functioning of **nutrient cycles** and energy flows within the ecosystems, there needs to be a reduction in wastewater from human development. The third principle is that enough water is currently available in the watershed to meet the restoration needs. However, this water needs to be made cleaner, which can only be done at significant social and economic costs. This is a clear example of the interaction between ecology and economics within ecosystem management.

The final principle is that the management of the Everglades ecosystem must be adaptive. The implementation of each management technique is treated as an experiment that can be modified in the face of the uncertainties inherent in any ecological system. Adaptive management, a concept that predates and improves ecosystem management, is the resource managers' answer to scientific uncertainty—the fact that management strategies must change to adapt to new scientific information regarding environmental systems. Adaptive management was previously applied to the Everglades ecosystems in various ways by both the state and federal government. First, the SFWMD designed a project for the purpose of reducing total phosphorous (a major water pollutant) entering the watershed and to provide a test model for a larger proposed system. The results of this experimental project were used to implement future management strategies.

The federal government is also attempting to apply adaptive management, on a large scale, to the Everglades ecosystem. The U.S. Department of State's Man and the Biosphere Program is a holistic attempt to combine geographic information systems and computer simulation models to develop a range of land- and water-use strategies. Each strategy provides different levels of environmental protection and economic development. These different strategies are then studied and debated by those with an interest in the Everglades ecosystem with the intent of implementing the program that best balances all interests.

The management of the Everglades is not without its problems. Control of water flow and pollution requires restrictions on the use of private property and economic development, possibly affecting short-term economic development. However, management of the Everglades is an important application of the concept that the environment is made up of several interacting systems.

FIGURE 17



Three-picture summary of historic, current, and restoration water flow in the Florida Everglades as provided by the U.S. Army Corps of Engineers in the early 2000s.

Source: Mitsch and Jørgensen, 2004

SECTION I SUMMARY

- Environmental science is the study of the impacts of human activities on environmental systems. There is no single environmental indicator that offers an accurate, objective assessment of the status of the entire Earth, but a number of indicators in different areas are used.
- There are roughly 8 billion people on Earth today. The total human population continues to increase, though the rate of growth has been steadily decreasing since the 1960s.
- While the background rate of extinction is an estimate (two mammal species per 10,000 species per one hundred years), it is certain that human beings have increased extinction rates on Earth today. Of the estimated 10 million to 30 million species on Earth, perhaps as many as 40,000—maybe more—are going extinct each year. Biological diversity gives a negative indication of the state of the Earth and shows that we are in a sixth mass extinction event.
- Atmospheric concentrations of carbon dioxide and other greenhouse gases are steadily increasing due to human activity. Global temperatures have risen during the 1900s, with a particularly rapid increase since 1980. It is clear that human activity is causing global temperature increase and climate change.
- Air and water emissions increased steadily in the early 1900s and decreased (in the U.S. at least) after the early 1970s due to stricter pollution regulations. However, pollution levels remain a global issue, particularly for some chemicals.

- Sustainability is the consumption of resources in the present that allows an adequate supply to remain for future generations. Resource consumption varies throughout the world and has different environmental impacts depending on both the number of people and the type and quantity of resources they use. As an environmental indicator, resource consumption shows a worsening state of the environment.
- Scientists often study the dynamics of environmental systems, which are sets of living and nonliving components connected in such a way that changes in one part of the system affect the other parts. Systems can be open or closed to exchanges of matter, energy, or both. Human activity almost always affects environmental system dynamics in some way.
- A system analysis determines what goes in, what comes out, and what has changed within a given system. Environmental scientists use mass balance analysis to calculate inputs and outputs to the system pool and the rate of flux through the pool. If there is no overall change to the pool, the system is in steady state. Changes in one input can affect an entire complex system, as illustrated by Mono Lake.
- Mean residence time (MRT), the average time that a portion of the pool remains in a steady-state system, is important for calculating how long pollution remains in water or the atmosphere. If a system is not at steady state, then the accumulation or depletion of a material, rather than MRT, is calculated.
- Systems are regulated by feedback loops. In negative feedback, changes in the system variable bring the system back to its stable set point. In positive feedback, changes in the variable lead to further changes, bringing the system further away from the set point.
- If there is too long a delay between the time between when a signal is generated and when it is received and responded to, the system may experience overshoot. In some systems, this may lead to exceeding the carrying capacity.
- Systems may comprise a complex interaction of subsystems, as illustrated by the elephant–human population system in Africa, the red spruce forest in the northeastern United States, and the Everglades ecosystem in southern Florida.

Section II

Biodiversity: From Local to Global

In this section, we will focus on the Earth as a living planet and explore the ways that life is organized from local to global scales. You will learn about the evolutionary processes that gave rise to the diversity of species on our planet, the biological and physical factors that regulate biodiversity from genes to species, and how living and nonliving components are linked together into systems—both small and global. The major elements you will cover are:

- *Evolution and Biodiversity* – Genetic variation resulting in environmentally adaptive traits has resulted in a diverse number and types of species.
- *Population and Community Ecology* – how populations grow, disperse, and interact with other populations
- *Ecosystems* – the integration of living and nonliving system components in specific geographic areas
- *Global Climate and Biomes* – variation in global patterns of temperature, sunlight, and rainfall are key in creating geographic regions distinguished by different dominant forms of plants and animals
- *Global Energy and Matter Cycles* – global biogeochemical cycles on which all ecosystems depend

BIODIVERSITY

What Is Biodiversity and Why Does It Matter?

A small plot of land or a tiny pond has dozens or hundreds of different kinds of plants and animals that even the untrained eye can distinguish, as well as thousands of different kinds of microscopic organisms. In contrast, a carefully tended lawn or a commercial tree **plantation** usually supports only a few types of grasses or trees. The total number of living things in the plantation may be the same as in an equivalent area of natural forest, but the diversity of organisms will be far less. The number of different species in any given place is the most common measure of biological diversity. Variety of species, however, is not the only way biological diversity can be measured. Recall from Section I that biological diversity, or biodiversity, is the diversity of all the genes, species, and habitats on Earth.

The great number of species on Earth is the result of the large amount of genetic diversity within and among species. Genetic diversity is the variety of **genes**, the chemical building blocks that provide the blueprint for how every **individual organism** develops. Current estimates are that humans have approximately 30,000 different genes, which can combine to form a virtually limitless variety of individuals. No two people, except for identical twins, will have exactly the same combination of genes. There is even more genetic diversity between individuals of different species.

Biodiversity also includes the different ways that groups of species are organized together on the planet. A forest community will contain different species of plants and animals than a community of organisms in a desert, a lake, or the ocean bottom. Finally, biodiversity describes different combinations of living and nonliving components in varied environmental systems of inputs, outputs, and feedbacks, such as the Mono Lake, African elephant, and red spruce ecosystems that we discussed in Section I.

FIGURE 18

A sample of the range of multi-cellular species diversity.

The Value of Biodiversity

While it is obvious that there is much biodiversity on Earth, it may not be as obvious why biodiversity should matter to you. Though we clearly need other animals and plants for food, most modern people actually eat very few species. In fact, although ancient humans (and the few remaining modern hunter-gatherers) used dozens, if not hundreds, of species of plants and animals, the food most people eat today comes from only a few plant species (corn, wheat, and rice). What of the millions of other species in the world—how do they matter?

Value can be characterized in two ways: goods, services, or information that provide benefits to people are said to have **instrumental value**. Objects, living or nonliving, that have **intrinsic value** have worth in and of themselves, independent of any benefit they may provide to humans and are by their nature priceless. People who argue that biodiversity has intrinsic value do not necessarily deny that it also has instrumental value. However, they argue that while its instrumental value may provide benefits to human society, its intrinsic value is what should drive its protection. Many environmental scientists who have made the study and protection of biodiversity their main goal do so because of their belief that biodiversity is a good independent of any economic benefit.

Genetic Diversity

At the most basic level, species are distinguished from each other by how different their genes are. If you have ever wondered why some camels have one hump while others have two, the answer lies in the unique set of genes possessed by virtually every organism on Earth. Genetic diversity is the ultimate source of biodiversity on Earth. The genetic differences between members of the same species can lead to physical variety such as different eye color, leaf arrangement, or number of humps; differences between members of various species can result in dramatically different body plans and capabilities. Over generations, blueprints can change so that sometimes the organism of today bears very little resemblance to its ultimate ancestor. This change is the result of **evolution**. Evolution occurs when the genes among groups of individuals within the same species change over time, so that the groups become different enough to be recognized as separate species. To understand how genetic diversity leads to species diversity, we need to understand some of the basic principles of genetic diversity.

All organisms inherit from their parents the genes that provide the blueprint for their development and function. Some genes contain most, or even all, of the instructions for relatively simple traits. More complex traits, such as body size and shape, are the result of the interaction of more than one gene. All of these traits, the simple and the complex, are referred to as an individual's **phenotype**, which consists of all of an individual's anatomical, physiological, and behavioral characteristics. All of an organism's genes together comprise its **genotype**, which is its unique genetic composition and the code for its phenotype. Genes are chemically made up of the molecule **DNA** and arranged within an organism's cells on structures called **chromosomes**.

Genes frequently have alternative forms that contain different instructions for what the gene will produce; each alternative form is called an *allele*. If a particular gene in a population has two alleles (we'll call them A and B), an individual in the population who has two copies of the gene will have one of three possible genotypes: AA, AB, or BB. The phenotypes produced by the AA and BB genotypes will differ in some way. For example, in pea plants the A allele (and therefore the AA genotype) produces purple flowers, and the BB genotype produces white flowers.

FIGURE 19

	Possible Alleles from Second Parent	
Possible Alleles from First Parent	A	B
A	AA	AB
B	AB	BB

Possible genotypes of offspring with two copies of a gene that has two possible alleles.

In some cases, the phenotype for the individual with the mixed genotype, AB, will be identical to the phenotype produced by the AA allele. For example, a pea plant with an AB genotype produces purple flowers, just like a plant with the AA genotype. In these cases, one allele masks the effects of the other allele. This is an example of an important aspect of genetics to which we will return later in our discussion of genetic diversity. In other cases, however, the AB genotype will produce a phenotype that is a mix of the AA and AB genotypes. In the snapdragon, for example, the AB genotype produces a pink flower rather than either the red or white phenotype produced by AA and BB plants, respectively.

Taken together, all the different alleles for a particular trait that occur in a population are a pool of genetic diversity. It is impossible to estimate the number of different alleles for genes of all individuals in any natural population, and thus all the potential diversity, but a familiar example can give you some idea of the possibilities. All the varieties of *Canis familiaris*, the domestic dog, share enough genetic material to be considered one species. However, by repeatedly breeding individuals with certain desired traits, breeders have produced dogs as varied as toy poodles and Great Danes. Each different breed is expressing a different combination of alleles that lead to variations in size, shape, coat texture, color, and so forth.

There is only one way a new allele can be produced: a *mutation*, an error made when genetic material is copied, can permanently alter the genotype an organism passes on to its descendants. Mutations occur spontaneously and randomly. Millions of copies of genetic material are made within cells, so it's only natural that some mistakes will be made. Mutations are even more likely under some environmental conditions—exposure to anthropogenic chemicals, such as those in tobacco smoke, for instance, or radiation.

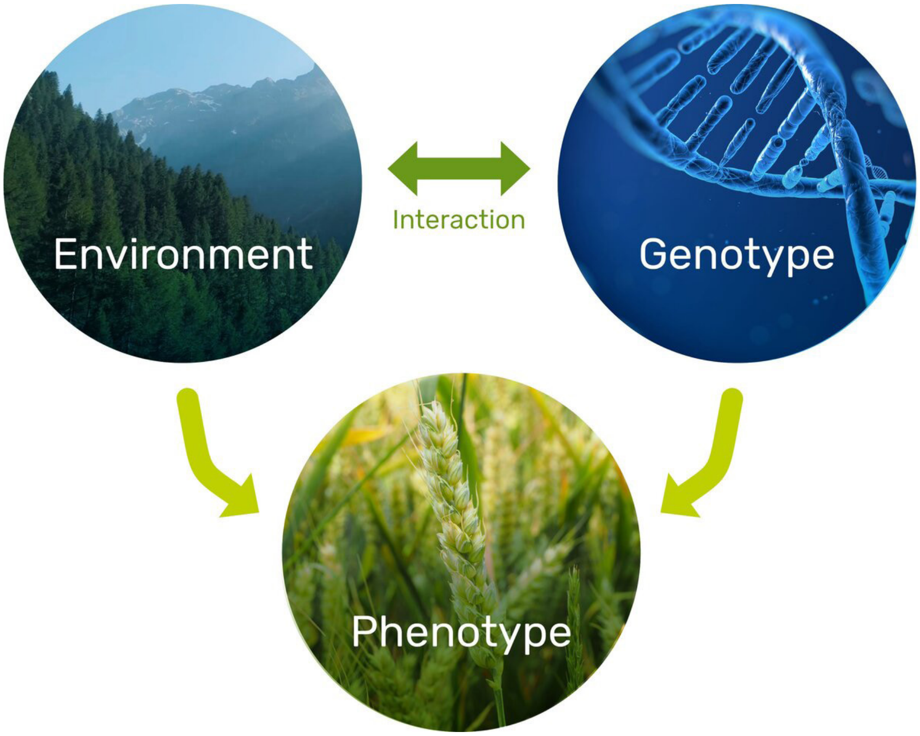
Though some mutations will have no effect on an organism, others are harmful. Most neutral or harmful mutations die with the organism. If the mutation occurs in the sex cells that produce offspring, however, the genetic change appears in the next generation. And if the mutation is beneficial to the organism in some way, making it more likely that the organism will survive and pass the traits to its descendants over successive generations, the trait may spread throughout a population, becoming one more allele in the pool of genetic diversity.

If there are many different alleles for a particular gene in a population, there will likely be a significant amount of genetic variation among individuals within the population, as different individuals are more likely to have a different combination of alleles. Further, large populations will usually have more genetic variation than small populations because the more individuals there are, the higher the likelihood that the population will have many different alleles for any one gene.

Expressions of Genetic Diversity

In some simple cases, a phenotype is simply the expression of a genotype. For instance, a person who inherits the genes for blue eyes will have blue eyes whether they live in tropical Africa or subarctic Alaska. However, most complex phenotypes (for instance, size) are the result of the interaction between the genotype and its environment; in other words, phenotype = genotype + environment. Two growing pine trees may have identical genotypes coding for height, but if one is grown in a nutrient-rich environment and the other in a nutrient-poor environment, the first tree will likely grow to be taller.

FIGURE 20

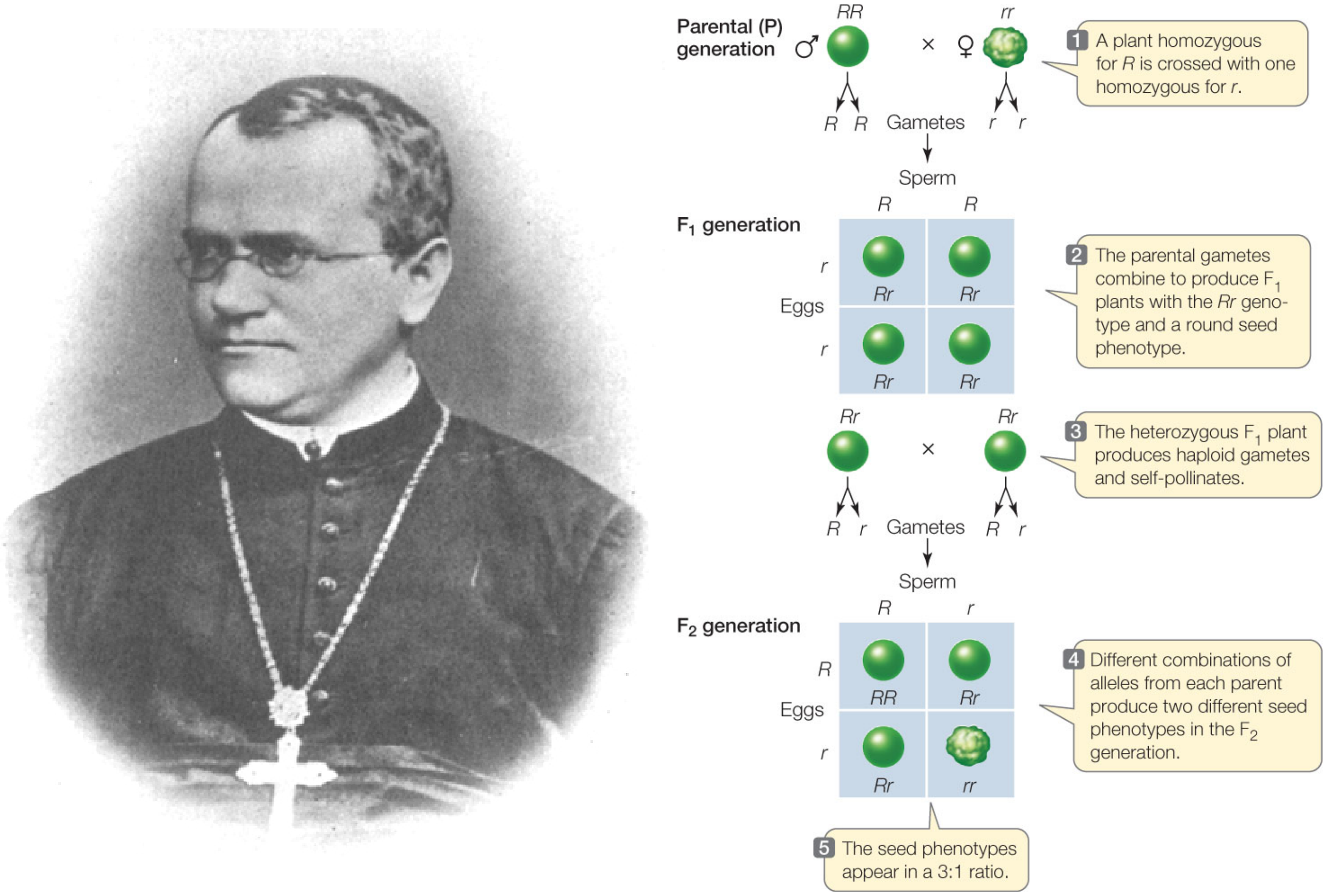


An individual's physical and behavioral characteristics (the phenotype) is a result of the interaction between genotype and the environment.

Source: Emphasis

Just as organisms with the same genes may have different phenotypes, individuals with similar phenotypes may have different combinations of alleles. The nineteenth-century Austrian monk Gregor Mendel was the first person to understand genetic variation within and among individuals. Mendel studied pea plants with two different phenotypes for various traits, such as red flowers and white flowers or smooth peas and wrinkled peas. When he crossed smooth pea plants with wrinkled pea plants, all the offspring (new plants) had smooth peas. However, when he crossed this second generation of smooth pea plants with each other, the result was a mix of smooth and wrinkled peas.

FIGURE 21



1 A plant homozygous for *R* is crossed with one homozygous for *r*.

2 The parental gametes combine to produce F_1 plants with the *Rr* genotype and a round seed phenotype.

3 The heterozygous F_1 plant produces haploid gametes and self-pollinates.

4 Different combinations of alleles from each parent produce two different seed phenotypes in the F_2 generation.

5 The seed phenotypes appear in a 3:1 ratio.

Gregor Mendel and his pea-plant experiment.

Source: Khan Academy

What is the explanation for this? Mendel proposed that there was a hereditary factor (what we now call a gene) that transmitted traits such as pea surface from generation to generation. The plants he used carried genes with two alleles for each trait, such as pea surface. If a plant inherited one smooth allele and one wrinkled allele, the smooth allele would dominate, masking the effect of the wrinkled allele, which would not show up in the phenotype. The allele for wrinkled peas would create the wrinkled pea phenotype only when the plant inherited two copies of it, one from each parent.

If two smooth pea plants or two wrinkled pea plants were crossed, they would always produce one phenotype—either all smooth or all wrinkled. However, crosses among the genetically varied plants would always produce a mixture of smooth and wrinkled peas. In other words, increased genetic variation within individuals will result in an increase in phenotypic variation in offspring. Darwin's results with pea surface were replicated with many other traits and later with many other organisms and became the basis of our understanding of how genes and alleles produce genetic diversity.

There are four types of genotypic diversity:

- *Variation within individual organisms* – A given individual can possess different alleles of the same gene, such as the pea plant's white and purple alleles.
- *Variation among individuals within a population* – Different individuals within a population can have different alleles for the same gene. However, if a population decreases in size due to hunting, habitat loss, or changes in the environment, the pool of genetic diversity, or the total number of different kinds of alleles, will also decrease.
- *Variation among populations* – When populations of the same species are isolated or partially isolated from one another, the types or relative number of alleles can vary from one population to another. The total genetic variation of a species is made up of the variation within each population and the variation among various geographically separated populations.
- *Variation among species* – Genetic variation will, on average, be greater among species than among populations within species. This is one means of distinguishing species from populations. One of the methods by which new species arise is through the genetic divergence of two isolated populations of one species. New and different alleles will arise and persist in each population. Eventually, these different alleles will produce such divergent genotypes and phenotypes that individuals in the two populations will no longer be able to interbreed successfully; they will have become different species. There are various estimates for how much genetic or phenotypic variation is required to distinguish two populations as separate species; most rely on quantitative estimates of the number different alleles at specific genes.

Species Diversity

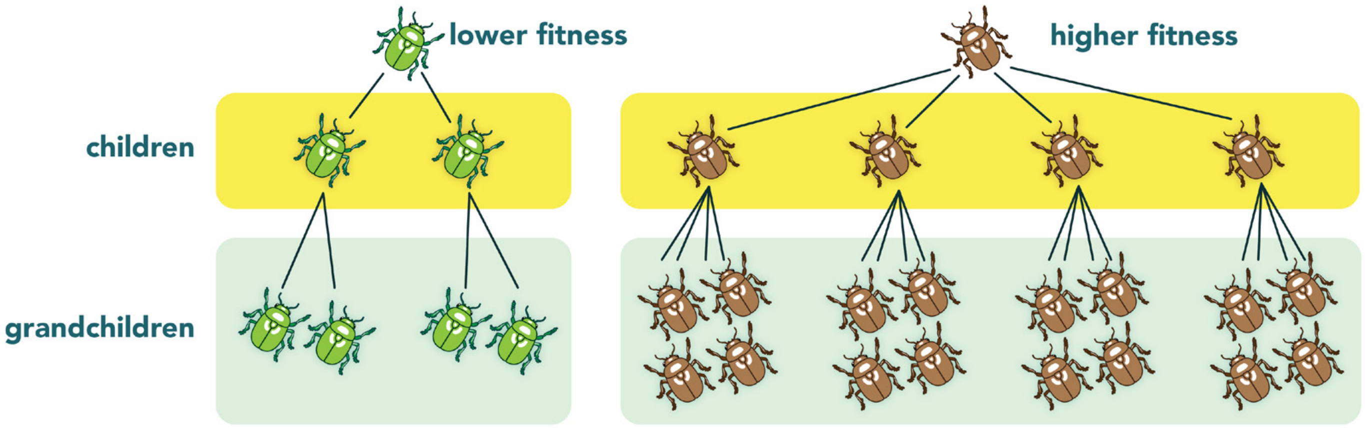
The most common definition of a species is a group of organisms that is distinct from other groups in morphology (body type), physiology, or biochemical properties and that can breed and produce viable offspring. Species diversity results from both adaptive and nonadaptive processes. Most new species arise as the genotypes and phenotypes of two or more populations diverge through processes that take place at the population level, such as the evolution of different adaptations in populations living in different environments or the decrease in migration between populations with a corresponding lack of genetic transfer. To understand these processes, let's begin by looking at some basic aspects of evolution.

EVOLUTION

As explained earlier, repeated change in genotype over time may result in a variety of phenotypes in a species. While some of these phenotypes will have no effect or an adverse effect on survival, others may help an individual survive in its environment. For example, a frog with longer legs than other frogs in its population may be able to hop faster and will probably have a greater ability to catch food or avoid predators. Thus, the frog with longer legs is more likely than its short-legged neighbors to live long enough to reproduce and pass its genes on to its offspring.

Fitness is a measure of the relative viability (ability to survive) and fertility (reproductive success) of an organism. The more likely that an individual will survive and the more offspring it leaves behind, the greater its fitness. The successful survival of the genes of more fit individuals over many, many generations of offspring can lead to a change in the average phenotype of the species. On the other hand, alleles that tend to be more harmful than beneficial to an individual will usually die out along with the individuals in a population that carry them.

FIGURE 22

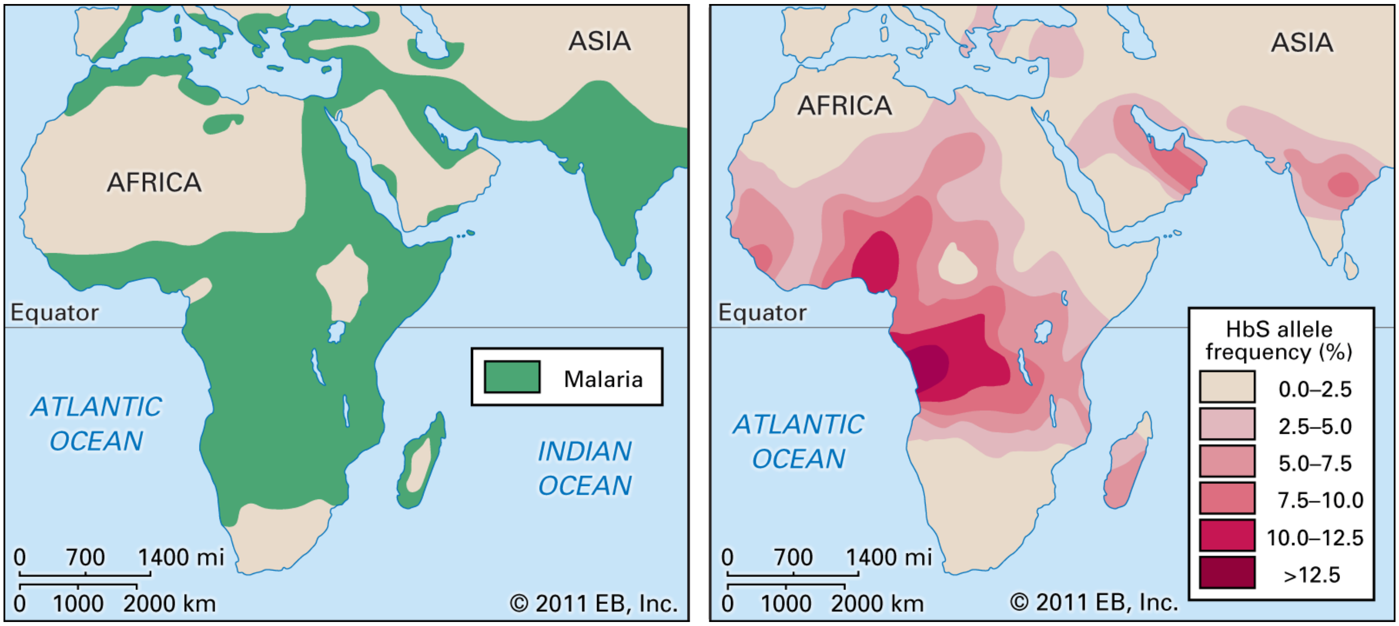


The number of offspring produced over a lifetime is a main indicator of an individual's fitness.

Source: [UC Berkeley: Understanding Evolution]

An example how different alleles produce individuals with different levels of fitness is the allele for sickle-cell disease, which reduces the oxygen-carrying capacity of blood and results in many severe mental and physical impairments and usually death, mostly among people of African descent. At the same time, this allele also conveys resistance to malaria, one of the most deadly diseases in Africa. Two copies of the allele are necessary to produce the disease. Individuals with only a single copy of the allele will not develop the disease but will have some natural protection against malaria and thus a higher likelihood of survival in an environment where that disease is common. Thus, the sickle-cell allele, although fatal to people who carry two copies, has persisted in the population because those people with only one such allele have been more likely to survive and pass the allele on to their descendants.

FIGURE 23



The geographic correlation between the prevalence of malaria and the allele conveying resistance to the disease.

Source: [Encyclopedia Brittanica]

FIGURE 24

	Possible Alleles from Second Parent	
Possible Alleles from First Parent	A	B
A	AA (normal resistance to malaria/no sickle-cell disease)	AB (increased resistance to malaria/no sickle-cell disease)
B	AB (increased resistance to malaria/no sickle-cell disease)	BB (sickle-cell disease; usually fatal)

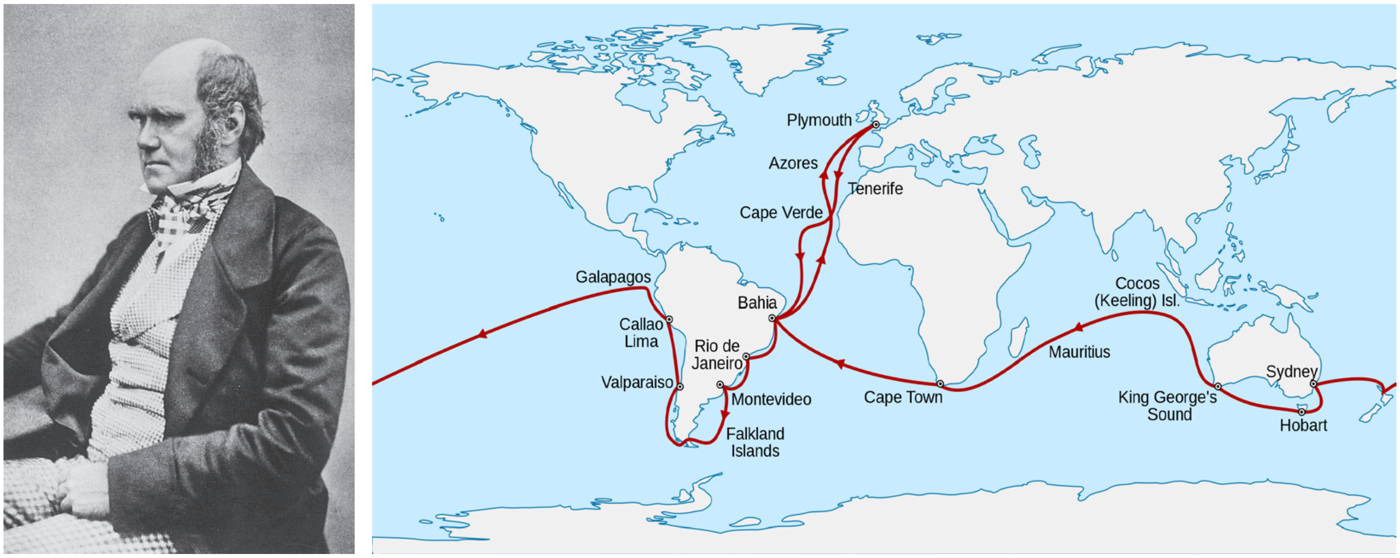
Inheritance of increased resistance to malaria and of sickle-cell disease.

Adaptation Through Natural Selection

The idea that species evolve over time had been suggested by a number of scientists and philosophers, but the concept of evolution through **natural selection** did not become synthesized into a unifying theory until Charles Darwin (1809–82) was able to put the various pieces together.

At age twenty-two, Charles Darwin became the ship's naturalist onboard the HMS *Beagle*, which was about to sail around the world. During his journey (1831–36), Darwin made a great many observations of phenotypic variation and fitness in a great variety of species. In addition to existing organisms, he found evidence of species that had not survived. Darwin observed that plants and animals produce many more offspring than are needed to replace the parents. In fact, in the case of many organisms, such as trees, fish, or insects, which produce hundreds or thousands of seeds or eggs, most offspring do not survive. Darwin questioned why some survive and some do not. During the decades after his journey on the *Beagle*, he synthesized his observations and developed them into a more robust theory. That theory, finally published in 1859, was called "The Origin of Species by Means of Natural Selection."

FIGURE 25



Darwin and the Voyage of the Beagle *(1831–36).*

The key ideas of *Darwin's theory of natural selection* are:

- Organisms produce many more offspring than are needed to replace the parents.
- Within any given species, individuals will express a range of phenotypes.
- In a given environment, some phenotypes will enable an organism to survive better than other phenotypes; in other words, some organisms will be more fit.
- The more fit individuals will have a better chance of reproducing; they will be selected for and over time will be well established in the environment.

Darwin's theory explains why individuals with certain traits survive and reproduce. The process of becoming most fit or most suited for a particular environment is called *adaptation*. Species differ in how well they adapt to a given environment and how well they adapt to a changing environment. There are also variations in how long it takes species to adapt. A species with more genetic variability will have a wider range of phenotypes in any given environment, and thus it is more likely that a successful phenotype for that environment will exist.

Adaptation to a Changing Environment

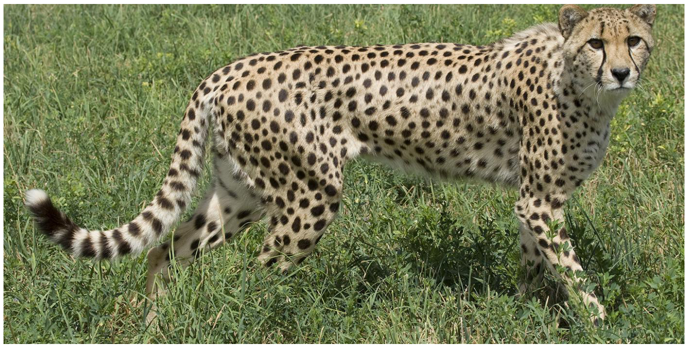
Many organisms can adapt to quickly changing environments by simple changes in their physiological or behavioral responses; they are tolerant to some degree of environmental change without the need to evolve new adaptations. For example, the panting of a dog or the sweating of a human are means to cool off on a hot day, while the dropping of leaves by plants at the beginning of the dry season is a means of conserving water. However, over centuries or more, a species' environment may change so dramatically that short-term physiological responses are no longer enough. As environments undergo major changes over a long period of time, species will either die out or adapt through natural selection. For example, as the environment in many parts of the world became drier, many plant species evolved similar adaptations to both conserve and acquire scarce water. These adaptations include thick, fleshy leaves with thick waxy surfaces, all of which better enable a plant to conserve water.

The ability of a species to adapt to environmental changes will depend greatly on how much, and how fast, that change occurs. Consider a tropical bird that has a strong beak that enables it to crack seeds with very hard shells. Imagine that over many years the shells of the seeds become even harder. The birds with stronger beaks will be more fit at opening the seeds than individuals with weaker beaks. Thus, those that can adapt to the change in their environment (harder shells) will be more fit and pass on their strong-beak genes to future generations. However, if the environment changes so fast that suddenly only extremely hard-shelled seeds are available, there may not be any birds with sufficiently strong beaks to open the shells, and the species will die out. Much of the current environmental change caused by humans is both dramatic and sudden, and most species, like our hypothetical tropical bird, may not be able to adapt in time.

Nonadaptive Evolutionary Processes

Evolution can also occur through nonadaptive processes. When individuals from one population migrate to another population, *gene flow* occurs. If the population from which the migrants come had more alleles of a particular type, or some unique alleles altogether, and if these migrants mated and produced offspring in their new population, they would introduce these new alleles into the population, and new forms of the resulting phenotypes would also be introduced. There is evidence that high rates of gene flow occur in species in which there is much dispersal of individuals. However, most populations of a species seem to be relatively isolated from each other and need to adapt to their environment with the genetic variation they possess. As we will see, this genetic isolation of most species is an important issue in the maintenance of biodiversity.

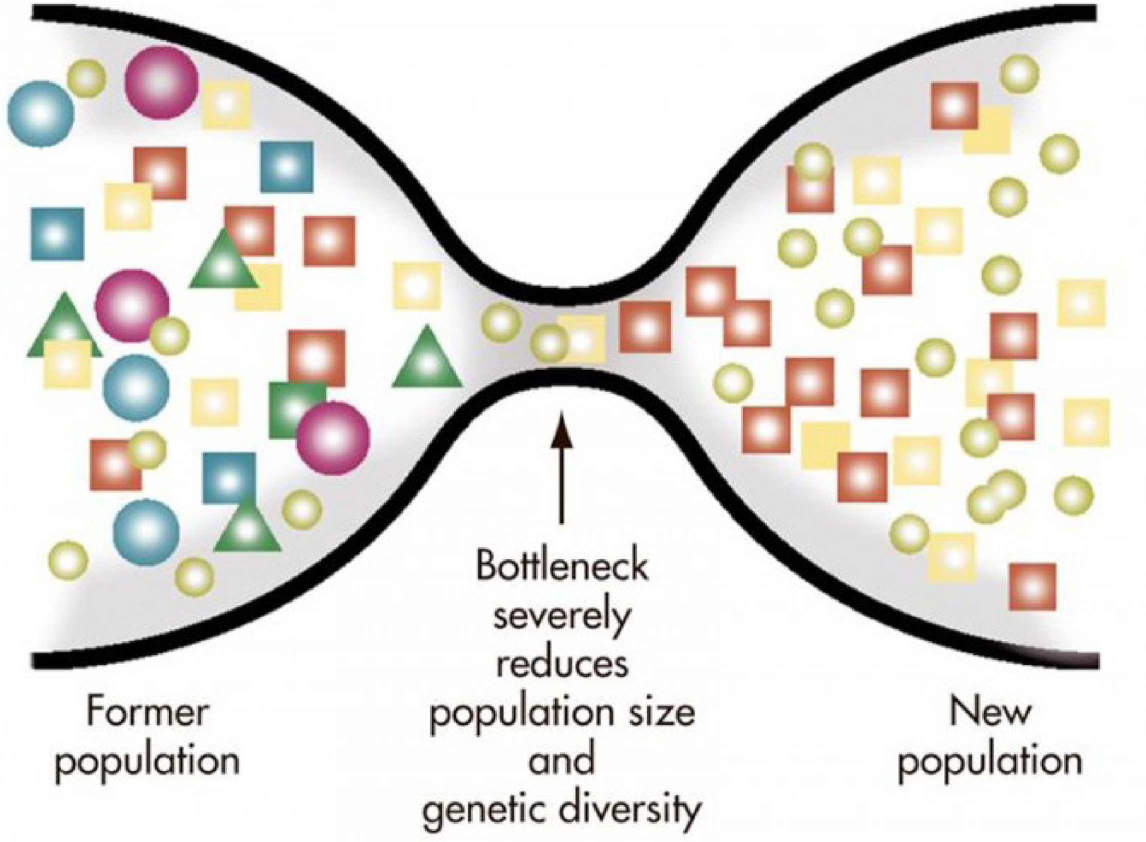
Another nonadaptive process, *genetic drift*, or random change in genotypes among small populations of a species, is known to be an important mechanism in evolution. When a population is small, not all possible alleles will show up in the relatively few offspring that are produced. Imagine a population of only twenty organisms, ten with allele A and ten with allele B. If only two of those individuals mate and produce offspring, they may well both have the A allele; the B allele will be lost in just one generation. The loss of alleles from one generation to another will result in genetic change and a corresponding change in phenotypes over time, a form of evolution not associated with fitness or selection.



The cheetah population has dramatically decreased due to hunting and loss of habitat. Today, the cheetah population is so small that there is almost no genetic variation.

One specific type of genetic drift is the *bottleneck effect*, in which a population is drastically decreased in size due to hunting, habitat loss, a natural disaster, or changes in the environment. The event that produces the decrease acts like a bottleneck, reducing the number of different alleles present in the population. The remaining population will thus have a smaller pool of genetic diversity. Environmental scientists who study the genetics of natural populations have discovered that low genetic variation is correlated to all kinds of potential problems, including increased risk of disease and low fertility.

FIGURE 26



An illustration of the bottleneck effect, which is a type of genetic drift.

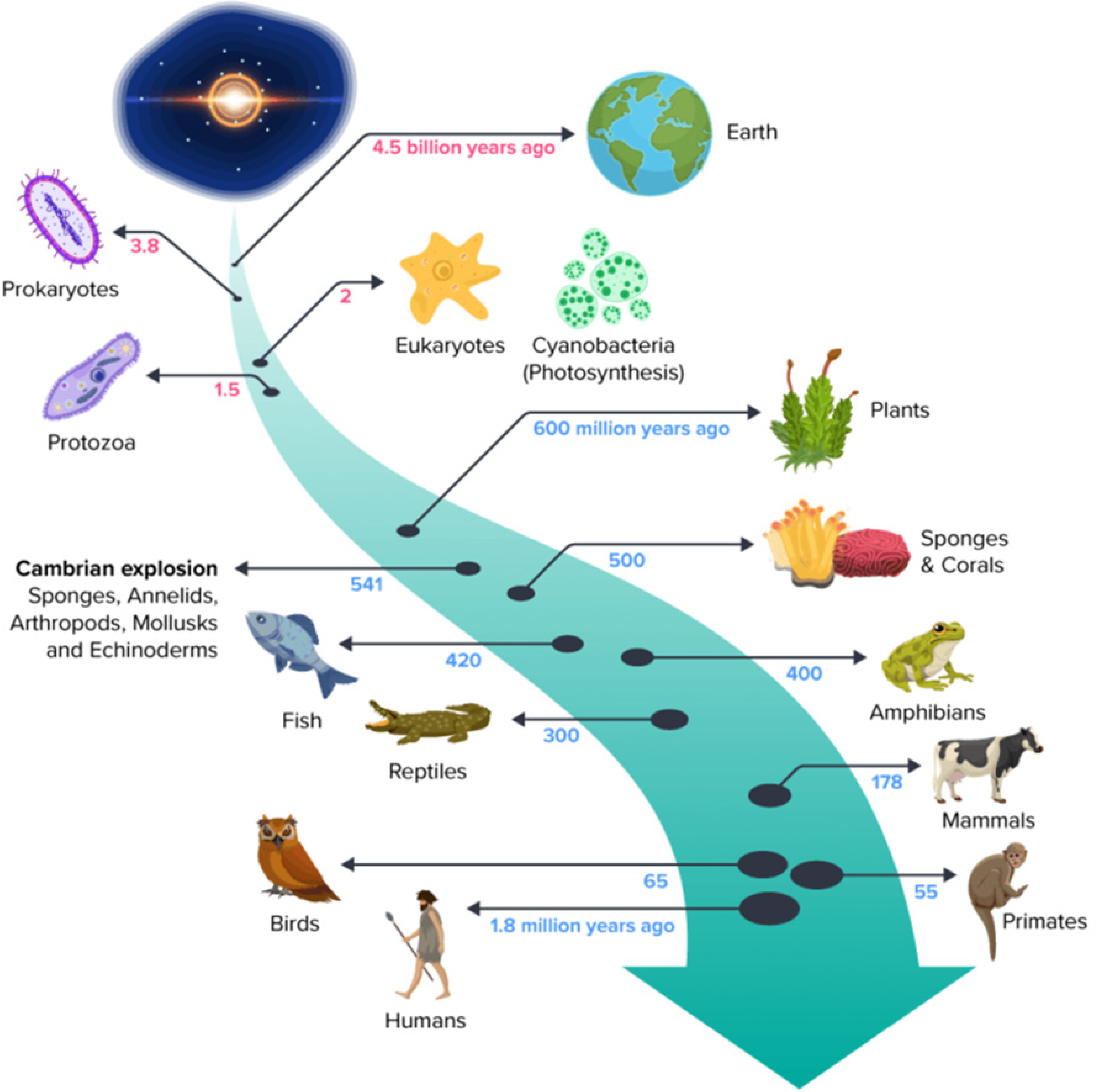
Source: Naturalis Historia

One well-known example is the cheetah, whose populations have dramatically decreased due to hunting and loss of habitat. The drastic reduction in cheetah population size over a short period of time resulted in the loss of all the alleles that had been present in the killed animals. Today, the cheetah population is so small that there is almost no genetic variation; individuals are essentially all identical twins. Cheetahs tend to have low fertility (males have 70 percent abnormal sperm cells) and high rates of disease, at least among zoo populations where most reliable studies have been conducted. It is uncertain if natural populations have the same reduced fitness.

The Pace of Evolution

How long does evolution take? A significant change in a species' genotype, such as an adaptation to a completely different food source, can take many hundreds to thousands of years. If we examine the evolution of life from single-celled organisms to primates and human beings, we can see that it has taken a very long time. Smaller scale evolutionary changes can occur over a much shorter time scale. (Keep in mind that "long" and "short" in the context of evolution are very different from our everyday sense of time.)

FIGURE 27



A timeline of the evolutionary history of life.

Source: Flexbooks

Three factors are particularly important influences on the pace of evolution by natural selection. First is the rate of environmental change to which a species must adapt. As we noted earlier, rapid environmental change forces populations to evolve quickly to adapt to the new environment or die out. Secondly, if a population has a large amount of genetic variation that produces traits that make individuals more fit, evolution can occur quite quickly, but if the population must generate new genetic variation through the accumulation of mutations, evolution will proceed much more slowly. Finally, new adaptive traits may be able to spread more quickly in small populations than in larger populations. Small populations are certainly more likely to undergo rapid evolution by nonadaptive mechanisms such as genetic drift and bottlenecks.

A ginkgo biloba leaf from the Eocene epoch from the McAbee fossil beds, British Columbia, Canada. The ginkgo tree, which exists in China and is an ornamental tree in many parts of the U.S., appears in the fossil record from 60 million years ago.

Source: CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=6532895

CHANGES IN ENVIRONMENTAL CONDITIONS AND EXTINCTIONS

While we do not know the actual number of species in the world today, we do know that number equals all the species that evolved over time minus all of those species that no longer exist. If the environment changes so that a population is no longer adapted to it, the population's growth rate becomes negative. Eventually, the population size will decrease to zero unless the population migrates to a new environment in which it can succeed or unless it adapts to the changed environment through evolution. In most cases, neither option works. There may be no favorable environment close enough for the population to migrate to or, if there is, it may already be populated by species the population cannot successfully compete with. In the second case, the environmental change may be so rapid that the species does not have the time to evolve new adaptations. Organisms that cannot adapt to environmental change will eventually go **extinct**; that is, no members of the species will remain on Earth. Almost every species that has ever lived on Earth has gone extinct—although this can mean that the lineage is lost to history, it can also mean that that they gave rise to new species before going extinct.

The Fossil Record

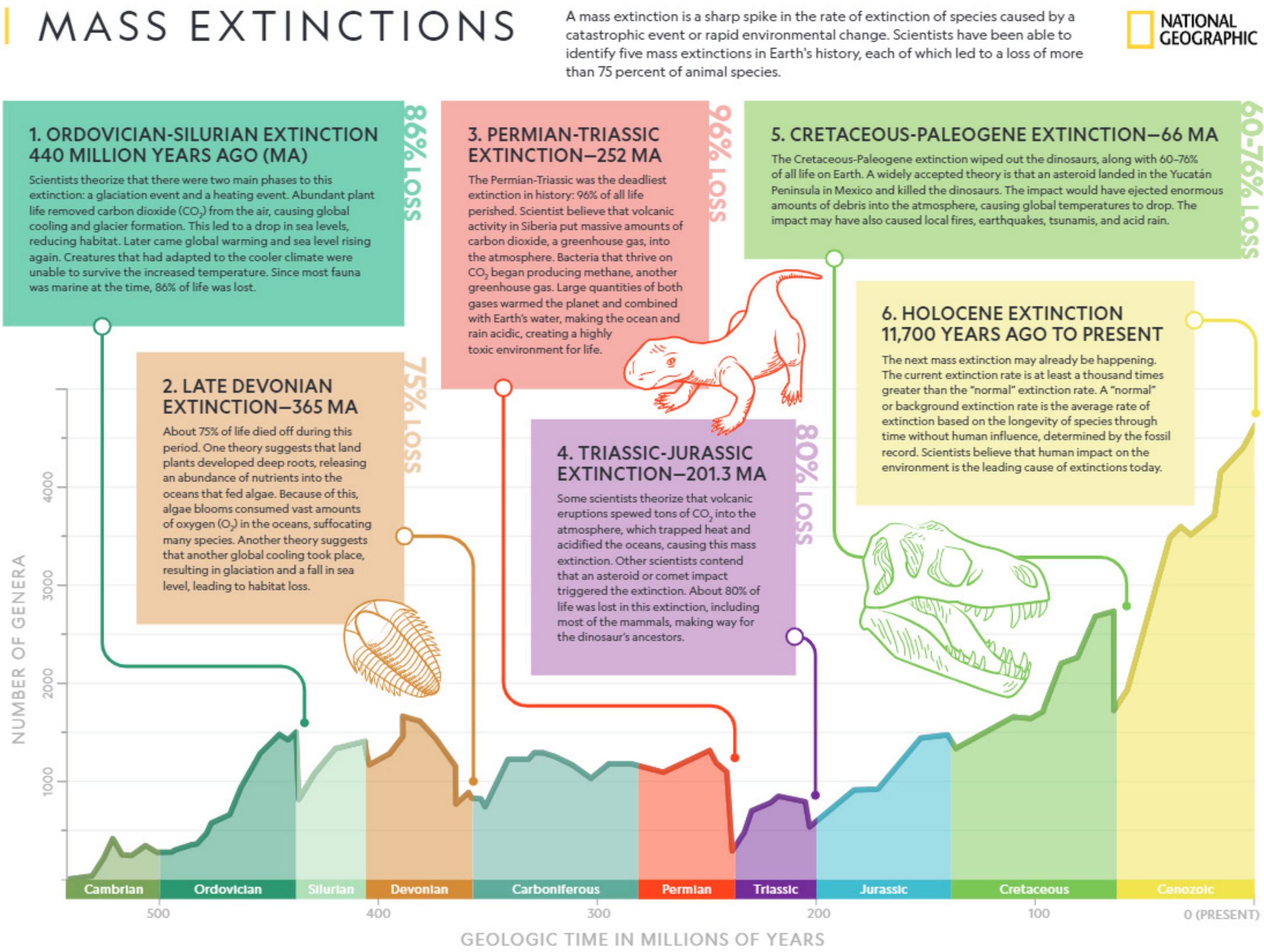
Most of what we know about the evolution of life is based on *fossils*, remains of extinct plants and animals that have been preserved in rock. When most organisms die, they decompose fairly rapidly, and the elements they contain are recycled; in this case, nothing of the organism is preserved. However, sometimes the hard parts of an organism (bones, shells, teeth, etc.)—and occasionally softer organic material—will be buried and protected by mud or other sediment, and after much time the material becomes fossilized, or hardened into rock-like material that is buried under increasing layers of sediment. When these layers are uncovered, they reveal a record of at least some of the organisms that existed at the time those layers were preserved. Because of the way layers of earth are deposited on top of each other over time, the oldest fossilized organisms are found in the deepest layers of the fossil record.

The fossil record is the basis of the *geologic time scale*, which divides time into various intervals from the formation of the Earth through the present, with distinctive events, such as the evolution of multicellular organisms or the extinction of the dinosaurs, characterizing the major time intervals. Bacteria appear in the fossil record as long ago as 3.5 billion years before the present; multicellular and shelled organisms are visible about 540 million years ago. In general, we can trace identifiable species for one million years (for example, mammalian species) to ten million years (for example, some clams and other marine species) of the fossil record. For the most part, species found in the fossil record from many millions of years ago do not exist today, and species that exist today are not found in the fossil record. There are some exceptions; the ginkgo tree, which exists in China and is an ornamental tree in many parts of the U.S., also appears in the fossil record from 60 million years ago. The fossil record has been the source of most of our knowledge of extinction as well as much information about the state of the environment today.

Mass Extinctions

The fossil record tells us that all species eventually go extinct. Over time, individual species evolve and go extinct continually, at random intervals. However, there are periods of mass extinction, in which the fossil record reveals that large numbers of species died in a very short time interval. The greatest mass extinction on record took place at the end of the Paleozoic Era. Roughly 90 to 95 percent of marine species and 70 percent of land **vertebrates** went extinct during this time. The cause of this mass extinction is thought to be related to the shutdown of ocean circulation combined with a massive, sustained volcanic eruption known as the Siberian Traps.[5] A better known mass extinction occurred at the boundary of the Cretaceous and the Tertiary Periods, known as the *K-T boundary*. This is the period 65 million years ago when many species, including the dinosaurs, went extinct. However, some species survived, including a small rodent-like mammalian species that would give rise to the human species.

FIGURE 28



MASS EXTINCTIONS

A mass extinction is a sharp spike in the rate of extinction of species caused by a catastrophic event or rapid environmental change. Scientists have been able to identify five mass extinctions in Earth's history, each of which led to a loss of more than 75 percent of animal species.

1. ORDOVICIAN-SILURIAN EXTINCTION 440 MILLION YEARS AGO (MA)

Scientists theorize that there were two main phases to this extinction: a glaciation event and a heating event. Abundant plant life removed carbon dioxide (CO_2) from the air, causing global cooling and glacier formation. This led to a drop in sea levels, reducing habitat. Later came global warming and sea level rising again. Creatures that had adapted to the cooler climate were unable to survive the increased temperature. Since most fauna was marine at the time, 86% of life was lost.

2. LATE DEVONIAN EXTINCTION—365 MA

About 75% of life died off during this period. One theory suggests that land plants developed deep roots, releasing an abundance of nutrients into the oceans that fed algae. Because of this, algae blooms consumed vast amounts of oxygen (O_2) in the oceans, suffocating many species. Another theory suggests that another global cooling took place, resulting in glaciation and a fall in sea level, leading to habitat loss.

3. PERMIAN-TRIASSIC EXTINCTION—252 MA

The Permian-Triassic was the deadliest extinction in history: 96% of all life perished. Scientist believe that volcanic activity in Siberia put massive amounts of carbon dioxide, a greenhouse gas, into the atmosphere. Bacteria that thrive on CO_2 began producing methane, another greenhouse gas. Large quantities of both gases warmed the planet and combined with Earth's water, making the ocean and rain acidic, creating a highly toxic environment for life.

4. TRIASSIC-JURASSIC EXTINCTION—201.3 MA

Some scientists theorize that volcanic eruptions spewed tons of CO_2 into the atmosphere, which trapped heat and acidified the oceans, causing this mass extinction. Other scientists contend that an asteroid or comet impact triggered the extinction. About 80% of life was lost in this extinction, including most of the mammals, making way for the dinosaur's ancestors.

5. CRETACEOUS-PALEOGENE EXTINCTION—66 MA

The Cretaceous-Paleogene extinction wiped out the dinosaurs, along with 60-76% of all life on Earth. A widely accepted theory is that an asteroid landed in the Yucatán Peninsula in Mexico and killed the dinosaurs. The impact would have ejected enormous amounts of debris into the atmosphere, causing global temperatures to drop. The impact may have also caused local fires, earthquakes, tsunamis, and acid rain.

6. HOLOCENE EXTINCTION 11,700 YEARS AGO TO PRESENT

The next mass extinction may already be happening. The current extinction rate is at least a thousand times greater than the "normal" extinction rate. A "normal" or background extinction rate is the average rate of extinction based on the longevity of species through time without human influence, determined by the fossil record. Scientists believe that human impact on the environment is the leading cause of extinctions today.

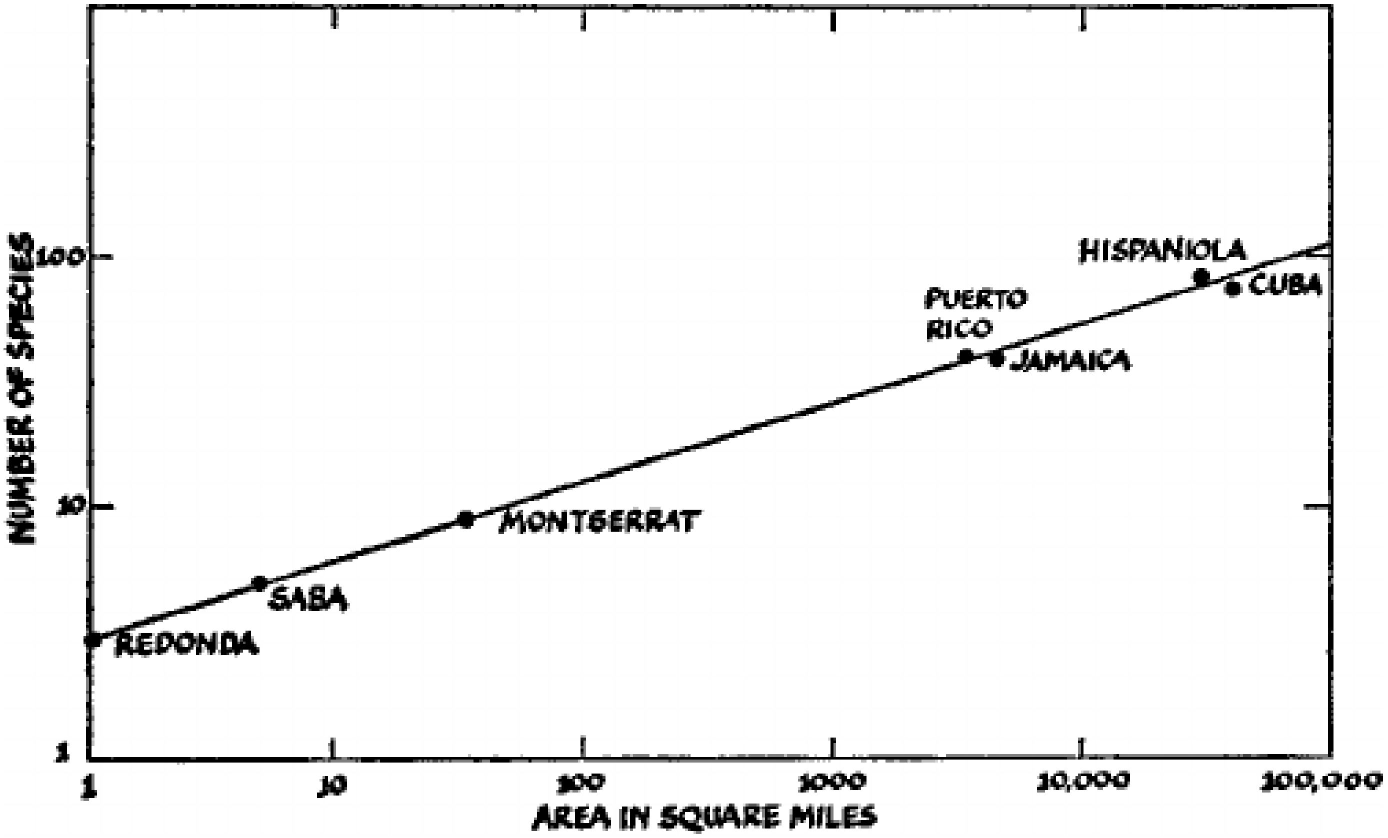
Five mass extinction events have occurred over various geologic time periods, and we may currently be experiencing a sixth mass extinction event.

Source: National Geographic

Estimating Extinction Rates from Habitat Loss

Estimating extinction rates is fraught with related problems—if we cannot know how many species there are, how are we to estimate how many we are losing each year? One way that environmental scientists get around this problem is by using a concept known as the *species-area relationship*. The basic concept is simple: in general, less habitat will support fewer species than more habitat. The species-area relationship was initially used to explain why larger islands have more species than smaller islands; it is now used both to estimate the number of species in a given area of habitat (**species richness**) and to estimate how many species are lost with a given loss in habitat. The tropical rainforest contains a minimum of 10 million species, and the area of tropical forest being cut down is about 2 percent a year. What does this mean with regard to the loss of biodiversity in the tropical rainforest? How many species are we actually losing each year?

FIGURE 29



Island biogeography and species-area relationship.

To find the effect of **deforestation** on species loss, we use a simple mathematical formula to compare the number of species in an area before deforestation with the number of species in the remaining area after deforestation: $S_1/S_0 = (A_1/A_0)^Z$ in which S_1/S_0 is the number of species after deforestation/number of species before deforestation; A_1/A_0 is the area of forest after logging/area of forest before logging; and Z is the rate at which species numbers vary by area (can change depending on the environment). While not perfect, this method has been used to provide useful estimates for the link between species and habitat loss for many types of ecosystems, in addition to tropical rainforests.

During the 1990s and into the twenty-first century, there has been a growing consensus among biologists that the Earth is in the beginning stages of a human-caused mass extinction of species, resulting largely from the destruction of habitat. The current mass extinction could reach the magnitude of the previous five mass extinction periods that have occurred sporadically over the last 450 million years. The recovery of biodiversity from those earlier mass extinctions took from 10 to 100 million years; recovering from the present mass extinction could take just as long and would probably require returning large portions of the Earth to their natural state so that new species could naturally evolve. Much of the current disagreement about policy among many environmental scientists and government officials stems from differing opinions as to how acute this **biodiversity crisis** is and how much science is required to solve it. In the next section, we will discuss current threats to Earth's biodiversity.

New housing developments can cause habitat destruction and/or fragmentation.

HUMAN ACTIVITY AND BIODIVERSITY

Human activity can alter biodiversity in a variety of ways. Species diversity can be reduced by direct removal of a species by humans (**overexploitation**), as when overhunting by European sailors stopping at the Indian Ocean island of Mauritius in the seventeenth century helped to exterminate the Dodo, a large flightless bird used as an easy source of meat. (The introduction of animals that competed with the dodo for food resources was also a significant factor.) Other direct removals such as fishing and overharvesting of plants can also directly reduce biodiversity. Humans can also affect biodiversity indirectly when their activities change animal and plant habitats. In addition, humans can cause extinction through habitat modification and fragmentation, the introduction of nonnative species, and other ways.

Habitat Fragmentation

Like the tropical rainforest example just discussed, human activity may fragment a large tract of land into smaller pieces through the construction of roads, housing developments, or shopping or industrial centers. Fragmentation of habitats has a number of major impacts on biodiversity. Fragmentation reduces the area of contiguous habitat, which can create barriers to the normal movement of a species for purposes such as feeding, mating, and migrating. While many species have minimal space requirements and thrive in fragmented areas, others—such as the mountain lion, wolf, and tiger—require large tracts of relatively uninhabited, undisturbed land.

Secondly, fragmentation generates more habitat that is along an edge. This consequence of fragmentation stems from basic geometry: a greater number of smaller tracts of land will contain more edge, even if the total area of land is identical to an unfragmented parcel of land. Edge habitat is in proximity to other kinds of habitat; in a forest, for example, the edge habitat is that area adjacent to clearings or other nonforested areas. Increased edge habitat will change the species composition of the habitat overall. For example, raccoons and skunks may increase in number along forest edges. Since there is now more edge closer to interior portions of land, these species will be more easily able to penetrate further into the forest, where they may eat plants, small mammals, bird eggs, and other organisms that normally would be relatively safe in the forest interior.

Third, habitat fragmentation will divide a population into several smaller populations. Gene flow between these smaller populations will usually be greatly reduced with the result that they will become genetically isolated and will likely lose genetic variation through genetic drift.

The Introduction of Exotic Species

Before the advent of widespread human travel, the free movement of many species was impeded by large bodies of water, deserts, mountains, and other land and water barriers. However, for quite some time, people have been capable of transporting species—knowingly or not—from one part of the globe to another. Species that are not native to an area but are introduced, deliberately or accidentally, by people are called *exotic species*.

In the process of moving themselves and their belongings from place to place, people have accidentally transported many species and diseases to new continents and new environments. The ballast water in ships often contains many species from the point of origin that get distributed in every port the ship visits. It is believed that the zebra mussel, a native of the Caspian Sea in Asia, entered the Great Lakes this way during the 1980s; since then, its population has grown exponentially there and throughout the eastern United States and Canada. With no known predators in North America, it has depleted food supplies, clogged water intake valves, and caused many other problems.

When an exotic species enters a new environment, it may encounter an unexploited resource that it can rapidly utilize. In the new environment, the organisms that keep it under control in its native environment are usually not present, nor are there naturally occurring predators. While a fair number of exotic species do not thrive in their new environments, some do survive and occasionally are successful enough to replace the native species that are more vulnerable to local pathogens and predators. Once an exotic species is successful in its new environment, it is rare for it to ever be brought under control.

It is believed that the zebra mussel, a native of the Caspian Sea in Asia, entered the Great Lakes during the 1980s; since then, its population has grown exponentially there and throughout the eastern United States and Canada.

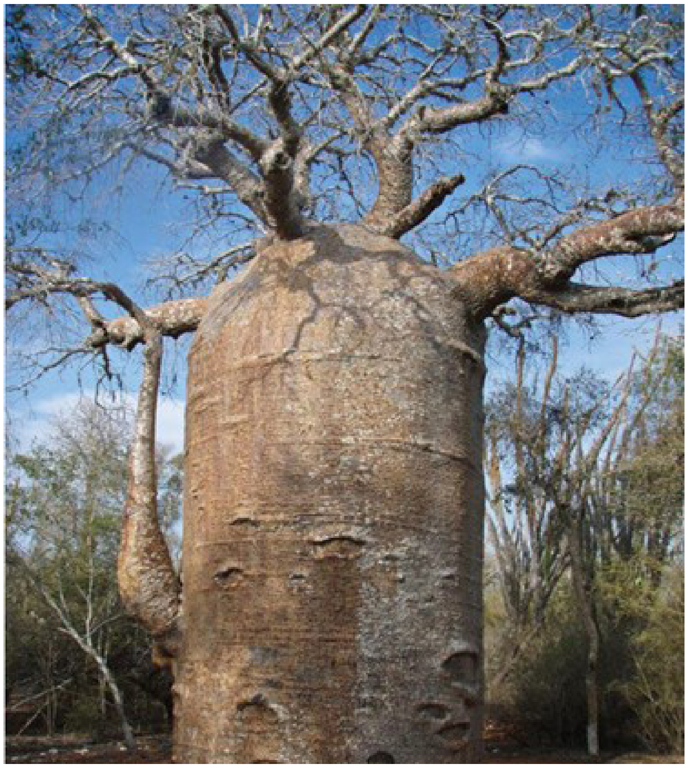
LINKING BIODIVERSITY AND EVOLUTION TO ECOLOGY

The Ecological Perspective

Evolutionary history provides the first step in understanding why some species are found or not found in various regions. However, to fully explore patterns of biodiversity, we need to know how species distribution and abundance is limited by current environmental conditions. This is the domain of **ecology**, the study of the relationship between organisms and their environment. The environment includes other individuals in an organism's population, other populations of plants and animals with which an organism and its population interact, and the abiotic environment—the physical and chemical factors that influence life. "Relationships" include such factors as the adaptation of an individual's physiology to environmental extremes, the killing and eating of prey by predators, and the flow of carbon through biotic and abiotic components of the environment.

To study such a diversity of natural phenomena, ecologists have traditionally divided the science into a hierarchy from individuals to large-scale ecological systems of interacting biotic and abiotic components. Different ecological processes occurring at these various levels will have different effects on biodiversity. We will begin our exploration at the individual level. The ecology of the individual is concerned with an organism's ability to live in the environment. Three things are critical to an individual's survival in a particular area: the abiotic environmental conditions; the availability of resources such as food and water; and a place, or habitat, for the individual to live.

Environmental Conditions



A baobab tree swollen with stored water.

Conditions are the chemical or physical factors in the environment that influence survival and growth. A wide variety of conditions determine which species and communities flourish in some habitats and not others. For terrestrial systems, the availability of light from solar radiation, the temperature of the air and soil, the amount of precipitation, soil type, and quantity of nutrients such as nitrogen or phosphorus are usually the major conditions that determine the presence or absence of certain species. These conditions vary with latitude and elevation. In aquatic systems, in addition to temperature and solar radiation, gradients in the amount of oxygen dissolved in the water, salinity, and pH (concentration of hydrogen ion) also play a role. These conditions vary with the depth of the water, the location in a stream (upstream, midstream, downstream), latitude, elevation, and many other aspects of the habitat.

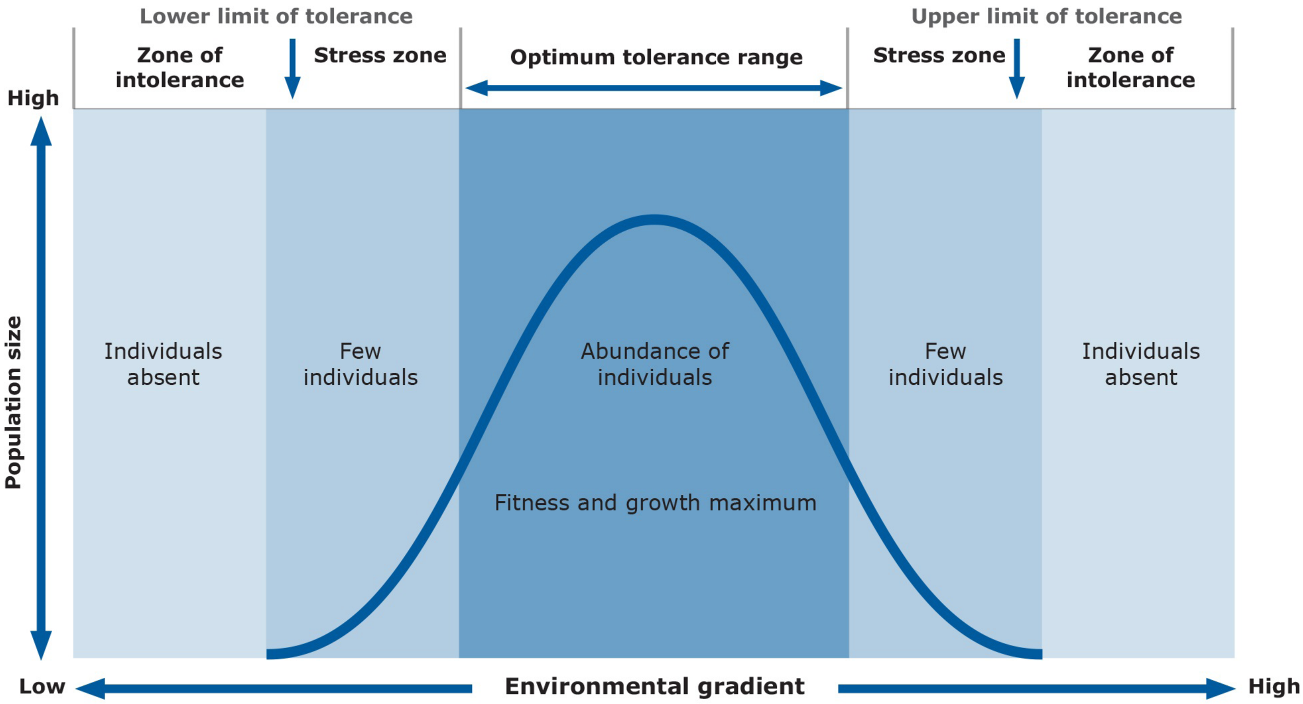
Over time, adaptations evolved through natural selection have allowed some organisms to survive, grow, and reproduce under any environmental condition on Earth. Bacteria and other microbes can be found in almost all conditions, including below ground and at the bottom of the ocean. Plant species can be found in the high-temperature/low-moisture conditions of a desert, as well as in the low-temperature **tundra** of the Arctic and mountaintops. Many insects and other **invertebrates**, and even some birds and mammals, can be found in the harshest terrestrial conditions, while all parts of the ocean are home to at least some species of fish and other marine life. Although some species may be found in almost any type of environment, the number of species, and the abundance of any one species, decreases as conditions become more extreme.

Organisms either adapt to the conditions in a particular region, or they don't live there. The baobab tree of East Africa, for example, drops its leaves during the dry season. Though this prevents the plant from photosynthesizing at that time, it avoids the loss of water through the leaves' stomates, openings that allow water vapor to escape as well as carbon dioxide to enter. During the rainy season, the baobab tree grows new leaves and swells with water stored for use during the dry season.

Solar radiation and moisture are the two most important abiotic environmental conditions controlling the distribution of species. Taken together, they can predict what type of large-scale habitat will exist in a given region. To measure the combined amount of solar radiation and moisture in any region, ecologists have developed a single index, **evapotranspiration**, or the total water lost from the land by evaporation and plant transpiration (loss of water during photosynthesis). The amount of water loss will depend upon both the amount of water in the ecosystem and the rate of evapotranspiration, which is mainly a function of temperature, or solar radiation.

For each environmental condition, there is a range within which a species can live. Under optimal conditions, individuals will thrive: they will survive, grow, and reproduce. As conditions become less optimal—for example if temperatures become significantly higher or lower than the ideal—individuals may survive and grow, but not reproduce. If conditions become even less desirable, individuals may survive, but not grow or reproduce. Finally, if conditions become even worse, individuals may not survive, and the species won't exist in that environment. The range within which a given species will exist is called its range of **tolerance**. For many factors—such as temperature, soil moisture, and exposure to most pollutants—the response curve to a range of conditions is like that shown in Figure 30.

FIGURE 30



Most species will have an optimal range of abiotic factors—such as temperature and rainfall—where they will thrive and show higher levels of growth, metabolism, and reproduction.

Resources

Salt marshes produce extremely high levels of biomass and act as a storage tank for large amounts of nutrients caught from the flow of rivers.

Resources are those aspects of the environment that individuals use to stay alive—food, water, light, and oxygen. Unlike environmental conditions, resources are consumed and thereby become unavailable to other organisms. The amount of available resources is important at all levels of ecology. Individuals require sufficient resources to grow and reproduce. Populations require sufficient resources to maintain a size that will prevent extinction. And communities require sufficient resources to maintain several different species in one habitat. Habitats with a large amount of resources are generally able to maintain both many individuals within each species and a large number of different species, but, surprisingly, in many habitats there is little direct correlation between the amount of resources and the number of species. The explanation for this rests with the varied abilities of individual organisms to use resources under various abiotic environmental conditions.

One example is the large salt marshes that extend along the eastern coast of the United States from Georgia to Cape Cod. Salt marshes produce extremely high levels of biomass and act as a storage tank for large amounts of nutrients caught from the flow of rivers. This high level of nutrients makes salt marshes an important nursery for many fish and shellfish species, as well as a source of energy for adjacent aquatic and marine habitats. However, the vegetation within salt marshes, while abundant, is not diverse; usually only a few grass species make up more than 95 percent of the total marsh biomass. These plant species dominate the salt marsh because they can process the nutrient-rich resources under the extreme environmental conditions.

The environmental conditions in a salt marsh include the increase in salt concentrations that results from the evaporation of water during summer low tide and the rapid decrease in salt concentrations during flooding or heavy rains. This means that plants must be able to tolerate both high- and low-salt concentrations and a dramatic switch between the two. In addition, salt marsh plants must be able to survive the low oxygen levels in the soil, a result of the high level of microbial decomposition that takes place in a salt marsh. This microbial activity also produces large amounts of toxins as a side-effect, yet another harsh abiotic environmental condition. The salt marsh grasses survive because of several adaptations, including special tissues that allow them to concentrate and excrete excess salt and air chambers in their roots that allow them to produce their own oxygen-rich microhabitats in the soil surrounding them. Another way that organisms adapt to their changing environments is to change the way they allocate energy.

POPULATION ECOLOGY

Population ecology studies factors that regulate population abundance and distribution. No single factor is more likely to increase the probability of extinction for a species or a localized population of a species than small population size. In the previous discussion of genetic diversity, you learned that small population size means less genetic variation, with a resulting decline in the ability to evolve in the face of changing environmental conditions or resources. Small population size also makes it more likely that random environmental changes such as floods and fires can wipe out an entire local population. Species with large populations, particularly if the populations are scattered over a wide geographic area, are more likely to survive and adapt to changes in the environment.

Therefore, to understand species distribution on Earth, it is critical to understand the factors that regulate the abundance and distribution of populations. This is the science of *population ecology*. Population ecologists focus on three aspects of populations:

- Interactions with abiotic environmental factors, particularly environmental conditions
- Interactions with other individuals within the population (intraspecific interactions)
- Interactions with individuals in populations of other species (interspecific interactions)

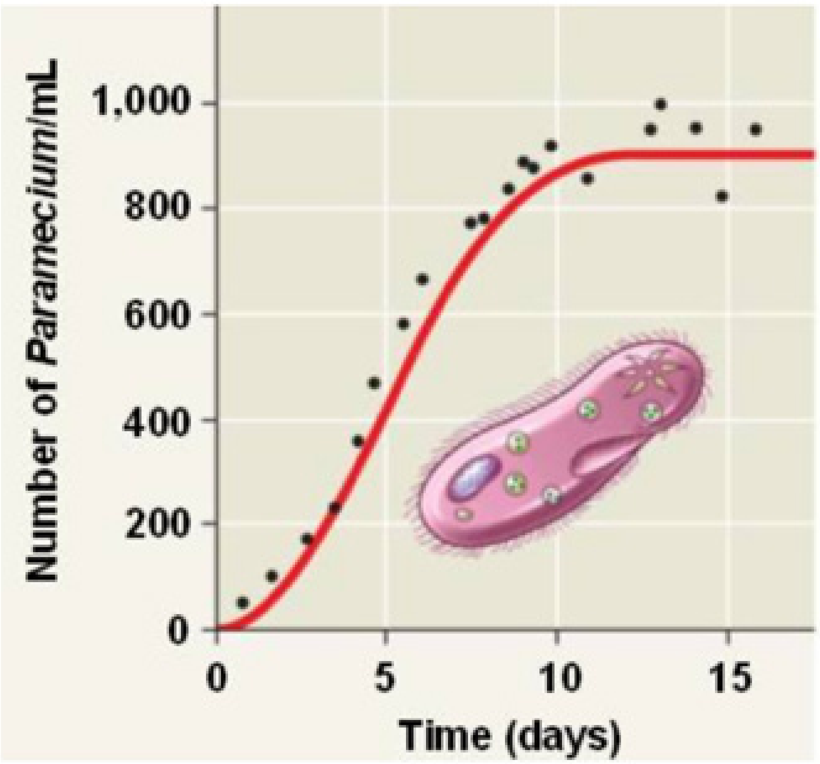
All population regulation factors can be classified as density-dependent or density-independent. *Density-dependent factors* are those whose effects on individuals in a population are directly related to the density of the population. Scarce food resources, for example, will have a greater effect on individuals in a crowded population than on those in a less crowded population. *Density-independent factors*, by contrast, are those, such as extreme weather, whose effect is the same on all members of the population, no matter what the total population size. Let's begin our study of these concepts by looking at a classic experiment that illustrated how population growth is influenced by density-dependent factors.

Density-Dependent Growth

In 1932, the Russian biologist Georgy Gause carried out some of the first laboratory experiments on the way resource and habitat limitation regulates population growth. Gause started with twenty *Paramecia* (single-celled animals) in a five cubic centimeter tube. Each day Gause added a constant quantity of food (bacteria) for the *Paramecia*. The tubes were kept at a constant optimal chemical environment and temperature for *Paramecium* growth, and waste products were regularly washed out. In other words, Gause provided the *Paramecia* with constant resources and optimal environmental conditions, but limited space.

The growth of the *Paramecium* population, shown in Figure 31, is an example of *logistic growth*. When the number of *Paramecia* was not limited by the size of the tube, the initial population growth rate was essentially unlimited. However, as the number of *Paramecia* increased, the size of the tube began to act as a constraint on further growth, and the growth rate decreased. Eventually, there was no space for more *Paramecia*, and population growth stopped; the population had reached the carrying capacity of the environment.

FIGURE 31



Logistic growth of Paramecium *in the laboratory.*

Source: Peter Chen, Principles of Biological Science

In Gause's experiment, population growth was limited by available habitat. Gause would have achieved similar results if he had provided less food in the tubes: population growth would have slowed and stopped when there was insufficient food for more *Paramecia*. In either case, the growth rate of a population slows as the population density increases and resources or space become harder to obtain. This is unlike exponential growth, in which the growth rate is not constrained by limited resources or space and continues to increase as the population size increases.

Gause's experiment was important because it showed that *density-dependent factors* slow population growth at high densities. Density-dependent factors do not affect only laboratory populations; they play a significant role in regulating most natural populations as well.

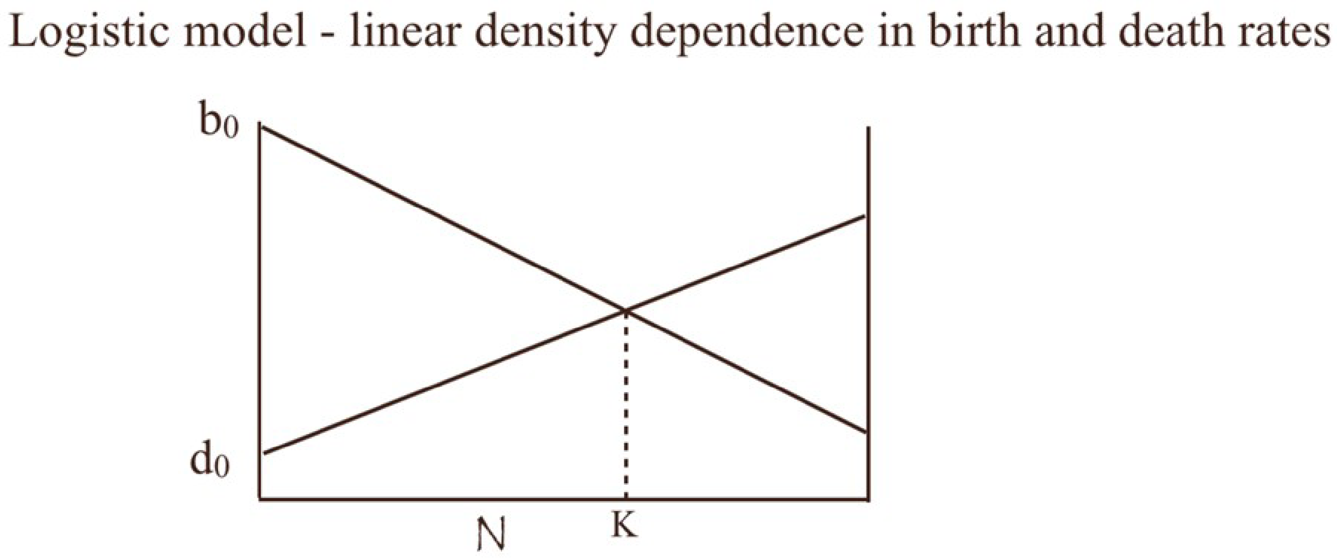
The Logistic Growth Model

The logistic growth model is one of the most important ecological models. Ecologists use the logistic model to predict the growth of real laboratory and natural populations. However, like all models that describe a simplified version of the real world, the effectiveness of the logistic model depends upon the satisfaction of several assumptions:

- The population has a *stable age distribution*. In other words, the proportions of different ages remain constant as the population increases.
- Population density is measured in *appropriate units*. For example, for small individuals in dense populations, biomass may be a better measure of growth than individuals per square meter.
- The relationship between population density and growth rate is *linear*. In other words, the population growth rate decreases in a predictable and smooth manner with increasing density, as seen in Gause's *Paramecium* experiment (see Figure 32).

- There are *no time lags* in the decrease of population growth rate as density increases. An example of a time lag in growth rate adjustment is when a population keeps growing even though prey is no longer plentiful, which can cause a population to overshoot the carrying capacity. This is particularly true for populations with high per-capita birth rates.

FIGURE 32



In the logistic (density-dependent) model of population growth, population birth rate (b) declines linearly as population density (N) increases, while population death rate increases linearly. (K is the carrying capacity, the population size a local area can sustain.)

Many populations in nature violate one or all of these assumptions, so the logistic model, at best, only approximates their present and future growth. For example, the growth curve of endangered whooping crane species is non-logistic and shows ten-year cycles of population fluctuations that may be due to a periodic increase in predation of hatchlings in the breeding areas by snowshoe hares. As a general rule, the more factors that affect a population's growth (intraspecific **competition** for resources or space, predation, climate, etc.), the more deviation from the logistic model it will show. Despite the fact that the logistic model does not always match the growth of real-world populations, it continues to be used to predict and manage many natural populations. The following example explores the benefits and problems of using the logistic model to manage commercially valuable species.

ENVIRONMENTAL SCIENCE CASE STUDY: The Challenge of Managing Population Growth

For decades, managers of commercially valuable tree, fish, and game species have wanted to maintain populations at a level that will produce **maximum sustainable yield (MSY)**—the maximum harvest of individuals that will allow the population to not go extinct—and still produce the maximum amount of economic profit from year to year. The maximum economic profit is obtained by taking as many individuals as possible. However, to sustain this profit, and the species, over many years requires that the population be allowed to recover after each harvest. Measuring harvest by the total biomass of adult fish taken, which most mangers and economists do, predicts that a sustainable harvest during a fishing season is one in which:

Biomass of new adults + biomass of adults remaining alive = loss of biomass from natural mortality + loss of biomass from previous harvest

Therefore, fishery managers must set limits that allow the population growth rate to replenish the individuals lost to the harvest.

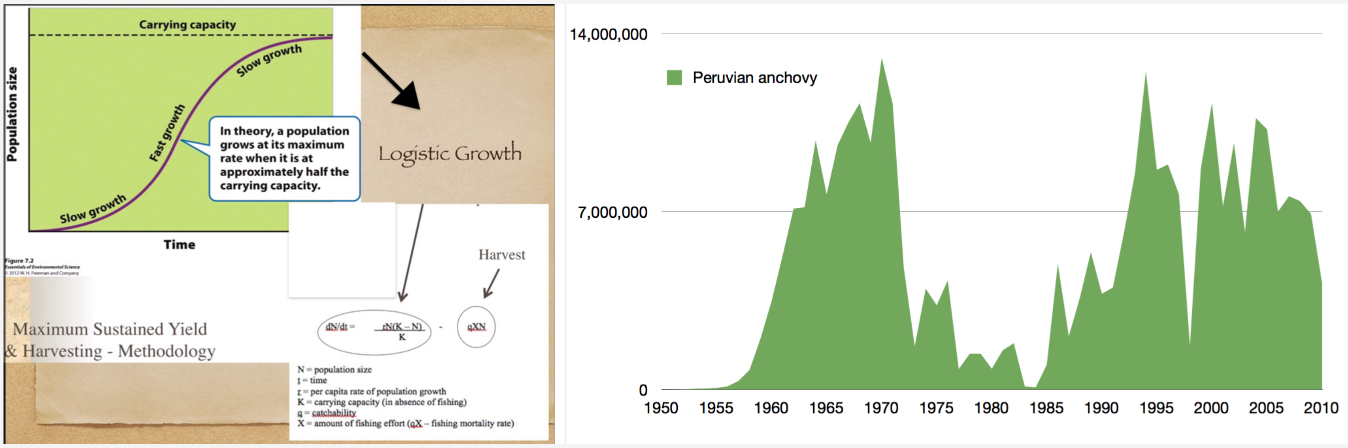
In 1935 the fishery biologist M. Graham used data from the catch of fish by trawlers in the North Atlantic fishery to develop a logistic growth model for setting fishing limits. Graham pointed out that the highest *production* (rate of biomass increase) in a fish population growing logistically occurs not when the fish population is most dense, but at the point where the logistic curve is at its steepest—at one half of the population's carrying capacity. Therefore, to maintain the maximum yield, the fishing quota should be set at a level that will keep the population at this point.

A Peruvian fisherman harvests anchovies.

Source: AP Photo/Rodrigo

This logistic model has been used to set catch limits for many fish stocks, including the Peruvian anchovy fishery which, until 1972, annually harvested the largest amount of biomass in the world. Fishery managers collected data on the total biomass harvested per year, the total biomass eaten by seabirds, and the total number of boats and/or days spent to catch a certain amount of biomass. To estimate the annual maximum sustainable yield (MSY), the managers first assumed that the anchovy population met the assumptions of the logistic growth model. Then, they fitted the logistic growth curve to their collected data; to predict the point of maximum growth rate for the anchovy population. (See Figure 33.) The end result was an estimated MSY of approximately 10 million tons of anchovies per year.

FIGURE 33



Setting a fishing quota requires adding fishing mortality onto the natural logistic growth of the commercial fish species (left). However, if the fishing mortality rate is set too high, the population will likely collapse as the Peruvian anchovy population did in the mid-1980s (right).

By Epipelagic - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=19091788

The logistic model and the Peruvian anchovy maximum sustainable yield were developed by averaging the data on catch over several years, which represented what the yield should be during average conditions. However, 1972 was not an average year. In that year the upwelling of cool, nutrient-rich water along the Peruvian coast, which provided the ideal conditions for the anchovies, was disrupted by the El Niño system, which moved warm tropical waters into the region. Despite these environmental changes, the fishery continued to harvest anchovies at the MSY even though that level did not account for the unexpected changes. Because of this change in environmental conditions, the number of young anchovies aging into the fishery fell drastically, resulting in the sudden ecological and economic collapse of the fishery. The anchovy fishery case tells us that when a population's growth conforms to the assumptions of logistic growth, the model can be used to estimate MSY, but only if managers account for changes in a species' carrying capacity that results from changes in environmental conditions.[6]

Density-Independent Growth

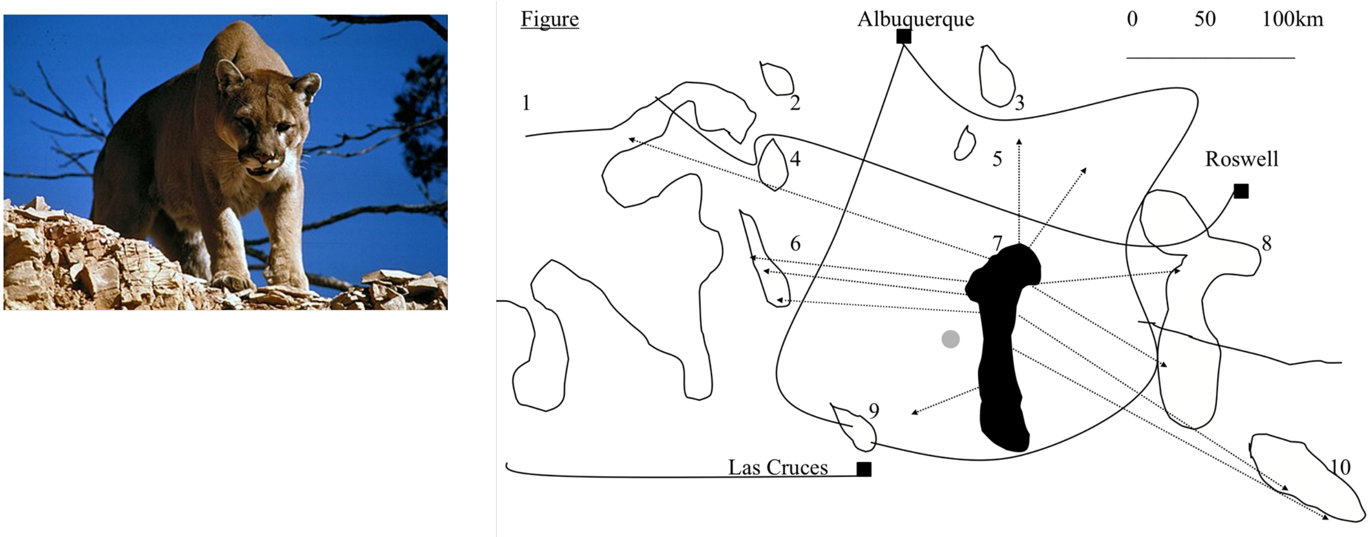
So far, we've looked at regulatory factors that have a greater effect as population density increases. However, there are many factors that act independently of population density. Density-independent factors tend to be major climatic events such as hurricanes or floods, or other types of disturbances such as fires or volcanic eruptions that will wipe out a constant proportion of a population regardless of its density.

A classic example of density-independent population regulation involves *Thrips imaginis*, an insect found on the flowers of many weeds and other plants in Australia. When the population is large enough, *Thrips imaginis* is a major pest of the apple crop. During the 1930s and 1940s, James Davidson and Herbert Andrewartha studied the factors that regulated *Thrips*' population size. They found that the most important factor was the decline in the plant populations that served as the insect's food source during dry periods of the summer. However, in contrast to the situations we described for density-dependent growth, the decline in food sources was not due to an increase in *Thrips* population density but rather was the result of climatic factors—the heat and lack of rain during the summer. In this case, the *Thrips* population is regulated through a density-independent, extrinsic factor.

Metapopulations

Cougars once lived throughout North America, but because of habitat destruction and fragmentation and overhunting, these large cats are now found primarily in remote mountain ranges of the Southwest and California. Like most large **carnivores**, cougars in New Mexico display a naturally patchy population distribution corresponding to the topography of the southwestern mountains. Populations are denser in mountain ranges covering large areas than in smaller mountain ranges. Cougars, primarily males, will disperse from the more densely populated areas across deserts to smaller mountain ranges, as shown in Figure 34, although long distances or geographic barriers may keep some suitable habitats from becoming home to a cougar subpopulation.

FIGURE 34



Metapopulation example: cougar dispersal among mountain ranges in New Mexico; there are sufficient levels of genetic connectivity among dispersed subpopulations to create a single "metapopulation."

In the past, each group of cougars living in a separate mountain range would have been considered a separate population. However, recent research shows that individuals travel from one mountain range to another to such an extent that there is no evidence of the genetic variation that normally distinguishes different populations within a species. Moreover, population density in one group will affect other groups as cougars move from high-density populations to low-density populations. This interconnection between groups has led to a new classification—the *metapopulation*, a population subdivided into several geographic groups that remain genetically and ecologically connected through the dispersal of individuals among groups.

Metapopulations exist at smaller spatial scales than half of New Mexico, but all share certain major characteristics. Although subpopulations form and disappear in space and time, the population as a whole remains; there is a changing mosaic of subpopulations over time. Further, not all suitable habitats will necessarily contain a subpopulation. Dispersal is not always successful because of distance, barriers, inability to find the patch, or inability of the dispersed individuals to produce a viable population. Finally, while each subpopulation will undergo its own density-dependent and density-independent regulation, both types of factors will be influenced by the connection between patches; that is, the dispersal of individuals among subpopulations will change the sizes of subpopulations independent of other population regulatory factors. The identification and management of metapopulations is a major feature of the current application of population level ecology to the protection of biodiversity.

Populations and Biodiversity

Populations go extinct when death rates are greater than birth rates. The factors that can cause extinctions are both *deterministic* (predictable) and *stochastic* (random and unpredictable). Most of the density-dependent factors we discussed above are deterministic. If food, for example, is limited by a known amount, the carrying capacity will change by a knowable degree. Many density-independent factors are stochastic. We cannot predict forest fires or storms, and we certainly cannot predict what their effect on populations will be. Nevertheless, there is one general rule that governs the relationship between population size, growth, and extinction: small populations are more likely to go extinct.

The increased likelihood of extinction for small populations is true for a multitude of reasons. Over the long term, the loss of genetic variation may prevent adaptations to changing conditions from arising within the population. In the shorter term, small populations are more vulnerable to catastrophic stochastic (density-independent) events, such as particularly harsh winters or other climatic factors. Small population size will also be more sensitive to changes in density-dependent factors, such as predation or human exploitation. A loss of 75 percent of the population is more serious if you are starting with only 100 individuals than if you are starting with 1,000 individuals.

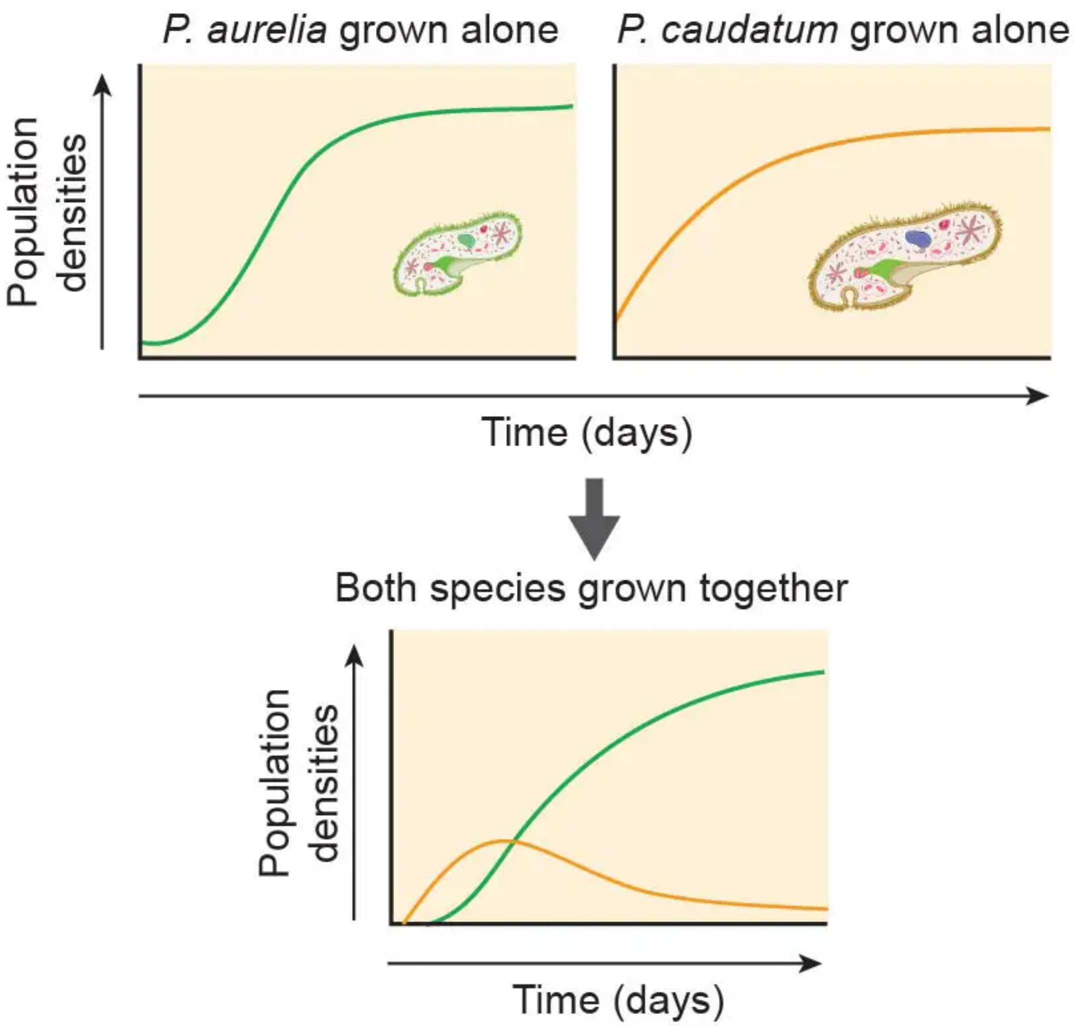
COMMUNITY ECOLOGY

In the previous section we treated populations as if each existed in isolation from all others, which is most certainly not the case. A population of one species interacts with populations of other species, and such interactions can function as both density-dependent and density-independent population regulators. Species interact with each other in three general ways: *interspecific competition*, *predation*, and *mutualism*.

Interspecific Competition

In 1934, two years after his experiments on logistic growth in one species of *Paramecium*, Georgy Gause studied how two different species of *Paramecium* affected each other's population growth. When the two species—*P. caudatum* and *P. aurelia*—were grown in separate laboratory cultures, each species thrived and reached a relatively high population density within ten days. (See Figure 35.)

FIGURE 35



Interspecific competition among paramecia.

When the two species were grown together, however, only *P. aurelia* thrived while *P. caudatum* did not. After ten days of growing together, the *P. aurelia* population was almost at the density it achieved when it was grown alone. *P. caudatum*, however, was at a very low density, and over time its density decreased further. Gause's observations, combined with additional experiments with other organisms, both plants and animals, led to the conclusion that two species cannot coexist on the same **limiting resource**, whether it is food, oxygen, space, or any other parameter.

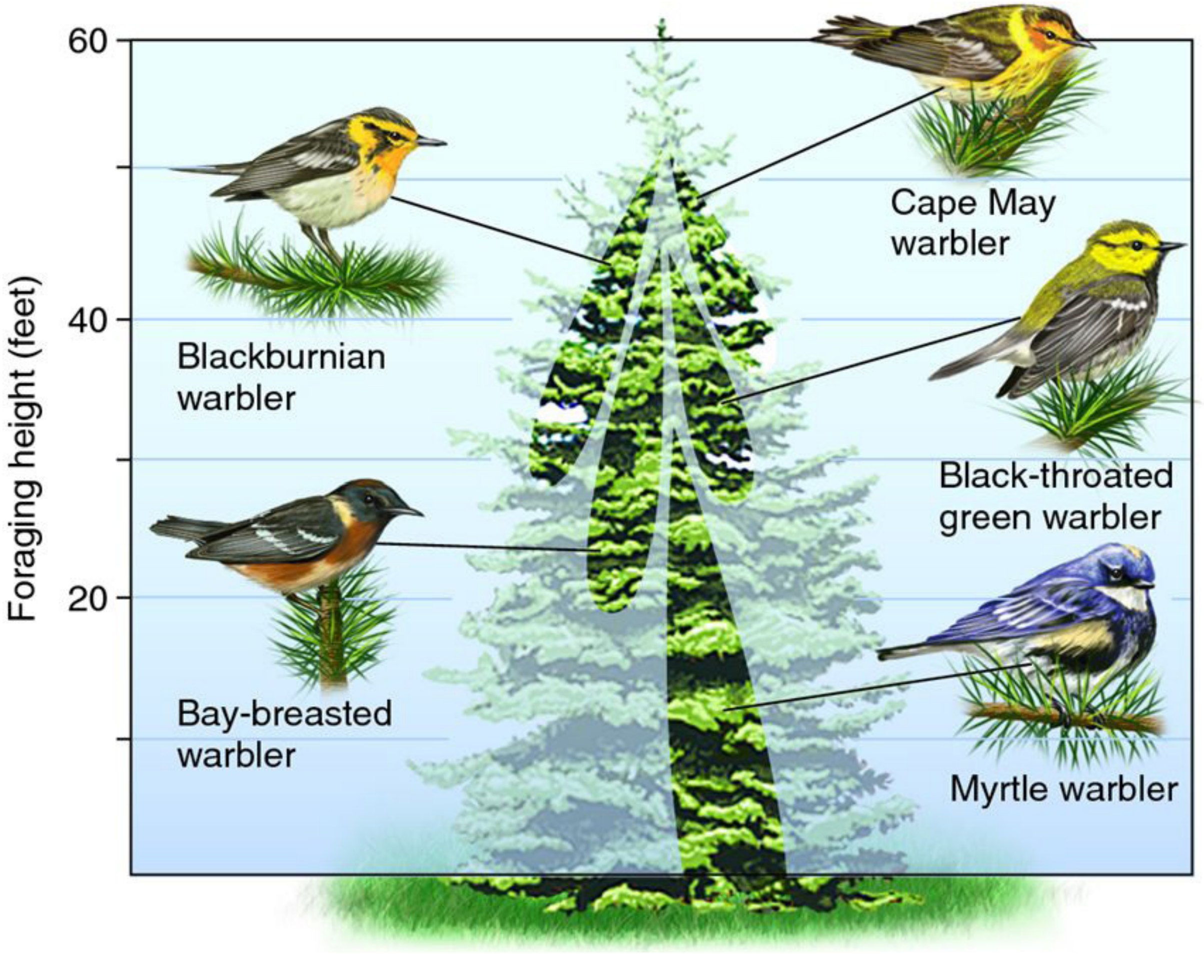
A limiting resource is the one on which a population depends and which exists in low, and usually variable, quantities. As the limiting resource decreases, so does the size of the population which depends upon it. Species can share food sources as long as those sources are not their limiting resource. If the food source, or any other resource, limits the growth and reproduction of the species, it cannot be shared: one species will succeed, and the other will go extinct, a principle known as *competitive exclusion*. Generally, when two species (A and B) compete for resources or space, four outcomes are possible:

- Species A always wins, and species B is excluded.
- Species B always wins, and species A is excluded.
- Either species A or species B wins, but the winner will depend upon chance events.
- Species A and B coexist.

Competition among species is not limited to animals. Plant ecologists have shown several instances of the effects of one plant species on the distribution and abundance of other species. For example, wild oat (*Avena fatua*) is an abundant weed in the Great Plains of North America that competes for space and resources with agricultural crops such as flax, wheat, and barley. Wild oats outcompete crop plants because their seeds ripen earlier, permitting oat seedlings to start growing before the other species. Only human intervention allows the agricultural crops to exist.

Closely related to the competitive exclusion principle is the concept of **niche**. Because of its use in nonscientific language, the term is often confused with *habitat*, the range of environments in which a species occurs. In ecology, niche is commonly defined as the role of an organism within a community—what it does and how it lives. Many ecologists rephrase the competitive exclusion principle by stating that two populations that fill the same niche, such as by feeding on the same limited resource, cannot coexist. However, if these same two populations partition the resources so that their niches do not overlap completely, they can coexist. (See Figure 36.)

FIGURE 36



Different species of warblers minimize competition by using different parts of trees.

Source : "Resource partitioning among five species of warblers feeding in North American spruce trees." Biology Forums Gallery.

Predation

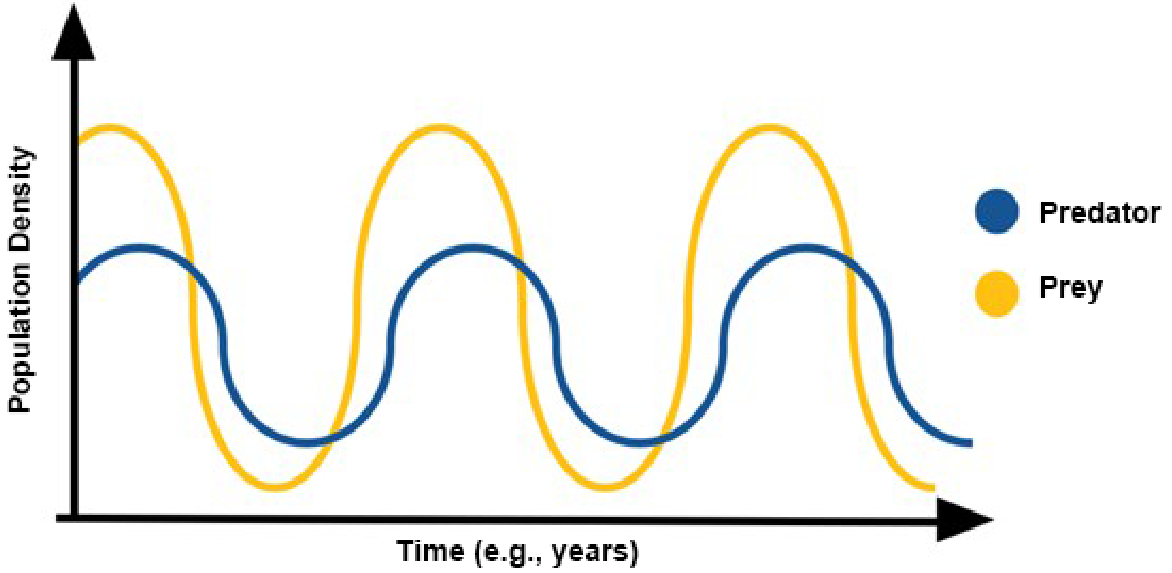
Most people think of predation only as a carnivore, such as a wolf or a lion, killing and eating another animal. In the broadest sense, *predation* is the use of one species as a resource by another species. This definition allows us to include two other species interactions:

- *Herbivory*, in which animals eat plants, seeds, or fruits
- *Parasitism*, in which animals, plants, fungi, or bacteria feed on or use as a habitat another organism, causing injury but usually not death

Predation is an important cause of natural selection and evolution and, in all its forms, is the process that establishes how energy flows from one population to another within a community and an ecosystem. Moreover, it is one of the key density-dependent population regulators.

Like competition between two species, predation will have density-dependent effects on both predator and prey, creating long-term cycles with increases in the predator population causing decreases in the prey population, leading to decreases in the predator population and a resulting increase in the predator population. (See Figure 37.) Environmental scientists have demonstrated such predator-prey cycles in simple laboratory systems. However, most of these systems lead to the extinction of the prey, followed by extinction of the predator, unless some other factor is added to balance the fact that the predator, if able, will eat all available prey.

FIGURE 37



Predator-prey oscillations.

It is harder to find examples of predator-prey cycles in nature. It is also true that most natural predator-prey systems involve more than one predator feeding on one prey. These other population interactions will weaken the population cycles caused by any one predator-prey interaction. Identifying real-world predator-prey cycles may require decades of data collection, which has rarely been done in ecological studies. Trying to determine why natural predator and prey populations do, or do not, cycle in the manner predicted by models or laboratory experiments is one of the current research focuses for ecologists interested in predation.

Though finding natural cycles in predator and prey populations is difficult, observing instances of density-dependent control of prey populations by predators (as in the wolf/deer populations) is common. Such density-dependent controls are regulated by two types of processes. Since the amount of available food is the most important factor determining population growth, when prey density increases, so will predator density. This is known as the *numerical response*. In the *functional response*, when prey populations decrease, individual predators change their behavior and switch from low-density to high-density prey. For example, many bird species will forage on whatever insect species is currently most abundant, which allows the low-density populations a chance to recover. There are enough examples of numerical and functional responses in nature to indicate that predation is a key cause of density-dependent growth.

Mutualism

The third major type of population interaction is **mutualism**. Mutualistic interactions are those that increase the survival probability or reproduction of both species. Though the term mutualism may lead some people to imagine species helping each other in a cooperative sense, ecologists see it more as "reciprocal exploitation" since each species is using the other to benefit itself. If the self-benefit to one population becomes too low, the interaction will no longer be of value and will no longer provide an adaptive advantage to either species.

A hummingbird drinking nectar from a flower while also serving as a pollinator is an example of mutualism.

CC BY-SA 2.5, https://commons.wikimedia.org/w/index.php?curid=763031

The most common type of mutualism involves interaction between plants and animals. Probably the single most important type of mutualistic interaction is the relationship between plants and their pollinators, such as birds and insects, since many plant species depend upon pollination for their reproduction and survival. Some pollinators pollinate many different species of plants, and many plant species are pollinated by many different species of animals. In these cases, the mutualistic interaction between any particular pair of plant and animal species is weak. In symbiotic mutualism, by contrast, one animal species pollinates only one plant species, and the plant is pollinated only by that one animal species. For example, there are about nine hundred species of fig trees, and almost every one is pollinated by one particular species of fig wasp. These types of mutualistic interactions are most likely due to resource partitioning in the evolutionary past.

ECOLOGICAL COMMUNITIES

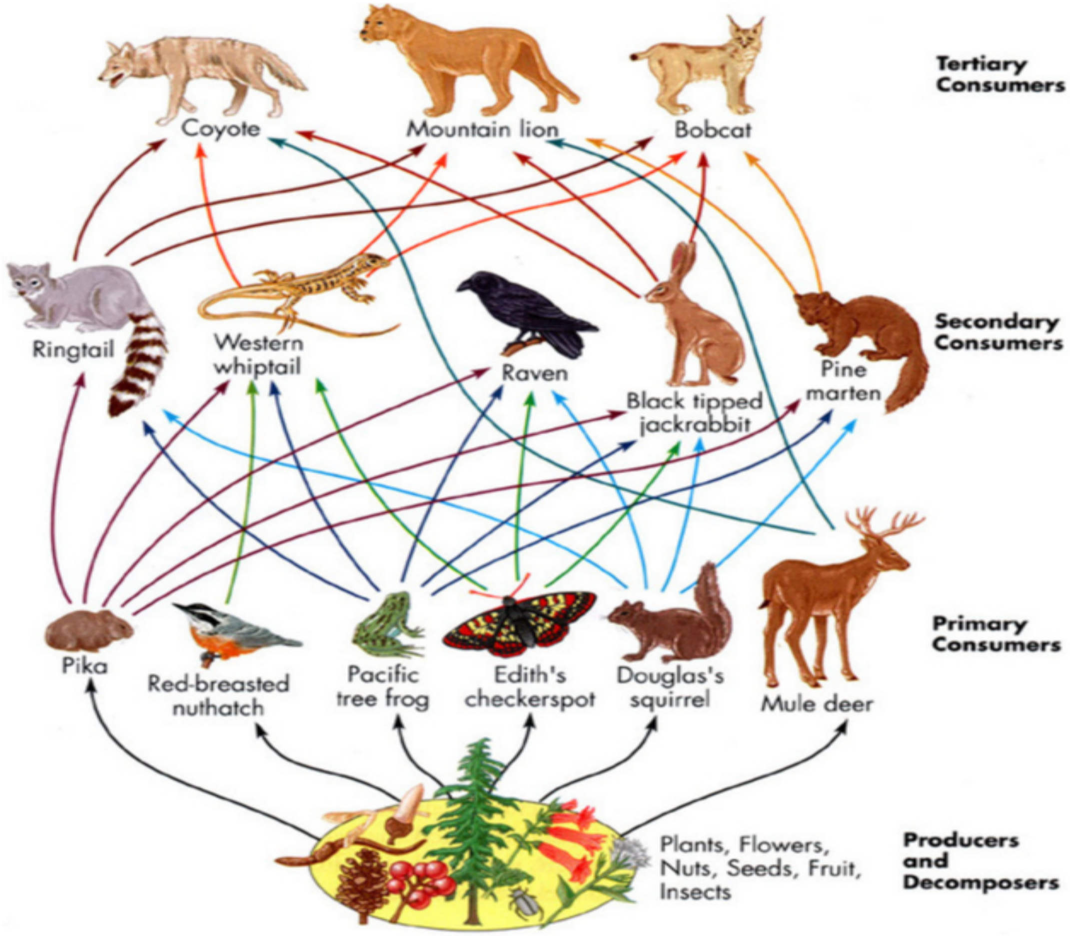
So far, we have seen how the interaction between two populations affects the survival and growth of each individual population. However, many of the most important ecological processes occur at a level of organization higher than the population (or two interacting populations)—the ecological community. A **community** is any assemblage of populations in a particular area or habitat. Community ecology studies groups of populations living in the same area.

Food Webs

A **food web** summarizes the species that make up a community and the ways they are linked by various predator-prey interactions to form pathways of energy flow. Food webs operate like food chains, but since they include all the species in a feeding relationship, they are much more complex, as you can see in Figure 38, which shows the Greater Yellowstone ecosystem food web. The photosynthesizers are primarily multicellular algae and single-celled phytoplankton. Single-celled animals (zooplankton) feed on the phytoplankton, and herbivorous fish eat the algae. Carnivorous fish prey upon zooplankton, insects, and herbivorous fish and are, in turn, eaten by the secondary carnivores—tarpons (the largest fish species in the lake) and several bird species.

As we have seen, interspecific competition will limit the species found at any one **trophic level**. In addition, individual- and population-level processes will limit both the presence and abundance of a particular species. In most cases, the extinction of one species is not critical to the long-term health of a community. The remaining species at that trophic level, or species from adjacent areas, can provide the necessary links for energy to flow. However, the loss of one species in a community can lead to the damage or extinction of the entire community.

FIGURE 38



Greater Yellowstone ecosystem foodweb highlighting only some of the many species in the ecosystem.

Source: https://yellowstoneinfo.weebly.com/food-web.html

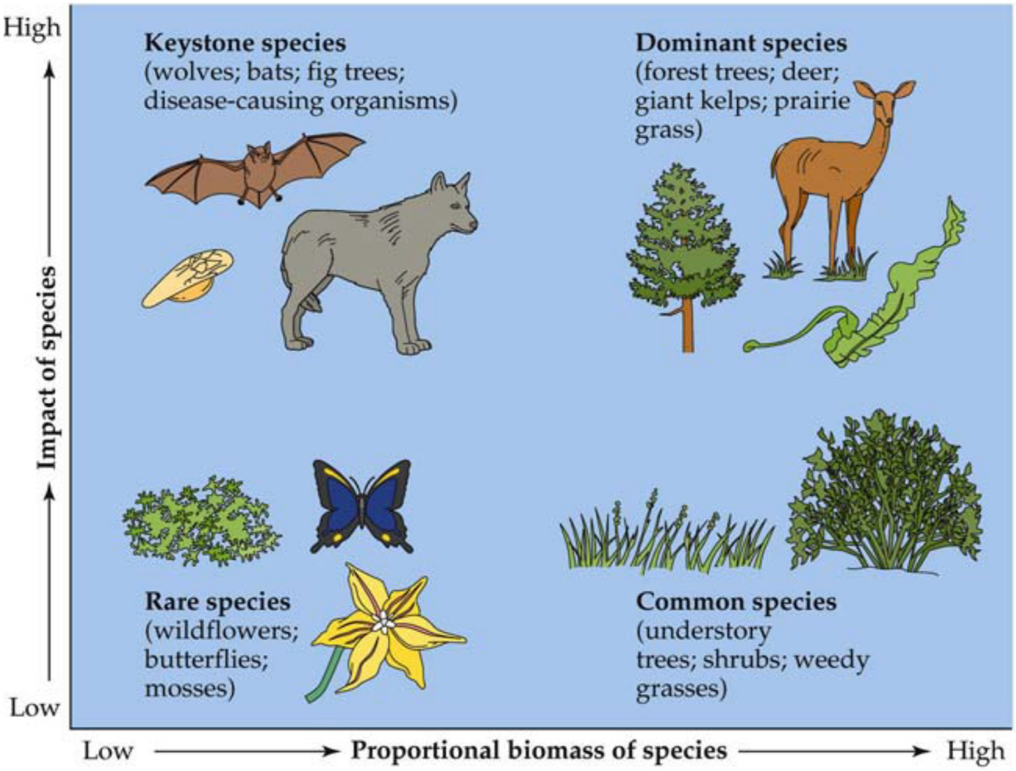
Keystone Species

A keystone species is one that, because of its position in the food web or some other population interaction, plays a role in the community that is far more important than its relative abundance would suggest (Figure 39). This means that species that are the most abundant species in a community or the major energy producers, while vital to the health of a community, are not considered keystone species. The keystone species concept was developed to explain the sometimes unexpected effect of removing a relatively rare species from the food web.

A keystone species may be the *key predator* in a community. This was demonstrated in an experiment on a Pacific Coast intertidal community that included the sea star *Pisaster*, which preyed on the mussel *Mytilus* and several other herbivorous species (Figure 40). When scientists removed *Pisaster* from the community, there was no longer any predator of *Mytilus*, so its population increased and out-competed all the other remaining species. *Pisaster* had been a key predator that kept the other populations in balance. It was the keystone species, whose loss resulted in the loss of eight other species.

Keystone species can be *food sources* that are present at a time of low food availability or provide essential nutrients. For example, figs, nectar, and a few fruits make up less than 1 percent of the plant diversity in the tropical forests of Central and South America. In most years, there is a three-month period in which the more abundant plant species produce less energy than what is required by the community's **herbivores**. During this

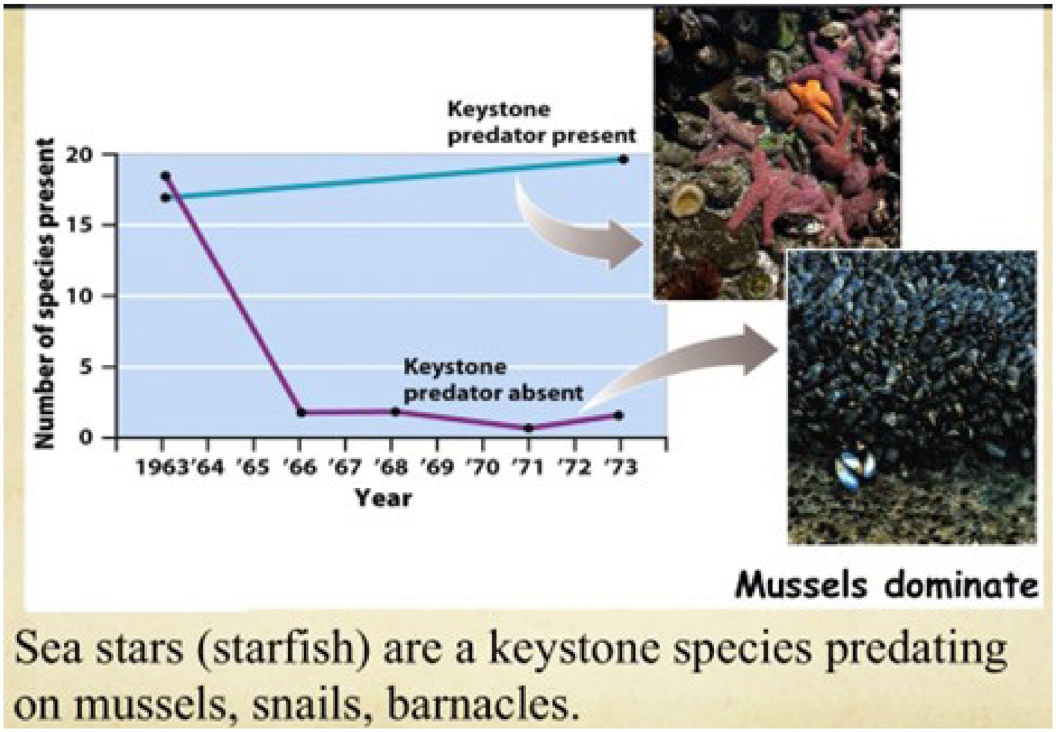
FIGURE 39



The importance of keystone species is much greater than their abundance in an ecosystem.

Source: Richard B. Primack, *A Primer of Conservation Biology 4th Edition*, Sinauer Associates (2008)

FIGURE 40



Sea stars are an example of a keystone species.

period, the herbivores that don't migrate rely on the less abundant figs and nectar, which are the keystone species in this community.

Three types of species are keystone species not because of their roles in a food web, but by virtue of other mutualistic interactions: irreplaceable pollinators, habitat modifiers, and species whose individual biological processes play an important community function. Pollinators that are very abundant or whose function can be taken over by other species don't qualify as keystone species. However, in some communities, one relatively rare species of *pollinator* is not replaceable and is a keystone species. For example, on many South Pacific islands, Old World fruit bats (flying foxes) are the only pollinator for hundreds of tropical plant species. Flying foxes have been hunted to near extinction, leading to the possible loss of entire island communities.

The North American beaver functions as a keystone species within a community by creating or maintaining habitat for other species.

Species can also function as a keystone species within a community by *creating or maintaining habitat* for other species. The North American beaver is a prime example of this type of "ecosystem engineer." Although they make up only a small percentage of the total biomass of the North American forest, beavers transform streams into ponds, creating a new habitat for pond-adapted plant and animal species.

The final type of keystone species is species whose importance is based on their *mutualistic interactions with other species*. This type is exemplified by the mycorrhizal fungi on and in the roots of many tree species. Increasing the tree's ability to extract nutrients from the soil, *mycorrhizae* play a critical role in the growth of tree species, which in turn provide most of the resources and niches for other members of a forest community.

In some cases, the introduction of a new species can have an effect on a community similar to the loss of a keystone species. The damage from such exotic species can be great, particularly if a keystone species is driven to extinction. Both the loss of a keystone species and the introduction of an exotic species show how dependent a community is on the health of its component species.

Succession

Even if keystone species are not lost and exotic species are not introduced, communities will not stay the same forever. The change of a community over time is just as natural as the evolution of a species. One of the major changes that occurs in virtually every community is **succession**, the predictable replacement of certain species by others over a number of years.

Ecologists have described two types of succession, which differ on the basis of the starting condition of the land. Since the terminology can be somewhat confusing, it is important keep in mind that the terms *primary* and *secondary* succession refer not to the relation of these two processes in time but to whether the process is beginning in a place where a biological community has not or has previously existed. *Late* successional species, on the other hand, do follow *early* successional species in time, in either primary or secondary succession.

Primary succession is the series of replacements that occur, on land or in water, after an event such as glacial scouring or a volcanic eruption creates a new surface devoid of life. In primary succession, bare rock is inhabited by plant species that are best suited to grow without soil. These first *early successional species* are usually lichens, mosses, and similar small plants. As these plants grow, they break up rocks into soil particles, and as the plants die and contribute organic matter to the soil, other, more advanced plants begin to colonize the site. The *later successional species* may be highly adapted to exploiting open, sunny areas without demanding large supplies of nutrients, which are lacking in newly formed soil. In each phase of succession, certain species are most competitive for resources. After some period of time, other species outcompete the established species, and succession proceeds. In some cases, the number of species increases as succession proceeds; in others, a late successional community will have fewer species than an early successional community.

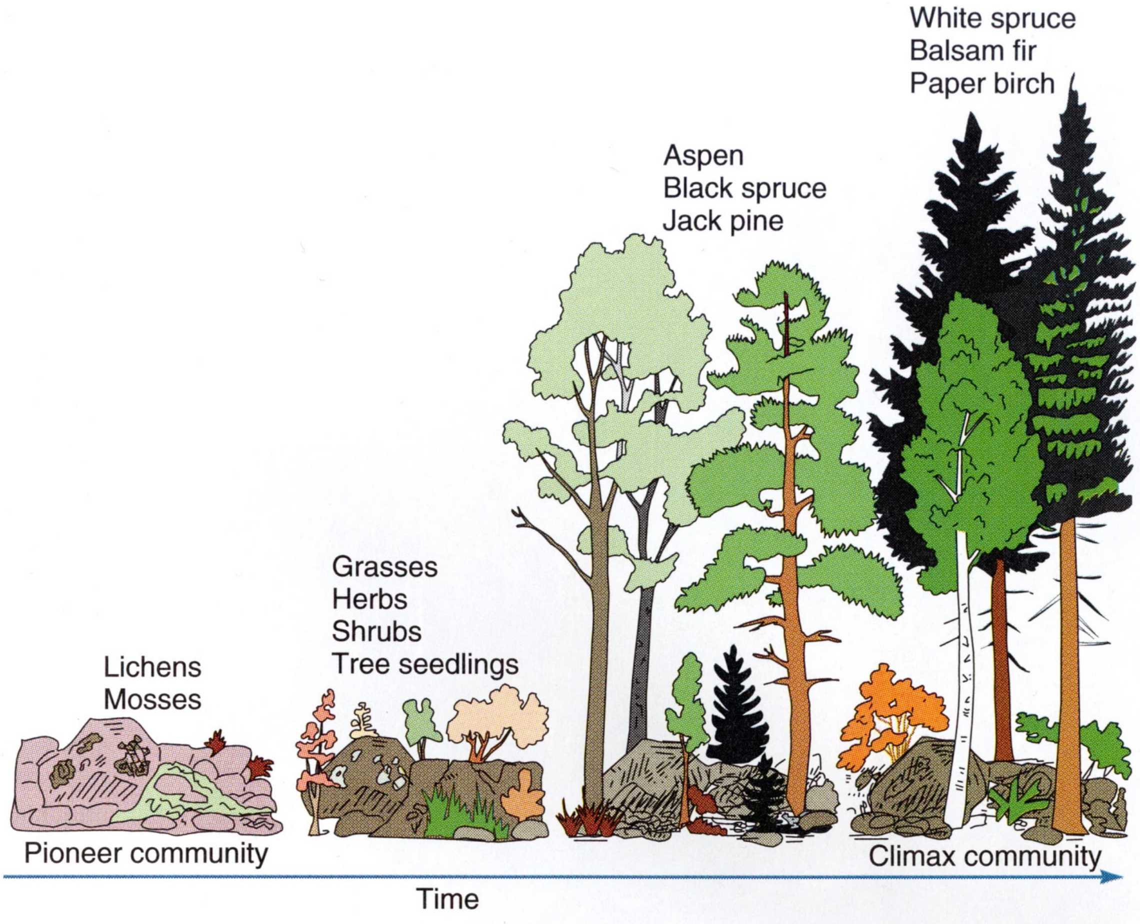
Secondary succession is succession that occurs on an area of land that is devoid of vegetation but hasn't experienced complete destruction of the soil surface. Secondary succession occurs after events such as forest fires, hurricanes, and land clearing by humans. Figure 41 shows an example of secondary succession in a forest.

In forests, late stages of succession were once called *climax forest* to signify that the last, or climax, stage of succession had been reached. It is now recognized that because natural disturbances such as fire, wind, and insect defoliations are a regular part of most forests, a late-successional stage is always a temporary, rather than a final phenomenon, so the term *climax* is no longer used.

Primary succession is the series of replacements that occur, on land or in water, after an event such as glacial scouring or a volcanic eruption creates a new surface devoid of life.

By Nevilley at the English Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1271226

FIGURE 41



Forest succession.

ENVIRONMENTAL SCIENCE CASE STUDY: A Simple Ecosystem—Organ Cave

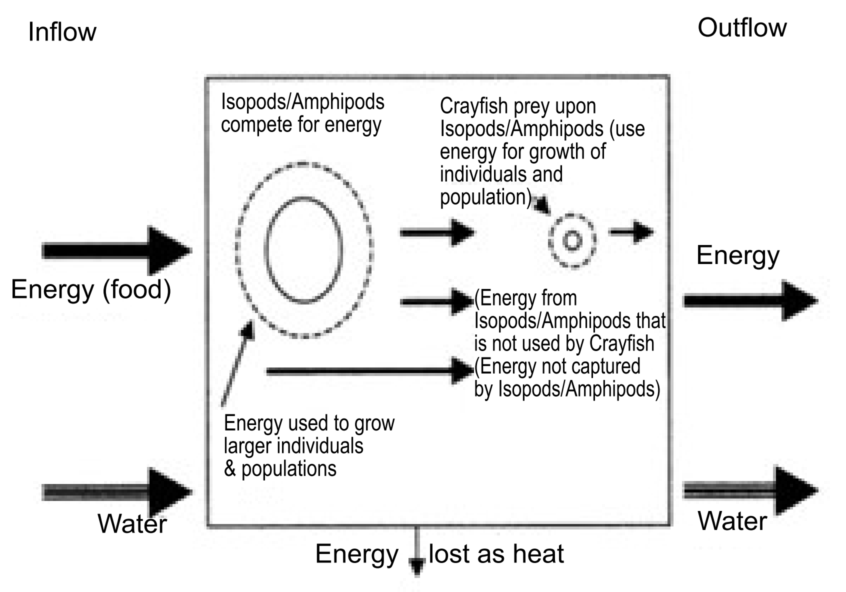
The deciduous forest of the southern Appalachia of West Virginia is a complex ecological system made up of a web of many producers (plants), consumers (herbivores and carnivores), and **decomposers** (bacteria and scavengers) interacting with the abiotic factors of water flow, landscape, and climate. Hidden just meters below this forest system is another ecological system containing only three or four species interacting with each other and with only a few key environmental variables: the cave stream ecosystem of Organ Cave.

As you enter Organ Cave, the largest cave in West Virginia, the first thing you might see is sleeping bats, resting up for their nighttime flight outside the cave in search of food. However, bats are only part-time residents of the cave; Organ Cave's full-time residents, and the main components of this ecological system, are small (< 1 cm) distant relatives of shrimp, and one species of crayfish, all of which live in the narrow streams that cut through the numerous cave passages. Their food consists of plant and animal tissue washed in from the surface and dead cave animals; the crayfish also prey on the isopods and amphipods.

Cave populations are good examples of how evolutionary processes affect the distribution of species on Earth (which we will deal with later in this section). Three of the Organ Cave species were probably present during the last ice age in both cave and surface streams. However, as the climate warmed, the surface waters became too warm for these species during the summer, and they became isolated in the consistently cold waters of the caves. Therefore, for these three species, what was once a wide-ranging distribution pattern became, due to changes in the abiotic environment, a patchy distribution of isolated populations.

Ecological processes, as well as evolutionary history, affect the distribution and abundance of species on Earth. These processes occur at several levels of biological organization, as we can see in Organ Cave. First, is the need of *individual* isopods and amphipods to be able to tolerate the environmental conditions of low food resources, consistently low water temperatures, and seasonal floods. Individuals who cannot find enough food or those whose body functions require more food or warmer temperatures, will not survive in the cave conditions.

FIGURE 42



Inflows and outflows of the cave system.

The survival of each species in Organ Cave also requires that the *population* remain abundant enough to be able to survive the inevitable environmental fluctuations, such as floods, that can drive small populations to extinction. The isopod, amphipod, and crayfish populations of Organ Cave do not live in isolation but *interact* in several ways, such as competing for proper sized rocks to which they can adhere to avoid being washed downstream and which provide traps for food material. Finally, this *community* of species and the energy and mineral nutrients from the abiotic environment make up the cave *ecosystem*.

Organ Cave is the largest cave in West Virginia.

The Organ Cave ecosystem can be thought of as a relatively simple input-output system of water flow bringing in energy and nutrients, species competition regulating the use of the energy, and water flow taking out any unused energy.

PRODUCTIVITY

There are many fewer carnivores, such as lions, than herbivores (plant-eating animals), such as zebra and wildebeest. Large, fierce animals are rare in nature because many energy conversions are required to feed them.

Photo by Frank Metcalf

If you have ever had the chance to visit the Serengeti Plains in East Africa, or seen them on a television documentary, you know that there are literally millions of herbivores (plant-eating animals) such as zebra and wildebeest but many fewer carnivores such as lions. Large, fierce animals are rare in nature because many energy conversions are required to feed them. Therefore, more organic matter and energy are stored within all the herbivores than within all the carnivores. The **laws of thermodynamics** tell us why: herbivores get their energy from green plants, which get their energy from the Sun. Carnivores get all their energy from herbivores, so there could never be more energy within carnivores than within the herbivores on which they feed (First Law). Furthermore, the transfer of energy from herbivores to carnivores is always going to be less than 100 percent (**Second Law of Thermodynamics**), so there will always be less energy contained within carnivores. This pattern is true in any natural system; let's see how this pattern drives one of the most critical variables of an ecosystem: **productivity**.

Primary Productivity

The Sun is the primary source of energy on Earth and the major energy input to a grassland system. Green vegetation (blades of grass) is the **primary producer**—it converts energy from the Sun, carbon dioxide, and water to grass, leaves, and wood. This process, known as **photosynthesis**, can be represented by the following chemical equation:

$$\mathbf{CO_2 + H_2O + \text{energy from the Sun} \rightarrow CH_2O + O_2}$$

The generic carbohydrate (CH_2O) makes up the grass and the roots below the blades of grass, which are collectively called *biomass*, the term biologists use to describe the weight (mass) of biological material. The amount of CH_2O produced in a given area over a given time yields the rate at which biomass is produced, or the **primary productivity** of a biological system. However, this does not give us an accurate picture of available energy in the system because primary producers use some of the energy they produce.

To understand energy use throughout an environmental system, we have to consider a number of other concepts. The *total* amount of solar energy converted to chemical energy by photosynthesis over a given time is known as the **gross primary productivity** (**GPP**) of a plant or environmental system. To fuel their own metabolism and growth, all biological organisms carry out **respiration**, which is the opposite of photosynthesis: cells convert carbohydrates and oxygen to energy and carbon dioxide and water. This uses some energy although not as much as the total amount the plant produces.

$$\mathbf{CH_2O + O_2 \rightarrow CO_2 + H_2O + energy\ (heat)}$$

Because of the energy expended during respiration, we must subtract the energy consumed by primary producers from the GPP to determine the **net primary productivity (NPP)** of the plant or system. In other words, NPP is the difference between GPP and respiration, which can be written as a formula:

$$\mathbf{NPP = GPP - respiration}$$

NPP, expressed as the amount of biomass or energy produced per square meter per year, is the most common term used to describe the productivity of a biological system.

Energy Transfer Efficiency

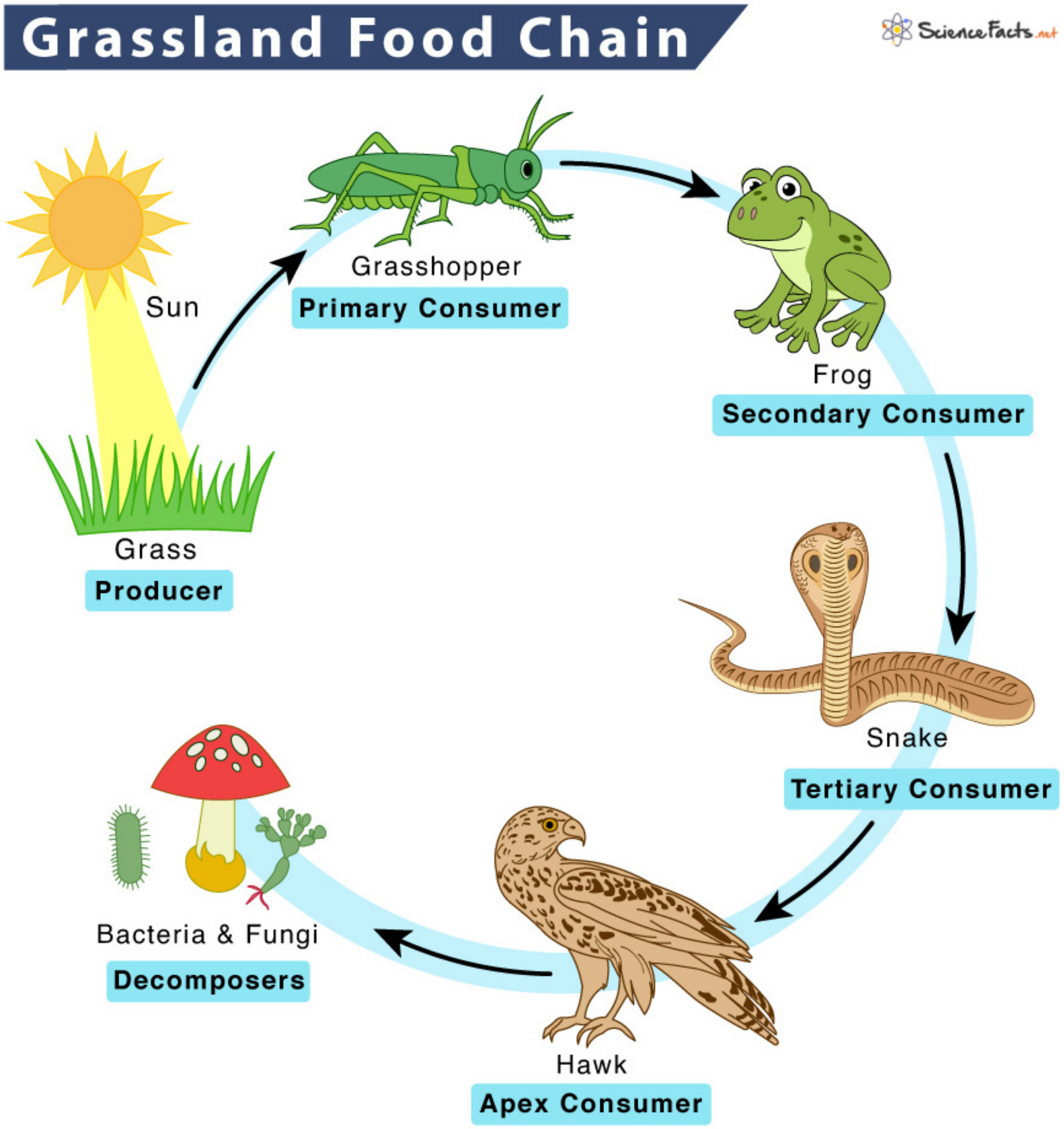
The energy efficiency for a particular ecological system is determined by the ratio of the NPP (the energy output, which is equivalent to the work desired) to the incoming solar radiation (the total input of energy into the system). Most primary producers are approximately 1 percent energy efficient. This means that in an open field of grass, for example, 1 percent of the solar radiation that reaches the grass is converted to biomass. For the purposes of this example, let's assume that we have determined that the biomass of the grass is 1,000 g/m^2, which represents a given quantity of energy. Let's also assume that only one species of grasshopper eats the grasses produced in the field and that the grasshoppers eat only grass. What biomass of grasshoppers could possibly exist in this field of grass?

The First Law of Thermodynamics mandates that there could never be more than 1,000 g/m^2 of grasshoppers (the consumer) because all the biomass from grass (the energy source for the grasshoppers) could not be converted at a ratio greater than 1.0. The Second Law of Thermodynamics mandates that, in fact, there will be less than 1,000 g/m^2 of grasshoppers because of losses during energy conversion. Furthermore, the grass uses some of its energy in respiration to support itself, and some portions of the grass may not be available or digestible by grasshoppers, so there will actually be much less than 1,000 g/m^2 of grasshoppers.

In fact, in **temperate grasslands**, there may be roughly 100 g/m^2 of **primary consumers**, organisms like grasshoppers that directly eat the primary producers (Figure 43). This efficiency of transfer of energy or biomass from one level of a system to another is called *transfer efficiency*. Our example system has a 10 percent efficiency; some systems may have efficiencies as low as 5 percent or as high as 20 percent, but 10 percent is an average value. Each level of such a feeding system is called a *trophic* level, from the Greek word for nourishment, *trophe*.

Let's look more closely at our grassland system and assume that one species of songbird eats only grasshoppers, and this species of songbird is the only organism in the system that feeds on grasshoppers. Here again, the First and Second Laws tell us that the biomass of these songbirds (the consumer) will be somewhat less than that of the grasshoppers (the source of energy). As before, respiration and indigestible parts of the grasshoppers will prevent all of the grasshoppers from being available for conversion to the next level of organisms. Assuming that energy content per gram is the same for grasshoppers and songbirds, and using a transfer efficiency of 10 percent, we can calculate that there may be roughly 10 g/m^2 of songbirds in this field. These birds are called **secondary consumers** because they feed on the first-level, or primary, consumers.

FIGURE 43



A grassland food chain.

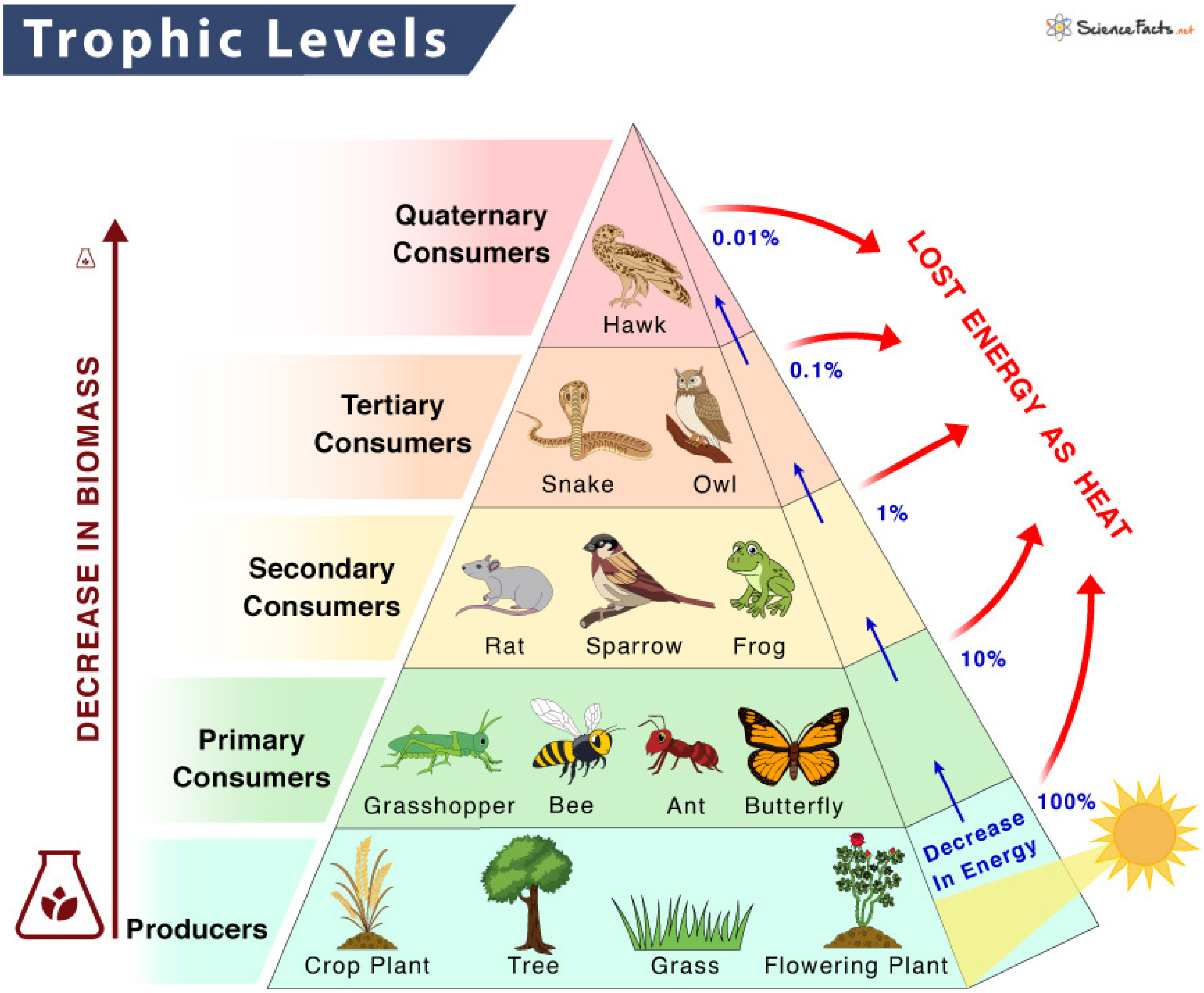
Source: Sciencefacts.net

Finally, if a predator such as one species of hawk eats only the songbirds, and if the hawks have a transfer efficiency of 10 perrcent, there might be 1 g/m^2 of hawk. In this scenario, hawks are *tertiary consumers*, or the third level of consumers. As you can see, there are not going to be very many hawks relative to blades of grass, grasshoppers, or songbirds. Not only is there less energy available at the highest level of transfer, but since a hawk is a larger animal, it will require more biomass to make up one individual than would a blade of grass, a grasshopper, or a songbird.

Ecological pyramids can also be used to show the amount of energy that transfers from one level to the next (Figure 44). We have said that only about 1 percent of the energy of the Sun is transferred to the primary producer. Most consumers obtain roughly 10 percent of the energy in the trophic level below.

One other level exists that feeds off of the waste products of the producers and consumers. This level is occupied by detritivores, organisms that feed on dead organic matter. Bacteria, fungi (including mushrooms), dung beetles, and earthworms are all detritivores.

FIGURE 44



Energy pyramids highlight the decrease in biomass and loss in energy as we move up from one trophic level to the next.

Source: Sciencefacts.net

The feeding relationships in the Serengeti Plain of Africa are much more complex than our example, but the same reasoning applies. This is why big, fierce predators such as lions (secondary consumers) are rare relative to blades of grass (primary producers) or zebras (primary consumers). This example also gives you possible insight as to why a fiercer, larger predator has never evolved to eat lions. Such higher-level predators would have to be even less densely populated than lions, and it would probably be too difficult for a species to survive given the relatively low density of its prey (lions).

MAJOR ASPECTS OF ECOSYSTEMS

Ecosystem ecology studies the combination of biotic and abiotic elements in a particular location. Gene Likens, co-founder of the Hubbard Brook ecosystem research project in the White Mountains of New Hampshire, has defined an **ecosystem** as "a spatially explicit unit of the Earth that includes all of the organisms, along with all components of the abiotic environment within its boundaries." This definition highlights the three important aspects of an ecosystem:

- The ecosystem's boundary—where does one ecosystem end and another begin?
- The biotic component—the individuals, populations, and communities that live within the ecosystem

- The abiotic (physical and chemical) component, including temperature, water, salinity, soil structure, and mineral nutrients.

Large-scale forest ecosystem research is being conducted at Hubbard Brook Experimental Forest in New Hampshire.

The ecosystem is the first level in the hierarchy of biodiversity that is self-contained. In contrast to individuals, populations, and communities, which depend upon other organisms for food and the physical environment for optimal conditions and habitats in which to live, an ecosystem contains all the living and nonliving parts required for long-term existence. However, an ecosystem is not just the components within it and the boundary around it. It is also the processes occurring within it. One of the major processes is the *flow of energy* from the Sun through the abiotic and biotic components. *Cycling of materials* is also central. So many different materials cycle through an ecosystem—water, carbon, nitrogen, and phosphorus, to name only a few—and they are all so important to the global environment as well as to any individual ecosystem. Here, we will focus on how biotic and abiotic changes create a diversity of ecosystems, as well as how changes at the ecosystem level produce variation in lower levels of biodiversity.

Ecosystem Boundaries

Organ Cave, which we discussed earlier, is an example of a well-defined system that contains identifiable biotic components—the cave animals and their resources—and abiotic components—water flow, temperature, and salinity. Energy enters the system mostly from water flow into the cave, and the few species exchange this energy through a food web. The cave system is relatively easy to study because the boundary of the system is relatively easy to see; it is everything from the point the stream enters the cave to the spring where it exits. Knowing the boundary of an ecosystem makes it easier to identify the biotic and abiotic components that make up the system.

Many aquatic ecosystems such as lakes, ponds, and streams are relatively easy to identify in nature because the ecosystem's boundary corresponds to the boundary between land and water. In most cases, however, determining where one ecosystem stops and another begins can be difficult. Environmental scientists usually estimate the boundary of terrestrial ecosystems by the range of the populations that make up the biological community or by particular ecological processes. Often the boundary of an "ecosystem," such as a national park or reserve, is set according to administrative rather than scientific criteria.

The Biotic Components of Ecosystems

The types of species within an ecosystem will influence how energy flows through the system. The conversion of energy from producers to the different levels of consumers can be modeled as a pyramid in which the amount of energy or biomass at each level of the ecosystem is represented by the relative size of that part of the pyramid. Energy pyramids will look relatively constant from ecosystem to ecosystem; most energy is always found at the producer level and decreases as we move up the pyramid. Biomass pyramids, however, vary from ecosystem to ecosystem depending upon the characteristics of the populations making up the various trophic levels, as well as the physical and chemical structure of the ecosystem itself.

The Impact of Ecosystem Change on Its Biotic Components

All ecosystem-level processes are subject to change. Certain kinds of ecosystem-level changes can be characterized as a **disturbance**, a process in which physical, chemical, and some biological agents cause the relatively rapid injury or death of organisms and the damage or collapse of the biotic component of the ecosystem. Some natural disturbances are hurricanes, ice storms, and natural forest fires; anthropogenic disturbances include clearcutting of


The Chesapeake Bay is an example of a current ecosystem restoration project.

forests, agriculture, and air pollution. The slow invasion of a lake by an introduced species is not usually called a disturbance, but is rather considered a *perturbation*, a much broader term that refers to any kind of change to the normal or equilibrium value in a system. The gradual increase in temperature by approximately 1°C that has occurred on Earth in the last one hundred years is a perturbation. A 2°C increase within one decade would most likely be characterized as a disturbance.

Resilience is the rate at which an ecosystem returns to its original state after some sort of disturbance causes a change. A highly resilient ecosystem would return to its original state rapidly; a less resilient system more slowly. For example, if a severe drought were to eliminate half the species in a highly resilient ecosystem, all the species would return by the following year. A less resilient ecosystem might not return to pre-drought conditions for many years, if ever.

Not only is some level of disturbance natural, it may be necessary for the maintenance and creation of species-level biodiversity. According to the *intermediate disturbance hypothesis*, in ecosystems that do not change, competitive exclusion will eventually lead to the domination of one species. On the other hand, if there is too much disturbance, most species will go extinct unless their population growth is high enough to counter the density-independent effects of major disturbances. When disturbances occur at an intermediate frequency, population sizes of major **competitors** never reach a level at which they can dominate an ecosystem, and population sizes of other species are never driven too close to zero.

Unfortunately, most human-caused disturbances—such as major building developments, clearcutting, or watershed draining—are so great that they lead not only to the local extinction of species, but to the elimination of entire communities and ecosystems. **Restoration ecology** is a new **discipline** that attempts to repair or even "regrow" natural ecosystems. Mono Lake and the Florida Everglades, discussed in Section I, as well as the Chesapeake Bay[7] are three examples of current ecosystem restoration projects.

BIOMES

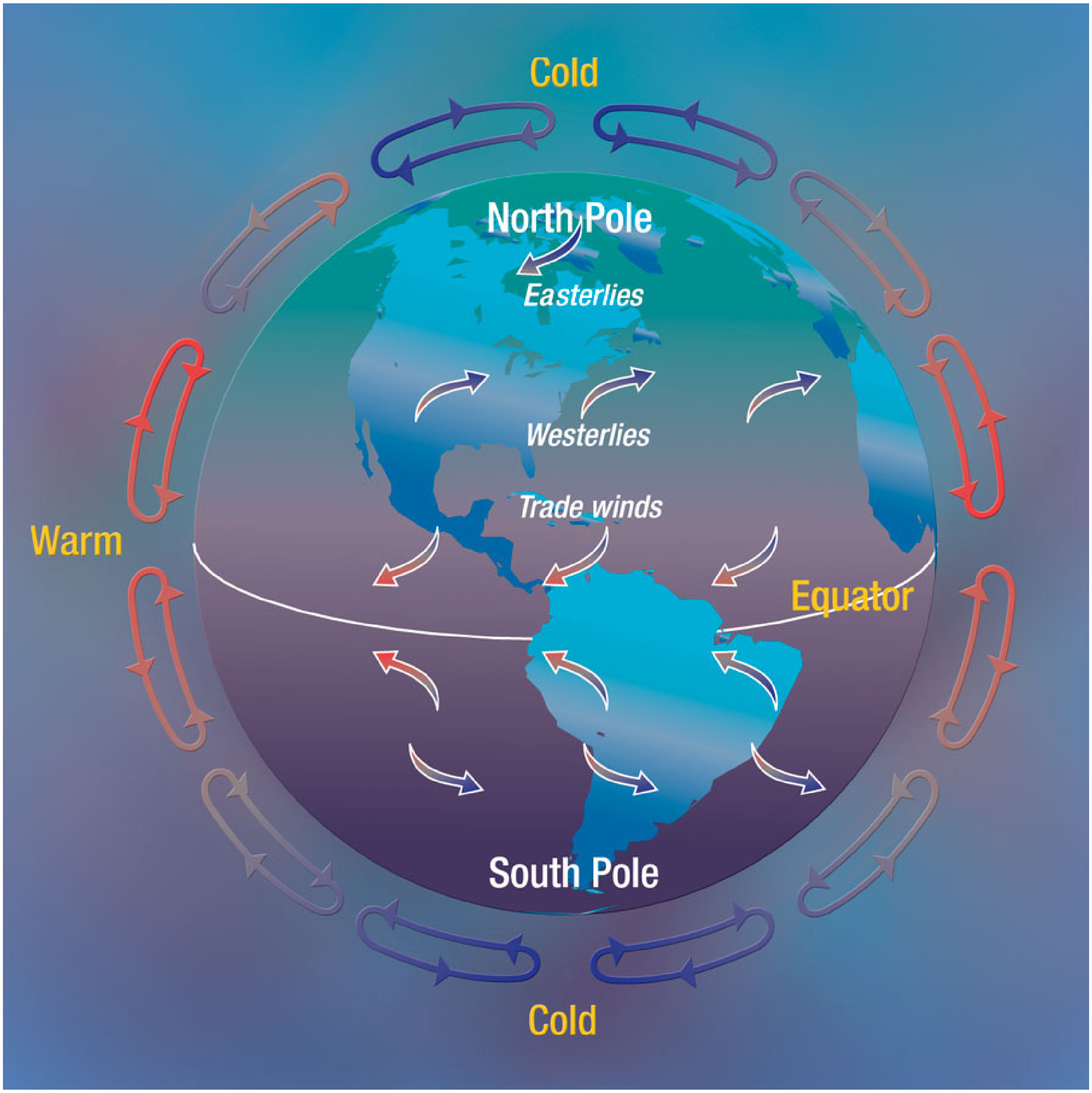
The Global Climate and Biomes

Biomes are major regions of differing vegetation and wildlife types. Global patterns of temperature and moisture are the two most important factors controlling the formation and distribution of biomes. Changes in these factors cause variations in the amount of energy available to the region and thus influence the variation in the biotic components. Geographic variation in temperature and moisture are caused by global patterns of air and water circulation. The Sun, which is the principal source of energy for communities and their populations, also provides the energy that propels air and water circulation. Global variation in the amount of the Sun's energy hitting different parts of the Earth, termed *solar energy flux*, is what causes both *global atmospheric circulation* and *global oceanic circulation.*

All parts of the Earth receive the same amount of total yearly sunlight—an average of twelve hours per day. However, the amount of solar energy that this sunlight puts into a particular part of the Earth will depend upon the angle at which the light reaches Earth. When the Sun is low in the sky, its light (and energy) passes through more atmosphere and is diffused over a larger surface area than when it is shining directly down. Therefore, even though the arctic region receives the same amount of total light over the year as the equator, the amount of total solar energy entering tropical rainforests is much greater than in the arctic tundra. This large-scale pattern of global solar energy flux will determine how much energy is available for various regions.

Patterns of global atmospheric circulation (see Figure 45) also create much of the large-scale diversity on Earth. As air is heated by the Sun, it rises, and the more it is heated, the higher it rises. Because the equator receives the most solar energy, its air rises the highest. As this air rises, air from the north and south moves into the equator region to replace it. The air that had risen at the equator descends at ~30° north and south latitude, replacing the air that moved to the equator. This cycle is known as the Hadley cell. The air rising over the equator cools as it ascends, and the water vapor condenses, which is the main reason that equatorial ecosystems tend to be very rainy. The descending air has lost its moisture and is dry, which is why most desert ecosystems are found at 30° from the equator.

FIGURE 45



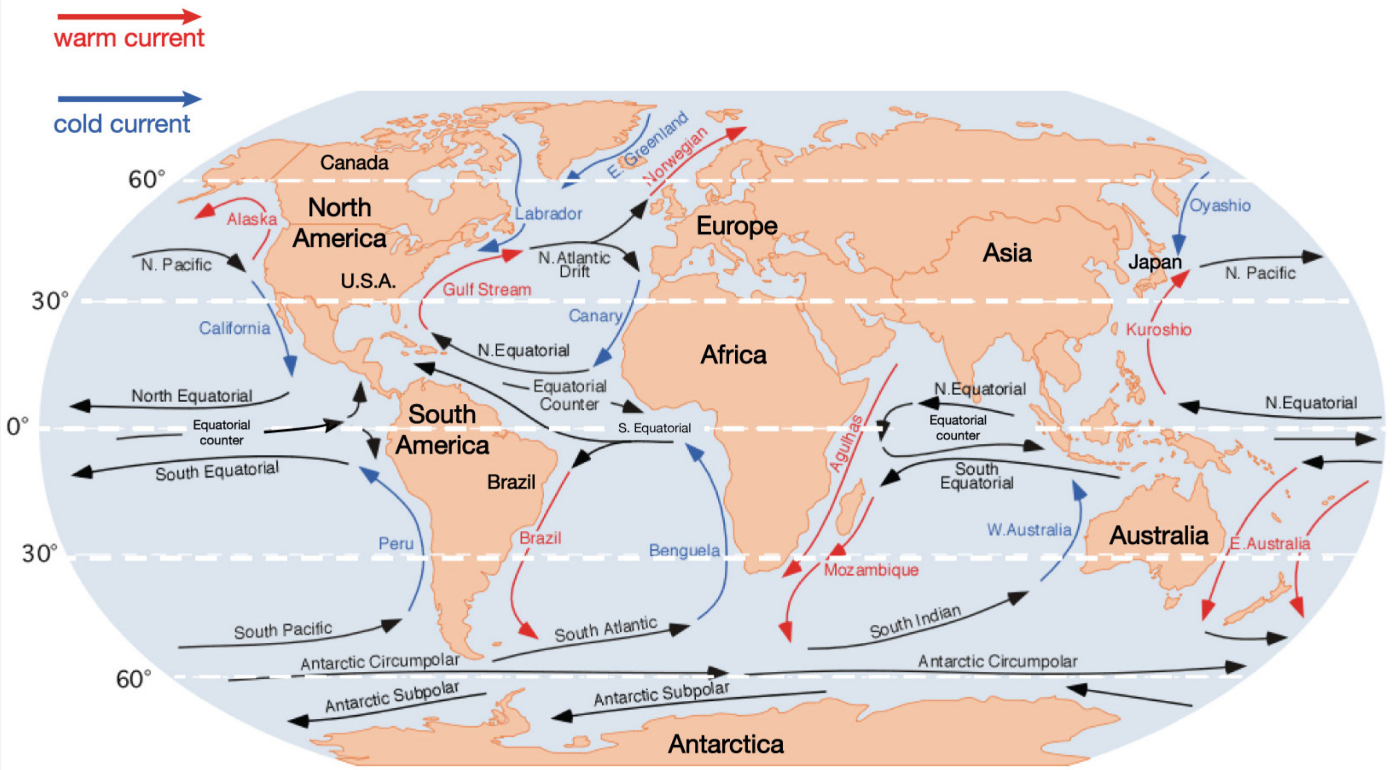
Global air circulation. Major east-west circulations are due to the Earth's rotation, while north-south circulation is due to the heating and cooling of the air.

Source: UCAR Center for Science Education

While the heating and cooling of the air produces north-south air circulation patterns, it is the spinning of Earth that creates the major west-east circulation patterns. At any given latitude, the air mass will move at the same speed that the Earth does at that latitude. However, as the air mass moves away from the equator, its direction is affected by the decreasing velocity of the Earth as we move away from the equator (like a spinning top, the Earth's velocity decreases with its circumference). In the Northern Hemisphere, air masses tend to move toward the right, and in the Southern Hemisphere, they tend to move toward the left. This deflection is called the **Coriolis effect**. Because the earth is tilted on its axis, there is a seasonal change in the latitude where the most solar energy falls, so the point where air will rise the highest also shifts with the season. The resulting seasonal variations in the patterns of warm and cold air movement across the globe are a major influence on the formation of different biomes.

Finally, global air circulation patterns drive the major global oceanic circulation patterns. (Figure 46) Winds blowing toward the equator from the northeast and southeast will cause water to move toward the equator and then west until it reaches a land mass, where it will divide into north- and south-flowing water masses. The movement of water along land masses, from the equator toward the poles, is a major source of heat for northern latitudes and explains why places like Anchorage, Alaska, and Iceland are not nearly as cold as their extreme latitudes would suggest.

FIGURE 46



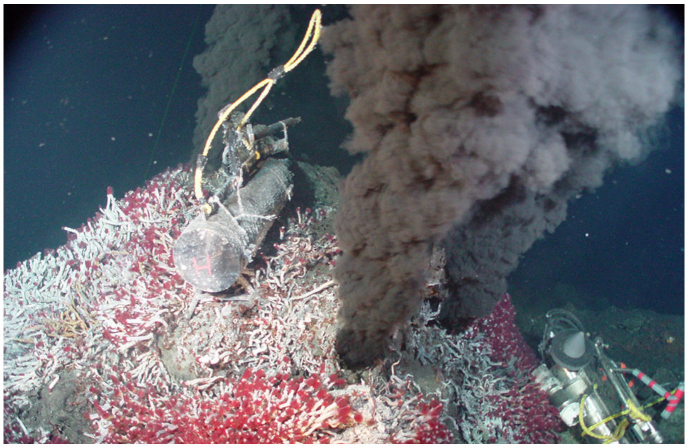
Global ocean currents.

Source: Earth and Space Science

This effect creates a general clockwise circulation pattern in the Northern Hemisphere and a counter-clockwise pattern in the Southern Hemisphere. However, both general patterns are modified by the location of land masses, which act to split and redirect flow. Like wind, ocean currents will change patterns of available heat through the patterns of movement of cold and warm waters. In addition, water tends to heat up more slowly in summer and cool off more slowly in winter than land, helping to moderate the temperature changes of adjacent land masses.

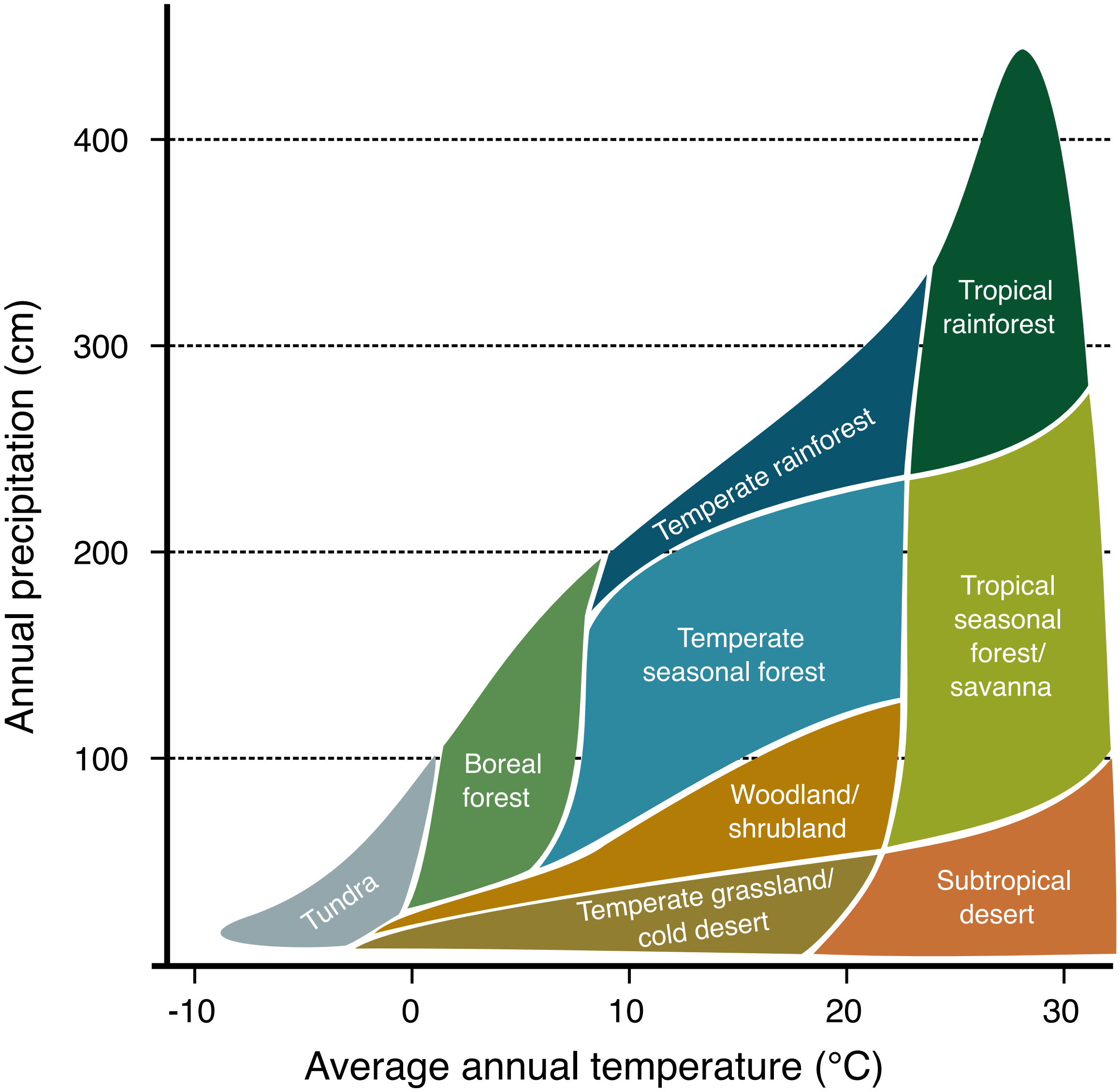
Biomes and Global Biodiversity

Environmental scientists have correlated the presence and extent of ten major types of terrestrial biomes with a region's mean annual temperature and mean annual precipitation (Figures 47 and 48).



A hydrothermal vent on the ocean floor.

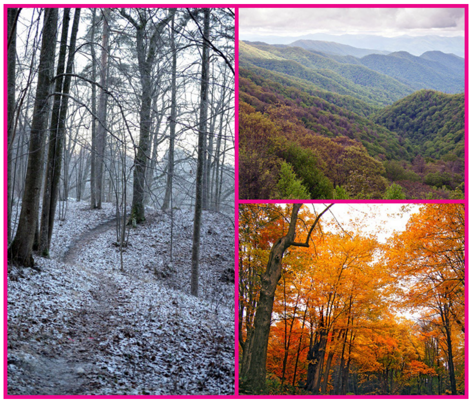
FIGURE 47



Average annual precipitation and temperature correlated with different biomes.

Source : OpenOregon Educational Resources

FIGURE 48

Tropical rainforest[8] **(evergreen)** The wettest and warmest biome is the tropical rainforest, such as those in the Amazon and in western and central Africa. **Key elements**: High plant and animal diversity Ecosystem productivity is high, but much of the ecosystem's energy and nutrients are tied up in the vegetation, and the soils are often extremely poor in mineral nutrients.	
Tropical dry (seasonal) forest[9] Some forests in the tropics experience a pronounced dry season. **Key elements**: Deciduous trees, which drop their leaves and flower during the dry season, are common. Productivity and diversity of both plant and animal species per meter are less than in tropical rainforests.	
Temperate rainforest[10] Tall coniferous trees are the dominant form in temperate zone rainforests such as the U.S. Pacific Northwest. **Key elements**: Mild winters, heavy rain, and frequent fog are the main factors creating optimal conditions for trees that are frequently 60–70 meters high. Productivity is roughly half that found in tropical rainforests. Soils tend to be rich in organic matter.	 Bigleaf maples in the rain forest are adorned with epiphytic mosses, ferns, and spike-mosses growing on their trunks and branches.
Temperate broadleaf forest[11] These forests occur in regions of moderate rainfall and high seasonal temperature variation and include deciduous-dominated forests in the eastern U.S., southern Canada, Europe, and eastern Asia. **Key elements**: Productivity is similar to that of temperate rainforests. Because most plants shed their leaves, a thick leaf litter will decompose into a rich soil. Both plant and animal diversity are much lower than in the tropics.	

Boreal coniferous forest[12]
As temperature decreases, the dominant deciduous vegetation in areas of moderate to high rainfall are forests almost exclusively of conifers, primarily spruces and firs that are 10–20 meters high.

Key elements:
Several large mammal species, such as moose, bear, wolf, and Siberian tiger are found in these forests.
Productivity is roughly one-third that of tropical rainforests, with low plant species diversity.
Yearly weather variation results in dramatic yearly variation in seed production, which causes dramatic fluctuations in bird and other animal populations.
Low temperatures and chemicals in foliage result in low leaf litter decomposition and relatively poor soils.

Temperate grassland[13]
When precipitation decreases to the point that there is not enough water to support dense forests, vegetation shifts to grasslands.

Key elements:
Grasslands are often called **prairies** in the U.S. and steppes in central Asia.
Productivity is usually about one-third of that found in tropical rainforests.
Organic matter accumulates in this biome because decomposition of dead vegetation is limited by low precipitation rates, resulting in rich agricultural land.

Tropical Scrub Forest and Savanna[14]
Savanna is most common in dry tropical regions of Africa, where rainfall ranges from 10–150 cm/year and is seasonal; during the driest three to four months of the year, there may be less than 5 cm per month.

Key elements:
Portions of this biome contain *scrub vegetation*, which is small and stunted due to limited nutrients and a short growing season.
Migrating herds of herbivores, such as wildebeests, follow the rain and move across this biome.
Fire and grazing are responsible for generating and maintaining the savanna biome.
Productivity and species diversity per square meter are significantly less than in tropical rainforests.

Mediterranean[15] Found in countries bordering the Mediterranean Sea, as well as California (where it is known as **chaparral**), this biome comprises dry areas that receive most of their rain in the winter, before the temperatures rise enough to permit plant growth. **Key elements**: Vegetation is made up mostly of dense, woody shrubs and small trees. Leaves tend to be small, leathery, and waxy—adaptations that help retain water. Fires are frequent, and many trees and shrubs have evolved fire-resistant bark to protect themselves. Several bird species and small mammals such as jackrabbits, kangaroo rats, and chipmunks can be found, along with mule deer and several species of lizards.	
Desert[16] Usually defined as areas receiving less than 25 cm of precipitation per year, desert biomes cover a fairly broad temperature and latitude range. **Key elements**: Although commonly considered hot, there are cold deserts in places such as Mongolia and Montana. Because of its low precipitation, Antarctica is classified as a desert. Most deserts are characterized by sandy or rocky soil. Sparsely spaced shrubs and grasses are common. Desert productivity ranges from 0 to roughly 5 percent of that found in tropical rainforests. Many desert species have evolved adaptations to the lack of water.	
Tundra[17] Tundra occurs in the arctic region beyond the tree line, the upper limit of tree growth at high latitude or elevation. **Key elements**: Vegetation consists primarily of grasses and grass-like sedges, lichens, and dwarf forms of trees. The soil (permafrost) is frozen all year round, though it thaws to a depth of 0.5–1 meters during the brief summer growing season. Mean productivity in the tundra regions is low, normally between 5 percent and 10 percent of what is found in tropical rainforests. Rodent species, such as lemmings, can be abundant, but their populations undergo dramatic fluctuations correlated with variation in resources. Though bird populations can be abundant in summer, most species will migrate south during the long winters.	

Ten Terrestrial Biomes

Without the variety of large plants used to characterize terrestrial biomes, aquatic regions have not been subdivided into as many different types and are not traditionally known as biomes. However, a few distinguishable types can be identified in the two major aquatic systems—freshwater and marine.

Freshwater systems can be divided into flowing (rivers and streams) and standing (ponds and lakes) waters with a relatively low salt concentration. Plants and animals that live on or near the bottom of rivers and streams are known as the *benthic* community. Lakes and ponds contain both a benthic community and an open-water community dominated by the major energy producer, phytoplankton—single-celled algae living in areas of the lake or pond with sufficient light for photosynthesis. Phytoplankton are fed upon by the primary consumer, zooplankton, which are small animals, mostly crustaceans. Lake and pond ecosystems are influenced by *thermoclines*, abrupt changes in the temperature of water with depth that prevents the mixing of the layers of water.

The ocean covers about 71 percent of the Earth, making it larger than all terrestrial biomes combined. The uneven distribution of light and nutrients, coupled with the variation in depth, currents, and shoreline and bottom characteristics, results in many different types of communities and sub-ecosystems. Below 100–200 meters, there is not enough light for photosynthesis, so most deep-water organisms must migrate toward the surface for food or wait for material to descend to them—with an exception being the volcanic vent communities found on the ocean bottom.

A major limiting factor of marine ecosystems is that while light near the surface is sufficient for photosynthesis, the nutrient content of these waters can be quite low. Therefore, species abundance and diversity near the surface is relatively low. In general, the peak species diversity in oceans occurs at depths of about 2,000–3,000 meters, an area of relative stability where descending food material tends to fall. Major exceptions to this general rule are areas in which there are major upwellings (some coastal and open ocean areas where winds blowing across the ocean surface will push some water away and allow nutrient-rich water below to rise to the surface) or coastal waters where nutrients wash in from the land. Most of the world's major fisheries are found in waters near the surface that are mixed with nutrient-rich waters, permitting high levels of productivity and supporting vast species abundance and diversity.

The final types of distinct regions are wetlands, which are transitional areas between the strictly terrestrial and aquatic. Salt marshes, **bogs**, **swamps**, and intertidal areas are examples of wetlands. There are three broad types of wetlands: a *marine wetland* (the intertidal region); an *estuarine wetland*, which is where salt and fresh water mix at the mouths of rivers, and freshwater wetlands, which make up 91 percent of all wetlands in the continental United States. Freshwater wetlands include bogs, marshes, swamps, and peatlands and differ from open waters (lakes, ponds, and rivers) by having water at or near the soil surface for most of the year, but rarely more than two meters deep. Some wetlands, like salt marshes, are highly productive and are important nesting and feeding sites for many animal species, including migratory birds.

THE CYCLE OF ELEMENTS WITHIN THE BIOSPHERE

The Elements on Earth

Carbon, hydrogen, and oxygen are often called the "building blocks of life" because they are the most abundant elements in plants and animals and are important in basic structures such as cell walls and membranes. They are obtained directly from air and water or recycled from other plants and animals. Six other essential elements—nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur—are considered *macronutrients* because they are required in relatively large amounts, usually greater than 0.1 percent of an organism's dry weight. The remaining seven plant-essential elements—manganese, iron, copper, zinc, chloride, molybdenum, and boron—are required in very small quantities and so are called *micronutrients*. While the atmosphere and rocks are the original sources of the nutrient elements, the soil is an important intermediate source for most plants.

Biogeochemical Cycles

Elements continually cycle within the **biosphere** and between the biosphere, soils, and water as plants and animals grow, die, and decompose. Some of these cycles, known collectively as *biogeochemical cycles*, have been altered by human activities that release excess amounts of an element into the atmosphere, soil, or water. These changes can have significant effects on ecosystems, landscapes, and the global system. For example, the release of nitrogen and phosphorus from agricultural fertilizers can result in the over-fertilization of natural ecosystems.

Much attention has been devoted to understanding nutrient cycles for different ecosystems to learn what limits plant growth in a particular landscape or to understand how the anthropogenic addition of certain elements alters natural processes. In this section, we will focus on the cycles of carbon and nitrogen because they are most important to soil fertility and plant productivity; however, cycles for other nutrients, such as phosphorus, potassium, magnesium, calcium, and sulfur, are also important, and their cycles are similar to those of carbon and nitrogen.

One of the main agents responsible for dissolving and transporting the chemical elements necessary for living organisms is water. Before we can understand how individual elements cycle, we need the framework of the **hydrologic cycle**, the movement of water through the atmosphere and over the surface of the Earth.

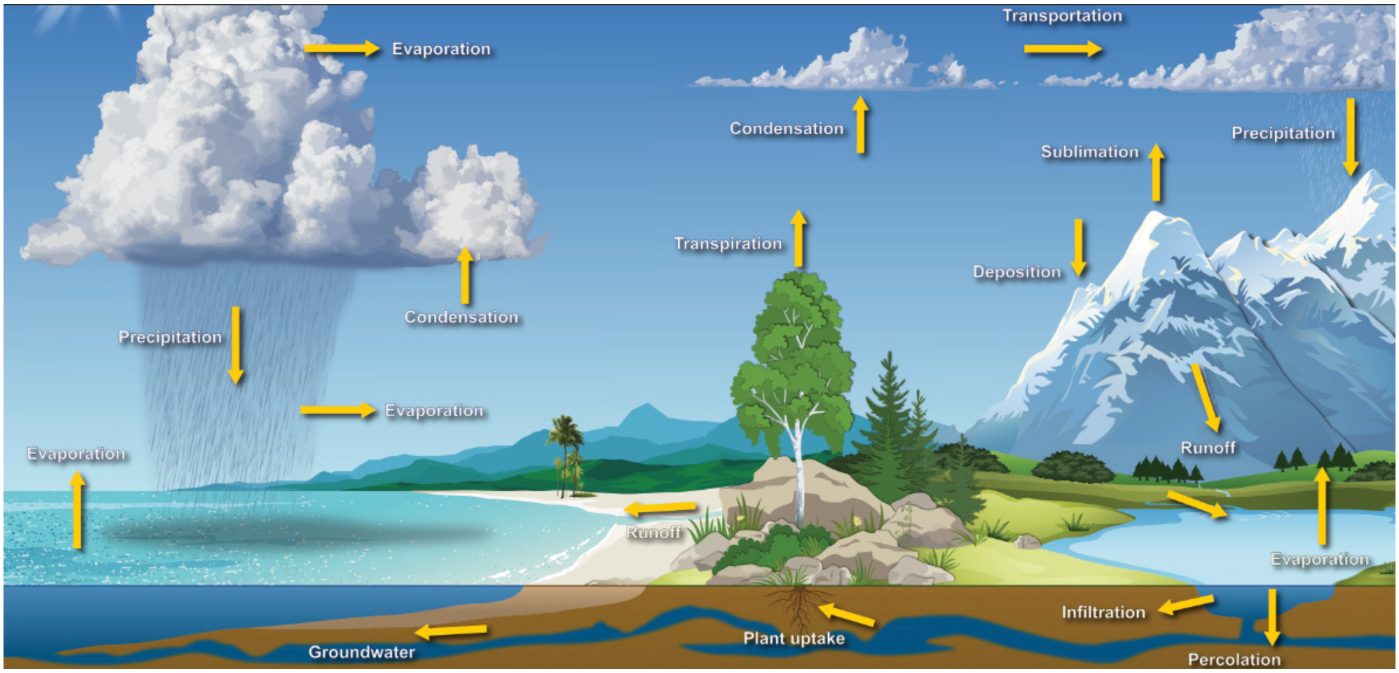
The Hydrologic Cycle

The hydrologic cycle is the driver of biogeochemical cycling on Earth. Water in the atmosphere falls to Earth as rain or snow. When water comes in contact with vegetation or soil, three things may happen to it:

- It may return to the atmosphere by evaporation, or—after being taken up by plant roots—it may return to the atmosphere through **transpiration**, the loss of water from the stomates (openings) in leaves during photosynthesis. The combination of evaporation and transpiration is called *evapotranspiration*.
- It may *infiltrate*, or penetrate, the soil and enter the **groundwater** system, the water that fills the spaces in rocks and sediments below the soil.
- It may move across the land surface in rivers and streams or as *runoff*, rainfall draining from the land into waterbodies or sinking into the soil.

Eventually, streams and groundwater reach the ocean, which is the ultimate reservoir of water on Earth. Water

FIGURE 49



The water cycle.

Source: NOAA

in the ocean evaporates and forms clouds, which can be released as precipitation over the oceans or blown over land, and then the cycle will begin again (Figure 49). Because evaporation from the oceans is crucial to the hydrologic cycle, and energy from the Sun drives evaporation, solar energy is the main energy source for the hydrologic cycle.

We can represent the hydrologic cycle with a simple equation:

$$\mathbf{PRECIP = ET + I + RO}$$

Here, PRECIP = precipitation, ET = evapotranspiration, I = infiltration, and RO = runoff. These four terms are the major components of the hydrologic cycle.

As a way of seeing how the hydrologic cycle moves water on the Earth and the time it takes for this movement to occur, we can look at the cycle in terms of the systems analysis introduced in Section I. The three major pools of water on Earth are the oceans, terrestrial water (water on land or in organisms), and the atmosphere. The oceans are the largest pool of water on Earth, and the greatest fluxes of water occur between the oceans and the atmosphere.

With slash-and-burn agriculture, forests are destroyed to produce short-term agricultural fields.

By mattmangum - Slash and Burn, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=33978429

Recall from Section I that mean residence time (MRT) is the average amount of time a quantity of a variable stays in a given pool. Using approximations for the size of the three pools and flux rates into each pool, the MRT estimates for the three pools are:

MRT (oceans) = 2,650 years
MRT (terrestrial water) = 403 years
MRT (atmosphere) = 8 days

The difference in these MRTs tells us that water in the atmosphere cycles rapidly in comparison to water in the terrestrial pool or oceans. This is important when we study the environment because it means that chemical compounds in the atmosphere, either anthropogenic or natural, are flushed out fairly quickly while compounds remain in the biosphere and oceans much longer.

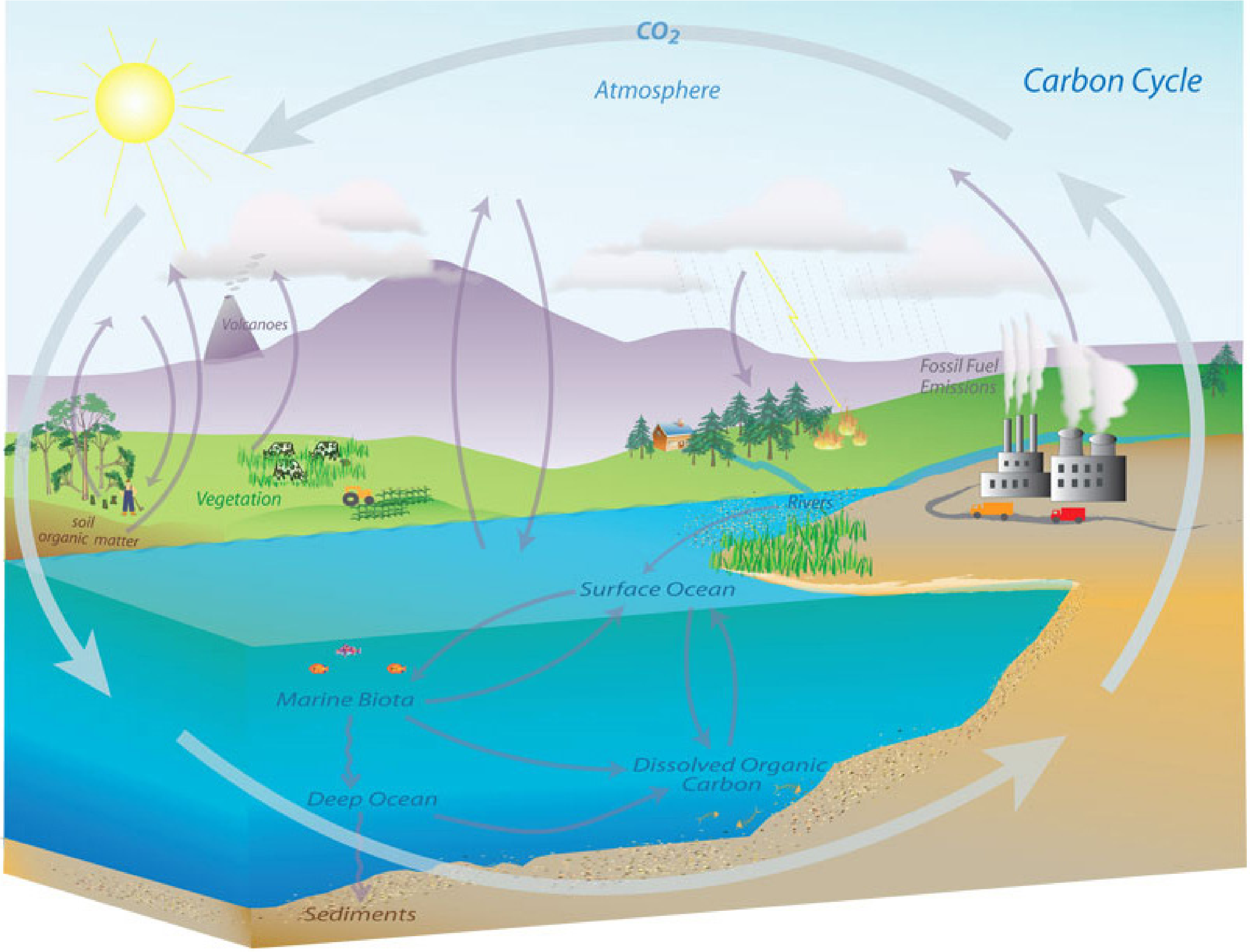
The Carbon Cycle

Four processes run the carbon cycle—photosynthesis, respiration, decomposition, and combustion. (Figure 50) As you have already learned, green plants on land and phytoplankton in the oceans have the ability to convert solar energy into chemical energy that is stored as sugars and other food. To do this, they remove carbon dioxide from the atmosphere (by terrestrial plants) and the ocean (by phytoplankton) and incorporate it into plant material such as leaves, roots, and shoots. This process is called *carbon fixation*.

Plant carbon is returned to the atmosphere when plants respire at night, and when animals and microorganisms, which ultimately derive their nourishment from plants, respire. When organisms die, the carbon that was part of the live biomass pool becomes part of the dead biomass pool and decomposes in the soil or ocean, allowing its carbon and other elements to continue the cycle. A very small fraction of organic matter present in the biosphere gets buried in sediments before it can decompose and can be fossilized and eventually may turn into coal, oil, and **natural gas**. Hence, these compounds are called **fossil fuels**.

Combustion, as occurs in a forest fire or the burning of fossil fuels, releases carbon back into the environment.

FIGURE 50



The carbon cycle.

Source: NOAA

Though respiration and decomposition are biotic processes while combustion is an abiotic process, respiration, decomposition, and combustion are chemically identical processes that break down biomass (abbreviated as generic carbohydrate):

CH_2O	+	O_2	→	CO_2	+	H_2O	+	**energy**
(carbohydrate)		(oxygen)		(carbon dioxide)		(water)		(heat)

The greatest amount of carbon on Earth is tied up in carbonate rock like limestone and organic matter in **sedimentary rocks** such as shale, but this abiotic pool does not cycle very rapidly. There is also a very large pool of carbon stored in the oceans, but it shows only a very small annual net gain. Despite this slow exchange, the chemistry of the oceans is starting to change, and the oceans are becoming more acidic as a result of the extra carbon dioxide in the atmosphere. The movement of carbon between the atmospheric and biospheric pools is the most important path in the carbon cycle because it cycles rapidly. In the absence of human disturbance, the carbon exchange between land plants and soils is in equilibrium with the atmosphere; there is no net flux of carbon between these pools. In other words, in the absence of human activity, the global carbon cycle is approximately in a steady state.

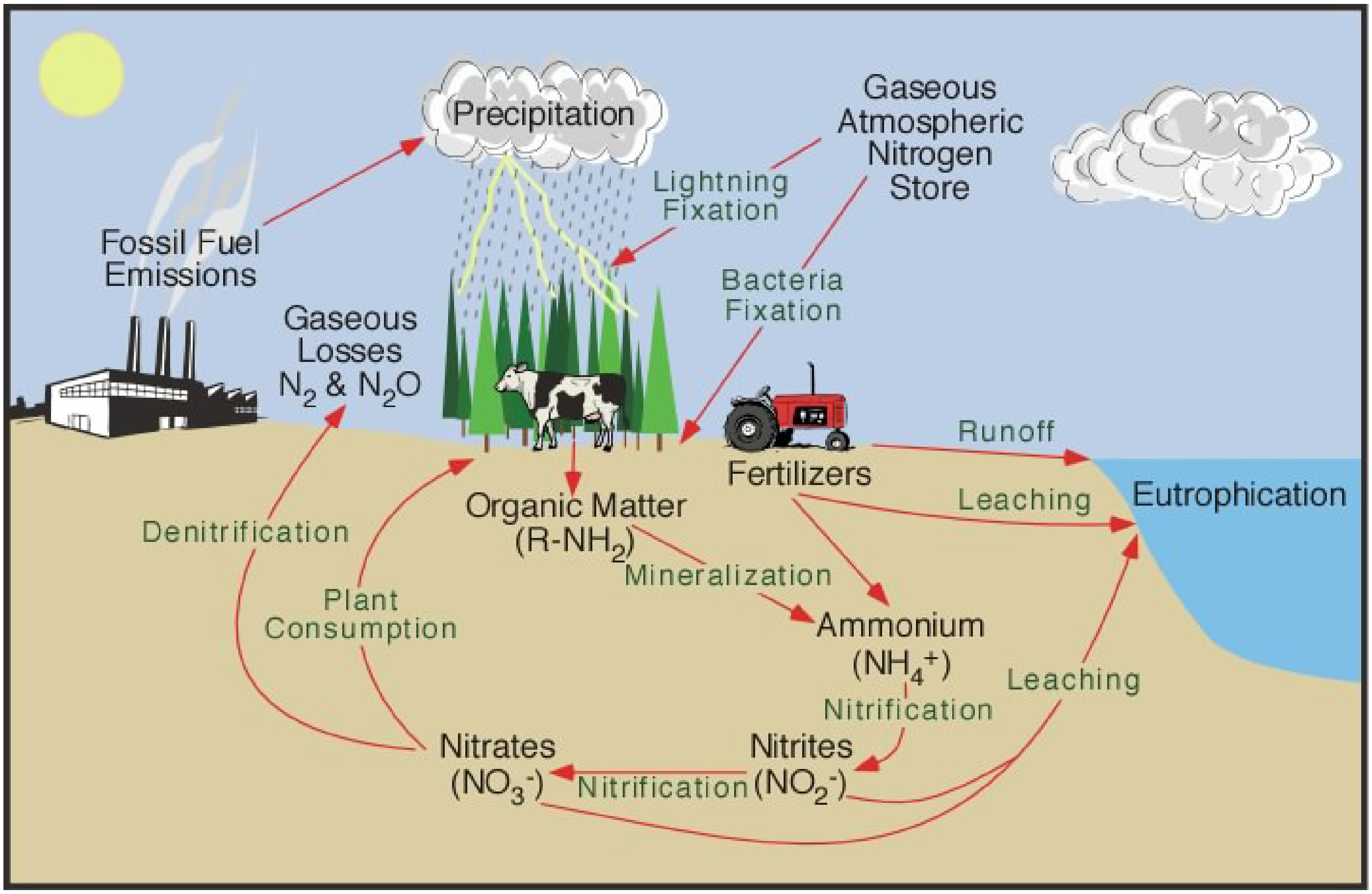
In fact, human activities have a major influence on the amount of carbon cycling at both the ecosystem and global levels. The best known and most significant human alteration of the carbon cycle is the burning of fossil fuels. Every time a person consumes coal, natural gas (methane), oil, gasoline, or other products derived from petroleum, fossil carbon that was not part of the contemporary carbon biogeochemical cycle is released to the environment.

The net destruction of vegetation through cutting and burning without replacement by similar vegetation has also created a steadily increasing amount of carbon moving from the lithosphere (the buried coal, oil, and natural gas) and biosphere to the atmosphere and oceans. Normally, if a forest is cut down and a new forest quickly begins to replace it, the net flux of carbon to the atmosphere is not that great, especially over the course of a few decades. In recent decades, large areas of forest, particularly tropical forest, have been converted to pastures, grassland, and crop lands, and the trees they contained have been burned and not replaced, a practice known as **slash-and-burn agriculture**. In addition to destroying a great deal of biodiversity, the net destruction of forest adds significant amounts of carbon to the atmosphere.

The Nitrogen Cycle

Nitrogen is critical for life on Earth because it is one of the elements in amino acids, which are basic components of all organisms. In terrestrial biomes, the movement of nitrogen from the atmosphere to plants, through many transformations within the soil, and then back into the atmosphere makes the nitrogen cycle one of the more interesting and complex cycles among all the elements. (A similar process occurs in aquatic ecosystems as well.)

FIGURE 51



The nitrogen cycle.

Source: Physicalgeography.net

Of the macronutrients, nitrogen occurs in the highest concentration in plants, and in many terrestrial systems, nitrogen is the limiting element for plants. Although the atmosphere is 78 percent nitrogen, most plants cannot use the dominant form of atmospheric nitrogen, N_2 gas. Only organisms capable of **nitrogen fixation**, the conversion of N_2 gas to a plant-available form, ammonium (NH_4^+), can make *direct* use of atmospheric nitrogen. Cyanobacteria in water and soils and bacteria and fungi associated with certain legumes, such as peas, and certain trees, such as alders, are nitrogen fixers. Virtually all other species must acquire nitrogen from intermediate sources, such as the soil.

Most plants use nitrogen that has already been converted to a mineral form. How does this conversion occur? Atmospheric nitrogen is fixed by lightning and by combustion processes, both natural and anthropogenic, and made immediately available for plant uptake in the form of nitrate anion (NO_3^-). Nitrogen that has been fixed by plants is contained within the organic matter of the plant. When the plant dies, the organic matter undergoes decomposition, and many of its nutrients become available for use as ammonium cation by other plants and microorganisms through a series of chemical transformations facilitated by bacteria.

The conversion of organic matter to ammonium, called **ammonification**, is driven by microorganisms that use the organic matter as a food source and give off ammonium cations. Ammonium is, in turn, converted to nitrite (NO_2^-) and then to nitrate in a two-step process called **nitrification**. Nitrite is of minor importance in natural ecosystems, though it can be toxic to human infants; nitrate, however, is an important plant nutrient.

Nitrate is susceptible to **leaching**—where an element or molecule is washed out of soil by moving water—which occurs in almost all ecosystems. If a site is disturbed, perhaps by logging or other human activities, nitrate leaching can be substantial and can have a significant impact on rivers and streams. A high accumulation of nitrate in wet soils can lead to **denitrification**, the natural conversion of nitrate to the gas nitrous oxide (N_2O), which is emitted to the atmosphere. Since N_2O is a greenhouse gas, denitrification has important implications for the environment. Though denitrification is a natural process, anthropogenic contributions to nitrate leaching can impact denitrification rates.

Because nitrogen is often the limiting element in terrestrial systems, the nitrogen cycle—and in particular, the conversion of organic nitrogen to nitrate—is extremely important in the regulation of net primary productivity and plant growth in many ecosystems. The nitrogen cycle is a complex cycle with significant effects on pollution and productivity.

SECTION II SUMMARY

Evolution and Biodiversity

- The term biodiversity refers to the diversity of all the genes, species, and habitats on Earth. Biodiversity has both instrumental and intrinsic value. Instrumental value is the value placed on things that provide benefits to human beings. Intrinsic value is the value of something for itself, independent of any benefits it might provide to people.
- Ultimately, all biodiversity derives from genetic diversity. Individuals inherit from their parents the genes that make up their unique genotype. Varying combinations of alleles, the alternative forms of genes, create a pool of genetic diversity within a population. An individual's genotype, in most cases interacting with the environment, produces the individual's phenotype.
- Because some alleles dominate over others, some traits may not be expressed even though the individual carries an allele for them. There are four types of genetic diversity: variation within individual organisms, variation among individuals within a population, variation among populations, and variation among species.
- Species diversity results from the divergence of genotypes and phenotypes through the process of evolution. Darwin's theory of natural selection posits that in a population with varying phenotypes, some phenotypes will better enable individuals to survive and reproduce and thereby pass their genes on to

succeeding generations. Adaptation is the process of becoming most fit for a particular environment.

- Evolution also occurs through nonadaptive processes such as gene flow and genetic drift (such as the bottleneck effect). A significant change in a species' genotype can take many hundreds to thousands of years. Human influence can speed the pace of evolution.
- There are approximately 1.8 million "known" (i.e., identified and catalogued) species on Earth today. The actual number of species, while highly debated, is likely to be more than ten times that number. Species diversity is measured as the number of species in a small area, the number of species in a larger area, or the rate of change in the number of species across a geographic range.
- Species that cannot adapt to environmental change will eventually go extinct. The fossil record, the source of our knowledge of species no longer living on Earth, tells us that over geologic time there have been a number of mass extinctions of species. The current extinction rate is commonly measured by estimating habitat loss. There is growing consensus among biologists that the Earth is in the beginning stages of a human-caused mass extinction of species.
- Human-induced changes are usually a threat to biodiversity. Humans can directly remove a species by hunting, fishing, trapping, and harvesting. Humans can also indirectly remove species by altering or fragmenting habitat, introducing exotic species, polluting the environment, or bringing about climate change.

Population and Community Ecology

- Population ecology is the study of the factors that control the abundance and distribution of species. Population ecologists focus on three aspects of populations: 1) Interactions with abiotic environmental factors, particularly environmental conditions; 2) Interactions with other individuals within the population (intraspecific interactions); and 3) Interactions with individuals in populations of other species (interspecific interactions).
- All population regulation factors can be classified as density-dependent or density-independent.
- Density-dependent factors are those whose effects on individuals in a population are directly related to the density of the population. Scarce food resources, for example, will have a greater effect on individuals in a crowded population than on those in a less crowded population.
- Density-independent factors, such as extreme weather, are those whose effects are the same on all members of the population, no matter what the total population size.
- A biological community is the assemblage of all populations in a particular area or habitat, and the study of how these populations interact is community ecology.
- Interactions between populations of different species can function as both density-dependent and density-independent population regulators. Species interact with each other in three general ways: interspecific competition, predation, and mutualism.
- Much of the interaction can be described as a food web, the complex flow of energy from the major photosynthesizing producers (green plants and algae) with herbivores that eat the plants and the predators that eat the herbivores. In most cases, the extinction of one species is not critical to the long-term health of a community; the remaining species at that trophic level, or species from adjacent areas, can provide the necessary links for energy to flow.
- It sometimes happens that the loss of one species, a keystone species, in a community leads to the damage or extinction of the entire community. Even if keystone species are not lost and exotic species are not introduced, communities will not stay the same forever.
- The change of a community over time is just as natural as the evolution of a species. One of the major changes that occurs in virtually every community is succession, the predictable replacement of certain species by others over a number of years.

Ecosystems, Global Cycles, and Biomes

- Ecosystems are specific places on Earth—such as a lake, a forest, a swamp, etc.—that are made up of interacting living (populations) and nonliving (climate, minerals, etc.) components.
- Global biogeochemical cycles of elements and nutrients drive the interaction of an ecosystem's living and nonliving components.
- Global patterns of temperature and moisture are the two most important factors controlling the formation and distribution of the major units of differing vegetation and wildlife types—the biome.
- Changes in temperature and moisture cause variation in the biotic components of a region and variation in the amount of energy available to the region. Environmental scientists have correlated the presence and extent of ten major types of terrestrial biomes with a region's mean annual temperature and mean annual precipitation, ranging from tropical rainforests to the arctic tundra.
- In addition to terrestrial biomes, there are several distinct water systems that are broadly divided between fresh water, from small ponds and wetlands to large lakes and rivers, and marine environments.
- Critical cycles include the hydrologic cycle, the carbon cycle, and the nitrogen cycle; water, carbon and nitrogen are considered the building blocks of life.
- The hydrologic cycle is the movement of water through the atmosphere and over the surface of the Earth.
- The carbon cycle is the movement of carbon compounds through the atmosphere, oceans, and living organisms. Carbon is taken up from the atmosphere and oceans via photosynthesis and is released back into the atmosphere via respiration and decomposition.
- Like carbon, nitrogen is a key component to life on Earth—nitrogen is an essential part of an organism's genetic and protein material. The nitrogen cycle is a set of processes in which nitrogen is converted into different forms as it cycles through the environment. This cycle is driven by microorganism fixation of atmospheric nitrogen and its conversion into a biologically useful form.

Section III

The Human Impact on Natural Resources

THE HUMAN POPULATION

In the previous section of the resource guide, we discussed the factors that regulate population abundance and distribution, with a focus on nonhuman species. We will start this section with a focus on the population whose growing exploitation of global resources is the primary impact on all environmental systems—the human population.

According to the United Nations World Population Prospects, the global human population reached its first 1 billion people in 1804. It then took 123 years for the population to double to 2 billion in 1927. However, from then, human population growth really took off, taking just thirty-two years to reach 3 billion and only thirty-nine more years to double to 6 billion. Then, sometime in November 2022, the United Nations estimated that we hit a population of 8 billion people. However, while from 1974 to 2022 we added 1 billion people to the population every twelve years, it is estimated that it will take approximately fourteen years to reach 9 billion and that the human population may well peak at a little over 10 billion by around 2100, if not sooner. In the first part of this section, we will look at how some of the density-independent and density-dependent factors that we dealt with in the previous section—that control nonhuman population abundance and distribution—also play a factor in human population growth. We will also touch upon some of the human-specific factors that regulate our population growth.

Growth Rate

Technically, the *growth rate* is the percent change that has occurred in a population in a given time period, usually a year. In 1963 the human population of 3.6 billion was growing at 2.1 percent per year; as of 2023, it is estimated to be growing at between 0.83 percent to 0.9 percent.[18] Growth rates are currently decreasing in most countries throughout the world. Because of this decline in growth rates, and despite the greater total number of people in the world today, the number of people added each year is smaller now (roughly 70 million additional people per year) than when the growth rate was 2.1 percent and there were 3.6 billion people (76 million additional people per year).

Four factors define the growth rate of a country or continent: births, deaths, *immigration* (the number of people who migrate into a country), and *emigration* (the number of people who migrate out of a country). The growth rate equals all the additions to the population minus all the subtractions from the population, divided by the total number in the population. This can be represented as:

$$\frac{(\text{births} + \text{immigration}) - (\text{deaths} + \text{emigration})}{\text{the total population}}\ 100 = \%\text{GR}$$

So, a village with 300 people that in one year had 10 births, 3 migrations, 4 deaths, and 2 emigrations has a growth rate of

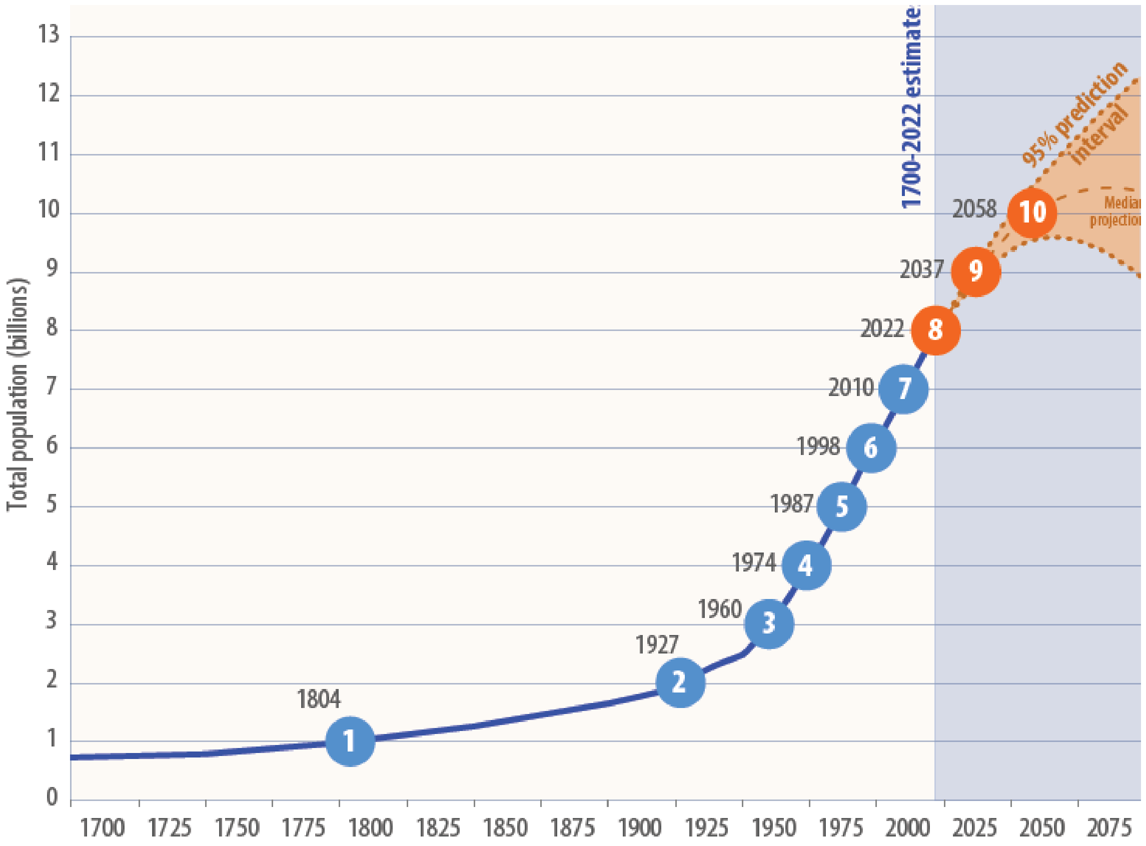
$$[(10 + 3) - (4 + 2)]/300 \approx .02$$

To obtain the growth rate as a percent, you multiply by 100 ≈ 2%

Migration and emigration are important when analyzing an individual country—for example, migration has

FIGURE 52

Global population size: estimates for 1700-2022 and projections for 2022-2100



Source: United Nations, DESA, Population Division (2022). World Population Prospects 2022.

Note: The solid blue line is the estimates from 1700 to today, the dotted red line the projection for the future up to 2100, and the dashed red line the upper and lower bounds of the 95% prediction interval for the projections.

Global human population growth from 1700 to the present and beyond.

Source: United Nations, DESA, Population Division

accounted for up to one-third of the population increases in the United States in some years. When we consider the entire world, because the numbers are so large, the human birth rate is normally expressed as the number of births per 1,000 individuals per year. This figure is often called the *crude birth rate* (CBR) because it is the crudest, or most basic, measure of birth rate. The number of deaths per 1,000 individuals in the population per year is the *crude death rate* (CDR). If we exclude migration, then the growth rate can be calculated based on the birth rate and death rate alone:

$$\frac{\text{CBR}-\text{CDR}}{10} = \%\text{GR}$$

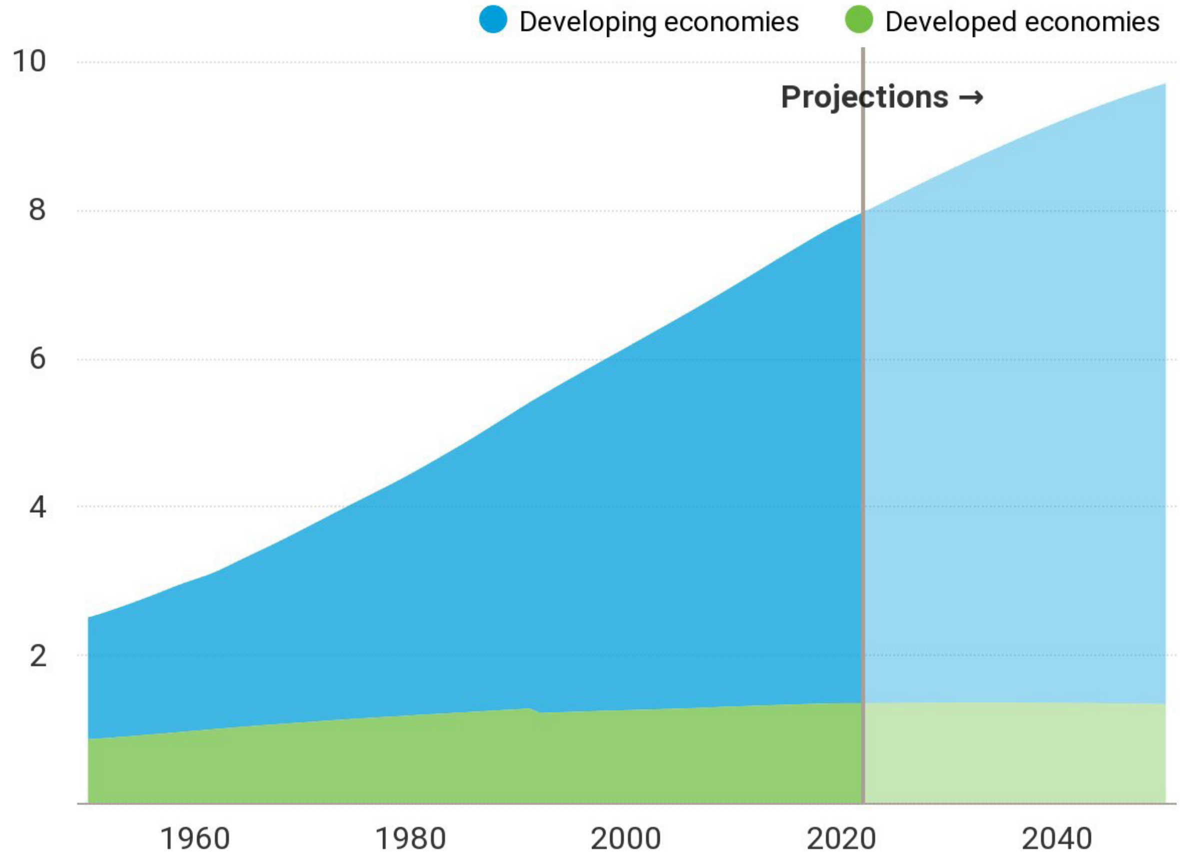
Here we divide by 10 because the CBR and CDR are expressed per 1,000 people in the population. To refer to the growth rate as a percentage (per 100 people), we must adjust the numbers accordingly.

The most effective way to see the changes that take place in growth rates over time is to plot the birth rate and death rate versus time for a given country. By looking at the difference between the two, it is possible to see the change in the growth rate on a year-to-year basis. If the birth rate is above the death rate, the country will experience positive growth. The greater the distance between the birth and death rates, the greater the positive growth rate. If there is no difference between birth and death rates, then there is no growth.

Lower- and Higher-Income Countries

Of the 8 billion human inhabitants on Earth today, 1.3 billion live in **higher-income countries** (Europe, North America, etc.), and 6.7 billion live in **lower-income countries**, those countries that haven't yet or are currently industrializing—in which we will include China and India for now. The population difference between more- and **less-developed countries** has not always been so large. In recent decades, populations in parts of the world, particularly sub-Saharan Africa, have continued to grow rapidly (an average of 1.5 percent per year) while population growth rates in the higher-income countries have almost leveled off (an average of 0.2 percent per year).

FIGURE 53



Source: UNCTADstat based on UN DESA Population Division, World Population Prospects 2022.
Note: The graph provides estimates from 1950 to 2021 and projections from 2022 to 2050 of total population

Population growth divergence: high- versus lower-income countries.

Source: United Nations Conference on Trade and Development (UNCTAD), based on United Nations Department of Economic and Social Affairs World Population Prospects 2022

Population Size and Resource Use

Every one of the eight billion people on Earth eats, drinks, and generates waste products. Provision of even the most basic foods, such as beans or rice, requires energy, water, and mineral resources. To raise beef or catch fish from far offshore requires even greater expenditures. Further, despite differences around the world, people generate a huge demand for wood, paper, plastic, steel, and energy to make homes, automobiles, and consumer products and to give and receive services. The mining and extraction, processing, use, and disposal of all these materials contribute to **environmental degradation**.

The overall impacts of 8 billion people are hard to appreciate and even more difficult to quantify. The following equation can be used to estimate environmental impact:

Energy use is a good indicator of the overall environmental impact of population growth. The larger the human population, the greater the consumption of fossil fuels.

By Walter Siegmund (talk) - Own work, CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=3413544

Environmental Impact = Population X Resource Use Per Person X Impact of the Resource Used

Energy use is one good indicator of overall environmental impact. In 1960, when the population was 3 billion, world fossil fuel consumption was almost 3,000 million tons of oil equivalents. In 1999, world fossil fuel use was 7,900 million tons of oil equivalents. While the population doubled, the use of fossil fuels more than doubled. And in 2022, our now 8 billion people used approximately 11,500 million tons of oil equivalents, continuing to increase at a rate greater than the human population. The consumption of fossil fuel has numerous environmental impacts, including land and water degradation from extraction and air pollution and carbon dioxide emissions resulting from combustion, so we can safely assume that environmental impacts increased considerably during this time.

Factors Affecting Population Growth

If we want to predict future trends in the human population, it is important to identify the factors that have caused the human population to grow slowly at times and quickly at other times.

FIGURE 54

Crude Birth Rate (CBR) = Total number of live births per 1,000 in population per year

Crude Death Rate (CDR) = Total number of deaths per 1,000 in population per year

Growth Rate (GR; also called the Rate of Natural Increase) = percent population growth per year = ((Yr 2 − Yr 1)/ Yr 1) × 100 or (CBR−CDR)/10

Total Fertility Rate (TFR) = Average number of children born to a woman during her child-bearing years

Doubling Time (Tdouble) = Time in years for population to double at current growth rate

Infant Mortality (IM) = Number of infants per 1,000 live births who die before first birthday

Life Expectancy (LM) = Average expected lifespan of an infant born in a given year
%<15/>65 = Percent of population below age 15/above age 65

Factors that affect population growth—terms and brief definitions.

Source: United Nations Conference on Trade and Development (UNCTAD), based on United Nations Department of Economic and Social Affairs World Population Prospects 2022

Fertility

We can consider the human population as a system comprising a pool of 6 billion people with births as inputs and deaths as outputs. In any given time period, the number of births in a population is dependent on the number of individuals in the population and the birth rate, and the number of deaths is dependent on the number of individuals in the population and the death rate.

In the United States, the total fertility rate (an estimate of the average number of children that will be born to each woman in the population throughout her child-bearing years) today is 1.84, which means that, on average, each woman of child-bearing age will have a little less than two children. As you would expect, the growth rate of a population and the total fertility rate correlate with one another; when we compare a number of countries, those with higher growth rates usually have higher total fertility rates.

Infant mortality, the number of deaths of infants (children under age one) per one thousand live births, together with life expectancy, can provide an accurate representation of health care in a given country.

By Kimberly Vardeman - CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=85075306

The **replacement fertility rate** is the number of children each woman must have on average to replace the current population. Replacement level fertility is usually 2.1: a total of 2.1 children, on average, are needed to replace two parents because some children never reproduce. Therefore, the United States is below replacement level fertility. Based on that statistic alone, we would expect the population in the United States to decrease over time. However, we must also consider immigration (remember the equation at the beginning of this section), which is projected to add almost one million people per year to the population of the United States as well as the individuals in the population that are not yet reproductively mature who will soon begin to contribute to the birth rate.

Life Expectancy and Infant Mortality

Life expectancy is the average number of years that an infant born in a given year can be expected to live, given the current average lifespan and the death rate. Life expectancy is often reported for the overall population of a country and for males and females within the population. In almost every situation, the life expectancy for men is shorter than that for women, reflecting greater hardships and dangers generally experienced by men in the workplace and different lifestyle choices. The gap between life expectancy for men and women is decreasing as more and more women enter the workforce. *Infant mortality* is the number of deaths of infants (children under age one) per one thousand live births.

Life expectancy and infant mortality together usually provide an accurate representation of the level of health care in a given country. If life expectancy is fairly high and infant mortality is fairly low, it is likely that the country has a relatively high level of health care. Note that crude death rate is *not* a good indicator of health care. Even with a high life expectancy and a low infant mortality, a country could have a high crude death rate because it has a large number of older individuals. For example, the United States has a higher crude death rate (9) than Mexico (5), which is a reflection of an older population in the U.S. than in Mexico.

Over a dozen developed countries have lower infant mortality rates than the United States, including Canada, Finland, Iceland, Ireland, Japan, Sweden, and France. What accounts for a U.S. infant mortality rate that is one to two deaths per thousand greater than other comparable countries, many of which spend less per capita on health care? Universal health care and more generous allowances for time off during the later stages of pregnancy are two reasons. The large disparity in the level of health care provided to Black Americans, Hispanics, Native Americans. and other minorities in the United States relative to whites is also a factor. The infant mortality rate for the entire

U.S. population is 5.4, but for Black Americans in the U.S., it is 10.4 and for Native Americans, 8.2.[19]

In addition to having less access to health care, less prenatal care, and poorer nutrition, minorities and lower socioeconomic groups are also disproportionately exposed to pollutants, which contribute to higher infant mortality and poor health.

Japan is one of a number of countries with negative population growth, and so its elderly population is larger than younger age groups.

Photo by Issei Kato

Age Structure

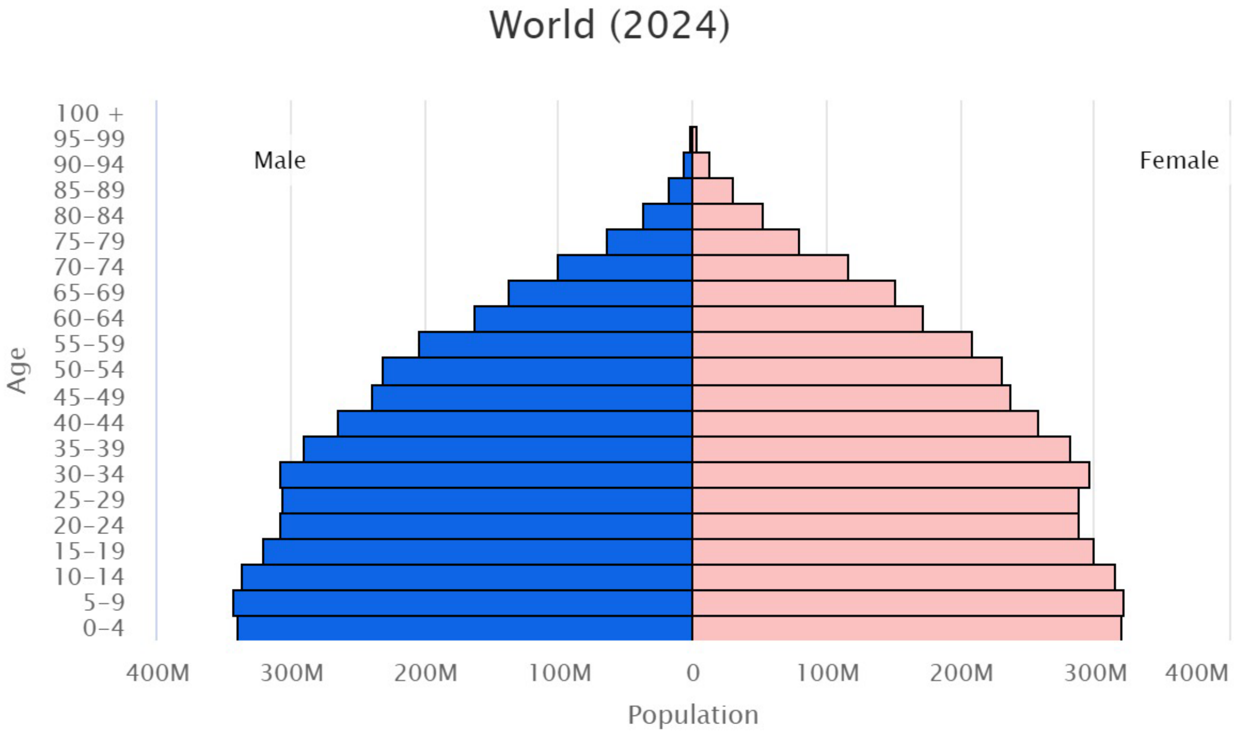
One method for assessing the age distribution of a population is to look at the percentage of the population under the age of fifteen and the percentage over sixty-five. Commonly reported as *%<15/%>65*, this value shows us the relative age distribution in a country. For example, the %<15/%>65 for Mexico is 24/8 while the value for the U.S. is 18/18.[20] This tells you that 24 percent of the population in Mexico is under age fifteen while in the U.S. 18 percent is under age fifteen. Eighteen percent of the population in the U.S. is over sixty-five; only 8 percent of the population in Mexico is over sixty-five. However, compared with other countries, Mexico's age structure is actually relatively close to that of the U.S. In Nigeria, part of the sub-Saharan region that is experiencing the highest population growth rates, 41 percent of the population is under fifteen years of age, while only 3.3 percent is over sixty-five!

In order to understand the potential environmental impact of a country, it is important to know how many young people there are and will be in the population. How many potential consumers of soft drinks or "fast fashion" will there be? How many potential drivers of automobiles or bicycles? How many future parents of more consumers? The %<15/% > 65 figure can give us some idea of the distribution of ages, but we don't know how many people are just about to turn sixty-five, or how many people are in their child-bearing years, having just moved out of the <15 category. How can we determine what a population will look like in ten or fifty years?

The most common procedure is to divide the population into different age groups by gender (all males between zero and five years, all females between zero and five years, all males between six and ten, etc.). When the population pattern is graphed, it produces a diagram showing the structure of each age group, and hence this is called an **age-structure diagram**. A brief examination of an age-structure diagram for a country can give an educated observer an idea of the growth and fertility rates, life expectancy, and even the consumption patterns of a particular country.

Though each country has a unique age-structure diagram, we can group countries very broadly into three categories. A country with an age-structure diagram that is widest at the bottom and smallest at the top has many more younger people than older people. This means its total fertility rate must be somewhat greater than the replacement level of 2.1 children per pair of adults, and its growth rate is positive. It is this type of age structure that has led to a common alternative term for an age-structure diagram: *population pyramid*. The pyramid pattern occurs in growing less developed countries—those that have growth rates of 2–3.5 percent. Figure 56 shows an age-structure diagram for Uganda, but Nigeria, Ghana, Haiti, and many other countries also display this pattern. As long as the youngest age group is larger than the age group above it, and that next group is larger than the next one above it, the population is a growing population. In a country where there are slightly more individuals in the younger age groups than in the older age groups, the age-structure diagram begins to look more like a column than a pyramid. Such a country is still growing, but at a relatively slow growth rate, and it could be called a stable population.

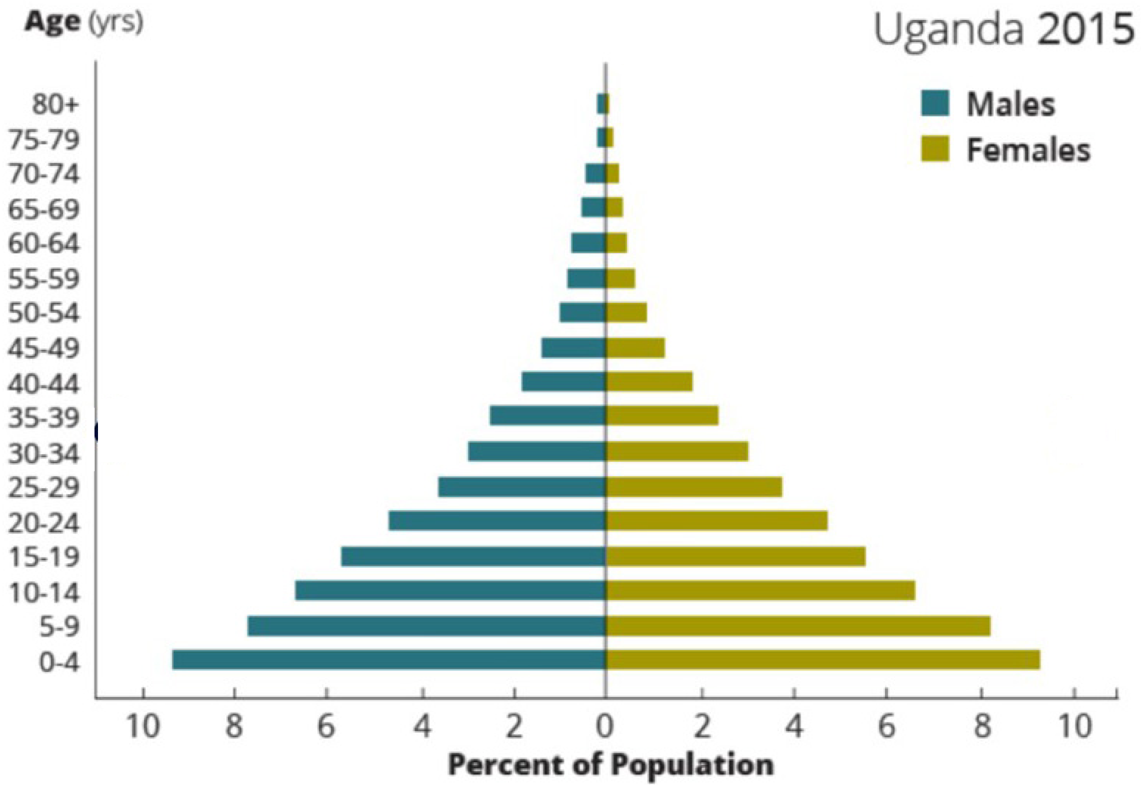
FIGURE 55



The global age-structure diagram (population pyramid) for 2024.

Source: U.S. Census Bureau

FIGURE 56

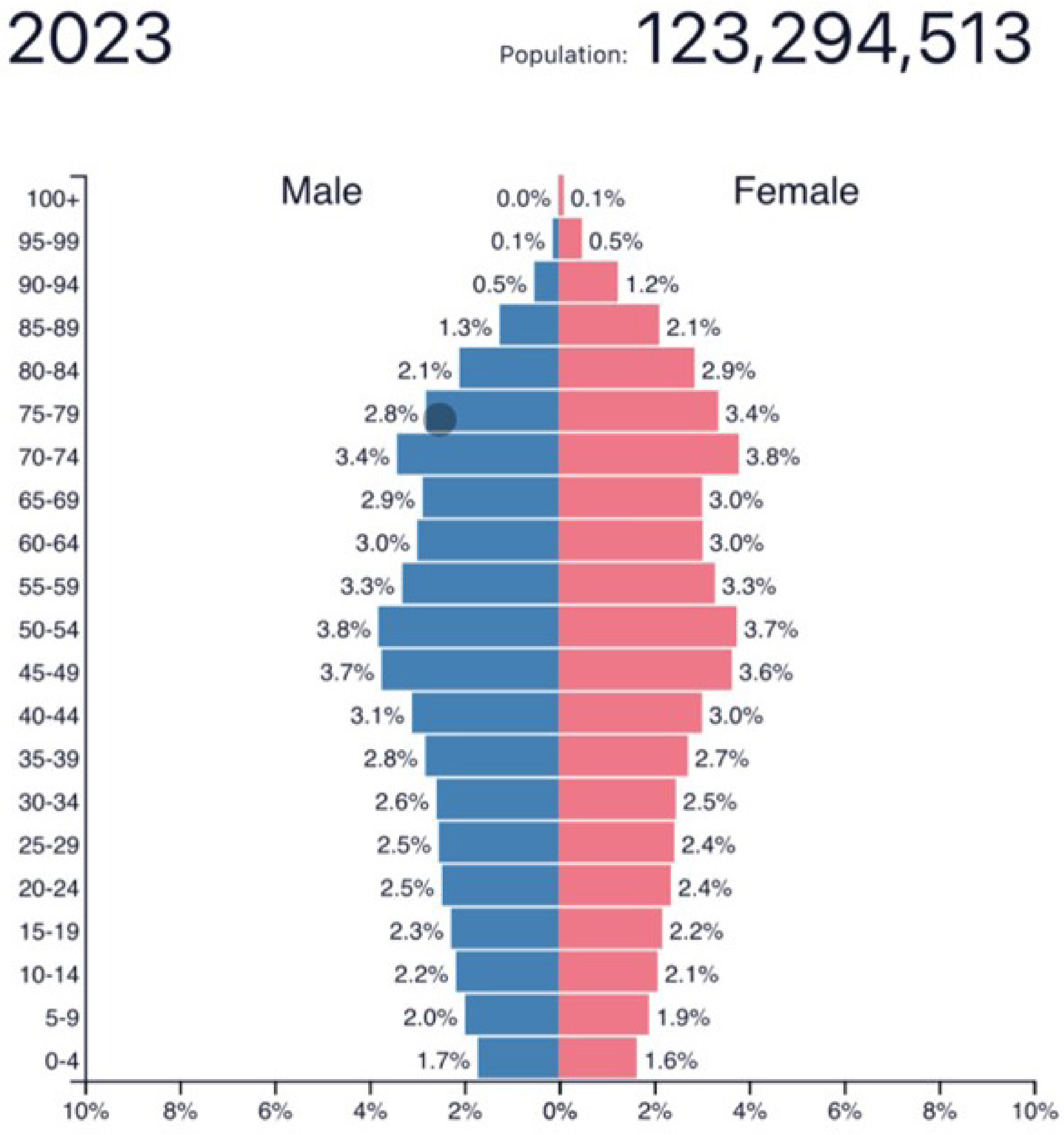


Population pyramid for Uganda—note the large proportion of young people.

Source: Demographic Dividend

Finally, some countries display negative growth—that is, they are shrinking in size, and so their total fertility rates must be below 2.1. Each successively older age group is larger than the age group preceding it. With time, this pattern will tend to an inverse pyramid (Figure 57). Italy, Japan, Germany, and a number of other countries display this pattern.

FIGURE 57



Population pyramid for Japan—indicative of an aging population.

Source: PopulatioPyramid.net

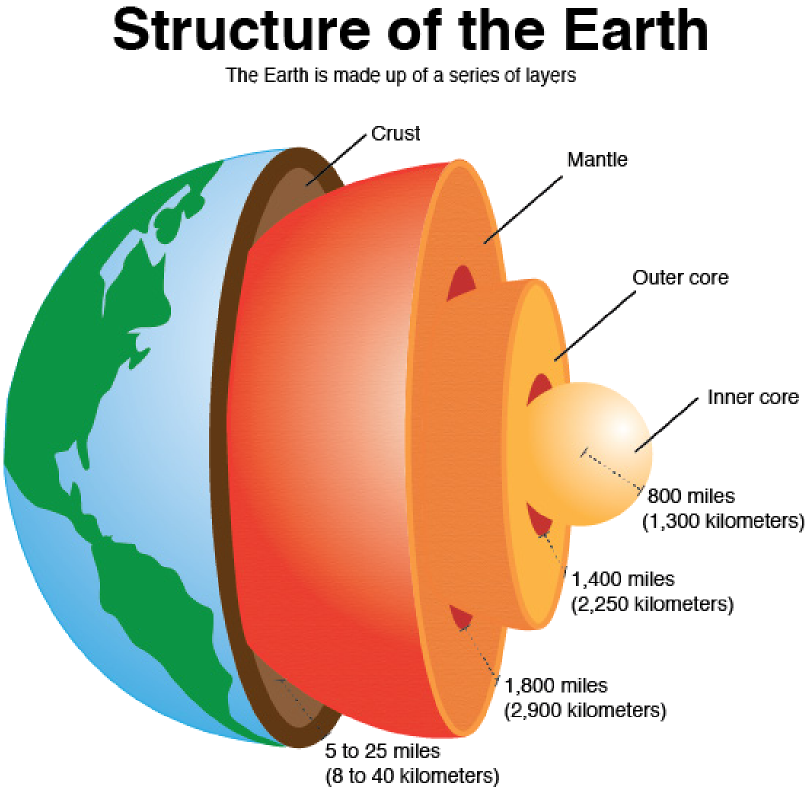
THE ELEMENTS ON EARTH

Weathering (physical or chemical breakdown) degrades mineral rock so that the elements are released, while erosion transports the elements via water and wind.

The elements found on Earth today are as old as the Earth itself. The Earth formed roughly 4.6 billion years ago, and within 500 million years, it had heated up to the point where there was much molten rock on Earth. Heavy elements in that material sank toward the center of the planet while lighter elements rose upward or remained close to the surface, where they stayed after the Earth cooled. This differentiation of material by its density resulted in the formation of three distinct layers to our planet: the dense inner **core**; the **mantle**, which makes up 80 percent of the volume of the Earth; and the lighter **crust** on the top (Figure 58).

Elements are not uniformly distributed due to the movement of heavy elements away from the Earth's surface and the movement of lighter elements toward the surface. For example, although the whole Earth is 35 percent iron (a heavy element), only 6 percent of the **lithosphere** (the crust and the topmost part of the mantle) is iron. The rocks, sand, and soil that form the rocky shell of the Earth are found in the approximately 100-km-thick lithosphere, where rocks undergo change over time through the *rock cycle* (Figure 59).

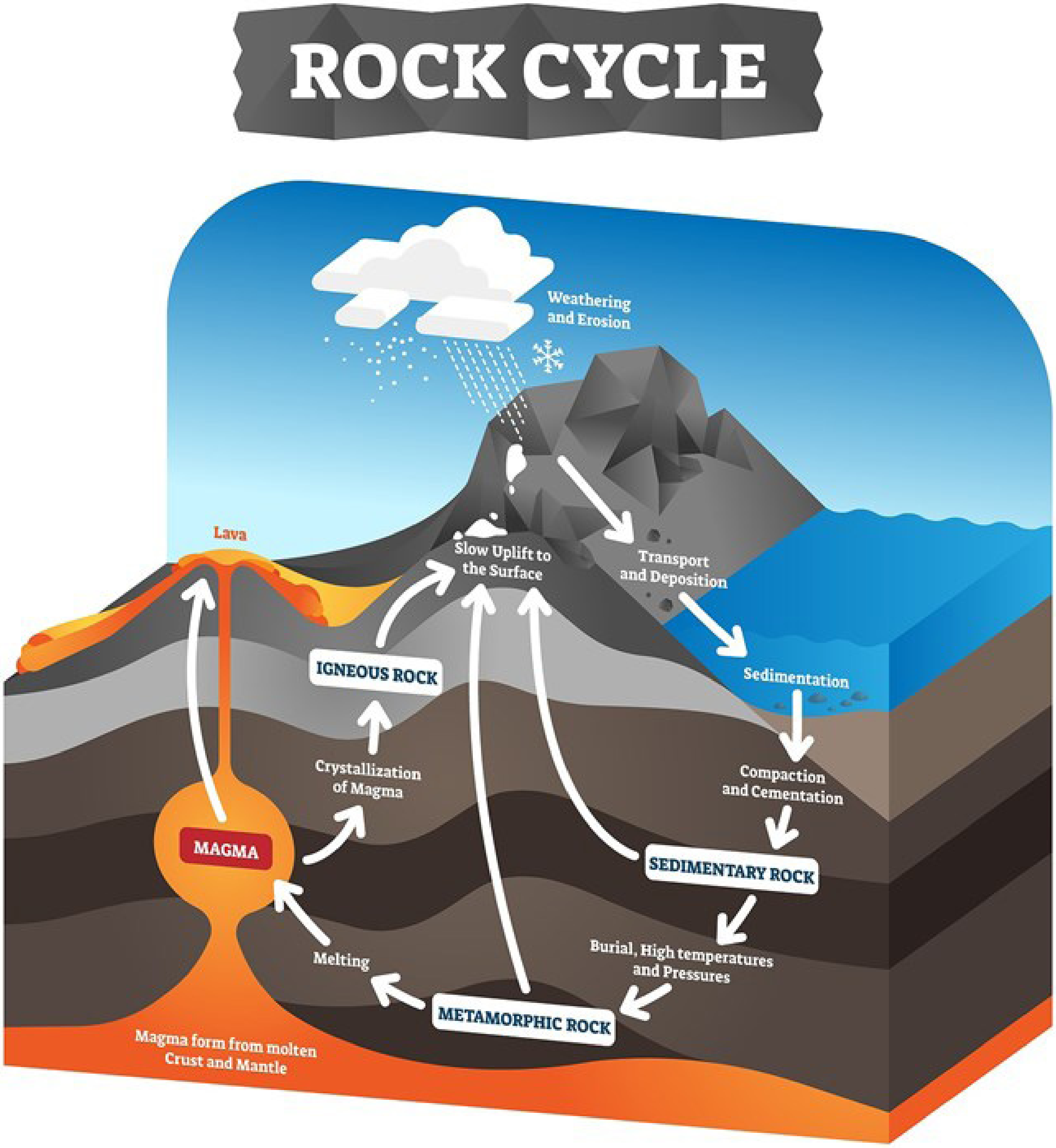
FIGURE 58



The layers of the Earth.

Source: GeologyScience

FIGURE 59



The rock cycle.

Source: USGS

The lithosphere is one of the two primary sources of elements for the biosphere; the other major source is the atmosphere, where the elements exist in gaseous form. The three most abundant gases in the atmosphere are nitrogen (78 percent), oxygen (21 percent), and argon (0.9 percent). Carbon dioxide (0.036 percent) is a trace gas. Carbon, hydrogen, and oxygen are often called the “building blocks of life” because they are the most abundant elements in plants and animals and are important in basic structures such as cell walls and membranes. They are obtained directly from air and water or recycled from other plants and animals.

Six other essential elements—nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur—are considered macronutrients because they are required in relatively large amounts, usually greater than 0.1 percent of an organism's dry weight. The remaining seven plant-essential elements—manganese, iron, copper, zinc, molybdenum, cobalt, and boron—are required in very small quantities and so are called micronutrients. Plants require the sixteen plant-essential elements in slightly varying proportions depending on the individual species. While the atmosphere and rocks are the original sources of the nutrient elements, the soil is an important intermediate source for most plants.

The "dust bowls" of the 1920s and 1930s in the western part of the United States were the source of large amounts of calcium and magnesium that were carried by the prevailing westerly winds and deposited in the central and eastern states.

In order to obtain the nutrients they need, plants take up elements in ionic form. All plant-essential elements (and many other elements as well) have an *aqueous phase*; in other words, they have one chemical form that is soluble in water. *Soil water*, the water in the pore spaces between soil particles, facilitates the exchange of dissolved elements (elements in their aqueous phase) between soil and plant roots.

In addition to moving water itself, the hydrologic cycle (see Section II) is instrumental in the movement of chemical elements. **Weathering** (physical or chemical breakdown) degrades mineral rock so that the elements are released, while **erosion** transports the elements via water and wind. In their aqueous phase, elements are then mobilized by the hydrologic cycle and carried to the oceans or taken up by plants and animals on land. Weathering of rock can be accomplished by water, wind, acid rain, other chemicals, and even the roots of growing plants.

The Cycles of Calcium, Magnesium, Potassium, and Sulfur

Calcium, magnesium, and potassium are derived primarily from rocks and decomposed vegetation. Calcium and magnesium can occur in very high concentrations in limestone, dolomitic limestone, and marble. Calcium and magnesium are often quite abundant in ecosystems overlying limestone and some other rock types. Calcium and magnesium are also a large component of terrestrial dust, so airborne dust deposition often translocates large amounts of these elements. The "dust bowls" of the 1920s and 1930s in the western part of the United States were the source of large amounts of calcium and magnesium that were carried by the prevailing westerly winds and deposited in the central and eastern states. Heat, drought, and wind, coupled with poor agricultural practices and other human land use that caused the destruction of the natural topsoil were the causes of the dustbowl. Calcium and magnesium combine with organic compounds and do not leach easily. However, potassium is susceptible to leaching from plant tissue and soils, so it may be more easily lost from systems than tightly held elements like phosphorus.

The sulfur cycle is similar to the nitrogen cycle in a number of ways. Sulfur has a gaseous component to its cycle, sulfur dioxide (SO_2). Plants take up sulfur from the soil primarily as the sulfate anion (SO_4^{2-}). Anthropogenic deposition of sulfur is even greater than the deposition of nitrogen, although clean air regulations have lowered sulfur deposition significantly in the United States since 1995, as we will see in Section IV. Sulfate is the second ion, along with nitrate, that comprises acid rain. Sulfate is also easily leached from soils and ecosystems. One major difference between the sulfur and nitrogen cycles is that there is a pool of sulfur in rocks and minerals. Volcanic emissions are a natural atmospheric source of sulfur.

SOIL

What Is Soil?

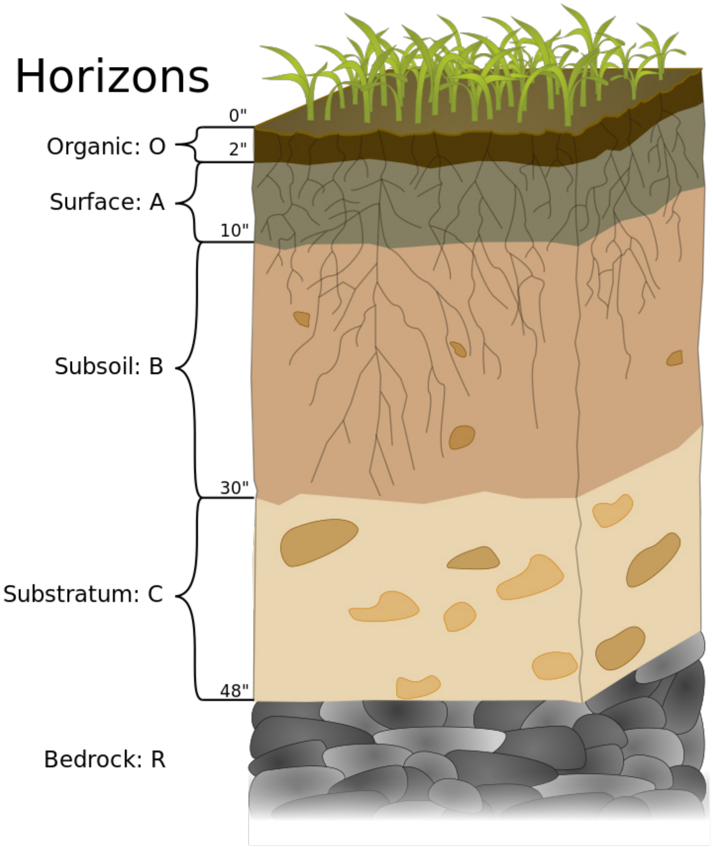
The various soils on Earth form a dynamic membrane that covers much of the land surface, connecting the overlying biology to the underlying geology. They also serve a number of functions that benefit animals, plants, ecosystems, and human beings:

- Soils are a medium for plant growth.
- Soils serve as the primary filter of water as it moves from the atmosphere into rivers, streams, and the groundwater system beneath most land surfaces.
- Soils are the habitat for a wide variety of living organisms from bacteria and fungi to insects and other animals and thus contribute greatly to the biodiversity of an ecosystem. In combination, soil organisms act as organic matter recyclers, taking dead plant and animal material and using it as an energy source. In the process, they break down the organic material and release mineral nutrients and other materials that benefit plants.
- Soils and the organisms within them filter chemical elements deposited from air pollution and sewage from household waste systems, retaining some and releasing some to the atmosphere above or groundwater below.

Soil Horizons

Although we aren't usually aware of it as we move over the ground beneath our feet, soils vary across a landscape, sometimes differing within only a few meters. A typical soil has three or more *horizons*, or layers categorized by their physical, chemical, and biological properties (Figure 60). The top layer of soil is usually the *A horizon*, which is a zone of both organic material (**humus**) and mineral (rock-derived) soil that have been mixed together. The mixing can be done naturally, by organisms such as earthworms and plant roots, or by human activity, such as plowing. In forests, the top layer of soil is the *O* (for *organic*) *horizon*, which is comprised of needles, leaves, woody material, and animal bodies or droppings in various stages of decomposition.

FIGURE 60



Soil Horizons

Source: Wikipedia

Sometimes an *E horizon* forms under the O or A horizon. The E horizon is characterized largely by what is *not* in it: most of the chemical elements have leached out, and the remaining soil is light in color. Chemical elements from the E and the overlying O and A horizons are normally leached to the *B horizon*, where they accumulate along with elements that have undergone weathering in place. In contrast to the E horizon, which occurs only in more acidic soils, all soils have a B horizon, which is the horizon where clay, iron, and aluminum (and other compounds) accumulate after being leached out of the A horizon by rain.

The *C horizon*, the least weathered soil horizon, always occurs beneath the B horizon. The C horizon is similar to the *parent material*, the rocky material from which the soil is derived. In humid regions, the C horizon may contain some plant roots and microorganisms but normally these extend only to the bottom of the B horizon.

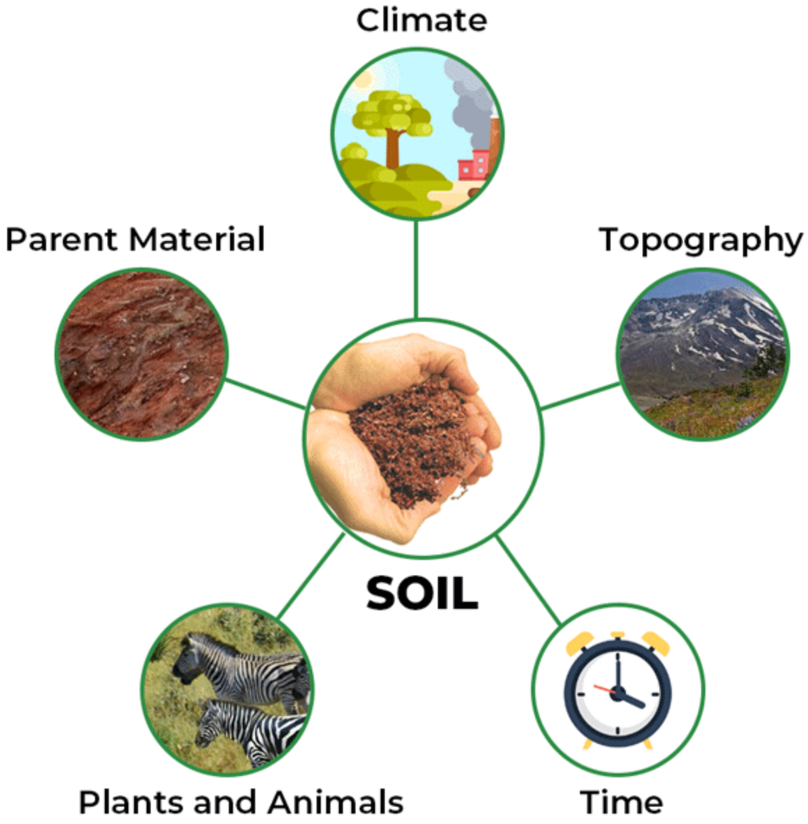
The different vegetation you see in the different biomes on Earth is in large part dependent on the varying proportion and composition of the soil horizons in those ecosystems. The presence or absence and size of different soil horizons can influence what kind of activities may occur in a given ecosystem, and they may also influence how effectively a soil will retain or release pollution deposited on it.

State Variables and Soil Formation

Soils form in two directions simultaneously. The breakdown of rocks and minerals provides the raw material for soils from underneath. The deposition of organic matter from vegetation and animals contributes to soil formation from above. Except in organic soils, such as the type that forms in bogs, the quantity of organic matter in a soil is normally quite low (only a few percent). However, organic matter greatly affects many soil properties.

Five so-called *state variables* (important factors that cause a soil to progress from an initial state) determine the nature of soils: *parent material*, *climate*, and *topography*, as modified by *organisms* over *time*.

FIGURE 61



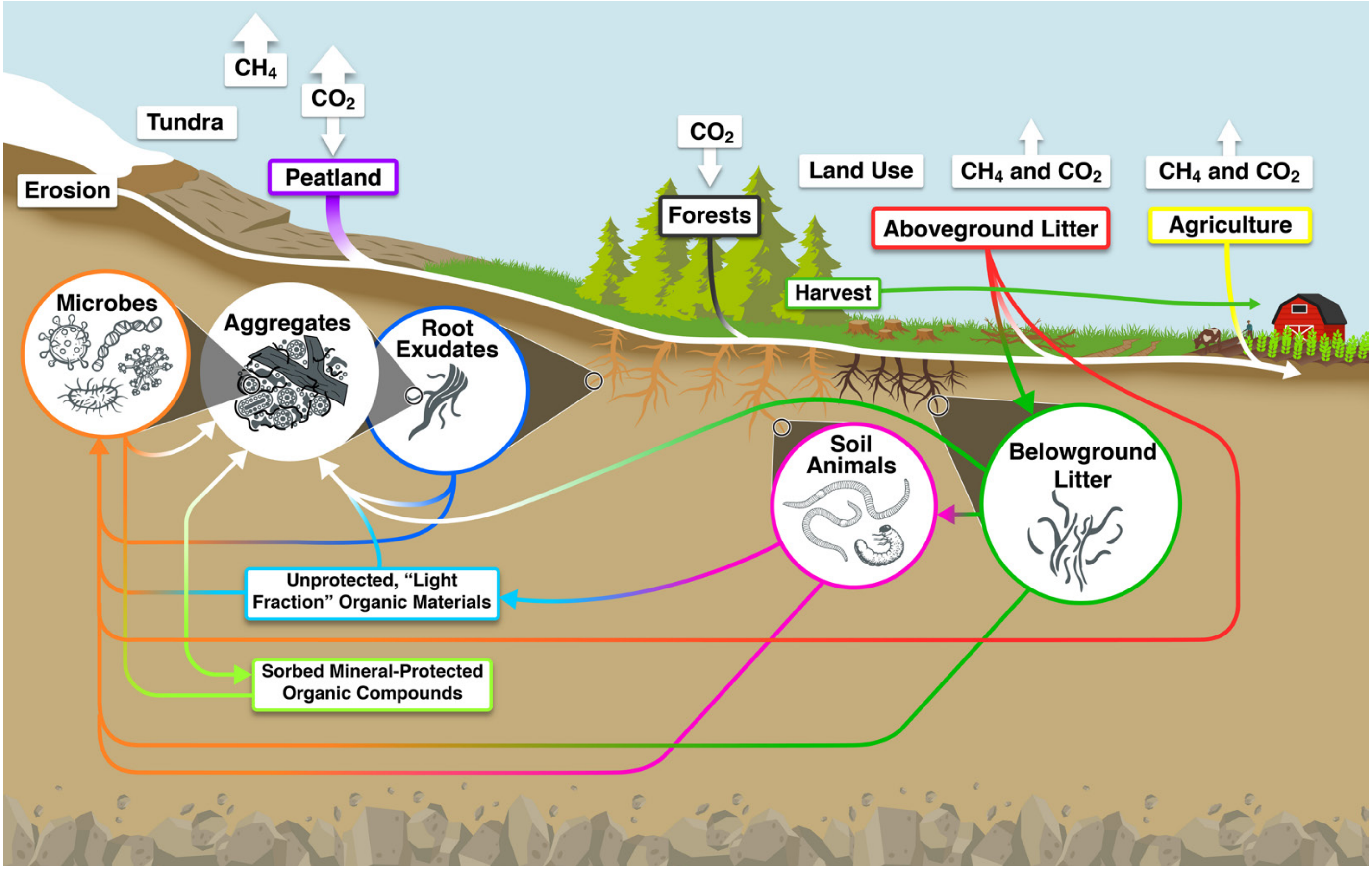
The five state variables of soil formation.

Parent material consists of slightly altered rocks and/or minerals that are immediately below the soil. *Bedrock* is the solid rock underlying the soil. Bedrock and parent material are sometimes synonymous, but they can be different. For example, if glaciers have spread a layer of rock and sediment over bedrock, then the parent material may be different from the bedrock. The parent material is representative of what the upper horizons may have been before they were altered by chemical and physical weathering and biological activity. Different kinds of soils will arise from different parent materials. For example, a quartz sand parent material will give rise to a soil that is relatively nutrient poor, as in most areas along the Atlantic coast of the United States. By contrast, a soil that has calcium carbonate as a parent material will contain an abundant supply of calcium—as in the area surrounding Lake Champlain in northern New York and Vermont—and support a high level of agricultural activity.

In terms of its influence on soil formation, *climate* is the sum of weather-related variables over a long period of time. The average temperature of a region is extremely important in soil formation, as higher temperatures will speed up weathering and other soil-forming processes. In addition, the more a soil freezes and thaws, the more mechanical breakage of rocks and minerals will take place, which creates new rock surfaces for chemical weathering. Precipitation—which is also a major cause of weathering—and temperature both influence how much leaching occurs. The more water that moves through a soil, the more leaching will occur, and warm tropical soils generally experience more leaching than cooler soils. Climate also has an indirect effect on soil formation by its influence on the type of vegetation that develops and the rate at which the vegetation decomposes after it dies.

Topography, or the surface configuration of a landscape, is a third influence on soil formation. Soils that form on steep slopes are constantly subjected to erosion and, on occasion, more drastic mass movement of material such

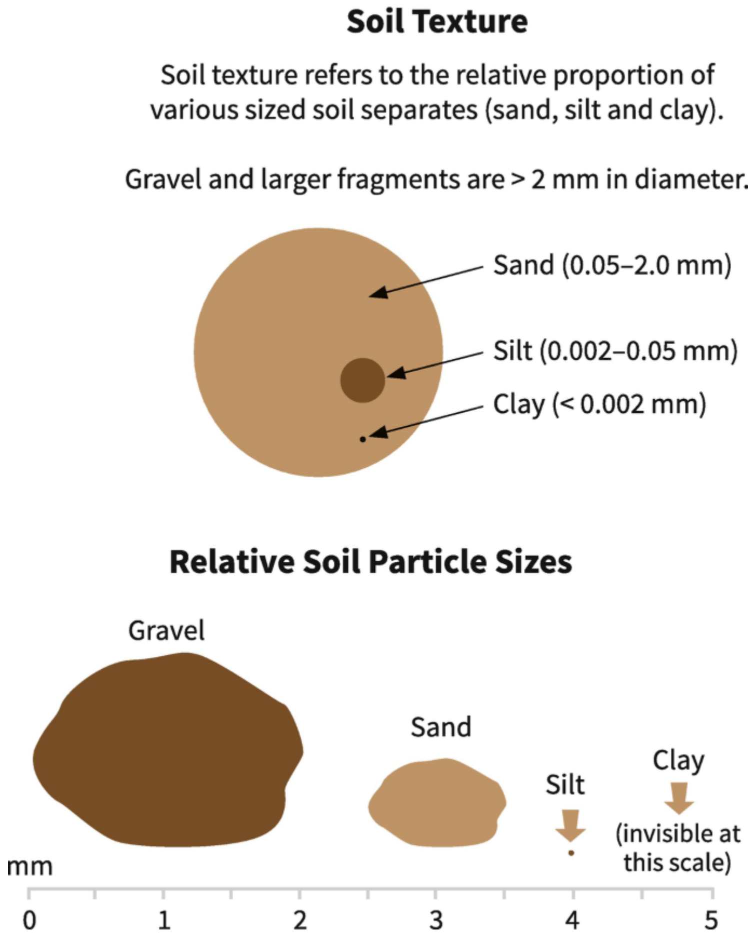
FIGURE 62



Soil organisms process plant litter in the soil and are responsible for the release of CO_2 and CH_4 (methane).

Source: SOCCR2

FIGURE 63



Soil particles are classified by size. Particle size affects the amount of water that can be absorbed and used by plants and animals.

as landslides. Soils that are subject to landslides are potential hazards for humans who live on or near them, and ecosystems in such areas are disturbed at frequent intervals. Despite these well-known dangers, people continue to build on such soils—often quite expensive structures—and seem surprised when they are destroyed. Soils that are relatively horizontal will have a greater chance to accumulate and retain material, and soils that form at the bottom of steep slopes may continually accumulate material from higher elevations. Soils on the windward side of a mountain may experience higher rates of water deposition from precipitation than those on the leeward side.

A diverse group of *organisms* populates the soil ecosystem. Three groups of organisms account for 80 to 90 percent of the biological activity in soils: fungi, bacteria/archaea, and protozoa (single-cell organisms, including algae). These organisms use live and dead plant material and some animal wastes (detritus) for energy and contribute to the breakdown of organic matter. Some soil organisms are herbivores that eat live plant roots as well as above-ground parts of plants. However, the majority of soil organisms are detritivores, consuming dead plant and animal tissue. A grassland meadow may have ten times the mass of soil detritivores as herbivores in the first fifteen centimeters of soil. Bacteria play roles in a variety of activities in soil such as the liberation of nitrogen or sulfur from organic matter, allowing the material to be used by higher plants.

In the temperate zone, the most important *macrofauna*, or large (relatively speaking) animals, in soils are earthworms, which can ingest a quantity of soil weighing two to thirty times their own weight each day. Earthworms greatly enhance soil nutrient status. Since they only partially digest what they ingest, their excretions contain a fair amount of nutrient-rich organic matter, which is available to plants. By their movement through the soil, earthworms aerate the soil, improve water drainage, and mix upper layers with lower layers. Most earthworm species are sensitive to acidic soils and do best in moist habitats that are approximately pH neutral.

Finally, *time* is an important influence on soils. The length of time a soil has existed in an unfrozen state influences the amount of soil development that will occur. New soils usually have undergone very little separation into different horizons. As soils age, they develop horizons and a variety of characteristics. The grassland soils that support much of the food and livestock feed produced in the United States are relatively old soils. Due to the hundreds of thousands of years of soil formation they've experienced, they've developed thick A and B horizons with a large supply of nutrients. Landslides, glaciers, volcanic eruptions, and other catastrophic events can set a soil clock back to the beginning, when there was bare rock.

The five state variables, working on physical, chemical, and biological factors, lead to the formation of different soils within ecosystems and across landscapes. Soils in the United States are classified into different types, depending on factors like the presence, absence, and thickness of the various horizons describe above, and by soil particle size.

Soil Degradation

For centuries, the use and abuse of land for agriculture, forestry, and other human activities has led to significant *soil degradation*, the loss of some or all of the soil's ability to support plants. One of the major causes of soil degradation is erosion, which occurs when *topsoil* (O and A horizons) is disturbed, for example by plowing, and then carried away by water or wind. Topsoil can be lost in a single growing season, yet it takes centuries to replace. **Compaction** from machines, nutrient depletion from intensive use of the land, irrigation, and chemical damage from the application of pesticides are also contributing factors. Soil degradation from various factors has become more widespread in recent decades; worldwide, it has led to at least a 17 percent reduction in food production and is most prevalent in Africa and Europe.

The projected impact of global climate change on soils is varied. In some locations, slightly warmer temperatures may increase decomposition activity and increase nutrient availability. In other locations, soils will become too dry, and decomposition will slow. There is no general pattern that can be described worldwide or even for a given continent. There has also been much speculation on how global climate change might affect carbon storage in soils, but again, no general patterns are certain.

Sometimes, physical and chemical additions can be made to improve the quality of a soil, but generally, once a soil has been degraded it takes many years of natural processes to restore it to its original state. Soils in zones of moderate temperatures and precipitation will probably be restored more rapidly than soils in zones with extreme amounts of moisture or extreme temperatures.

WATER RESOURCES

The Long-standing Challenge of Accessing Clean Water

The ancient Romans are almost as famous for their aqueducts as they are for their roads. The impetus for building such an elaborate system of pipes and supporting structures to transport water over long distances is less well known: water pollution. Ancient Rome was very congested, and streets were used not only as passageways, but also as waste receptacles and sewers. The local springs and shallow wells that supplied residents of Rome with water soon became polluted. In addition, according to Sextus Julius Frontinus, a Roman water commissioner whose writings have survived, the Tiber River, which was used as the first major source of water in Rome, was not protected and received too much wastewater, thereby becoming contaminated and losing its value as a water source. As a result, it became necessary to bring clean water in from farther away. The demand for aqueducts was present by the year 312 BCE, when the first Roman aqueduct was constructed. Some of the aqueducts extended for more than 60 km. By 19 BCE, there were more than 400 km of aqueducts throughout the Roman Empire.

The Romans foreshadowed not only our current reliance on water transported over long distances, but also many

Water pollution motivated the Ancient Romans to build an elaborate system of aqueducts, pipes, and supporting structures to transport water over long distances.

of our contemporary water pollution problems. There are reports of Roman aqueduct water containing too much sediment, so settling basins were constructed to allow the sediment to settle out. Archaeologists have found aqueducts leading to the Roman Forum that were made of lead. When water travels through a lead pipe, some of the lead from the pipe goes into solution, thereby increasing the lead concentration of the water. It has been hypothesized that the decline of the aristocracy in the Roman empire was due to the neurotoxicological impacts of lead poisoning (although wine that was stored for long periods in lead vessels was perhaps a more significant factor than water from lead pipes). And Frontinus may have been the first to consider the use of gray water (wastewater that does not contain sewage), explaining that "it was. . . determined to separate them all and then to arrange so that [one of the aqueducts] should serve wholly for drinking purposes, and that the others should be used for purposes adapted to their special qualities. For example, Old Anio [aqueduct] should be used for watering the gardens, and for the more dirty uses of the city; because the further from its source its waters are drawn, the less wholesome they are."

Many of the problems experienced during the Roman Empire still exist in modern societies. In this section, we will look at where we get our water, how we pollute it, and how we are attempting to safeguard our water supplies in the present and for the future. A law passed in ancient Rome—"No one shall with malice pollute the waters"—is a mandate that is as true today as it was then.

Water's Importance to Earth's Environmental and Human Systems

We can see how water fits into Earth's environmental systems by thinking back to the hydrologic cycle that we discussed in Section II of this guide. Though water covers 75 percent of Earth's surface, surprisingly little of it is available for our use. The oceans are the largest repository for water, so virtually all the water on Earth is saltwater. Only about 3 percent of total water is fresh water, and most of that is tied up in glaciers and icecaps; only a little more than 1 percent of all water on Earth is potentially usable by humans and other terrestrial organisms. Fresh water is the primary subject of our discussion in this section.

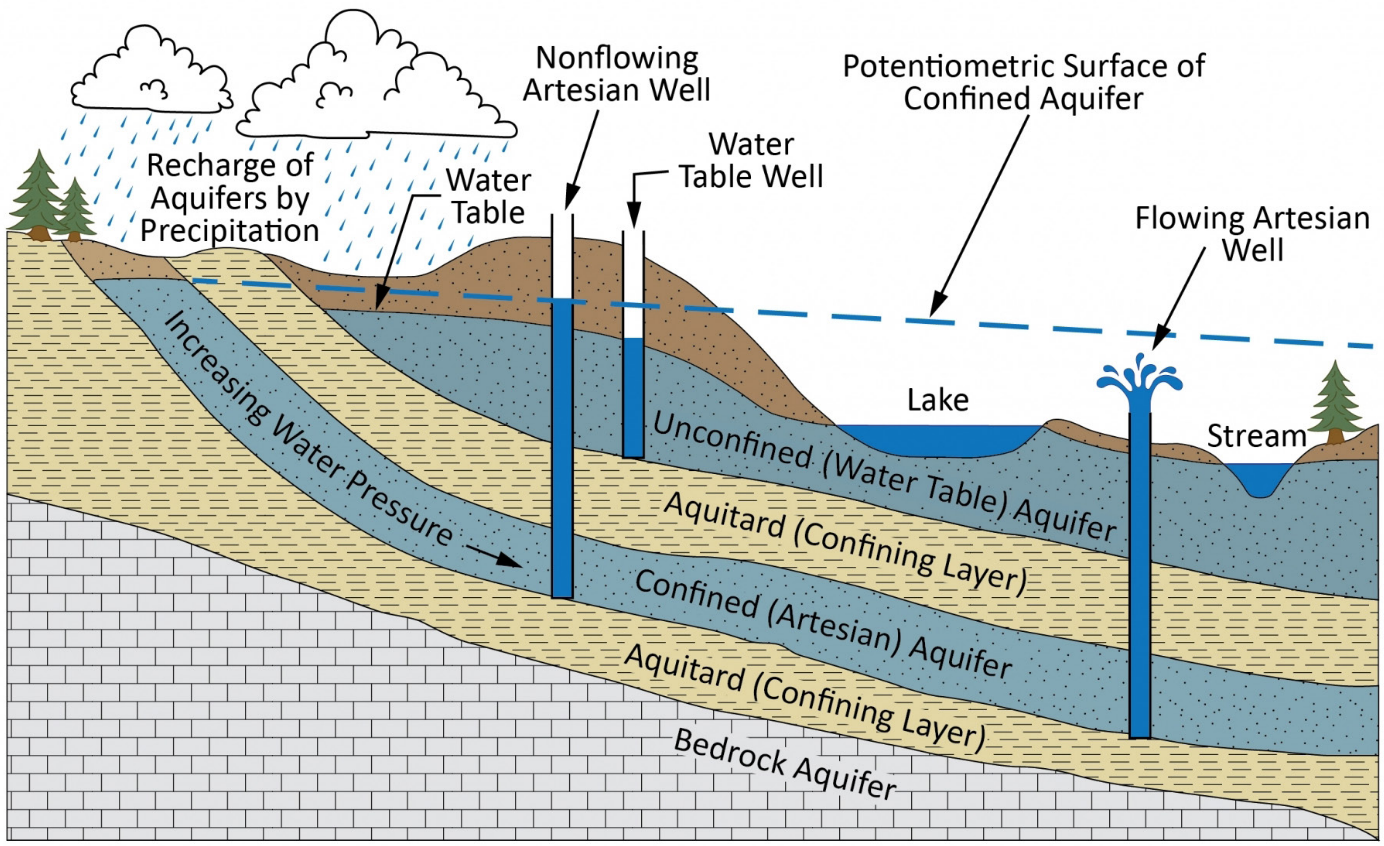
Most of Earth's fresh water is contained underground. Lakes, rivers, and reservoirs, which supply more than half the drinking water in the United States, comprise only 0.009 percent of the water on Earth. There is even less water (perhaps 0.001 percent) tied up in the atmosphere and even less than that (0.0001 percent) contained within organisms. Of course, water moves between these different compartments, and at any given time, there might be slightly more or less water in any compartment. Nevertheless, these proportions demonstrate how little of the water on Earth is accessible.

Groundwater and Surface Water

Groundwater comprises all water that is below the ground in **aquifers**, permeable layers of rock and sediment that hold water. Water enters the groundwater system through infiltration of precipitation and discharge of rivers and streams. It usually stays in an aquifer indefinitely unless human interference disrupts it, or some kind of tectonic activity shifts the orientation of the aquifer so that the water flows due to gravity. Some aquifers intermittently flow into streams, rivers, or the ocean. It is possible to extract water from an aquifer by drilling a hole into it (called a well), much like drilling into an oil reserve, and pumping the water out.

The most basic aquifer is porous rock such as sandstone or other consolidated sediments, covered simply by soil. Water fills up the pore space within the rock, forming what is known as an *unconfined aquifer* because it is not constrained on the top by any confining rock. The part of the aquifer that is filled with water is called the saturated zone, the top of which is the *water table*. In some cases, an underground layer of impermeable clay may act as an impenetrable barrier, called an *aquiclude*, that impedes the flow of groundwater from the aquifer. Groundwater confined above and below by an aquiclude is a *confined aquifer*. A well drilled into a confined aquifer is called an *artesian well*. Water flows spontaneously from an artesian well without the need for pumping. An unconfined aquifer gets charged or recharged—in other words, receives new water—when water infiltrates through the soil.

FIGURE 64



Groundwater and aquifers.

Source: Utah Geological Survey

Surface water is all the water on the surface of the Earth, including lakes, ponds, streams, rivers, and constructed and natural reservoirs. (Oceans are also surface water but as we are considering specifically fresh water here, we will not include them in this discussion.) Most surface water originates as precipitation from the atmosphere. Some bodies of surface water, however, are fed by groundwater. A spring, for instance, is a small stream that just "springs up" out of the aquifer to the surface during wet times of the year. Because surface water receives little or no filtration (unlike groundwater), it is highly vulnerable to contamination.

Transport of Water

Do you know where your water comes from? If you live in an urban area, chances are good that, just as in the ancient Rome, it comes from a distant location. Though transporting water may ensure its cleanliness or solve problems of inadequate local supply, long-distance transport introduces problems of its own. Construction of an aqueduct in a desert or grassland environment introduces many of the same habitat fragmentation problems that occur when roads are built: vegetation is disrupted, soils are disturbed, and animal habitats are altered or destroyed. Even if an aqueduct is buried as an underground pipeline, a great deal of disruption occurs during the construction process. And once an aqueduct or pipeline is constructed, the pipes will degrade over time.

In Jordan and the Occupied Territories of Israel, for example, perhaps as much as 55 percent of water carried through aqueducts is lost as a result of leakage from old or damaged pipes.

Desalination plants remove salt from naturally salty water, usually via distillation or reverse osmosis.

Desalination

One of the ways that water-scarce countries get their fresh water is through *desalination*, the removal of salt from naturally salty water, usually sea water. Countries of the Middle East and North Africa are responsible for more than 50 percent of the fresh water produced worldwide through desalination technology. Most desalination is achieved through distillation or reverse osmosis. In *distillation*, water is evaporated by boiling, leaving behind salts. The steam produced is condensed, yielding pure water. The disadvantage of distillation is that energy is required to boil the water and then condense it. *Reverse osmosis* is a newer technology that is more efficient and often less costly than distillation although the amount of energy used is still significant. In reverse osmosis, water is forced through a thin membrane at a very high pressure. The water that passes through the membrane is very pure; the water left behind, called *brine*, has a salt concentration greater than seawater. The brine is usually pumped back into the ocean where it can adversely impact local marine ecosystems by increasing salt content and depleting oxygen levels.

Water Use

In 2023, the 334 million people in the United States used a total of 408 billion gallons of water each day, or an average of approximately 1,300 gallons per person per day. This includes all direct and indirect use of water including domestic use (inside and outside homes), commercial and municipal use, irrigation, and water for cooling in electrical power plants. Water use in just about every other country in the world is lower.

Worldwide, approximately 40 percent of food production benefits from irrigation. It takes roughly a thousand tons of water (250,000 gallons) to produce one ton of grain. Depending on where and how the irrigation is implemented, a large fraction of that water can be lost to evaporation. Conventional irrigation, in which water runs through a ditch alongside a row of crops, is only about 60 percent efficient. Drip irrigation, in which a tube buried in the ground releases water slowly, can be up to 95 percent efficient, but it requires large investments of capital, which often are not feasible for farmers that are barely making a living already.

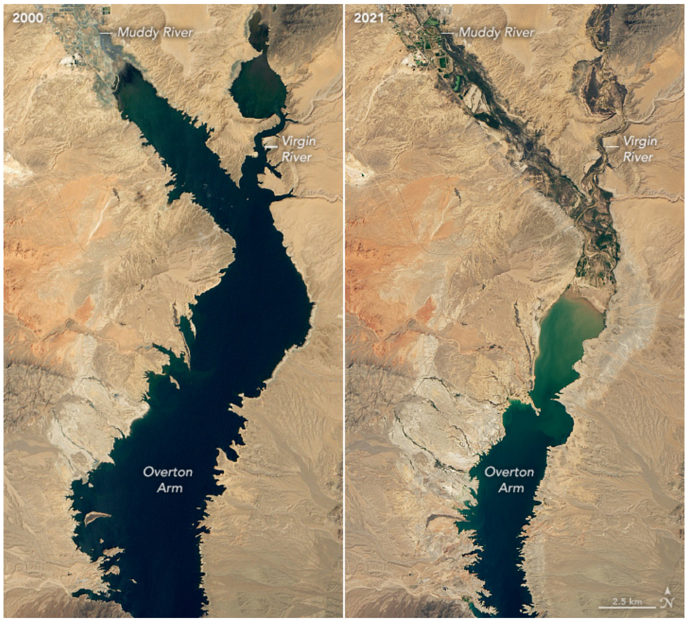
Other agricultural uses—livestock and fish farming—are relatively small consumers of water in the United States, as are mining and industry. The relative amounts of water used in all categories have not changed much over the last two decades. Water impounded for hydroelectricity generation is not included in any of the U.S. Geological Survey's use categories because it is ultimately discharged in the same location it would have gone to before **impoundment** and is therefore not "used up."

Water Shortages

In many parts of the world, drought—an extended period of limited precipitation—caused by either natural climatic change or human activity is a common occurrence, often of disastrous proportions—such as the ongoing drought in the Horn of Africa that has impacted Ethiopia, Kenya, Sudan and other East African countries since 2020. Beyond the immediate cost to human life and livestock, drought has long-term effects on the land. Prolonged droughts will desiccate the soil to such an extent that the topsoil (the O and A horizons) blows away in the wind. Once the fertile topsoil is lost, the land may be useless for agriculture for decades. Land that has become severely parched is also subject to erosion from flooding when sudden heavy rain falls on earth that can no longer absorb large quantities of water in a short time.

Most aquifers contain some water even during the longest droughts, though aquifers that are heavily pumped sometimes go dry during extremely severe droughts. If at any time an aquifer is pumped more rapidly than it is recharged—in other words, if output exceeds input—the water supply may be depleted. And even if an aquifer contains plenty of water, certain sections of it can become over-pumped, leading to local water shortages, usually manifested by one or more wells going dry.

The irrigation of cropland is responsible for the over-pumping of aquifers in many countries. In the U.S., the best-known case of groundwater depletion is occurring in the Ogallala Aquifer, which ranges from Texas and New Mexico up to South Dakota. Over-pumping a well can also result in a reduction of water quality in that well; if a well adjacent to a coastline is drawn down, the nearby saltwater will be drawn toward the aquifer, and over time the well water will become saltier, a process known as saltwater intrusion. This is common in a number of coastal areas.



These aerial photos of Lake Mead show the dramatic decline in water in the nation's largest reservoir.

Photo: NASA

Floods

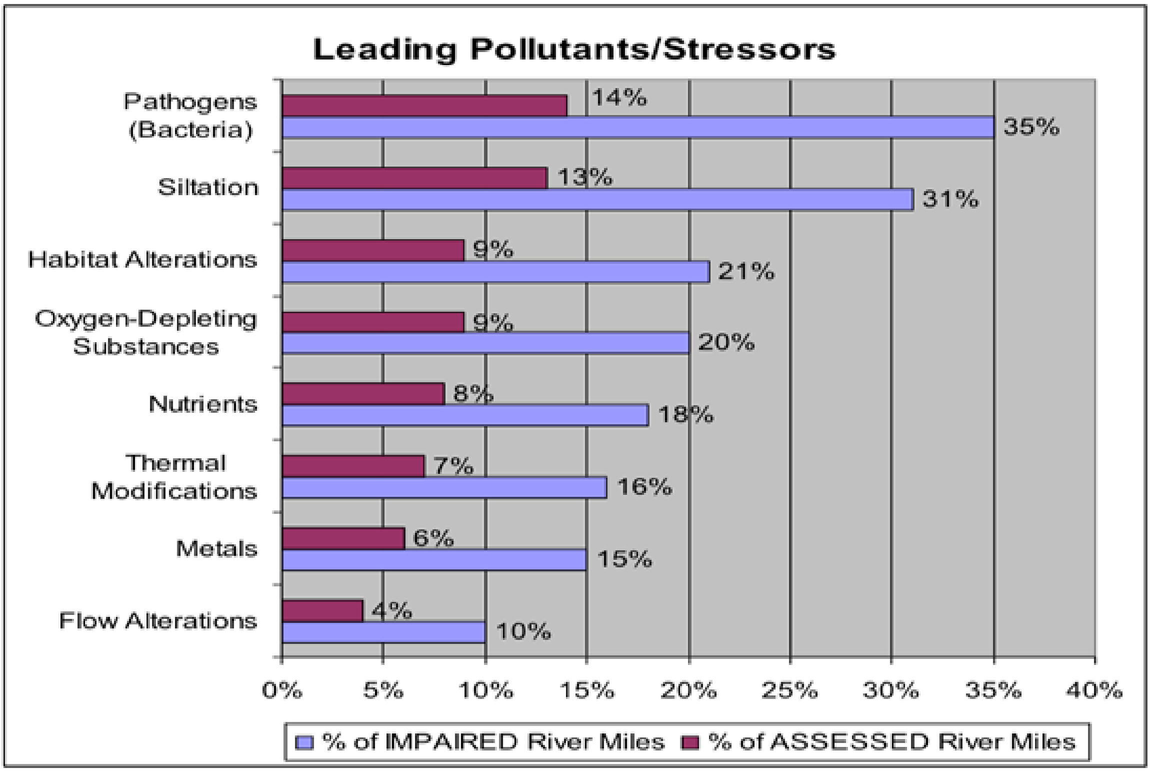
Though floods can be devastating anywhere in the world, they normally have the worst impact in developing countries where home construction may not be as strong, and where there may not be a transportation infrastructure to help people evacuate the area. A flood in West Bengal, India, in 2000 destroyed more than 800,000 homes and killed hundreds of people. And, even more recently, flooding in 2023—driven by increasingly intense storms—occurred across the globe, from Pakistan to New England. Water management systems use elaborate systems of levees and canals to control the movement of water in flood-prone areas. Ironically, floods, hurricanes, and torrential rains can have environmental benefits. When water floods the banks of a river or lake, nutrient-rich sediment improves soil quality in the adjacent areas.

WATER POLLUTION

Throughout the world, many people routinely consume water from surface water such as rivers and streams and from dug wells. Sometimes the same body of water serves as the supply for drinking, bathing, washing, cooking, and the disposal of human and other waste. Such a body of water can easily become polluted and a source of infectious diseases. Between 1 billion and 2 billion people on Earth, most of them in the developing world, do not have access to safe drinking water. In addition, bodies of water have been degraded in ways that cause significant damage to the environment.

Water can be polluted in many ways, as Figure 65 shows, but regardless of the specific pollutant, the sources of pollution can be characterized as point source or non-point source. **Point sources** are distinct, confined locations, such as a particular factory or the pipe leading from a **sewage treatment** plant. *Non-point sources* are diffuse areas, such as an entire farm or a farming region, a suburban community with many lawns and septic systems, or runoff from parking lots. It is important to differentiate the type of source because it can help in controlling pollutant inputs to waterways. For example, if a municipality can determine that the bulk of waterway pollution is coming from one or two point sources, it can target the owners of those specific point sources. It is much more difficult to control pollution from non-point sources.

FIGURE 65



Sources of water pollution (Adapted from USEPA 2000).

Types of Water Pollutants

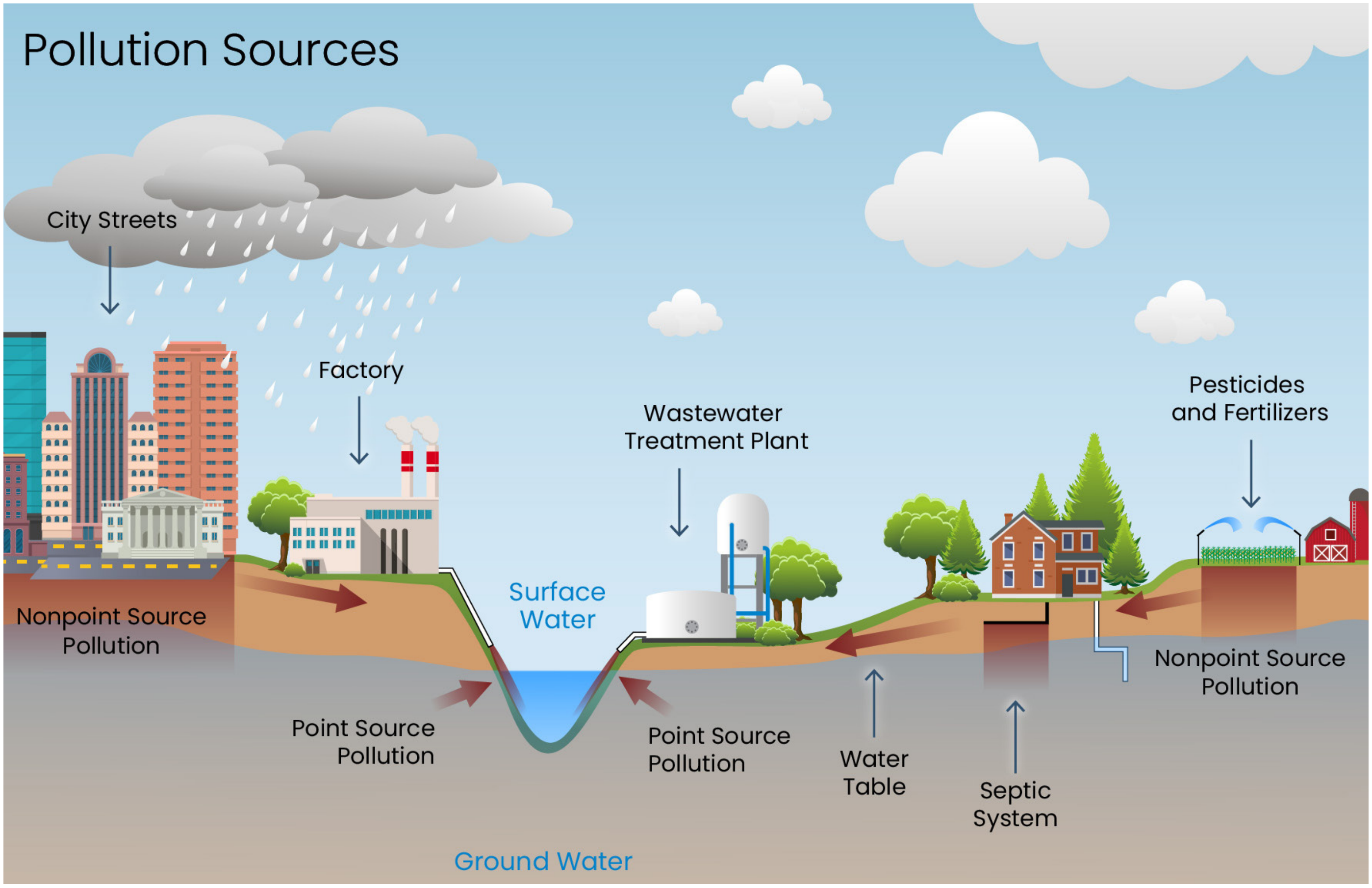
Disease-causing organisms, or pathogens—parasites, bacteria, viruses—are responsible for a number of diseases that can be contracted by humans or other organisms who come in contact with or ingest the water containing them. Large-scale disease outbreaks from municipal water systems are relatively rare in the United States, but they do occur occasionally. Disease outbreaks from municipal water systems are, however, relatively common in many parts of the developing world.

Pathogens can enter the water supply from both point and non-point sources. A malfunctioning sewage treatment plant or septic system can be point sources of pathogens entering into rivers or lakes. Wildlife can also contaminate reservoirs with disease-causing organisms. Worldwide, the major water-borne diseases are cholera and hepatitis. Cholera, which claims thousands of lives annually in developing countries, is not terribly common in the United States, but hepatitis A is appearing increasingly frequently, usually originating in unclean restaurants. The bacterium *Cryptosporidium* has caused a number of outbreaks of gastrointestinal illness in the U.S. Though we may think that our mountain rivers are pure enough to drink from, the influx of hikers into the back country has transmitted the intestinal parasite *Giardia* into untreated natural waters.

Oxygen-demanding waste is material that contains organic matter, such as leaves and twigs that get washed into a body of water during a rainstorm. The material will decompose, and bacteria will grow on it, using oxygen to survive and thereby depleting available oxygen. Food scraps, human waste, and animal waste are all oxygen-demanding waste that can enter the water supply.

Oxygen-demanding waste is measured in terms of **biochemical oxygen demand** or **BOD**—the amount of oxygen a defined quantity of water uses up over a specified period of time (usually five days) at a specified temperature (usually twenty degrees Centigrade). The lower the BOD, the more pristine or unpolluted the body of water; the higher the BOD, the more oxygen-demanding material is in the water. If there is no organic material in the water,

FIGURE 66



Point-source and non-point source water pollution.

Source: Mississippi Department of Environmental Quality

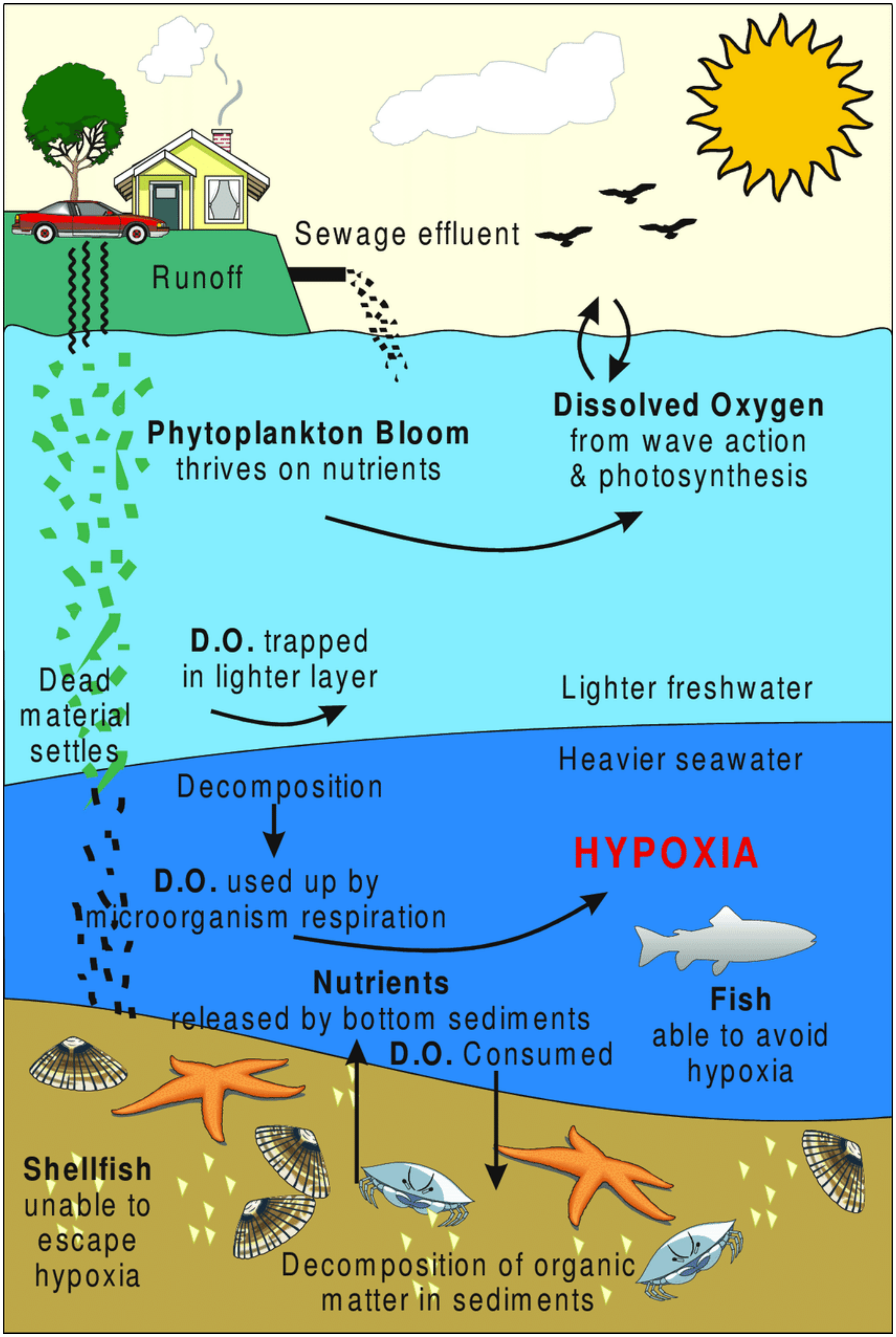
any bacteria occurring there won't have a substrate to feed on and so won't survive and use oxygen. Domestic sewage from a household might have 200 mg of BOD per liter of water over five days. Natural waters might have a 5 to 20 mg BOD, coming from leaves and twigs and perhaps dead organisms.

Another important measurement in determining water purity is *dissolved oxygen*, the amount of oxygen that is dissolved in water at a given temperature, measured in parts per million. When the dissolved oxygen is high, BOD is low and vice versa. Water with low BOD and high dissolved oxygen—say, 8–9 ppm—is high-quality water. Natural waters with such a dissolved oxygen level are ideal places for fish to spawn, plants to grow, and other organisms to thrive. In polluted environments, with dissolved oxygen around 4 ppm, fish will have trouble functioning. Figure 67 illustrates the impact of oxygen-demanding waste on a marine ecosystem.

If too much nitrogen and phosphorus are present, they can overfeed a body of water, leading to eutrophication, the excessive growth of algae due to an oversupply of nutrients.

By Felix Andrews (Floybix) - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1092921

FIGURE 67



Impact of oxygen-demanding organic waste.

We introduced *inorganic compounds*—chemical compounds that don't come from animals or plants—in different terms when we discussed nutrient cycles in Section II. Perhaps the most important are the two elements most likely to limit growth in the receiving lake or stream: nitrogen and phosphorus. If too much nitrogen and phosphorus are present, they can overfeed the body of water, leading to **eutrophication**, the excessive growth of algae due to an oversupply of nutrients. Eventually the algae die and decompose, BOD increases, and the fish population declines. The major terrestrial sources of nitrogen are farm runoff, sewage treatment plants, and acid precipitation; and the sources of phosphorus are naturally occurring rocks and minerals, fertilizer runoff, and, in the past, detergents.

Other inorganic pollutants can come from non-point sources such as acid precipitation (nitrate and sulfate) or point sources such as by-products of sewage treatment (chloride) or industrial plants (metals). Metals such as lead, copper, arsenic, and mercury are among the most toxic water pollutants. In the early 2000s, mercury received a great deal of attention as an inorganic water contaminant of global proportions. According to a 2002 United Nations report:

> *Mercury has caused a variety of documented, significant adverse impacts on human health and the environment throughout the world.... Human exposure to mercury can result from a variety of pathways, including, but not limited to, consumption of fish, occupational and household uses, dental amalgams and mercury-containing vaccines.*

Coal- and oil-fired electric power plants constitute the largest source of mercury emissions in the United States. The mercury that is emitted is deposited on land and in waterways. Inorganic mercury (Hg) itself is not particularly harmful; its dispersion throughout the environment is harmful because of the chemical transformations it undergoes. In the wet, **anaerobic** environment of wetlands, aquatic sediments, and temporarily saturated soils, bacteria convert inorganic mercury to methylmercury, which is highly toxic to human beings. Methylmercury damages the central nervous system, including coordination and the senses of touch, taste, and sight, particularly in developing embryos and children.

Persistent Organic Pollutants (POP) are toxic chemicals created by humans for industrial purposes that persist in the environment for decades or longer and can accumulate in organisms, including humans, through food webs. One group of organic compounds that is causing many problems is polychlorinated biphenyls, or *PCBs*, which are highly toxic and carcinogenic. PCBs were used in manufacturing plastics and insulating electrical transformers until 1979. Although they are no longer manufactured or used in the United States, because of their **persistence**, they are still present in the environment. An ongoing case concerns a General Electric plant in New York State that was once a point source of PCBs into the Hudson River. In 2002, the EPA ruled that General Electric must pay for the dredging and removal of approximately 2.65 million cubic yards of PCB-contaminated sediment from a forty-mile stretch of the upper Hudson River. Under the terms of a 2006 legal agreement between the EPA and General Electric, the dredging of the river bottom started in 2009 and was completed in 2015. However, the EPA continues to monitor the river for PCBs in case additional cleanup becomes necessary.

Nonchemical Pollutants

Sediments such as sand, silt, and clay that become mobilized when soil is disturbed are another source of water pollution. Housing and shopping center development and road construction, along with agriculture, are major sources of sediment. When a dam is constructed, sediments settle out of the unmoving water. If the water is later remobilized, a great deal of sediment will end up in downstream water. Sediment can clog fish gills and otherwise hinder fish from obtaining oxygen, particularly bottom dwellers such as oysters or clams. In addition, increased sediment in the water column reduces the infiltration of sunlight, which can reduce the productivity of aquatic plants.

Any time human beings alter water flow so that the water moves more slowly, receives more sunlight, or enters a shallower waterway, the temperature of the water is likely to increase. Water is also heated when it is used for cooling in industrial processes and electricity generation (e.g., fossil fuel-fired and nuclear power plants). The result is **thermal pollution**. Increasing water temperature reduces the amount of oxygen that can be dissolved in the water. At the same time, in warmer waters organisms normally increase their respiration rate, which means they will use more oxygen and further reduce the dissolved oxygen in the water. Increased respiration rate is a stress that can make organisms more susceptible to disease. Increased water temperature may also affect reproduction.

Ocean and Shoreline Pollution

Although our major focus in this section has been on fresh water, pollution of Earth's oceans and shorelines is an environmental problem of major proportions. Perhaps the greatest culprits are crude oil and other petroleum products, which are highly toxic to many marine organisms, including birds, mammals, and fish, as well as the algae and microorganisms that form the base of the aquatic food chain. Oil is a persistent substance that can spread across the water for hundreds of miles and leave a thick, viscous covering on land that is extremely difficult to remove.

A pelican is coated in oil following the Deepwater Horizon oil spill in 2010.

By Louisiana GOHSEP - Flickr: Oiled Pelicans, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=30525946

Oil and other petroleum products enter the oceans through multiple sources, most notably from spills from off-shore drilling and oil tankers. Perhaps the most notorious recent spill was the Deepwater Horizon oil spill of 2010 in the Gulf of Mexico. In that case, 210 million gallons of oil covered miles of ocean and coastline and dramatically impacted one of the most productive marine ecosystems on Earth. Cleanup efforts continue to the present day. Cleanup includes physical methods such as floating booms to keep a spill from spreading, followed by skimming oil from the water's surface. It also includes the use of chemical dispersants that break down the oil into particles small enough to be broken down by sunlight and bacteria.

Solid Waste Pollution

Though the **dumping** of **solid waste** in open waters has been reduced since the early 1980s, it is hard to walk along a beach without finding at least a few bottles, cigarette butts, or food packages. Various forms of solid waste can be dropped on beaches by negligent people or washed into the ocean from open landfills and travel long distances before they are washed up on another beach far from where they started. Not only is such beach garbage unsightly, it can be dangerous to both marine organisms and people. Toxic medical waste poses a threat to people on the beach, particularly children, and plastic holders for beverage six-packs and plastic bags, for instance, are known to strangle many animals. And the extent and dangers of plastic pollution goes far beyond just this. Plastic debris in landfills or waterbodies can degrade over time into microplastics, particles smaller than 5mm, or nanoplastics, particles smaller than 0.0001mm.[21] Microplastics have been found to be a potential health risk in both animals and humans, which can intake them via eating contaminated seafood, as well as from multiple other sources.[22]

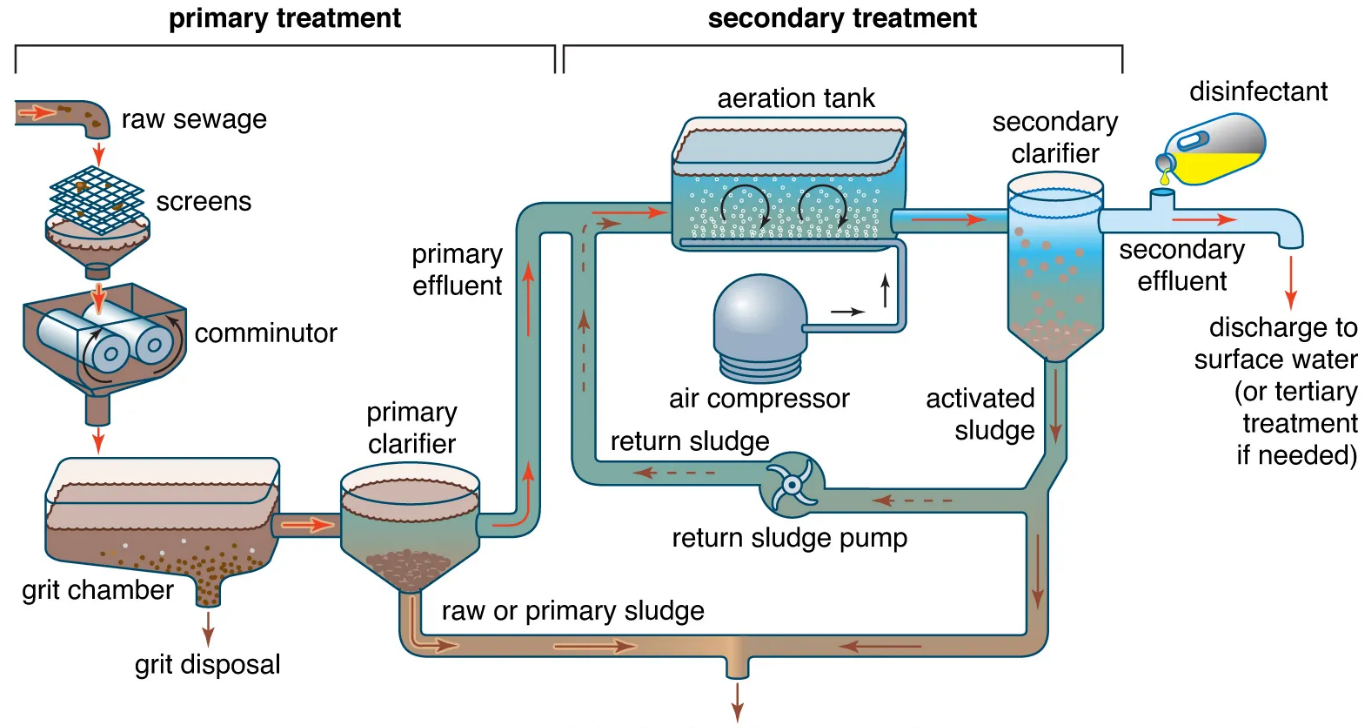
Wastewater Treatment

The term *wastewater* refers to all water from houses and buildings that is destined for a sewage treatment plant or septic system. In fact, wastewater is highly varied. Obviously, wastewater from toilets contains material that is harmful and must be treated before it can be returned to the environment. But water from sinks and showers, while possibly containing high BOD food components or high inorganic contaminants from soaps and detergents, is much less harmful to the environment. Wastewater from sources other than toilets, called *gray water*, is sometimes reintroduced into the environment without treatment for purposes such as watering lawns.

Human sewage is high BOD material that may contain pathogenic organisms and high levels of phosphate, nitrate, and other compounds. Whether raw sewage is dumped into a free-flowing river or stream and "treated" naturally or passed through a human-made system, such as a sewage treatment plant, septic system, or solar aquatic system, the basic processes are the same: bacteria break down the organic matter into carbon dioxide and inorganic compounds like nitrate and phosphate; dissolved oxygen levels in the water are reduced; and eventually BOD goes down; and oxygen levels recover. Wastewater treatment facilities replicate this natural process to varying degrees, usually more quickly. In addition, decomposing the sewage in a treatment plant prevents polluting a natural body of water.

In a traditional sewage treatment plant, which might be used in most municipalities in developed countries, wastewater treatment is accomplished in two phases, primary and secondary treatment. *Primary treatment* removes 40 to 50 percent of the solid waste material. Solid material that settles out during the process is eventually dried and classified as **sludge**. Sludge usually contains significant amounts of metals, particularly if the effluent comes from a municipality that includes industrial businesses. After removal of the sludge, the water undergoes *secondary treatment*, which effectively accelerates the breakdown of organic matter that would occur if the sewage were left to decompose naturally. At the end of secondary treatment, roughly 85 to 90 percent of the original pollutants in the water have been removed. The water is disinfected to kill pathogens and then returned to the river or lake it originally came from and is once more part of the **water cycle**.

FIGURE 68



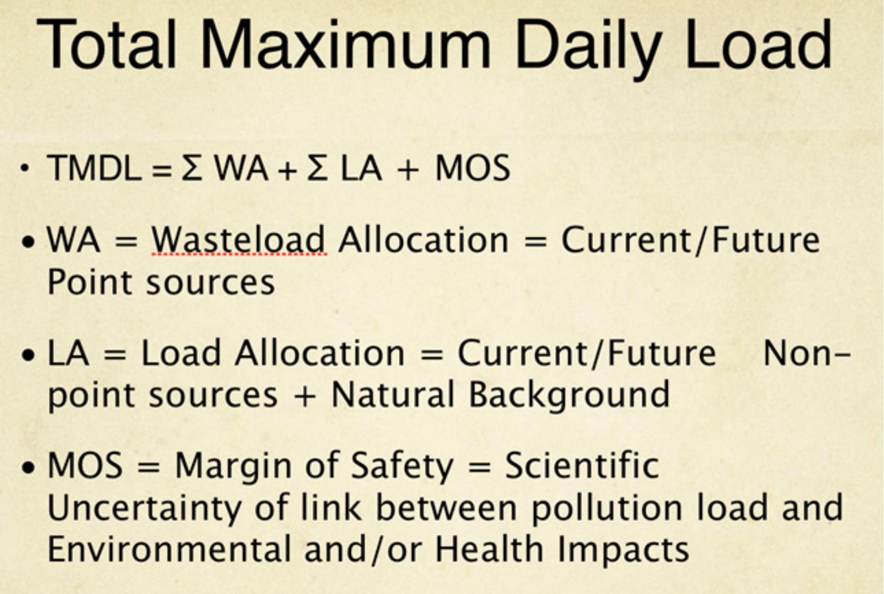
Wastewater treatment process.

Source: Encyclopedia Britannica

Improvements in U.S. Water Quality

Water quality in the United States has improved in most categories over the past few decades. Forty to fifty years ago, many harbors and waterways were badly polluted. The Clean Water Act, passed in 1972 and amended a number of times since then, the Safe Drinking Water Act of 1986, and the Water Resources Development Acts (1986–92) have worked in concert to protect surface water by managing the water supply, wastewater, flood control, navigation on waterways, and hydroelectric power. The Clean Water Act also requires the establishment of Water Quality Standards that place an upper limit on the concentration of specific pollutants in major water bodies. To achieve these standards, the Clean Water Act also requires the establishment of a Total Maximum Daily Load for each pollutant—the maximum amount of a pollutant that is allowed to enter a waterbody—that is based on the total amount of the pollutant discharged from point sources (factories, wastewater treatment facilities, etc.) and non-point sources (atmospheric deposition, farms, and other runoff from the land). In terms of the system analysis that we discussed in Section I, Water Quality Standards are the maximum size of the "pool" of each pollutant in the system (the waterbody) and the Total Maximum Daily Loads are the maximum allowable "inputs" of pollutants into the system.

FIGURE 69



Total Maximum Daily Load

- TMDL = Σ WA + Σ LA + MOS
- WA = Wasteload Allocation = Current/Future Point sources
- LA = Load Allocation = Current/Future Non–point sources + Natural Background
- MOS = Margin of Safety = Scientific Uncertainty of link between pollution load and Environmental and/or Health Impacts

Total maximum daily loads.

Under the Safe Water Drinking Act, the EPA is responsible for establishing *maximum contaminant levels (MCL)* for seventy-seven different elements or substances that can be found in municipal drinking water sources—either surface or groundwater. The MCL is the enforceable level that a contaminant must not exceed. "Enforceable" is a key word here; an MCL reflects the concentration at which harm is thought to occur, but it also takes into account the feasibility of achieving such a standard based on existing technology and the cost of treating water to obtain such levels.

While water regulations have greatly reduced contamination of waters and have almost eliminated major point sources of water pollution, nonpoint sources such as oil from parking lots and nutrients from suburban lawns, to name only two, are not well controlled under existing regulations.

AGRICULTURAL RESOURCES

The Beginnings of Agriculture

For most of human history, human beings subsisted by eating whatever edible matter was at hand, scavenging, gathering plants, and hunting animals, activities collectively known as *hunting and gathering*. Roughly 12,000 years ago, people began to cultivate the soil, **domesticate** and raise animals, and domesticate or modify certain wild species of plants and turn them into crops. The coming of agriculture was a major event in human history because it enabled people to move beyond a subsistence level of existence. At the same time, it has had some negative consequences. The abundance of food is one factor that led to the start of what would become the exponential growth of the human population. The deliberate cultivation of food was also the beginning of a level of environmental degradation never before experienced on Earth. Some people contend that agriculture collectively has been the most harmful human endeavor in terms of its impact on the environment.

Agriculture developed in several locations in the world simultaneously—the Fertile Crescent (part of the present-day Middle East); China; Mesoamerica (southern North and Central America); and perhaps Africa, Southeast Asia, and lowland South America—and spread, adapting to local culture and habitats. Local constraints on agricultural development included the availability of suitable plants for domestication, climate, settlement patterns, and population density.

In semi-arid environments such as the Serengetti ecosystem in Tanzania, the only viable way for people to use the soil is nomadic herding.

Traditional Agricultural Methods

The variation in traditional agricultural patterns around the world illustrates that many approaches can be used to manage soil and crop resources, depending on local conditions. For example, in a flood plain such as that along the Mekong River in Southeast Asia, where water periodically overflows the banks of the river and floods the surrounding valleys, nutrients and soil particles are delivered to the surrounding soils, making them superb for agriculture. In semi-arid environments such as the Serengetti ecosystem in Tanzania, the only viable way for people to use the soil is nomadic herding, in which they move herds of animals, often over extremely long distances, to seasonal feeding grounds. Any more intensive use would degrade the dry, fragile and nutrient-poor soils to the point where they would not be viable for any production at all, a process called **desertification**.

In locations with a relatively warm climate and moderately nutrient-rich soils—for instance, the rainforests of Central or South America, where a good portion of the nutrients are in the vegetation rather than in the soil—slash-and-burn agriculture has been practiced for centuries. In order to clear land to grow crops or graze animals, people cut down the vegetation that is present. This might mean cutting large forest trees, as was done when Europeans colonized North America, or woody vegetation or brush as in Central America and the Amazon Basin. The vegetation is then usually dragged into piles and burned. The resulting ash is rich in potassium, calcium, and magnesium and therefore makes a good fertilizer for crops or grasses. However, after a few years, the nutrients from the ash are depleted. Moreover, if the deforestation has occurred in an area of heavy rainfall, some nutrients may be washed away along with some of the soil, which further reduces the nutrient content as well as the thickness of soil.

Thus, the farmer usually moves on to another plot and repeats the whole process. If a plot is used for a few years and then abandoned for a number of decades, vegetation has a chance to regrow. Over time, the nutrient supplies in the soil begin to increase, and even other soil properties, such as organic content and soil structure, may begin to recover. However, if the land is used continuously without a chance to recover, its productivity decreases. At best, this type of agriculture can provide for the subsistence of a family, but it will not allow for much surplus to be generated for sale. A broader side effect of slash-and-burn agriculture is the release of carbon emissions from burning into the atmosphere.

A typical subsistence farmer in India, Kenya, or Thailand does not use chemical fertilizers because they are not available or affordable, but instead applies animal and plant wastes as fertilizer. Such traditional farmers may also practice *intercropping*, in which two or more crop species are planted in the same field at the same time to promote a synergistic interaction between them. For instance, corn, which requires a great deal of nitrogen, could be planted along with a nitrogen-fixing crop such as peas. *Crop rotation* achieves the same effect by rotating species in a specific order. Some of these traditional practices are being revived in **organic agriculture** in the United States and Europe.

The Green Revolution

Norman Borlaug in a Mexican wheat field in 1970, holding the so-called "miracle" wheat that he developed by crossing a native Mexican strain with a Japanese dwarf variety.

Photo by Arthur Rickerby, National Portrait Gallery, Smithsonian Institution.

Beginning in the 1940s, researchers in Mexico devised techniques to increase agricultural output in order to help developing nations feed their growing populations. They developed strains of wheat that were disease resistant and used fertilizers and irrigation to produce greater crop yields. Wheat production in Mexico increased so much that Mexico became an exporter of wheat, enabling countries such as India and Pakistan to avert famines. The leader of the project, American crop scientist Norman Borlaug, was awarded the 1970 Nobel Peace Prize for his work.

After Mexico's success with wheat, a similar project was developed in the Philippines with rice, and from the 1950s through the 1970s many countries, particularly those in the developing world, underwent similar shifts in the way agriculture was practiced. The so-called **Green Revolution** combined development of better varieties of domestic animals and crops with intensive use of synthetic fertilizers, management techniques, and machinery to increase food production rates. It was also characterized by a significant intensification of agriculture—**monocultures** (agricultural plantings of a single species), irrigation, and increased intensity and/or frequency of cropping. One legacy of the Green Revolution was that from the mid-1960s through the mid-1980s, world grain production increased by a factor of two. By the 1990s, there were at least eighteen centers around the world promoting and developing the new techniques of the Green Revolution.

Of course, the Green Revolution is not without its downside. Its critics maintain that it requires large amounts of synthetic fertilizers and irrigation, and because it encourages large plantings of single crops, it reduces the variety of crops being planted. In addition, the production of synthetic nitrogen fertilizer—which has, by itself, been a major factor in increasing the productivity of farmland—relies on the use of fossil fuel (natural gas) and is a major source of the non-point source water pollution discussed previously. Moreover, these practices tend to exclude small, lower-income family or subsistence farms and support larger commercial farms. The result has been a significant increase in poverty among rural farmers and their displacement to cities. In addition, there has been a loss of individually held land to larger agribusinesses. In 1960, there were roughly 4 million farms in the United States; today there are approximately half that number.

The Status of World Food Production

Roughly 38 percent of the global land surface, or 5 billion hectares (50 million square kilometers), is currently classified as agricultural lands, with about one-third being used as cropland and two-thirds consisting of meadows and pastures for the grazing of livestock.[23] Though grain production increased, the amount of land that is currently under grain cultivation has actually gone down steadily since about 1950, reflecting the improvements that enabled growers to get more output from the same or smaller land area. However, production increases that were due to the Green Revolution have largely been realized, and we are now starting to face limitations of *arable* land (land suitable for plowing and growing crops) and water.

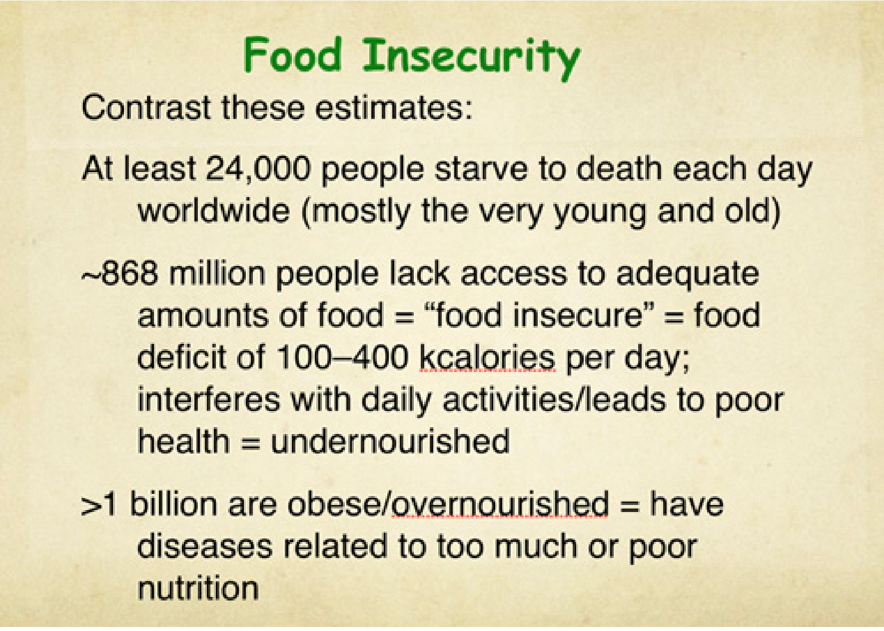
Currently, approximately thirty plant species provide 95 percent of the calories and nutrition for human beings, with only six crops providing about 80 percent of the calories in the human diet: wheat, rice, maize (corn), potatoes, sweet potatoes, and manioc. Eight other crops are important for human beings because they round out a balanced diet for human beings: sugarcane, sugarbeet, common beans, soybeans, barley, sorghum, coconuts, and bananas. The top four food crops worldwide are wheat, rice, corn, and potatoes, in that order. Wheat, rice, and corn, along with other crops such as barley, oats, and rye, are grasses. The fruits of these grasses, called *cereals*, are a good source of carbohydrates and of calories. Cereals also contain protein, oils, vitamins, and minerals. The relative proportions of nutrients vary for each crop, but any of the cereals can serve as basic foods, and they do for many people in the world. Potatoes, which are tubers, are the staple carbohydrate in much of the developed world and have been for centuries. The amounts grown in each country or region depend on factors such as growing temperatures, available moisture, and available sunlight.

Food Insecurity—Hunger in the World

The World Health Organization (WHO) estimates that as many as 828 million people lack access to adequate amounts of food. Chronic hunger, or undernourishment, is not having enough calories to exist in a healthy state. An average person needs roughly 2,200 kilocalories per day, though of course this amount varies with age, size, and sex. With a food deficit of only 100 to 400 kilocalories per day—in other words, an intake of about 1,800 kilocalories—a person will not have enough energy to carry out daily activities at full capacity and will be more susceptible to poor health.

The most common—and intuitive—response to this situation is to conclude that we should grow more food by further utilizing modern agricultural techniques. This perspective is based on the assumption that there is not enough food in the world. However, on a global scale, we currently produce enough calories per day of food to provide everyone on Earth with a healthy diet—although the United Nations also predicts that we will need to increase food production by 60 percent to feed the larger human population of 2050 and after.

FIGURE 70



Food Insecurity

Contrast these estimates:

At least 24,000 people starve to death each day worldwide (mostly the very young and old)

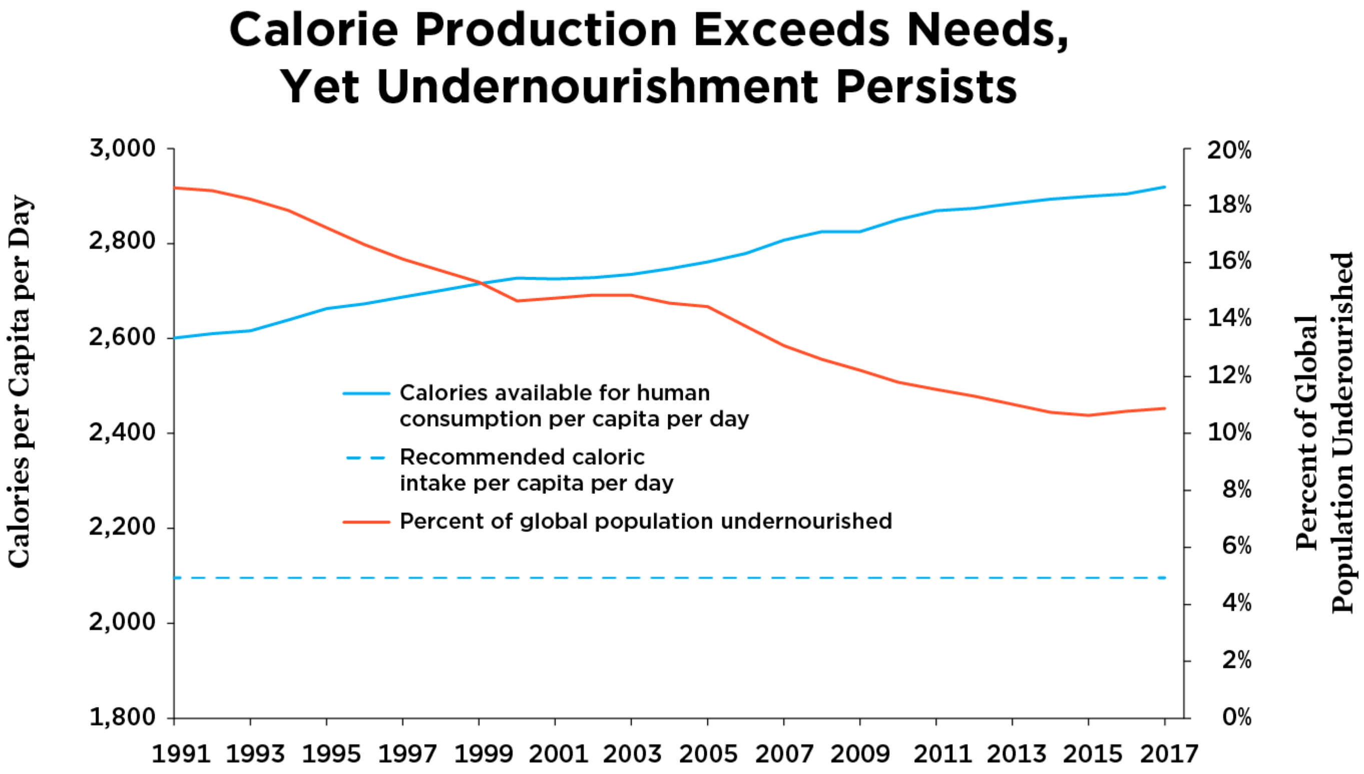
~868 million people lack access to adequate amounts of food = “food insecure” = food deficit of 100–400 kcalories per day; interferes with daily activities/leads to poor health = undernourished

>1 billion are obese/overnourished = have diseases related to too much or poor nutrition

Food [in] security.

Why then is starvation a worldwide problem now? First of all, half the grain grown in the world goes to feed livestock. In the United States, two of the top cereal crops, corn and soybeans, are fed mainly to animals. People in the U.S. eat a very large quantity of meat compared to the rest of the world—an average of 270 pounds (approximately 123 kg) of meat per year, which suggests that some people are eating more than a pound of meat every day. Recall the discussion in Section II regarding the energy efficiency of eating grain rather than meat. Of course, if humans were to eat grains exclusively, to avoid malnutrition, we’d have to eat the right combination of grains and legumes to get enough protein, and other vegetables to get the necessary vitamins and minerals. Nevertheless, if humans were to eat the grain directly rather than feeding it to animals, we would be able to feed far more people with the same amount. One way to think about the difference is in terms of the grain multiplier, the

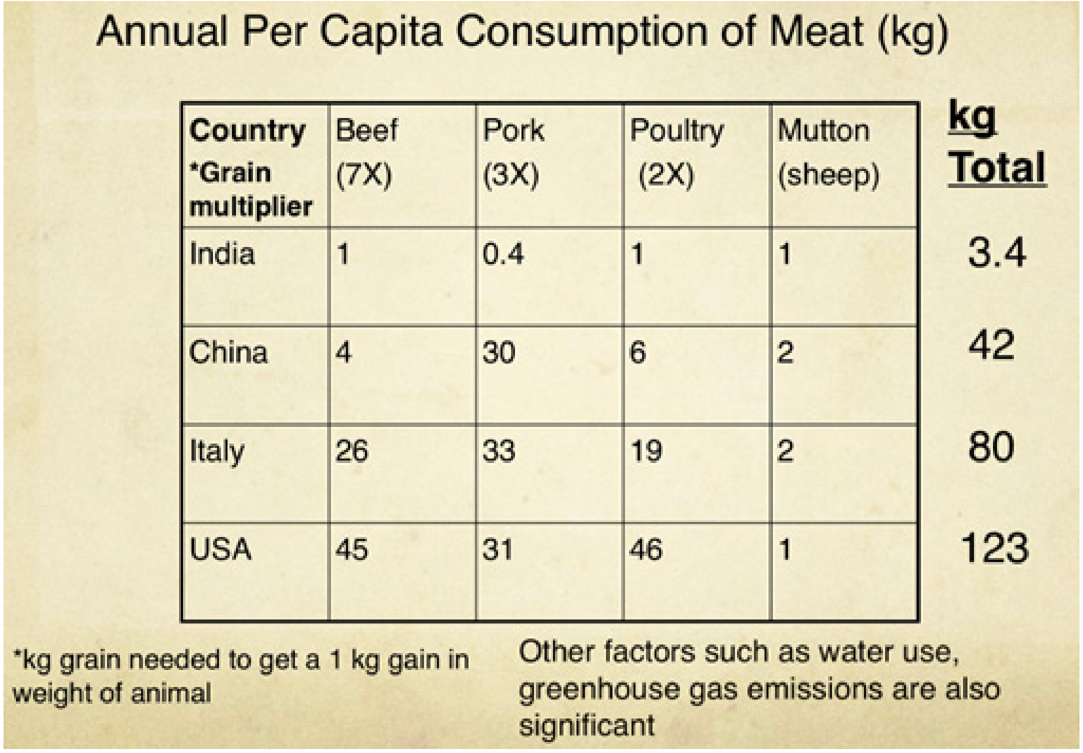
FIGURE 71



Calorie production exceeds current needs.

Source: Union of Concerned Scientists

FIGURE 72



Annual Per Capita Consumption of Meat (kg)

Country ***Grain multiplier**	Beef (7X)	Pork (3X)	Poultry (2X)	Mutton (sheep)	**kg Total**
India	1	0.4	1	1	3.4
China	4	30	6	2	42
Italy	26	33	19	2	80
USA	45	31	46	1	123

*kg grain needed to get a 1 kg gain in weight of animal

Other factors such as water use, greenhouse gas emissions are also significant

Meat consumption among sample countries.

quantity of grain in pounds that must be fed to animals to get a pound of meat. The multiplier for beef is 7; the multiplier for chicken, 2.7. In other words, for every pound of beef we eat, people could be eating 7 pounds of grain.

However, most food experts suggest that, ultimately, starvation on a global scale is mostly the result of unequal distribution rather than absolute unavailability. The food is produced, but not everyone has access to it, partly for logistical reasons (wars), partly because of the choices we make as to how it is used. Most important, many people simply can't afford to buy food or can't afford to buy enough or adequately nutritious foods, a problem that cannot be solved simply by planting more grain or using more technological production methods.

One of the greatest changes in modern Western agriculture in the last century is the amount of mechanization that now exists. Tractors, harvesters, and other machines perform virtually every process that takes place on a farm.

Conventional Land-Use and Planting Techniques

Mechanization and Intensive Working of the Soil

One of the greatest changes in modern Western agriculture in the last century is the amount of mechanization that now exists. Tractors, harvesters, and other machines perform virtually every process that takes place on a farm, from plowing and tilling to planting and harvesting. In addition, the transportation, processing, and storage of food are much more mechanized than they were a hundred years ago.

Plowing and tilling turn over soil, loosen it so that it can be planted, and aerate it. When soil is completely turned over annually, drainage and root penetration are improved, and seeds germinate more easily. Light tilling during the growing season allows a farmer to bury weeds, thereby controlling them without the use of pesticides and at the same time adding the organic matter in the weeds to the soil. Large-scale agriculture normally uses tilling techniques that leave large areas of soil uncovered for periods of time.

If heavy rains or windy dry periods occur before seedlings are established, the soil will be susceptible to erosion. Globally, perhaps 16 percent of soil has been lost to erosion, in both developed and developing countries. In addition, frequent passing over fields with the heavy machinery used on large farms compacts the soil and counteracts some of the benefits of tilling. Every time the soil is plowed or tilled, soil particles that were attached to other soil particles or to plant roots are disturbed and broken apart and are now susceptible to movement by **wind** or water.

Plowing can have very significant effects on land; in fact, some argue it has the greatest consequences of all agricultural practices. Soils may take hundreds or even thousands of years to develop as organic matter accumulates and soil horizons form. In natural systems, as plants die and decompose, the nutrients within them return to the soil, enriching it and becoming part of the global biogeochemical cycles. In conventional agriculture, however, farmers generally remove the bulk of the byproducts of an agricultural crop from the soil so that it won't interfere with future plantings. Studies that monitor the amount of organic carbon in soil (SOC) have provided evidence that SOC in agricultural fields decreases over time; however, field studies show that the SOC will build up again over time if a field is left alone.

Approximately 40 percent of the cropland in use worldwide has been degraded to some degree by erosion, compaction, or waterlogging and **salinization**. If alternating portions of previously cultivated land were put aside and allowed to lie *fallow* (idle during the growing season) for a certain time, we could perhaps improve the health of the soil throughout agricultural areas; however, this would have a short-term negative impact on food production.

(a) Furrow irrigation

(b) Flood irrigation

(c) Spray irrigation

(d) Drip irrigation

Types of irrigation.

Irrigation

Another practice that affects the soil is *irrigation*, or the artificial addition of moisture, usually large quantities of water pumped from a river, lake, or underlying aquifer. In parts of the world where the food supply is limited by the amount of rainfall, irrigation can increase growth rates, or even enable crops to grow where they were traditionally absent. In the United States, irrigation has turned approximately 1 million acres of former desert in the Imperial Valley of southeastern California into an important source of fruits and vegetables—particularly during winter—for many parts of the country. A 2016 estimate suggests that only 20 percent of world agricultural land is irrigated, but this land produces 40 percent of global food. Irrigation is one of the practices common to both large-scale agribusiness and organic farming, though the methods used may differ in the two cases. However, over time irrigation can have a number of negative consequences, including depleting the underlying groundwater table and “drawing down” aquifers so that neighboring wells run dry.

Monoculture

In *monocropping*, a single crop species, or monoculture, is planted over a large area. In the United States, large-scale agriculture is based on monocultures; hundreds of acres at a stretch are cultivated with, for example, soybeans or corn. Even in developing countries, certain lands previously unused for agriculture or used for subsistence agriculture have now been planted with large monocultures. For example, good farmland in central Kenya is used for growing tea, while further west in Kenya land that was not previously farmed has been covered with wheat fields.

The advantage to a monoculture is that all the land in one expansive area can be treated identically: it can receive the same regimen of plowing, planting, fertilizer and pesticide application, watering, and harvesting. A farmer can sow seed, apply fertilizer or pesticides, or harvest crops for an entire day without changing the settings on the tractor or the application rate of the compound being applied. To some extent, this leads to an economy of scale; it is more energy and dollar efficient to grow one crop on a hundred acres than to grow a number of different crops on the same area of land. The main disadvantage of monocropping is the loss of crop diversity and consequent vulnerability to pests or diseases. For example, the Colorado potato beetle is a major pest of potato plant foliage but, for the most part, it does not feed on other foliage. If the potato beetle becomes established, it could destroy a potato monoculture, but if three or four different species were planted on that acreage, the non-potato crops would survive.


A crop-duster sprays pesticides on a field.

Chemical Fertilizers

All fertilizers contain the chemical elements that are plant essential nutrients: primarily nitrogen, phosphorus, and potassium. In contrast to the organic fertilizers used in traditional farming, which come from **composting** vegetation or animal wastes, the chemical fertilizers used by modern agribusiness are synthesized by human beings with fossil fuel energy. The synthetic process might entail combusting natural gas in the atmosphere and capturing the nitrogen that is fixed during the combustion process, or it might use machinery to grind up rock in order to obtain the minerals contained within.

The widespread use of synthetic chemical fertilizers has increased crop yields tremendously since the Green Revolution. Worldwide fertilizer use increased from 20 million metric tons to over 200 million metric tons between 1960 and 2020, but the amount of food produced increased even more rapidly. It is possible to argue that without synthetic fertilizers, we could not feed all the people in the world. However, the increase in fertilizer use is also responsible for a worldwide increase in nutrient runoff from agricultural fields to adjacent rivers, streams, other waterways, and even aquifers. Further, in contrast to the slow release of nutrients from **compost**, synthetic fertilizers release nutrients rapidly. Because plants can take up only a certain amount at any given time, much of the nutrient may actually be leached away by water and end up as runoff. Chemical fertilizers do not add any organic matter to the soil or contribute to soil structure as organic fertilizers such as humus or compost do. And, of course, the production of synthetic chemical fertilizers uses fossil fuels and contributes to the release of fossil carbon to the atmosphere.

Chemical Pesticides

Pesticides are substances, either natural or synthetic, that kill or control organisms that people consider pests. Those used most commonly in conventional agriculture to increase productivity are **insecticides**, which target insects, and **herbicides**, which target vegetation that is competing with commercially desirable species.

The pesticides used by agribusiness are normally *petrochemicals*, meaning that they are synthesized from petroleum.

High-density farming has many environmental and health consequences.

Chemical pesticides normally reduce the targeted pests for a period of time after application. However, over time, as the pesticide dissipates, the pests tend to rebound or recover, requiring an additional application. Eventually, insects or other pests can build up a resistance to a pesticide, at first requiring more pesticide and eventually requiring the use of stronger chemicals. In addition, pesticides can affect many species other than the target organisms. For example, one widely used herbicide, glyphosate (sold commercially under the brand name Roundup®), is used to control annual and perennial plants including grasses, broad-leaved herbaceous species, and trees. But because glyphosate is a general, or *broad-spectrum*, herbicide, it works nonselectively; in other words, it will kill whatever vegetation it is applied to. Insecticides also can affect non-target organisms; while killing insects that are considered pests, they may also remove naturally occurring organisms that are beneficial to crop productivity. In the United States, in the year 2020, approximately 400 thousand tons of pesticides were applied to food crops, cotton, and fruit trees—more than any other country (although Brazil was not too far behind at 375 thousand tons). This total includes 300 million pounds of herbicide and 74 million pounds of insecticide.[24]

Like fertilizers, chemical pesticides run off to surrounding surface waters and potentially to groundwater. Their toxicity to humans and other species is a subject of much debate. Farmworkers, grounds workers, and others who apply pesticides are at particular risk of exposure to high doses of the active ingredients, especially if they do not have or use the proper safety equipment. The Environmental Protection Agency estimates that as many as 20,000 physician-treated pesticide poisonings occur each year among the roughly 3.8 million U.S. agricultural workers; it is not known how many poisonings go undiagnosed and untreated.

High-Density Farming of Animals

In addition to producing plant crops, modern agribusiness is heavily involved in the farming of livestock. In recent years, over 10 billion animals annually have been raised and slaughtered for food in the United States. Roughly 9 billion of these are chickens. By using antibiotics and nutrient supplements, farmers can increase the density of animals in a confined area and reduce the amount of sunlight and exposure to the out-of-doors without the adverse health effects and diseases that would normally occur. This high-density animal farming includes feedlot beef cattle, dairy cows, pigs, and chickens, all of which are constrained or allowed very little room for movement during all or part of their life cycle. Such feedlot farming of animals allows an extremely high output of meat from a small area of land.

High-density animal farming has many environmental and health consequences. Large amounts of manure and urine accumulate, requiring removal on a regular basis, but they are not always disposed of properly. Sometimes animal wastes are stored in lagoons adjacent to feedlots, and during heavy rains, storm runoff contaminates nearby waterways. Animal wastes have also been dumped, either inadvertently or intentionally, into public waters. For example, chicken farms in Maryland have been found to have dumped chicken waste into local rivers that eventually feed into the Chesapeake Bay, contributing to infectious disease outbreaks as well as nitrogen pollution. The Environmental Protection Agency has concluded that hog, chicken, and cattle waste has led to some level of pollution along 35,000 miles of rivers in twenty-two states and some degree of contaminated groundwater in seventeen states. There is some evidence that antibiotics in animal feed are transferred to humans who eat the animals, with the possibility that antibiotic-resistant strains of microorganisms are developing in human beings as a result. High-density animal farming has other ramifications for human health as well.

GMOs

“Frankenfoods,” square tomatoes, animals that glow in the dark—these are some of the images that have been summoned up in the popular reaction to *genetically modified organisms*, or *GMOs*. In fact, genetic modification of plants (and later animals) has been going on for about 10,000 years, roughly since the start of agriculture. Darwin even wrote about it in the first chapter of *On the Origin of Species*. He called the process by which people breed domesticated species to maintain certain traits while letting others diminish **artificial selection**, similar to the natural selection that is the basis of evolutionary change. Some of our best friends—the poodle and the golden retriever, for instance—and some of the foods that we eat commonly—cabbage, broccoli, and collards, among many others—have been developed by people through artificial selection. Why, then, are we afraid of the current GMOs when we happily bite into a piece of seedless watermelon? To understand why it might be reasonable to have concerns about genetically modified crops, we have to explain a bit of the biology behind genetic modification.

Genetic Engineering

Traditionally, people have modified plants or animals by interbreeding strains of the same species to emphasize desired traits, such as size or hardiness or by interbreeding closely related species to create *hybrids*. For example, transferring pollen (cells that contain many different genes) between a plum and an apricot, both members of the genus *prunus*, has produced the hybrids plumcot and pluot. By contrast, *genetic engineering* requires isolating a specific gene from one organism and transferring it into the genetic material of another organism, often one from an entirely different kingdom of life.

Let’s consider a specific example. Corn is subject to attacks from the bollworm, European corn borer, and other insects. *Bacillus thuringiensis* is a natural soil bacterium that repels such insects. Through genetic engineering, the bacterium’s insecticidal gene, known as *Bt*, has been inserted into the genetic material of corn plants, producing a corn plant with a natural insecticide in its leaves. By 2002, 34 percent of all corn planted in the U.S. was *Bt* corn (virtually all of it is fed to livestock). Toxicity of the Bt corn to corn borers and bollworms has been confirmed, and as a result, growers have been able to use less synthetic pesticide on corn plants.

A similar technique has been used to create plants that are resistant to the herbicide Roundup®, which we mentioned earlier. The so-called Roundup®-Ready gene has become widely used in corn, soybean, and cotton plants, allowing growers to spray the herbicide on their fields without fear of destroying crop plants along with weeds. In this case, less weed control is done through tilling, and erosion is reduced. However, large quantities of the chemical glyphosate are introduced into the environment. Genetic engineering allows for the rapid acquisition of desirable traits and in some cases acquisition of traits that might otherwise not be transferrable. For example, while there might be a small amount of variation in the cold tolerance of strawberry plants, genetic engineering has allowed a substantially greater cold tolerance gene to be spliced into a strawberry plant.

The GMO Controversy

Genetically engineered crops and livestock clearly offer the possibility of less waste, greater efficiency, in some cases a reduction in pesticide use, and higher profits for the agribusinesses that use them. They are also seen as a way to help reduce world hunger by reducing loss to pests and environmental conditions and increasing output. But they are the source of considerable controversy.

Some people are concerned that the ingestion of genetically modified crops by human beings may be harmful although so far there is little evidence to support these concerns. Researchers are studying the possibility that GMOs may cause reactions when people eat foods containing genes transferred from another food they are allergic to. More significant for the environment are concerns about the accidental release or proliferation of GMOs in the natural environment after their introduction to specific agricultural locations. In this case, there is some evidence of harmful effects, such as mortality in nontarget organisms.


(Photo: © anacotrin/Shutterstock.com)

Intercropping trees with vegetable crops (sometimes called agroforestry) allows vegetation of different heights to act as wind breaks and catch soil that might be blown away by wind.

For example, in one study Monarch butterfly caterpillars died after ingesting pollen from *Bt* corn. Though corn is not the Monarchs' favored food, and they are unlikely to ingest a great deal of corn pollen, it is possible that *Bt* pollen could spread from fields of corn to nearby milkweed plants, which are the Monarchs' usual food. However, repeated studies have shown little effect on Monarch caterpillars.

Opponents to GMOs also worry that new toxins or compounds created by GM crops could kill soil organisms that are beneficial to crops. Another fear is that if crop plants are able to breed with wild relatives, the newly added genes will spread to the wild plants, with the possibility of altering or eliminating natural varieties. Attempts have been made to plant buffer zones around GMO crops and to make sure that wild species related to crop species are not in the areas where GMO crops are planted. However, wind-borne pollen does not necessarily respect such borders. One method for eliminating all transfer of GMOs to wild varieties would make GMO crops sterile; that is, the seeds would be nonviable.

There are negatives (and positives) of using GMOs that we are more certain about. For one, the use of genetically modified seed is already contributing to a loss of genetic diversity in our food crops. Large-scale commercial agriculture relies more on genetically modified seed each year; by 2002, 34 percent of the corn, 75 percent of the soybeans, and 71 percent of the cotton planted in the United States came from genetically modified seeds; by 2020, those figures had reached over 90 percent for all three crops.[25] Not only does such a practice contribute to the overall worldwide loss of biodiversity, it also makes world crop production susceptible to insect infestations or a great reduction in output, similar to that discussed for monocultures. However, GMOs have also had the very positive impact of decreasing pesticide use due to the creation of insect-resistant strains of crops.[26]

Sustainable Agriculture

Is it possible to produce enough food to feed the world's population without destroying the land, polluting the environment, or reducing biodiversity? *Sustainable agriculture* attempts to combine economic viability with reduced environmental impact. It emphasizes being able to continue agriculture on a given piece of land indefinitely, conservation and build-up of soil, and **integrated pest management**. Many of the practices used by sustainable farmers are similar to those of traditional farming.

As we discussed earlier, intercropping allows crops with different nutrient demands to benefit from being grown near one another. Intercropping trees with vegetable crops (sometimes called **agroforestry**) allows vegetation of different heights to act as wind breaks and catch soil that might be blown away by wind. Farmers in East Africa, for example, have planted trees in rows adjacent to rows of vegetable crops. While wind does remove some soil from the rows of vegetables, the soil particles travel only a few feet to the rows of trees, where the soil is captured, so erosion is greatly reduced.

Alternative means of land preparation and use also help to conserve the soil. For instance, contour plowing—plowing and harvesting parallel to the topographic contours of the land—allows for the least amount of erosion while still gaining the practical advantages of plowing. Some farmers plant a crop of winter wheat during a time when the fields would normally be unplanted so that the land does not remain uncovered. Yet another approach, still under development, is the use of perennial crops that do not have to be replanted every year. These methods also have a dramatic impact on improving the ability of the soil to retain carbon that, through conventional farming methods, becomes part of the increase in atmospheric carbon levels.

FISHERY RESOURCES

Overfishing and the Decline of Fisheries

In the final part of this section, we will consider two systems—forest and marine ecosystems—that, unlike agriculture, appear, on the surface at least, to be "natural" ecosystems like those we dealt with in Section II. However, many, if not most, forests and marine ecosystems are being managed today for the "harvests" that they can supply to use in the way of timber (and other forest products) and fish. Harvest (and harvesting) is the apt term to use since the harvesting of forest products and fish will include many of the same concepts as found in agriculture.

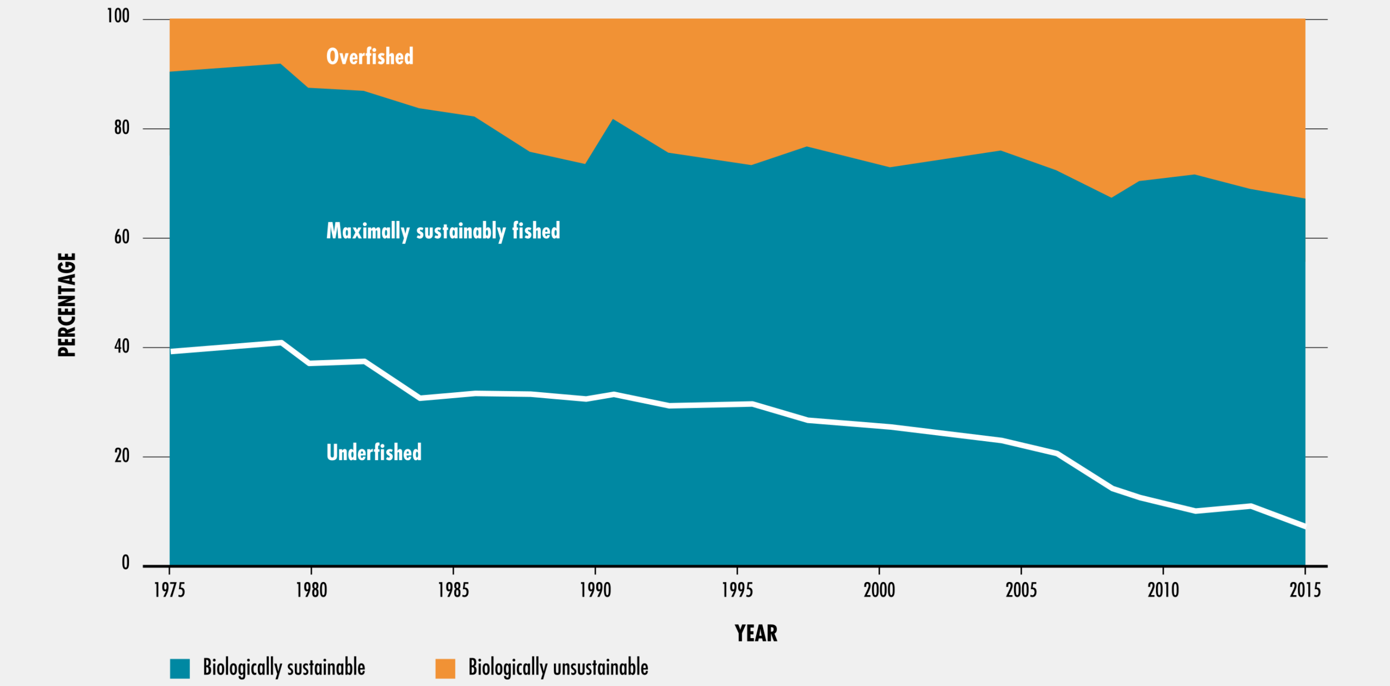
In May 2003, the journal *Nature* published an article that made the headlines on CNN and added to the increasing evidence that many of the world's marine fish species are in danger of extinction from overfishing. The article summarized an analysis of the number of large predatory ocean fish, such as tuna and swordfish, caught in thirteen major global fisheries. The results show a dramatic decline in the number of fish caught over fifty years, even though both the number of fishing ships and amount of time spent have increased over that time. While there had been plenty of warning signs in previous years, this study represented the first major study quantifying the decline for multiple fisheries across the globe. And the news has not been getting better, with a recent study of the status of the world's fisheries showing a steady increase in the number of fish species being harvested at an unsustainable level.

The Scientific Management of Fisheries

We saw in Section II, with the example of the collapse of the Peruvian anchovy fishery, that one cause of the decline of ocean fish populations is the failure to account for environmental uncertainty when establishing fishing quotas. Quotas that are set too high are a direct cause of overfishing. A more significant cause is the

FIGURE 73

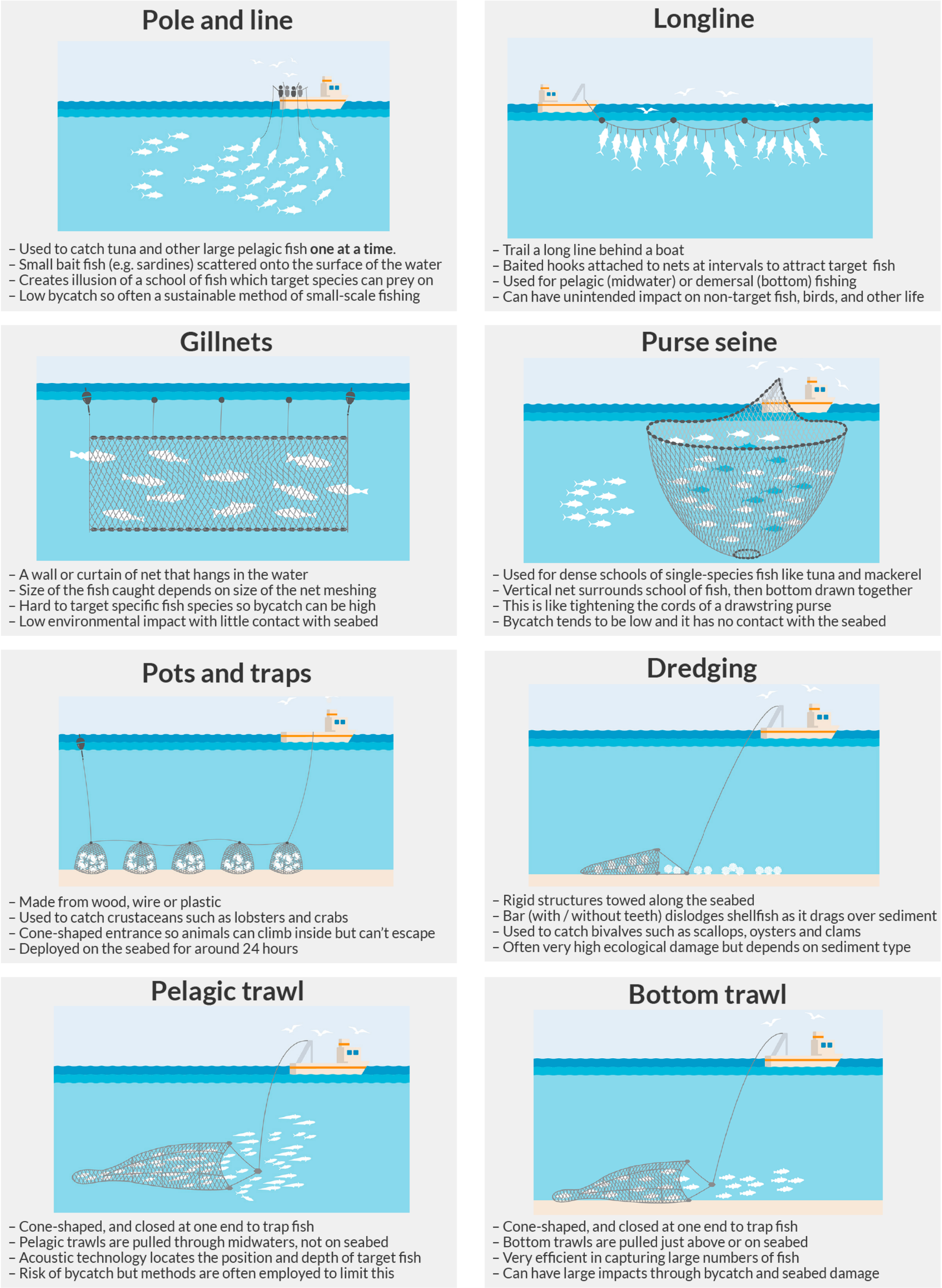
GLOBAL TRENDS IN THE STATE OF THE WORLD'S MARINE FISH STOCKS, 1974–2015



The state of the word's marine fish stocks reflects the impact of overfishing.

Source: Food and Agriculture Organization of the United Nations change in fishing technology. Just fifty to sixty years ago, large-scale fishing, such as the harvest of cod from the Grand Banks off Newfoundland, Canada, involved tedious, dangerous, and low-yield methods in which individuals in small dories dangled lines with a few baited hooks. The very low-tech nature of this method served as an important contribution to the sustainability of the fishery; individual dory fishers simply could not catch enough to deplete the fish populations. Technological advances in fishing methods, along with economic

FIGURE 74



Pole and line

- Used to catch tuna and other large pelagic fish **one at a time**.
- Small bait fish (e.g. sardines) scattered onto the surface of the water
- Creates illusion of a school of fish which target species can prey on
- Low bycatch so often a sustainable method of small-scale fishing

Longline

- Trail a long line behind a boat
- Baited hooks attached to nets at intervals to attract target fish
- Used for pelagic (midwater) or demersal (bottom) fishing
- Can have unintended impact on non-target fish, birds, and other life

Gillnets

- A wall or curtain of net that hangs in the water
- Size of the fish caught depends on size of the net meshing
- Hard to target specific fish species so bycatch can be high
- Low environmental impact with little contact with seabed

Purse seine

- Used for dense schools of single-species fish like tuna and mackerel
- Vertical net surrounds school of fish, then bottom drawn together
- This is like tightening the cords of a drawstring purse
- Bycatch tends to be low and it has no contact with the seabed

Pots and traps

- Made from wood, wire or plastic
- Used to catch crustaceans such as lobsters and crabs
- Cone-shaped entrance so animals can climb inside but can't escape
- Deployed on the seabed for around 24 hours

Dredging

- Rigid structures towed along the seabed
- Bar (with / without teeth) dislodges shellfish as it drags over sediment
- Used to catch bivalves such as scallops, oysters and clams
- Often very high ecological damage but depends on sediment type

Pelagic trawl

- Cone-shaped, and closed at one end to trap fish
- Pelagic trawls are pulled through midwaters, not on seabed
- Acoustic technology locates the position and depth of target fish
- Risk of bycatch but methods are often employed to limit this

Bottom trawl

- Cone-shaped, and closed at one end to trap fish
- Bottom trawls are pulled just above or on seabed
- Very efficient in capturing large numbers of fish
- Can have large impacts through bycatch and seabed damage

Marine fishery methods.

Source: Marine Stewardship Council

pressures to increase fishing harvests, have made these practices a thing of the past.

Figure 74 shows several of the current methods that make it easy to achieve huge catches. The schooner and dories of the past have been replaced by large factory ships that can stay at sea for months at a time, processing and freezing their harvest without having to return to port. Most marine fish are now caught either by huge trawler nets or drift nets pulled behind one of these ships or by very long fishing lines bearing multiple hooks and bait. Groundfish (species that live on or close to the ocean bottom) and many shellfish are caught by dredging, in which special trawler nets are weighted so that they can be pulled across the ocean floor.

Besides reducing the abundance of the adults of commercial species—the direct target of a harvest—large-scale, high-tech fishing can adversely affect other species as well. Because many commercial fish are keystone species, decline or loss of their populations can have a cascade effect throughout a biological community, resulting in the decline or loss of other species. This is true of the large predatory fish that act as major population control as well as of species lower on the food web that serve as a critical food source for others. In addition, drag nets can damage ocean bottom habitats by disturbing or destroying rocks, coral, and sea plants.

One of the most serious consequences of intensive fishing for biodiversity is the loss of juveniles or noncommercial species that are accidentally caught in nets and lines. This **by-catch**—noncommercial species caught unintentionally along with targeted species—has significantly affected populations of fish species such as sharks. By-catch also includes many marine mammals such as dolphins caught in tuna nets and endangered sea turtles caught and drowned in the shrimp nets commonly used in the Gulf of Mexico.

Managing Fisheries for a Sustainable Future

Economic pressures, fueled by the high cost of the new technologies as well as by local and international competition, have further contributed to the overfishing of the world's fisheries. In response, fishery managers often set fishing quotas on the high side rather than setting quotas that would better reflect the uncertainty of their knowledge. In the interest of creating and supporting sustainable fisheries, many countries around the world have developed fishery management plans, often in cooperation with each other. International cooperation is particularly important because fish migrate across borders, important fish ecosystems span borders, and many of the world's most important fisheries lie in international waters. Some current management strategies of marine fisheries try to increase the economic incentive for users to practice sustainability and to enforce sustainable public management through laws, regulations, and plans based on environmental science.

An Economic Approach to Fishery Management

Commercial salmon fishing by non-Native Americans in the waters off Alaska began in the early 1800s. Until relatively recently, salmon fishing was open to anyone with a large enough boat and the right equipment. Whenever the catch dropped, fishery managers would initiate controls until the population recovered. After 1940, however, increased demand for salmon coupled with improved fishing technology began to outpace controls, resulting in a long, steady decline in the salmon population. By 1970 the population was so reduced that the Alaska salmon fishing season lasted only five to six days.

High scientific uncertainty about the ecology of salmon had made it impossible to develop effective scientifically based management plans. Consequently, in 1973 fishery managers decided to take a different approach, putting the major responsibility for managing the salmon stocks on the fishers themselves. They did this through a system of *individual transferable quotas (ITQs)*. Before the start of each fishing season, fishery managers establish either fixed or variable amounts of total allowable catch. These quotas are first distributed to individual fishers or fishing companies with a history of long-term participation in the fishery. Fishers with ITQs have a secure right to catch a set amount in a set area, so there is no need to spend money on bigger boats and better equipment in order to out-compete others. If a fisher cannot catch enough to remain economically viable, they can sell all or part of their quota to another fisher instead of putting more effort into fishing. Like herders using the commons for grazing, salmon fishers with ITQs have a property interest not only in the fish they catch now, but in the fish that their quota will allow them to catch in the future. Since the beginning of the ITQ program, the salmon population (and harvest) has increased slowly.

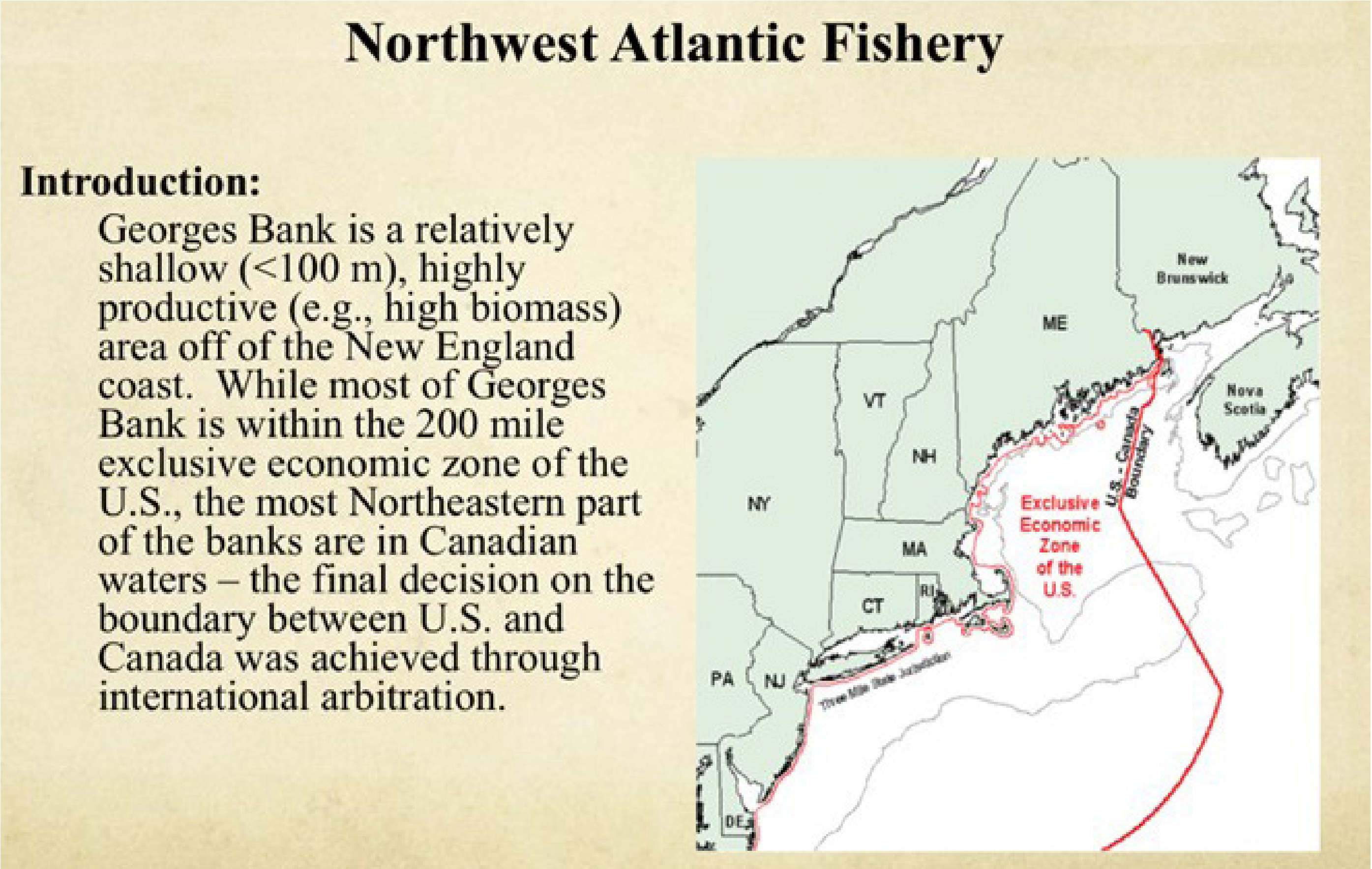
In Alaska ITQs are sold primarily to small family-run fishing operations. However, ITQs have also been used effectively in New Zealand to control overfishing by large fishing companies. The ITQ system is being used successfully in many other fisheries around the world.

Integrating an Ecological Perspective into Fishery Management

Successful long-range fisheries management must include not only the economic interests of the fishing industry, but also both local and cross-border political concerns and environmental science that will help control damage to fish species and ecosystems. Many countries have established exclusion zones ranging up to two hundred miles around their fisheries. In 1976 the United States established a two-hundred-mile exclusive fishery zone around the U.S. managed by the National Marine Fisheries Service (NMFS) within the Department of Commerce and eight regional councils made up of government and industry representatives and advised by NMFS fishery scientists. The focus was largely on preserving U.S. fisheries as an economic resource. However, the fisheries collapse of the 1990s, particularly in the Northwest Atlantic region, showed that this approach was not sufficient.

The U.S. Northwest Atlantic fisheries comprise several marine shelf ecosystems that stretch from the northeastern United States to southeast Canada. Except for a small area of Georges Bank on the Canadian side, the area is under the jurisdiction of the United States. The Northwest Atlantic fisheries were historically among the world's most productive. However, by the early 1990s they had experienced catastrophic depletion of fish stocks, particularly cod and pollock, primarily as a result of overfishing by international fleets of factory ships.

FIGURE 75



Northwest Atlantic Fishery

Introduction:

Georges Bank is a relatively shallow (<100 m), highly productive (e.g., high biomass) area off of the New England coast. While most of Georges Bank is within the 200 mile exclusive economic zone of the U.S., the most Northeastern part of the banks are in Canadian waters – the final decision on the boundary between U.S. and Canada was achieved through international arbitration.

The Northwest Atlantic fishery.

The fisheries were forced to close down because of the depleted stocks, and the Canadian government imposed a moratorium on ground fishing in the area, as did the United States in much of the Georges Bank.

In response to the collapse, and in order to restore depleted stocks and manage the ecosystem as a whole, the U.S. Sustainable Fisheries Act was passed in 1996. This act changed the focus of fishery management from economic sustainability to an increasingly **conservation**-minded, species-sustainability approach. Since the passage of this act, the National Marine Fisheries Service has developed a plan organized around sustainable fisheries, recovery of protected species, and healthy marine habitat. For many species, such as those listed under the Endangered Species Act (ESA) or otherwise considered to be in danger, a "sustainable" fishery means no fishery—for example, the closure of the cod fishery—until populations recover. Protecting critical habitat is required for species listed under the ESA and is important for the long-term sustainability of other fish species as well.

Although most of the Sustainable Fisheries Act requirements are for the purpose of conservation, restoration, and management, they do not specifically mention environmental science or ecology, nor are they particularly ecologically minded. Therefore, fishery managers must do more to actually incorporate environmental science into the management plan. One place where environmental science has been, and is being, implemented is the Georges Bank fishery, described in the following Environmental Science Case Study.

ENVIRONMENTAL SCIENCE CASE STUDY: Managing an Endangered Fishery[27]

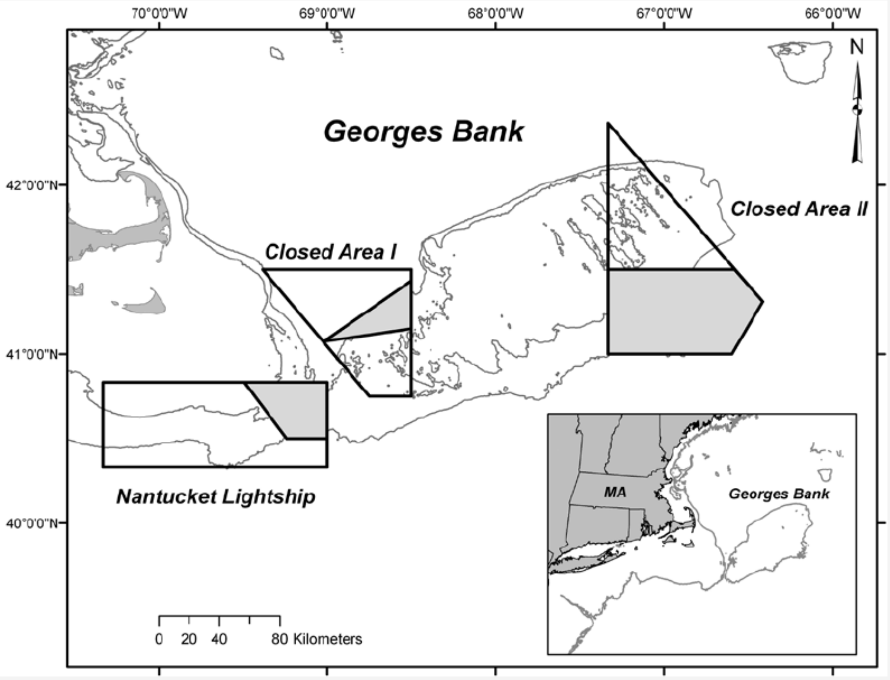
In the late 1990s, Michael Fogarty and Steven Murawski, both then scientists with the National Marine Fisheries Service, collected and analyzed decades of data on the Georges Bank, producing one of the most complete pictures of how fishing has impacted individual species, a complex food web, and an entire ecosystem. Fogarty and Murawski found that variations in which species were harvested and in the total fishing effort led to changes in both the biological communities and the physical habitat in the Georges Bank area.

In the early 1960s, before the two-hundred-mile limit was established, heavy fishing by the foreign fleet reduced the populations of commercial species such as mackerel and herring and led to increased populations of species with little or no commercial value at that time. Once the two-hundred-mile limit was established in 1977, the domestic fishing fleet that dominated the fishery targeted cod, flounder, and haddock, which resulted in the decline of these populations and, at the same time, a return of the formerly targeted species. The recovered populations of herring and mackerel exerted increased predatory pressure on the juveniles of several other fish species, as well as on zooplankton.

Changing fishing patterns also brought about changes in the spatial distribution of species. Before the domestic fleet's heavy fishing of cod, flounder, and haddock, these species were widely distributed throughout the Georges Banks. Today, adults of most of these populations are found in the various "Closed Areas" shown in Figure 76—areas where these populations were originally high and where the most intense fishing once occurred, but which were closed to fishing in 1994 in order to allow species to recover. When these once-rich fishing grounds were no longer available, fishers moved to adjacent areas, where they continued trawling for the various groundfish species. As Fogarty and Murawski point out, trawling for groundfish results in damage to the ocean bottom habitat, which is particularly detrimental to the cod and flounder juveniles that concentrate in bottom gravel. The problem is further exacerbated by large-scale scallop harvesting in these areas, which uses drag nets that greatly disturb the ocean bottom.

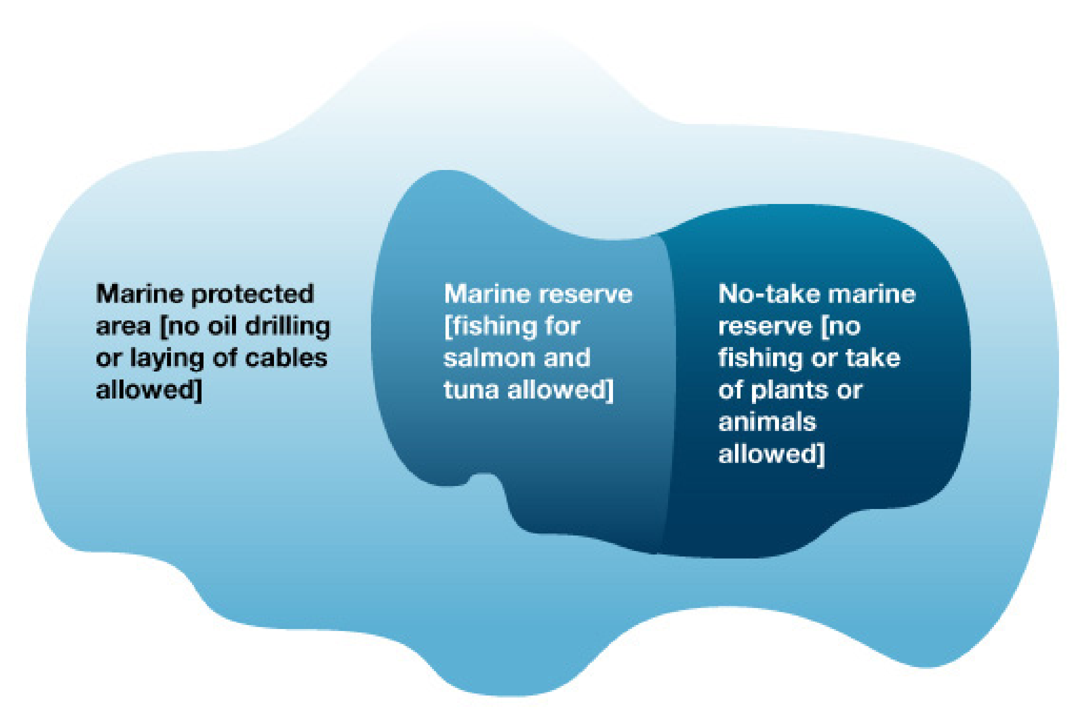
Fogarty and Murawski's study provides clear evidence that intensive fishing will affect not only commercial species, but also other noncommercial species that belong to the same food web. Further research showed that attempts to manage the U.S. Georges Bank from 1982 to 1994 with quotas and control of mesh size

FIGURE 76



*A habitat/**ecosystem approach** to fishery management—"closed areas" in the Georges Bank.*

FIGURE 77



Marine protected area.

Source: Pacific Fishery Management Council in nets failed to reverse the declines in many fish species, partly because these measures failed to account for the disruption in food webs that fishing caused. Only with closures of large areas of important habitat has the decline of commercial species begun to reverse. Fogarty and Murawski's work shows us why long-term monitoring of the population size and distribution of fish species is necessary to improve ecosystem management strategies and restore a sustainable fishery.

Marine fishery management today is building upon studies like that by Fogarty and Murawski to move away from the reliance on quotas and to look at the fishery from a more holistic, ecosystem level. This is being done by expanding the "closed areas" concept—discussed by Fogarty and Murawski—to include large areas of a species' critical ecosystem in systems of Marine Protected Areas (MPAs).

FORESTRY RESOURCES

Principles of Forestry

Forestry, or *silviculture* (from the Latin *silva*, forest), is the management of natural or planted forest ecosystems for human benefit. The management of forest ecosystems is the most analogous to agricultural systems. A forest used for timber is connected to the "natural" ecosystem through the nutrient and water cycles that provide resources and the organisms that pollinate and fertilize the trees. In a commercial forest, humans add inputs—for example, by planting nursery-bred trees—and change the outputs by removing large amounts of timber to the encompassing human-dominated techno-ecosystem. Though the specific products differ, the aims of forestry and agriculture are the same: the domestication and manipulation of ecosystems in order to maximize commercially valuable species. The continued production of wood requires attention to two different concepts: renewability and sustainability. *Renewability* refers to the ability of a piece of land to support continuous *rotations*, the cyclical replanting and harvesting of trees. *Sustainability* means that the various forest species can be maintained over several generations of rotations. Like agriculture, forestry draws on environmental science to aid in achieving these aims.

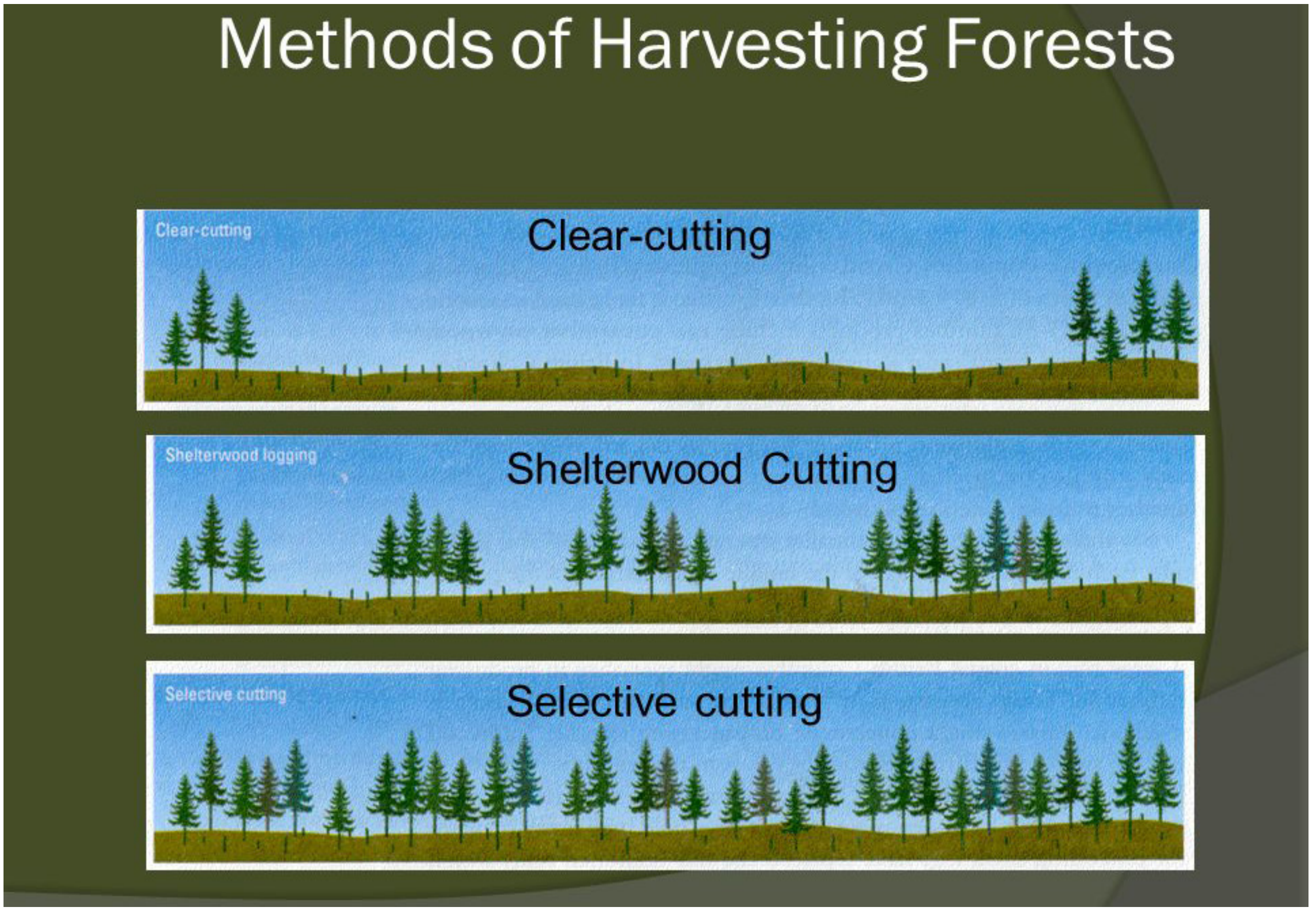
Harvesting Methods

The principal unit of forest management is the *stand*, an area of forest that is relatively homogenous in age, species composition, and physical environment. One of the main determinants of stand structure is the method used to harvest the trees. Though there are several different ways to harvest timber, most fall into one of two main types: even-age and uneven-age harvesting.

In *even-age harvesting*, all the trees that are harvested are of the same age, which requires the removal of all the original trees in a stand, or **clearcutting**. When a stand has been clearcut, regeneration generally results from replanting or reseeding by foresters, producing an even-age tree plantation. Clearcutting is ideal for fast-growing species that need a lot of light to obtain maximum growth rates. It is the easiest harvesting method and, in most cases, the most economical, although it may not be economically efficient when the commercially valuable tree species make up only a fraction of any one stand; this is particularly true in many tropical forests.

Uneven-age harvesting, in which harvested trees are of various ages, is often achieved through the **selective cutting** of single trees or groups of trees. This method creates many small openings in a stand for young trees or seeds to be planted, so the regenerated stand is of uneven ages. Since seedlings and young trees must grow next to larger trees, selective cutting will produce optimum growth only among shade-tolerant tree species. Another method that produces uneven-age harvesting is *shelterwood cutting*, in which a stand is harvested over several years through a series of cuttings. After each cutting, regrowth occurs in the understory so that, by the time of the next cutting, the new generation is large enough to ensure successful and rapid regeneration. Shelterwood cutting is the most complicated method to carry out and, therefore, the least used. The three methods of harvesting have differing consequences for the forest and its surrounding ecosystems. Since selective and shelterwood cutting are less extensive than clearcutting, their environmental effects are less.

FIGURE 78



Methods of harvesting forests.

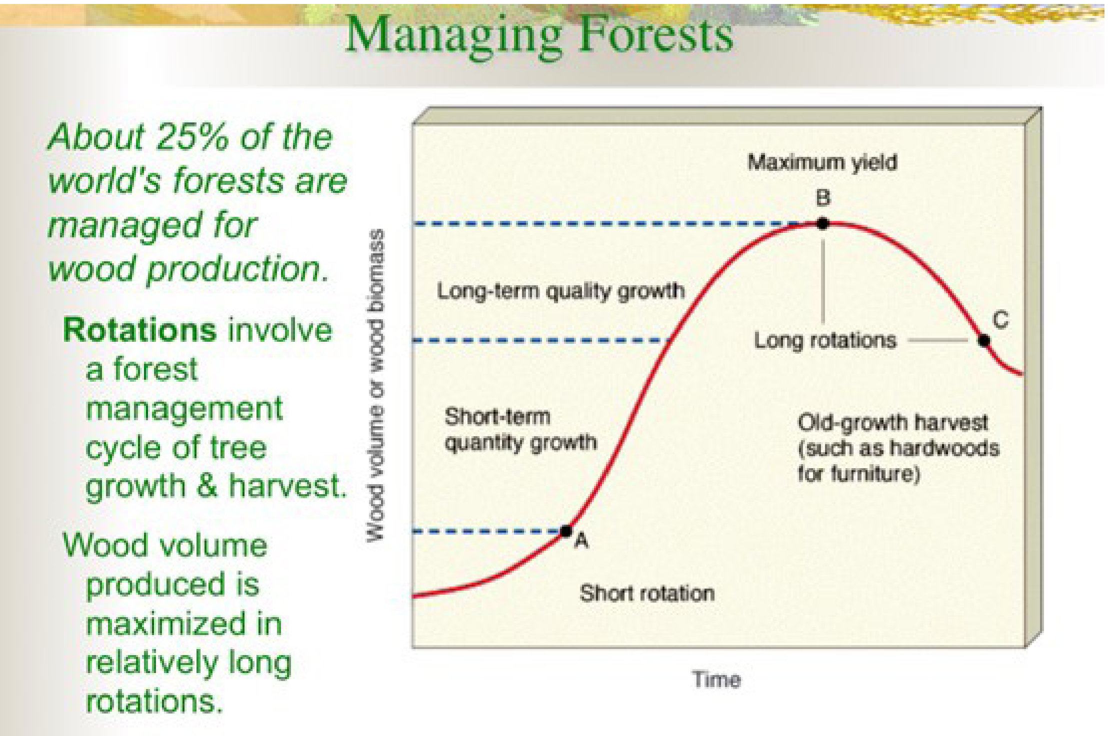
Intensive Forestry

To achieve continuous production of goods and services, foresters have traditionally relied on intensive forestry, which has been the cornerstone of worldwide forest management in both public and privately owned forests. Like intensive agriculture, intensive forestry aims to maximize short-term gain by producing as much timber each year as possible. A number of methods, used separately or in combination, have greatly increased forest growth rates.

Just as animal and plant breeders will select for faster growing cattle or wheat, foresters select and breed fast-growing genotypes. For commercial tree species, a single population or stand will contain most of the genetic variation for that species. For example, a single stand of loblolly pine trees, the major commercial timber species in the southern U.S., will represent 92 percent of the total genetic diversity of the species. By 1992, 90 percent of all new loblolly plantings in the Southern U.S. (about 1.5 million acres) were made up of genetically selected trees, whose growth cycle had been reduced by almost fifteen years over a twenty-year period. Foresters estimate that these trees will show a 12 percent gain in wood volume per harvest over the non-selected trees—which corresponds to more timber and more money per harvest. However, as with agricultural plant crops and animal stocks, over time intensive selection tends to reduce genetic variation and thus reduce fitness. Consequently, foresters try to maintain overall genetic variation, while at the same time continuing to select for desired traits, by using some "natural" trees in a selective breeding program or cross-breeding individuals from different populations.

Vegetation management reduces or eliminates noncommercial plants from a stand, thereby increasing the growth rate of young commercial trees because they no longer have to compete for limited resources. Traditionally, foresters have used herbicides that kill noncommercial species such as deciduous trees, shrubs, and grasses without adversely affecting commercial species. However, as environmental scientists have discovered the effects

FIGURE 79



Managing Forests

About 25% of the world's forests are managed for wood production.

Rotations involve a forest management cycle of tree growth & harvest.

Wood volume produced is maximized in relatively long rotations.

Intensive forestry—achieving maximum sustainable yield.

of herbicides that are introduced into ecosystem pathways, this method has become controversial. Moreover, removing species can have long-term adverse effects on community structure. Noncommerical crops play an important role in the function of a healthy ecosystem—even one as domesticated as a commercial forest stand—by replenishing nitrogen in the soil; aiding in restoration of the stand after a disturbance; and increasing conifers' resistance to insects, pathogens, and fire. Instead of automatically trying to remove all noncommercial species, many modern commercial foresters are attempting to control the density and spatial distribution of competitors through the stand—using them where they are needed and removing them where they are not.

Though intensive forestry has improved forest production, if the focus is only on short-term production and profits, environmental problems often result even when scientific methods are used. Intensive forestry has caused biodiversity losses both directly from the loss of habitat and species and indirectly through the fragmentation of forests into isolated "islands."

Ecologically Sustainable Forestry

Ecologically sustainable forestry is an attempt to address the environmental problems caused by intensive forestry. Aldo Leopold, who helped create this new approach, summarized its goals as treating "land as a community of interacting and interdependent parts, all of which must be cared for." Increasing growth rates remains important, but maintaining species, community, and ecosystem levels of biodiversity is equally so. Therefore, the goal of ecologically sustainable forestry is the maintenance of all species—commercial and noncommercial, plants and animals—in as close to a natural ecosystem as possible. Trees are removed for lumber, but in ways that will not unduly affect the viability of other, noncommercial species. Currently, ecologically sustainable forestry is the stated goal of management by the U.S. Forest Service in American National Forests and is practiced in several, though not all, other countries.

Forestry in the Tropics

Between 1985 and 1990 alone, over 200 million acres of tropical forest were destroyed, and the destruction is continuing at a rate approaching two percent of the total per year.

Tropical forests are not just the lush jungles that we see in movies but are dozens of different types of forests, each a subdivision of the two major tropical forest biomes (see the discussion of biomes in Section II). Tropical forests once covered over 15 billion acres (6.2 billion hectares) of the globe. However, between 1985 and 1990 alone, over 200 million acres (85 million hectares) of tropical forest were destroyed, and the destruction is continuing at a rate approaching two percent of the total per year.

Tropical forests are home to a vast majority of the world's biodiversity. And because they produce many products that are found nowhere else—including rubber, many medicinal plants, various fruits and nuts, and many types of wood—tropical forests are also of great economic value. The consumer demand for fine tropical woods such as mahogany and teak, an $8 billion annual industry, is one of the major causes of tropical deforestation. A further complexity is that most existing tropical forests are in the developing countries of South America, Africa, and Asia, where many indigenous people depend on the forests for water, fuelwood, and land for farming. Any reduction in tropical forestry must be coupled with some way for these indigenous people to earn a livelihood.

In a stand of tropical forest, commercial species usually make up only ten to twenty percent of the trees. Therefore, sustainable commercial forestry in the tropics today must rely on a combination of selective logging in natural forests and the planting of commercial monocultures in plantations. While selective logging leaves the forest canopy relatively intact, it is not without adverse environmental impacts, as the following example shows.

ENVIRONMENTAL SCIENCE CASE STUDY: Selective Logging and Butterfly Diversity in Borneo[28]

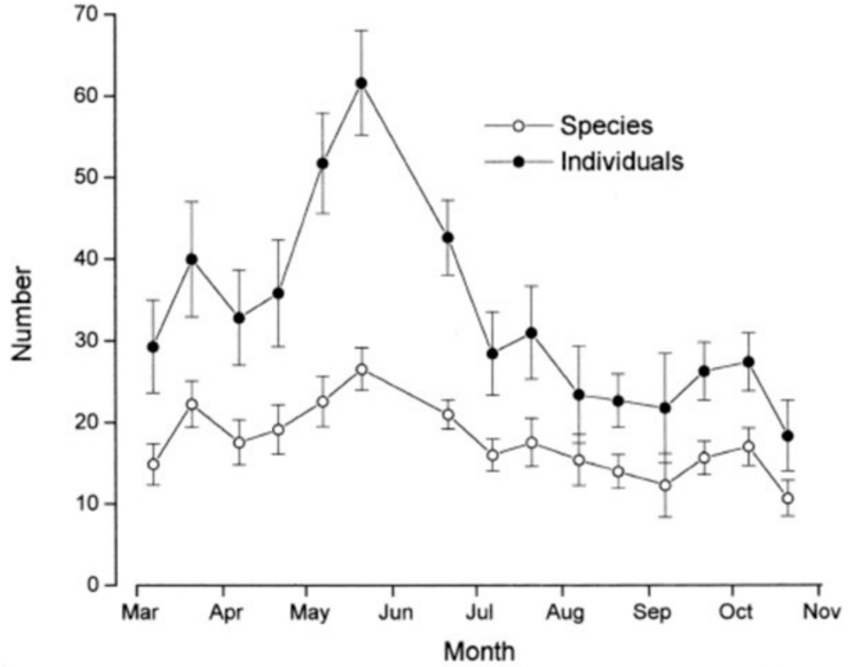
The Borneo birdwing butterfly.

By Notafly - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=11636972

Selective logging is the primary method of logging for timber in Southeast Asia, including Borneo. The selective logging method used in Borneo involves the harvesting of all commercially valuable trees of a specified minimum size. Trees are extracted from the forest by bulldozer or by overhead cable systems. While less destructive than clearcutting, this method does produce collateral damage: a large percentage of smaller trees are destroyed from the logging or road-building operations. In addition, the number and abundance of various vertebrate species has changed after selective logging.

Since forest communities depend upon insects for much of their pollination and other important ecological functions, John Willott and his colleagues studied how selective logging affects the abundance and diversity of butterfly species, which are

FIGURE 80



Changes in the number (mean ± SE) of butterfly species and individuals in bimonthly intervals throughout the sampling period.

Impact of forestry practices on butterfly species in Borneo.

particularly important pollinators. From March to November 1995, Willott and his colleagues studied butterflies in four primary, or non-logged, forest sites; four previously logged forest sites; and two open areas resulting from road construction and other development. The logged areas had been harvested six years earlier, allowing time for the biodiversity to reach a new “normal” level for a disturbed forest area.

The scientists found that the number of butterfly species and individuals fluctuated over the course of the year. Interestingly, there was little variation between logged and non-logged areas in the total *number* of species or individuals of different families (groups of related species) of butterflies. However, there was quite a bit of variation in *which species*, and how many individuals of each species, were found in each area. Some species with large populations in one habitat type were found, if at all, only in low numbers in the other habitat type. So, while selective logging seems to have had little effect on the total species-level biodiversity, it did have a significant effect on community-level biodiversity: the species present changed as the habitat changed.

If you compare these results to the earlier example that focused on the Georges Bank fishery, you can see that both selective logging and selective fishing had the same effect of changing the structure of the biological community even when total biomass stayed roughly the same. While there are many differences among ecosystems that managers must account for, some principles can be applied by environmental scientists to all ecosystems.

North American Forests

Approximately fifty percent of all commercial timber in the world is produced in the United States and Canada.

Despite the prevalence and importance of tropical forests, approximately fifty percent of all commercial timber in the world is produced in the United States and Canada. In these two countries, deforestation is not an issue; there has been an increase in forestlands in both countries over the last several decades. However, these forests are not the **old-growth forests** of past generations but are mostly plantations, primarily in the southern U.S., and new forests growing on abandoned agricultural lands. Biodiversity at both the species and community level is not as great in new forests as in older forests. Further, because there has not been enough time for functioning biological communities to develop in many of these newer forests, they do not provide the same quality or quantity of **ecosystem services** as older forests. And even in older-growth National Forests, several species of plants and animals are endangered or **threatened** by habitat loss through logging. Such environmental concerns are becoming important in the management of North American forests.

North American forest management varies considerably, depending on whether it involves private or public lands. Much of the private forestland is owned by individuals with little or no interest in commercial forestry. At the same time, millions of acres of North American forestland are owned or leased by commercial forestry companies that historically have not been very concerned with the effects of forestry practices on biodiversity and ecosystem functions, though this is beginning to change. By contrast, the management of public forests in the U.S., particularly the National Forests administered by the U.S. Forest Service, is the main global example of how noneconomic values are being incorporated into an ecosystem management program, though not without a struggle.

While logging, recreation, and other human uses are important purposes of National Forests, so is the protection of biodiversity. The National Forest Management Act (NFMA), originally passed in 1982, requires the U.S. Forest Service to “provide for diversity of plant and animal communities based on the suitability and capability of the specific land area in order to meet overall multiple-use objectives….” The Forest Service’s main method of meeting this requirement has been through the establishment of NFMA-based regulations that outline the ecological, economic, and social variables that must be accounted for in planning and carrying out the management of each National Forest under its administration.

Most recently, the Forest Service has created new regulations that capture the concepts and tools of conservation biology that the Sierra Club was trying to force them to use in the 1990s. For the Sierra Club, this is an example of losing the battle, but winning the war.

SECTION III SUMMARY

The Human Population

- The number of people on Earth continues to increase, but the growth rate is slowing. Of the 8 billion people on Earth, roughly one-fifth live in more developed countries, and four-fifths live in less developed countries. The growth rate in less-developed countries is much higher than it is in more-developed countries.
- Each person on Earth has an impact on the environment. The overall effect on the environment is influenced by both the number of people and the quantity and type of resource used per person. Consumption of resources is much greater in more-developed countries than in less-developed countries.
- A number of population parameters can be used to describe the current and future patterns in a population. Fertility rate and **doubling time** give an indication of the growth likely to occur in a population. Life

expectancy and infant mortality are fairly good indicators of the level of health care in a country. Age-structure diagrams allow a view of the current and likely future distribution in the age of a population.

- Exponential growth occurs when there are no limits on a population. Populations growing exponentially increase as a percentage of the numbers already in the population. Arithmetic growth increases by a fixed amount each year, regardless of the population size. Eventually, all populations reach their carrying capacity, and rapid growth stops.
- A variety of biological, social, and economic factors affect population growth and carrying capacity. Countries have undergone transitions from rapid growth to stable population size. The ultimate causes for these transitions are not always known. Ultimately, it appears that social factors are going to limit and reduce the human population on Earth.

Minerals and Soils

- Carbon, hydrogen, and oxygen are the chemical building blocks of life on Earth. Six other elements are essential macronutrients, and seven micronutrients are essential for plant life. Elements move between the atmosphere, biosphere, and soils in biogeochemical cycles.
- The hydrologic cycle—the movement of water through the atmosphere and over the surface of the Earth—carries chemical elements as ions in their aqueous phase. The hydrologic cycle can be summed up as “precipitation = evapotranspiration + infiltration + runoff.”
- The global carbon cycle is the composite of photosynthesis, respiration, decomposition, and combustion. Human activities have a major impact on the carbon cycle, adding large amounts of the element, largely through fossil-fuel use, to what would otherwise be a steady-state process.
- Although the atmosphere is 78 percent nitrogen, the dominant form of atmospheric nitrogen, N_2 gas, is not biologically usable by most organisms. The processes of nitrogen fixation, ammonification, and nitrification convert nitrogen to nitrate or ammonium that plants can use directly. Because nitrogen is the limiting element in many terrestrial systems, the nitrogen cycle is extremely important in the regulation of primary productivity. Excess nitrate can accumulate in soil or leach into water, creating pollution in ecosystems.
- The phosphorus cycle has no gaseous component. Phosphorus comes primarily from rocks and minerals. It cycles with water but is a conservative element, strongly retained by soils and biota. Phosphorus is very important in agriculture. Anthropogenic inputs of phosphorus in aquatic systems, now largely from fertilizer runoff, can cause very destructive **algal blooms**.
- Calcium, magnesium, potassium, and sulfur are other elements important in ecosystems.
- The Hubbard Brook project, underway since 1962, has studied many ecosystem processes including the effects of clearcutting on a small watershed system in New Hampshire. It demonstrates how human activity, element cycling, and hydrologic cycling interact to affect an ecosystem.
- Soils are an important reservoir for nutrients. Soils develop differently depending on five state variables: parent material, climate, topography, organisms, and time. The proportion and composition of soil horizons can vary over small or large distances and are in large part responsible for the character of Earth’s different ecosystems.
- Soils are comprised of sand, silt, and clay particles in varying proportions. Depending on those proportions, soils can have very different properties. Because of the way they affect nutrient availability, a soil’s cation exchange capacity and degree of base saturation are often important determinants of ecosystem productivity. Soil degradation is increasingly widespread around the world.

Water Resources

- Though water covers over 75 percent of Earth’s surface, only about 1 percent of it is available for use by humans and other organisms. Most of Earth’s fresh water is locked up as ice. Of the unfrozen water, the greatest amount is contained in underground aquifers and can be pumped to the surface in wells. Surface fresh water in rivers, streams, ponds, and lakes must be chlorinated and usually filtered before human consumption. Some water is transported over long distances from the original source to the end user, with consequences to the environment it passes through. Desalination removes salt from seawater so that it may be used for drinking in very arid areas and also reclaims water with high salt concentrations resulting from evaporation.

- Cooling for the various kinds of electricity generating plants and irrigation for agriculture are the two greatest uses of water in the United States. Irrigation is also a major use in many other countries around the world. The domestic and public water supply includes both municipal use and household use, categories that are much greater in the United States than in the rest of the world.
- In many parts of the world, drought caused by either natural climatic change or human activity is a common occurrence, often with disastrous consequences. Severe drought can not only kill people and animals directly, but can destroy topsoil, making land unusable for agriculture for decades. Less severe water shortages may result from human overuse or misuse of water supplies. Floods can be equally devastating for humans and the environment.
- Water can be polluted from either point sources or non-point sources. Waterborne disease-causing organisms are relatively common in the developing world. Oxygen-demanding waste becomes a food source for bacteria that decompose it. This leads to a depletion of the oxygen content of a body of water, killing plant and animal life.
- Inorganic compounds such as mercury can be toxic to people and animals directly; others, such as nitrogen, can lead to eutrophication of lakes, which may result in harm to plants and animals. Synthetic organic compounds such as PCBs can be toxic, cause mutations and genetic defects, or interfere with growth and sexual development. Nonchemical water pollutants include sediments and thermal pollution. Oil spills on the oceans have created some of the most extensive environmental contamination in history. Solid wastes such as shoreline litter continue to despoil our shorelines.
- Wastewater from toilets is treated via passage through municipal sewage treatment plants or home septic systems before returning to the natural water system. Gray water from other sources is sometimes reintroduced into the environment without treatment.
- In the United States, water quality is monitored and controlled primarily by the Clean Water Act, the Safe Drinking Water Act, and the Water Resources Development Acts. In general, the water in all municipal water systems in the United States is safe drinking water.
- Because usable fresh water is such a small portion of the global water cycle, human well-being—and perhaps even our lives—may depend on sustainable water use. Individuals can conserve water by using new water-efficient appliances or by behavioral changes such as using drought-resistant landscaping instead of grassy lawns.

Agriculture

- Agriculture is the primary domesticated ecosystem. It has been called a human-dominated techno-ecosystem, receiving inputs from both natural systems and human technology. Beginning roughly 12,000 years ago, agriculture has been a positive force in human history but has changed the environment enormously.
- Traditional agricultural methods such as nomadic herding, slash-and-burn, and intercropping have been used for centuries and still continue in many parts of the world and have relatively low environmental impact.
- Starting in the 1950s, the Green Revolution combined the development of better varieties of domestic animals and crops with the intensive use of fertilizers, management techniques, and machinery to provide food for millions of people, particularly in the developing world.

- The Green Revolution shifted agriculture from small, individual farmers to large-scale agribusiness. Roughly 12 percent of the global land surface is currently under some type of cultivation, with only six crops providing 80 percent of the calories in the human diet.
- As food yield gains resulting from the Green Revolution have begun to taper off, millions of people suffer from starvation, undernourishment, or malnourishment.
- Though the world is producing enough grain to feed its population, many people cannot afford or do not have access to sufficient food, so producing more food alone is not the answer to world hunger. Conventional Western agriculture, a very high-input system, is dominated by agribusiness, particularly a few very large international corporations.
- To increase production as much as possible, conventional agriculture uses a great deal of mechanization and intensive working of the soil, irrigation, monocultures, and synthetic chemical fertilizers and pesticides, all of which are environmentally detrimental.
- The high-density farming of animals allows an extremely high output of meat from a small area of land.
- All these processes involve large inputs of fossil-fuel energy and water; Western agriculture has the highest energy subsidy, or amount of energy expended above the solar energy input.
- Highly technological genetic engineering has enabled humans to modify plants and animals to a degree that goes beyond traditional artificial selection.
- Genetically modified organisms have generated a great deal of controversy, particularly due to concerns related to accidental release to and proliferation in the wild with the possibility of altering or eliminating natural varieties of crops.
- The extensive use of genetically modified seed is already reducing the genetic diversity of food crops. In an attempt to produce enough food to feed the world's population without destroying the land, polluting the environment, or reducing biodiversity, some people are turning to alternative agricultural techniques.
- Sustainable agriculture attempts to combine economic viability with reduced environmental impact, emphasizing the continuation of agriculture on a given piece of land indefinitely. Organic farming, which may or may not be sustainable, uses ecological principles and minimizes synthetic inputs.

Natural Resources—Fisheries and Forestry

- Many of the fisheries, forests, and rangelands in the world are owned and managed by governments. These and other public lands are domesticated ecosystems with unique management requirements that arise from public ownership. In an attempt to avoid the tragedy of the commons, most environmental policy, laws, and management plans for public resources throughout the world have been based on the resource conservation ethic. Public lands are classified by the uses allowed on them. For decades, the principle of multiple use has underlain U.S. public land management.
- Fisheries, like agriculture, are ecosystems manipulated by humans for economic benefit. Natural marine ecosystems are affected by actions and changes within fishery systems. Many of the world's marine fish are in danger of extinction because of overfishing and the introduction of high-tech intensive fishing practices. Because most fishing takes place in international waters, countries are developing cooperative management plans for sustainable fisheries. Individual transferable quotas and exclusion zones are two of the main methods that have helped to reduce overfishing and restore some populations. Technology, such as turtle exclusion devices, can limit loss of by-catch.
- Forests cover approximately 33 percent of Earth's surface. The ancient practice of forestry manages natural or planted forest ecosystems, whether publicly or privately owned, for human benefit—primarily for timber production, with biodiversity protection a secondary, though increasing, interest. Stands of trees are harvested according to various methods, ranging from clearcutting to shelterwood cutting, with differing effects on renewability and sustainability. Intensive forestry, like intensive agriculture, aims to maximize short-term gains by producing as much timber each year as possible.

- Forests in the tropics are home to a vast majority of the world’s biodiversity, and many species are in increasing danger of extinction as tropical forests are cleared for agriculture or development. In developing countries, sustainable forest management plans must include ways for indigenous people to benefit economically. North American forests are increasing, but the replacement of old-growth trees with monoculture tree plantations is removing habitat and endangering biodiversity. While logging, recreation, and other human uses are important purposes of U.S. National Forest management, so is the protection of biodiversity.

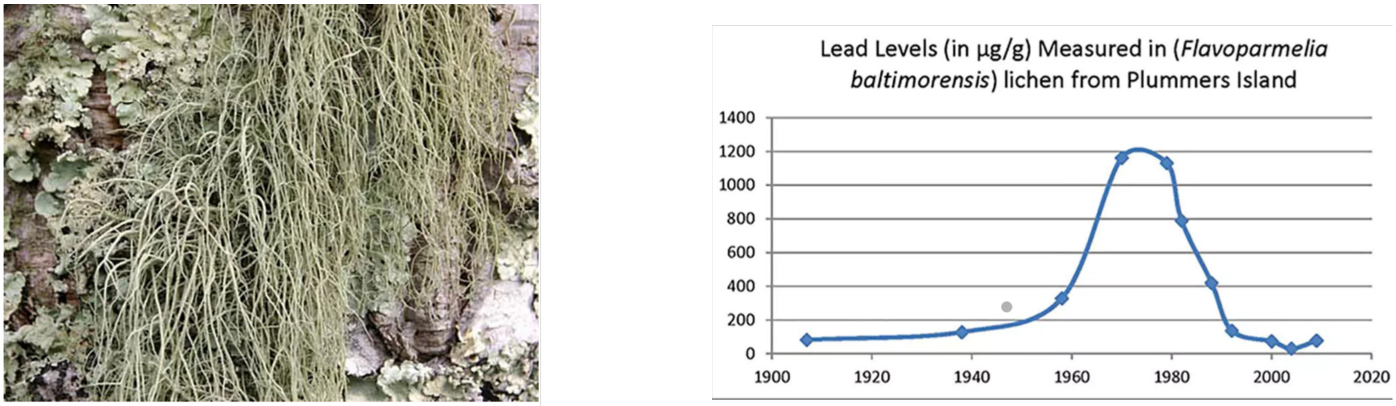
Section IV

Science for a Sustainable Future

AIR POLLUTION AND ATMOSPHERIC SCIENCE

Lichens, the gray-green or orange growths you may have seen on rocks and trees, are a complex **symbiosis** between two separate organisms—a fungus and an alga. The green algal cells (cyanobacteria) live within the fungal filaments and carry out photosynthesis, providing energy both to the alga and the fungal part of the lichen. While fascinating themselves, lichens are also indicators of changes in the levels and ecosystem effects of many air pollutants, particularly sulfur dioxide, nitrogen oxides, ozone, and toxic metals.

FIGURE 81



The pollution-sensitive lichen Usnea ceratina.
Paul Diederich

Lichen as an air pollution indicator.

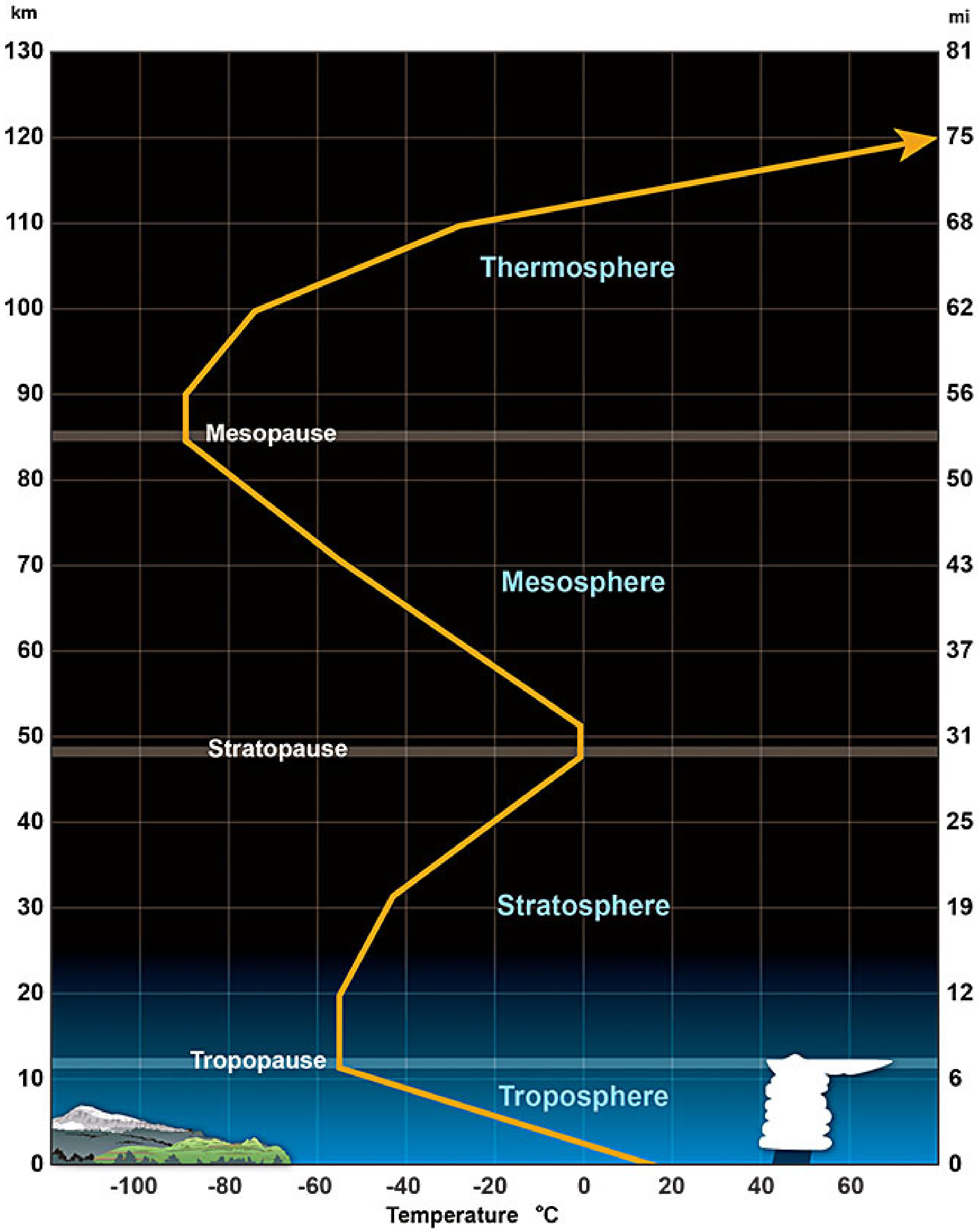
Two characteristics of lichens make them useful as pollution monitors. First, different species of lichens will respond to various pollutants in ways ranging from tolerance to death. The absence of a lichen species in regions where it once existed can indicate that pollutants have increased to levels intolerable for that species. For example, the absence of some species of lichens from the eastern United States (except for parts of Florida and Maine) has been correlated with high levels of sulfur and nitrogen pollutants.

Second, lichens will rapidly accumulate pollutants into their tissue, providing a sensitive bioassay (use of an organism to measure levels of chemicals) for changes in pollutant levels as well as a measure of pollutant effects on ecosystem processes. Lichens are being used as bioassay organisms in many areas, including the South Ural Mountains of Russia, one of the most polluted regions in the world. A team of environmental scientists, led by O. William Purvis from the Natural History Museum in London, used lichens to monitor a major point source of gaseous and particulate emissions—the copper smelter in the town of Karabash.

Unlike sites in the U.S., where the EPA and the Clean Air Act require careful monitoring of both pollutant emissions and biogeochemical uptakes, no data are available in Karabash. To see where the levels of pollutants were highest relative to the emissions source, Purvis and his colleagues transplanted over six hundred lichens from a nonpolluted area upwind of the smelter to areas at various distances downwind. After two and three months, they collected the transplants along with samples of native lichens. Analysis of transplants is a good estimate of short-term pollutant absorption (which reflects short-term variation in emissions), whereas analysis of natives is a good estimate of long-term accumulation of pollutants.

The results of the analyses showed that significant levels of many pollutants, including lead, zinc, and uranium (resulting from radiation exposure), and particulates, such as coal dust, were found in both the transplanted and the native lichens. Further, the closer the transplanted species of lichen were to the smelter, the more likely they were to exhibit tissue damage, which explained why these species were no longer growing normally in the transplant sites and provided a measure for the adverse effects of pollutants on the ecosystem.

FIGURE 82



Layers of the atmosphere.

Source: NOAA

This is but one example of the role of science in monitoring air pollution. In general, science is used to study and manage the impact of air pollution on human health and environmental systems. In this first part of Section IV, we will focus on the environmental system impacts of air pollution—particularly air pollution that results from conventional energy production (e.g., emissions from power plants). Later in the section, we will turn our attention to environmental health, including the human health impacts of air pollution and other sources of environmental contaminants.

Air pollution is the emission of compounds into the atmosphere at levels high enough to harm plants, animals (including humans), and buildings (and/or other nonliving materials) as well as adversely impact the structure and function of ecosystems. Air pollution can be produced by natural sources, such as volcanoes and fires, or by human sources such as automobiles, power plants, and factories. Air pollution usually refers to pollution in the **troposphere**, roughly the first ten km (six miles) of the atmosphere above Earth's surface. Tropospheric pollution is sometimes called ground-level pollution. Other layers of the Earth's atmosphere also contain pollution, but for now we will focus on the troposphere.

Major Air Pollutants

The atmosphere, like most of the oceans, is considered a global commons that is protected by governments that regulate the activities producing air pollutants. Environmental science was used in the development of these regulations, including the U.S. Clean Air Act (CAA) of 1970. As part of the development of the CAA, scientists identified the six most common and widely harmful air pollutants, and these pollutants remain a primary focus of air pollution regulation and are the criteria by which the air in cities, regions, and states is judged to be significantly polluted. These six *criteria pollutants* are sulfur dioxide, nitrogen oxides, carbon monoxide, lead, particulate matter, and ground-level ozone.

Sulfur Dioxide

Sulfur dioxide (SO_2) is a gas released in nature by volcanic eruptions and by humans, primarily through the burning of fossil fuels such as coal and oil. All living things contain various amounts of sulfur, and thus fossil fuels formed from long-ago plants and animals. This sulfur is released when fossil fuels are burned.

SO_2 harms mammalian respiratory systems, including reducing lung function. While this is particularly harmful for people with asthma or other respiratory illnesses, it can irritate the lungs of anyone. Sulfur dioxide can also harm plants, as SO_2 in the atmosphere can undergo a chemical reaction to form sulfuric acid, one of the main components of acid rain.

Nitrogen Oxides

The atmosphere is 78 percent nitrogen gas ($N_{2)}$), and all combustion in the atmosphere leads to the formation of a wide variety of nitrogen oxides (NO_X). Atmospheric NO_X gases can be harmful themselves, but they also play a role in forming ozone and other common components of urban air pollution. Like SO_2, NO_X can undergo chemical reactions in the atmosphere to form nitric acid, which also is harmful to ecosystems.

Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless gas that is formed during incomplete combustion of most organic matter, such as gasoline, which makes it a major part of automobile emissions. Carbon monoxide binds with hemoglobin (an oxygen transporting protein in the mammalian body) and interferes with the transport of oxygen, which—if exposure is high enough—can lead to health impacts such as dizziness, headaches, confusion, loss of consciousness, and even death.

Lead

Lead (Pb) is a naturally occurring element that is part of the Earth's crust and can be found in air, water, and soil. Airborne lead, such as when lead was used as an additive in gasoline and emitted from tailpipes, is only one of the ways that lead may impact humans. The use of leaded gasoline ended in the U.S. in the 1970s and globally in

2021 when the final stocks of leaded gas were used up in Algeria. Lead can also be found in lead-based paint and lead plumbing, both of which can still be found in some homes and communities. Lead, regardless of the source, can adversely impact an animal's blood production, producing anemia but, even more critically, it has been found to have a wide range of adverse neurological impacts, particularly on young children.

Air pollution has a significant impact on human health. Particulate matter is suspected of causing lung cancer and other lung ailments.

Particulate Matter

Particulate matter refers to solid or liquid particles suspended in air. Particulates come from most combustion products, including wood, coal, oil, and gasoline. They are most commonly known as a class of pollutants resulting from "dirty burning" fuels such as coal and oil or low-efficiency wood stoves (which are a major source of air pollution in many northern states and countries). Forest fires and volcanoes are two natural sources of particulates.

Particulates range in size from 0.01 microns to 100 microns in diameter, which is approximately the thickness of the average human hair. Most air pollution particulates are in the 2.5 to 100 micron range with oil smoke on the smaller side (+/– 2.5 microns). Particulates smaller than 10 microns (PM_{10}) can be inhaled and accumulate in the respiratory tract and lungs. Particulates between 10 microns and 2.5 microns are generally categorized as *coarse*. *Fine* particles—those smaller than 2.5 microns ($PM_{2.5}$)—pose a greater health risk than larger particles since they travel further along the respiratory tract before depositing deep in the lungs. Particulates of various sizes are suspected of causing lung cancer and other lung ailments in humans. Particulates also block sunlight. If the atmospheric concentration of particulates is high enough, as it is immediately following a large forest fire or a volcanic eruption, photosynthesis in the region can even be reduced.

Ground-Level Ozone

Photochemical air pollutants (e.g., ozone) are a class of air pollutants that are formed as a result of action by the Sun on compounds that are oxides, such as nitrogen oxide and sulfur oxide. Photochemical pollutants are among the compounds that comprise photochemical **smog**, a comprehensive term that refers to the haze that appears over cities, particularly cities like Los Angeles where surrounding mountains will trap the smog.

The formation of photochemical pollutants is complex, but we can represent it in simplified form as:

$$\textbf{sunlight} + \textbf{NO} + \mathbf{O_2} + \textbf{VOCs (Volatile Organic Compounds)} =$$
$$\mathbf{O_3} + \mathbf{HNO_3}\ \textbf{(nitric acid)} + \textbf{organic compounds}$$

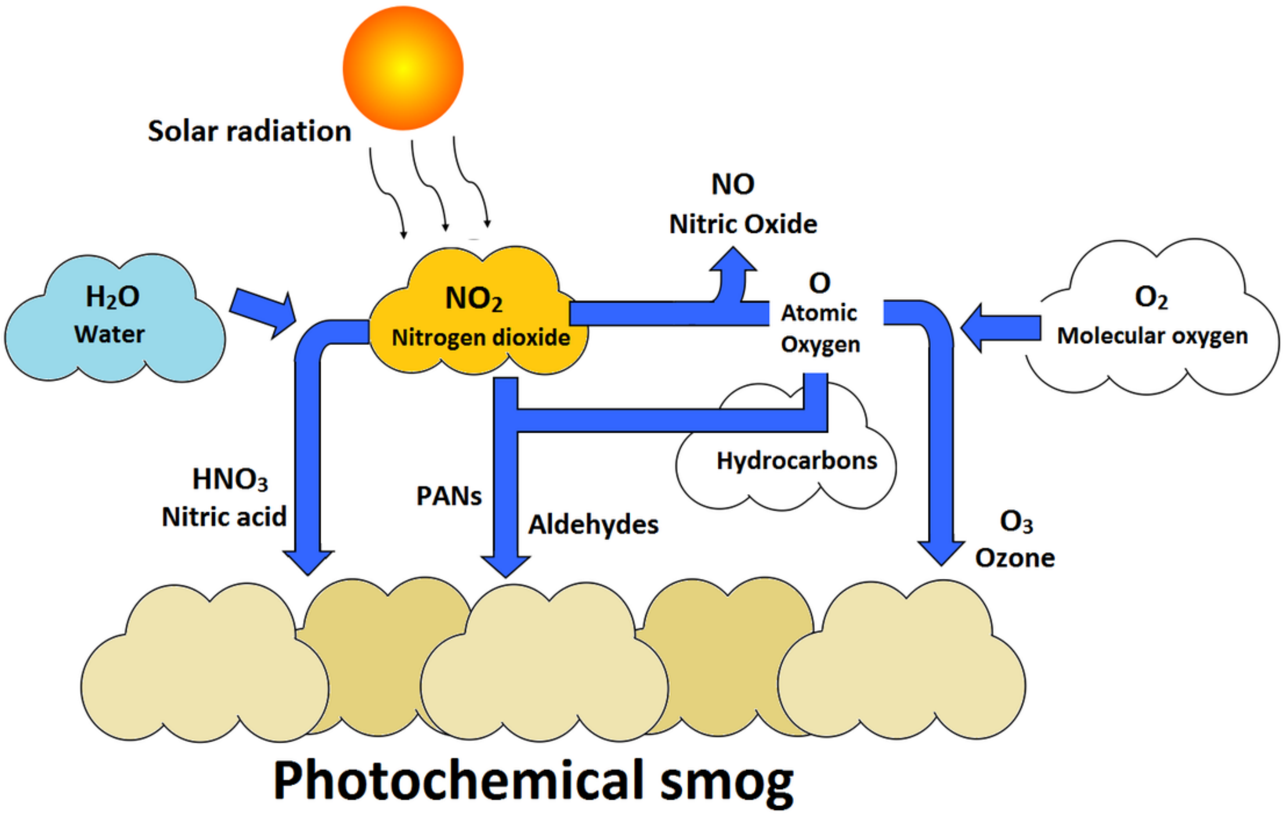
There are many photochemical pollutants, but ozone (O_3)—three oxygen molecules bound together—is the most important for its positive and negative impacts. Ozone forms in the **stratosphere**, where it absorbs ultraviolet light and thereby removes harmful ultraviolet radiation, keeping it from reaching the Earth. In the troposphere (closer to the Earth's surface), ozone is an oxidant harmful to plants and animals. **Volatile organic compounds**, which are human-produced air pollutants that are used and produced in the manufacture of paints, pharmaceuticals, and refrigerants, are another significant component in creating smog.

While criteria pollutants are common air pollutants with known adverse health impacts and are regulated under their own part of the Clean Air Act—the National Ambient Air Quality Standards—there are many other air pollutants, such as mercury (primarily produced through the burning of coal for energy), that adversely impact human health and ecosystems. Many of these pollutants are regulated under different parts of the Clean Air Act, such as the Hazardous Air Pollutant section. Regardless of the regulatory method, the initial step is for scientists to set standards for how much of a certain pollutant should be allowed in the atmosphere (e.g., the ambient air) or can be emitted from a source (e.g., a car or a power plant). These standards are primarily based on the impact of various levels of pollutants on human health (which we will discuss later in this section) or on ecosystems, such as the impact of acid rain on forests and aquatic systems.

Secondary Pollutants

Most of the criteria pollutants are classified as **primary pollutants** because they remain in the form that they are emitted from the power plant, factory, car, or other source. However, some pollutants, such as smog and acid rain, result from chemical reactions in the atmosphere in which primary pollutants are transformed into **secondary pollutants**. Solar energy powers some of these reactions, such as the formation of smog, and they rely on **atmospheric water** and the higher temperatures found near the Earth's surface. Smog is a secondary pollutant—smog is not emitted from a smokestack or tailpipe. Instead, like sulfuric acid and nitric acid, it is created by chemical reactions in the atmosphere.

FIGURE 83



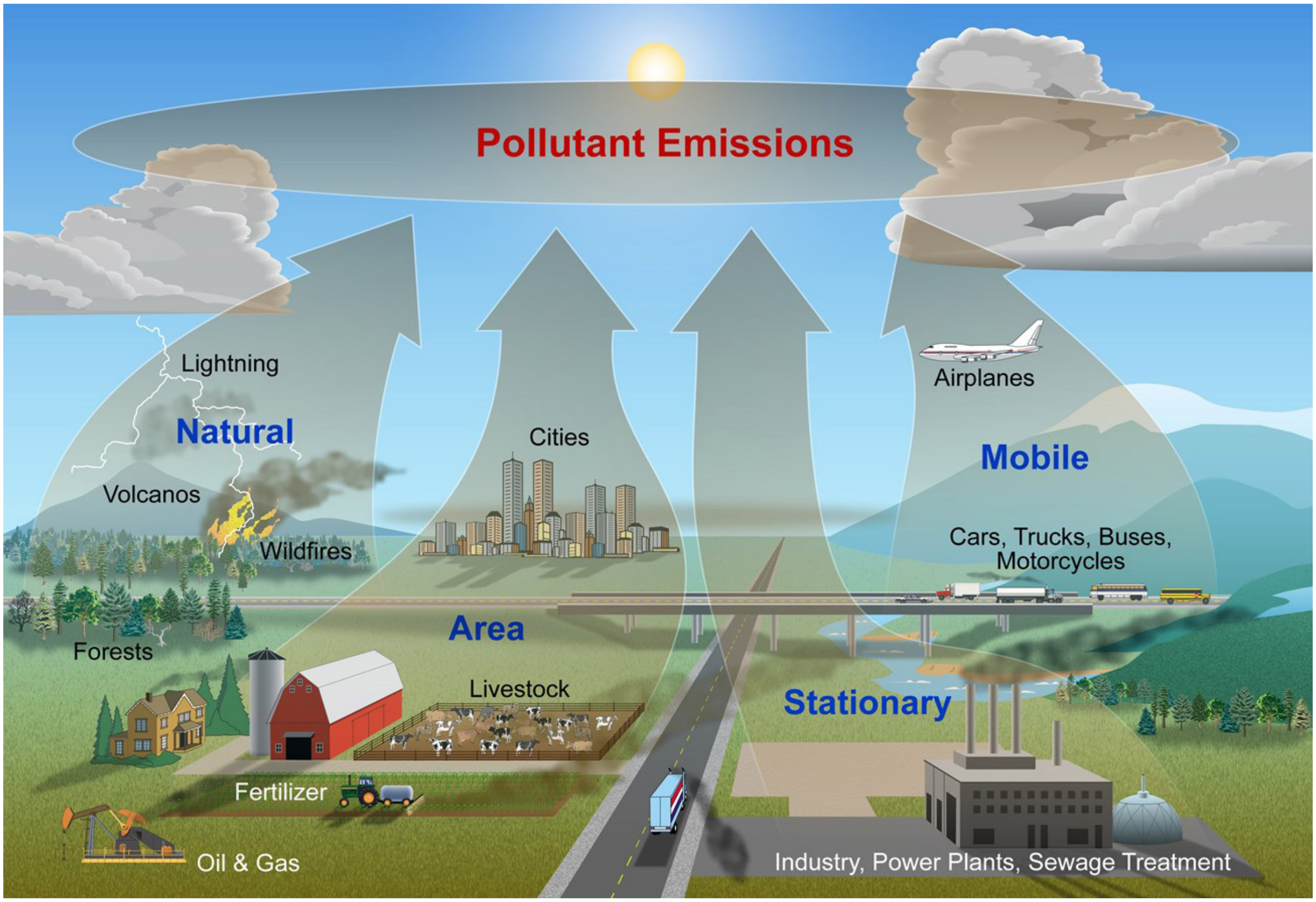
The formation of smog.

Source: University of Calgary: Energy Education

Natural Sources of Air Pollution

Though we tend to think of air pollution as caused by human activity—and most of it usually is—a significant percentage of air pollution comes from natural sources. Volcanoes, forest and grassland fires, living plants, and dead plants all release compounds that can be classified as pollutants. Volcanoes release SO_2, particulates, CO, and NO_X. Forest fires release particulates, CO, and NO_X. The summer of 2023 provided a critical example of how wildfires can impact air quality as wildfires in the Pacific Northwest and, in particular, northern Canada produced high levels of particulate matter and other pollutants, causing extremely unhealthy air quality in much of North America and even impacting Europe. In addition, the 2023 Canadian wildfires more than doubled the previous annual high for Canada's level of carbon dioxide emissions. While we can classify the pollutants produced from these wildfires as "naturally produced," a 2023 study concluded that climate change—mainly due to human-caused greenhouse gas emissions—more than doubled the likelihood of the extreme weather conditions in eastern Canada.[29]

FIGURE 84



Causes of air pollution.

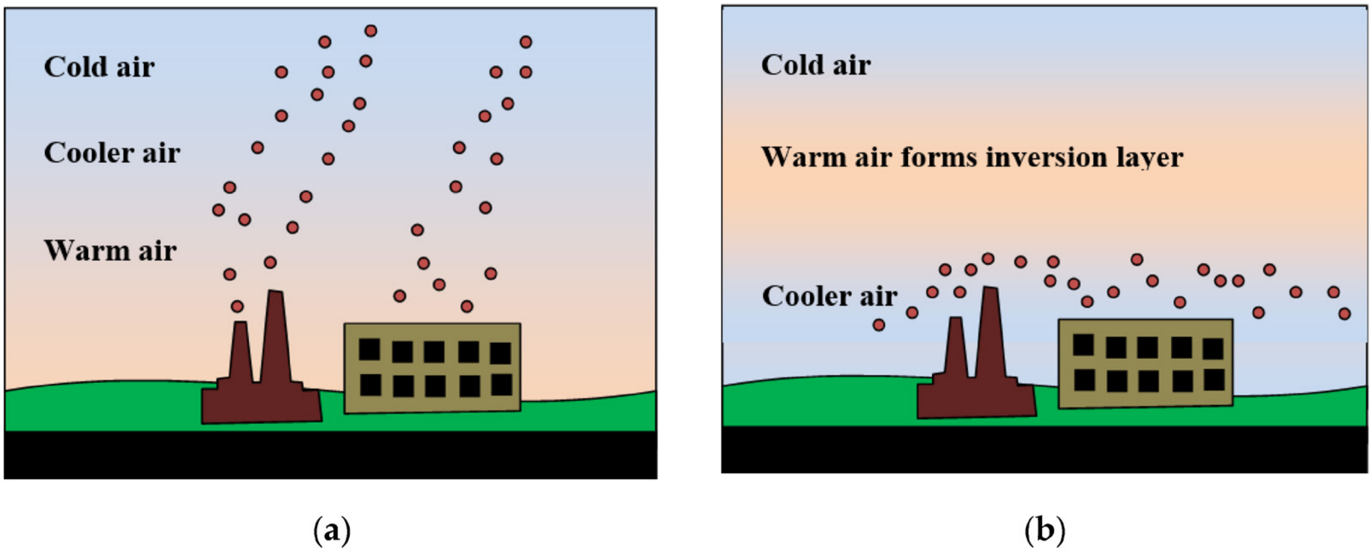
Source: NPS

Even without wildfires, living plants release a variety of VOCs, including ethylene and terpenes (which cause the fragrant smell from conifer trees and the smell from citrus fruits). Long before human-caused pollution was common, the natural VOCs from plants gave rise to smog-like haze and photochemical pollution—hence the names of the forested mountain ranges in the southeastern U.S.: the Blue Ridge and Smoky Mountains. Large nonindustrial areas, such as agricultural fields, can give rise to particulate matter when they are plowed, as happened in the dustbowl of the 1930s. Even the intestinal tracts of domestic livestock contribute to air pollution through the release of methane, a greenhouse gas.

Atmospheric (Thermal) Inversion

Atmospheric temperature contributes to the formation of smog. Normally, temperature decreases with increasing altitude. But when a warm layer of air at mid-altitude blankets a cooler layer below it, an **atmospheric inversion** occurs, and pollutants released at ground level—whether natural or anthropogenic—accumulate in the troposphere, often causing a severe pollution event. Atmospheric inversions are particularly common in cities where high concentrations of vehicle exhaust and industrial emissions are easily trapped by an *inversion layer.*

FIGURE 85



(a) (b)

Temperature inversion.

Source: MDPI

ENVIRONMENTAL SCIENCE CASE STUDY: Using Models to Predict Pollution[30]

In order to develop measures to prevent or control pollution, it is very useful to be able to predict its occurrence and effects. For example, scientists have shown an association between exposure to photochemical smog and the incidence of childhood asthma. One tool that helps researchers understand where the greatest incidence of asthma will occur is the *predictive air pollution model*. Given certain known conditions, researchers can predict where pollution concentrations will be greatest, and public health officials can concentrate their efforts on asthma education and prevention in those areas.

Mathematical modeling is one of the key methods used by environmental scientists to predict how various emission limitations affect distribution from pollution sources. In fact, the use of mathematical models is so important in this area that the Clean Air Act makes models the preferred method of estimating emission distribution, and they are a required component of most state implementation plans. Models are critical because it is not possible to collect enough data from enough different sites and enough different times to make accurate predictions.

Because pollution levels and distribution are a function of both the individual characteristics of the source—such as smokestack height or production per hour—and local topography and weather patterns, no one model can be used to predict emission levels and pollution distribution for all types of sources in all places. To address this problem, environmental scientists have collected, tested, and modified several models that can be used in different situations. Many models use equations based on the known physical relationships between the movement of pollutants and various weather/topographical variables. Some of the models approved by the EPA include those that model the emissions release and downwind movement from aluminum reduction plants and similar sources; estimate concentration of pollutants from highway traffic; model the dynamic ways that weather conditions vary over time and location to affect pollutant transport; and account for the settling and deposition of particles as a function of downwind distance, separation of individual point sources, and more.

ENERGY USE AND SOURCES

Units of Energy

The British thermal unit (Btu) is the most common unit for the comparison of energy sources. One Btu is the quantity of heat required to raise the temperature of one pound of liquid water by 1º Fahrenheit (F) at the temperature water has its greatest density (approximately 39º F).[31]

Below are the amounts of energy, in *Btu*, from some common sources of energy:

- 1 barrel (42 gallons) of crude oil produced in the United States = 5,684,000 Btu
- 1 gallon of finished motor gasoline (containing about 10 percent fuel ethanol by volume) = 120,214 Btu
- 1 gallon of diesel fuel or heating oil (with sulfur content less than 15 parts per million) = 137,381 Btu
- 1 gallon of heating oil (with sulfur content at 15 to 500 parts per million) = 138,500 Btu
- 1 barrel of residual fuel oil = 6,287,000 Btu
- 1 cubic foot of natural gas = 1,036 Btu
- 1 gallon of propane = 91,452 Btu
- 1 short ton (2,000 pounds) of coal (consumed by the electric power sector) = 18,820,000 Btu
- 1 kilowatt-hour of electricity = 3,412 Btu

As you can see from the above list, one Btu is a small amount of the energy consumed by a household, let alone a nation; in 2021, the United States used about 97 *quadrillion* Btu of energy. One quadrillion can be written out as a 1 followed by 15 zeros: 1,000,000,000,000,000.[32] For large amounts of energy, we will use *quadrillion Btu* or *quad Btu*, for short.

Worldwide Patterns of Energy Use

Figure 86 shows the global consumption of the major energy sources from 2017 to 2021.

FIGURE 86

Global Energy Consumption (in quad Btu)	2017	2018	2019	2020	2021
Total Consumption	584.674	598.521	600.899	576.605	603.321
Coal	164.109	165.807	164.191	158.757	166.72
Natural gas	136.81	143.77	146.138	143.292	150.35
Petroleum and other liquids	196.802	198.201	197.23	178.963	186.714
Nuclear	26.237	26.784	27.773	26.968	28.031
Renewables and other	62.032	65.295	66.917	69.794	72.842

Global energy consumption.

In 2010, China passed the U.S. as the major energy-consuming country in the world and in 2021 consumed 165.168 quad Btu compared to the U.S.'s 97.907 quad Btu.

The Current Fuel Mix in the United States

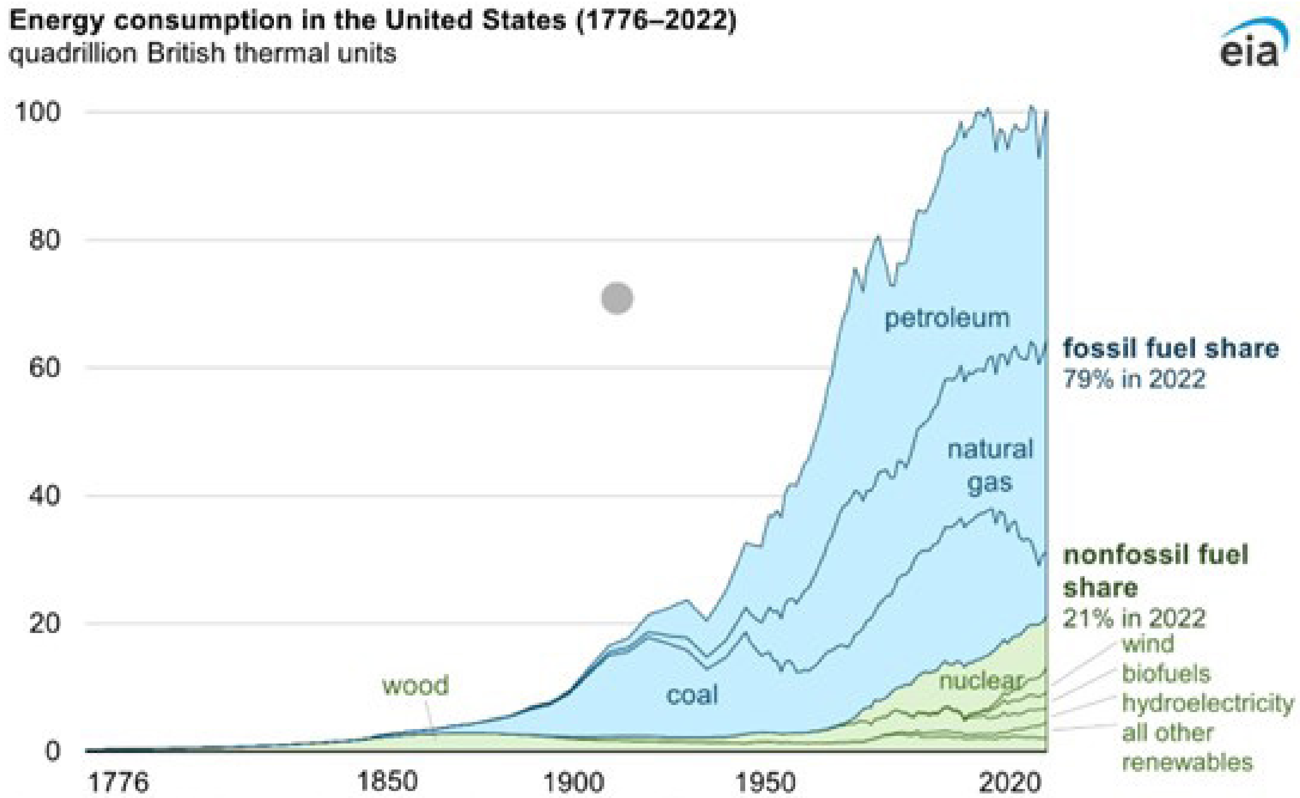
We can consider the energy requirements and end uses in the United States today as the inputs and outputs of an enormous system. The boundaries of the system are both physical (the borders of the country and the ground) and social/technological. For example, oil inputs enter the U.S. energy system both from other countries and from beneath our own soil. Hydropower comes from flowing water within the physical boundaries of the country, but it is not an energy input until we move it to a technological system (a hydroelectric dam). Outputs from the system are not energy moving out of the country but rather the end use of the energy—again, a movement from a raw form (say, oil) to a human use (transportation).

Figure 88 shows energy consumption by source in the United States in 2022 (in which total energy consumption rose to 100.41 quad Btu from the 2021 level) and also shows the end use sector (what the energy sources are being used for). In 2022, 79 percent of energy consumed came from fossil fuels: coal, petroleum, and natural gas; 8 percent from nuclear power; and 13 percent from renewable energy. The patterns in other developed countries are fairly similar, although specific details vary since countries tend to utilize the resources that are most abundant and local. Energy use in the developed world, however, is not typical of the world as a whole.

FIGURE 87

JUNE 29, 2023

Nonfossil fuel energy sources accounted for 21% of U.S. energy consumption in 2022



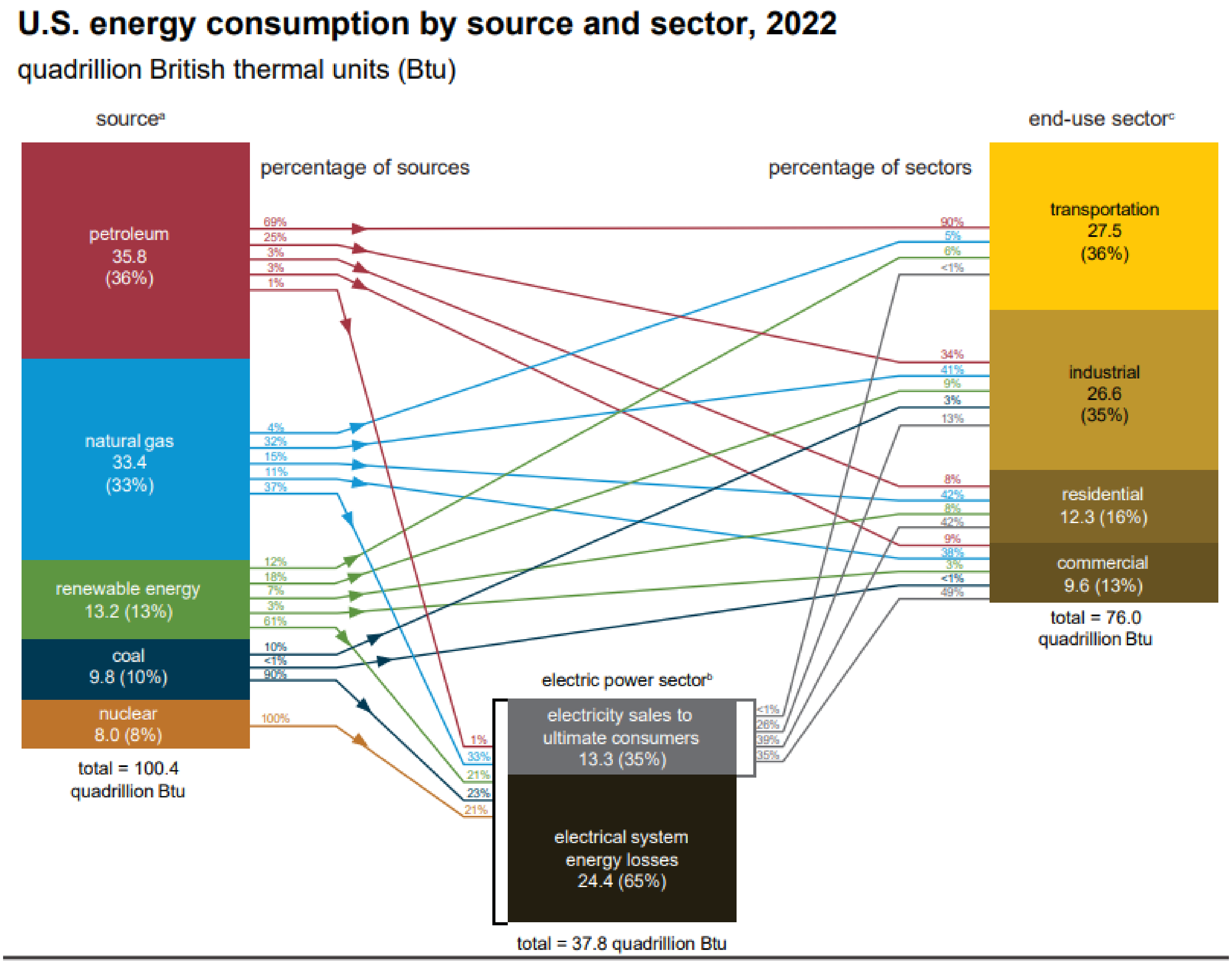
Data source: U.S. Energy Information Administration, *Monthly Energy Review*

Primary energy consumption in the United States was 100.4 quadrillion British thermal units (quads) in 2022, a 3% increase from 2021. About 21% of U.S. energy consumption in 2022 came from nonfossil fuel sources such as renewables and nuclear—a tie with 2020 as the highest share since the early 1900s, according to data in our *Monthly Energy Review*. Fossil fuels—petroleum, natural gas, and coal—accounted for 79% of total U.S. energy consumption in 2022.

U.S. Energy Consumption, 1776–2021.

Source: EIA

FIGURE 88



U.S. Energy Consumption in 2022.

Source: EIA

Nonrenewable fuels are those that have a finite amount present on Earth, at least in the context of thousands of years. If we wait long enough, more coal or oil will form, but this will take millions of years. For our purposes, coal, oil, and natural gas are nonrenewable. Uranium is also nonrenewable because as an element, the total amount of uranium on Earth is decreasing. Renewable fuels are those that are replenished by a process such as the shining of the Sun, the blowing of the wind, or precipitation. By definition, the use of fossil fuels is not sustainable because future generations will not have access to these fuels if we completely use them up over the next few decades.

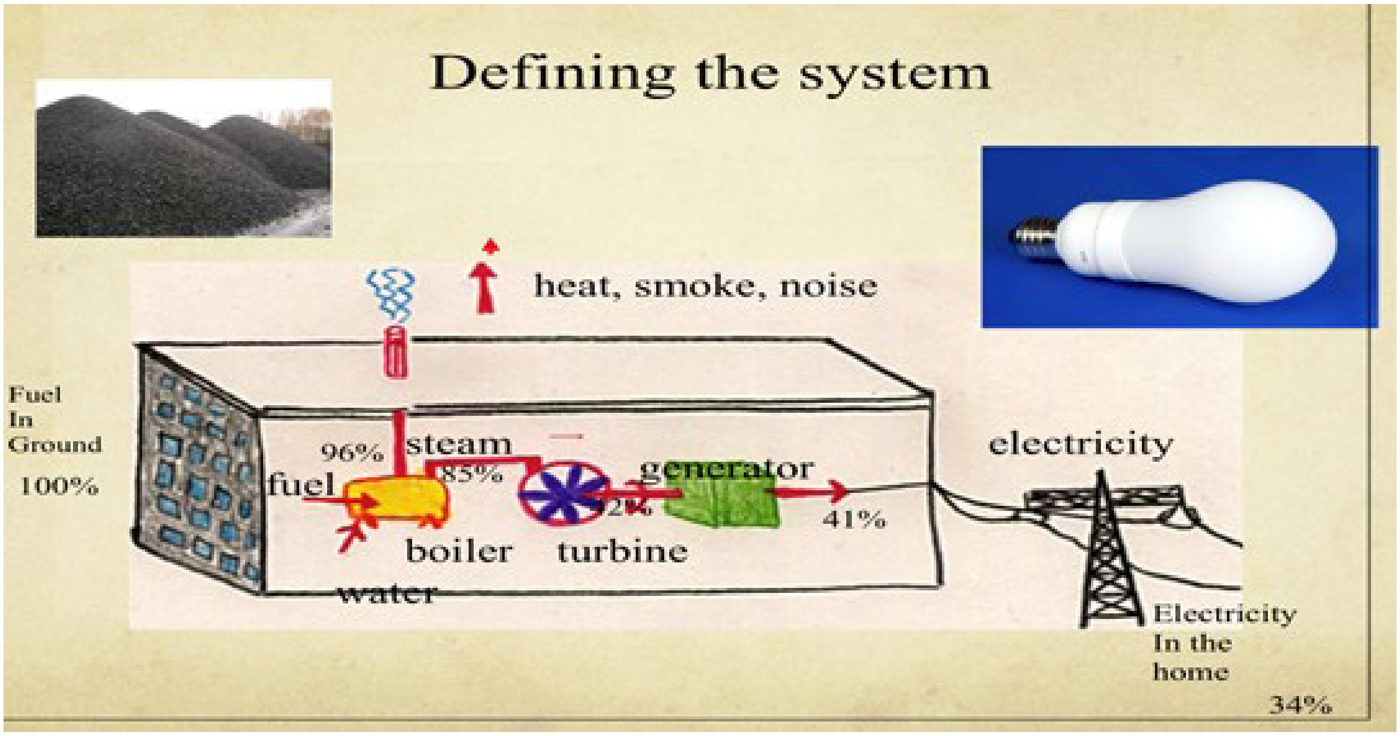
Fuel mix varies by region of the country and time of the year for certain sectors. For example, energy-intensive industries in the central U.S., such as steel manufacturing, use coal to produce the energy needed for production and as a component in the manufacture of the steel, making steel production one of the most carbon-intensive industries. In contrast, high-tech electronics industries in California and the Pacific Northwest use electricity from predominately renewable energy sources. For electricity generation, more coal is burned in the Midwest and Southeast than in the Northeast, which uses more nuclear, natural gas, and hydropower for electricity generation. These trends have to do mostly with where the resource exists (more coal is found in the Midwest than in other parts of the country, for instance). Also, coal combustion for electricity, which creates the most air pollution, is less common in areas of high population density. In northern parts of the United States, more oil and natural gas are used during the winter months to meet demands for heating than in summer.

Energy Efficiency

The goals for energy use in a sustainable society are to increase efficiency while reducing costs and pollutants. Because we use energy in a variety of ways and for a variety of purposes, it's a challenge to evaluate how well we achieve different tasks. By quantifying energy conversions from one form to another, and by quantifying how efficiently we use the converted energy, we can get an appreciation for how effectively we use energy, including the efficiency, financial cost, and the amount of pollution produced for a given task.

Energy efficiency is a measure of how effective we are at getting usable work from a given input of energy (i.e., the amount of energy or work output—in the desired form—divided by the total energy input). No energy source is ever 100 percent efficient; some energy is always lost at each conversion, usually as heat leaving the system. Figure 89 shows a coal-energy system from the point of coal extraction to the point of turning on a light at home. At each step in the process, some energy is lost. By the time you turn on the light, you only have 34 percent of the energy that you started with at the coal mine. And the more steps there are in the process of turning an energy source into work, the more opportunities there are for a loss of energy and the more *inefficient* the system is. Overall, the United Nations Development Program World Energy Assessment (2015) estimates that global energy efficiency is about 37 percent.

FIGURE 89

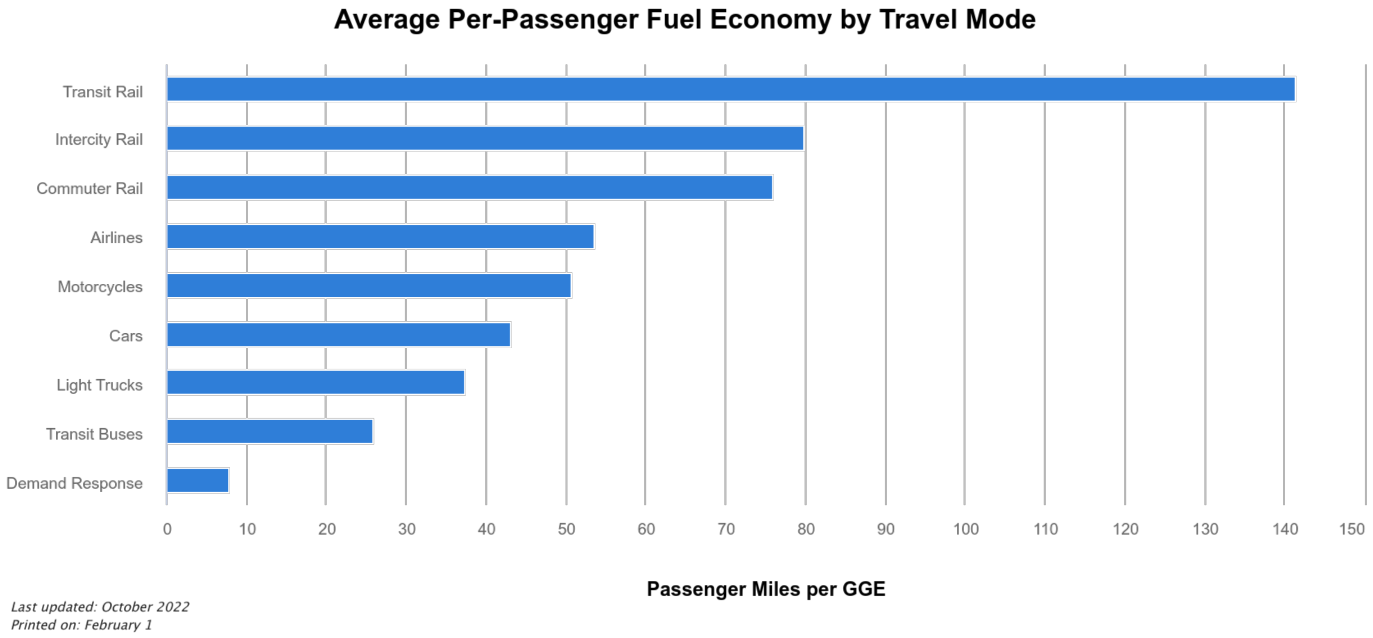


Energy efficiency of a coal to electricity system.

Energy Use for Transportation

Transportation—personal travel by automobile, bus, train, airplane, and ship, as well as the distribution of goods by these vehicles—accounts for about 36 percent of the total energy used in the U.S. and over two-thirds of oil use. In addition, gas-powered vehicles contribute to much of the country's air pollution and greenhouse gas emissions. While driving a gas-powered car is relatively energy inefficient because of the loss of energy at each stage from drilling for oil to burning gas in an engine, there are other factors to consider in calculating the efficiency of any means of transportation, including how many people travel in a given vehicle and the relative efficiencies of different types of mass transport.

FIGURE 90



Fuel economy by travel mode. GGE is gasoline gallon equivalent, which is the amount of energy contained in a gallon of gasoline.

Source: U.S. Department of Energy

We can start by defining the "work" we want. For personal transportation, we need to transport a person from Point A to Point B by train, bus, airplane, or car. Figure 90 shows the average fuel economy per passenger for different means of travel. Note that the energy values report only energy consumed per passenger mile traveled and do not include the energy used to make the cars, trains, or planes.

To better under the impact of various forms of transportation, let's work through the example of an automobile with a driver and no passengers. The average car in the United States can travel 25 miles on one gallon of gasoline, so we can state that the driver travels 25 passenger miles per gallon. A gallon of gasoline contains 113,738 Btu of energy. Therefore, 113,738 Btu / gallon divided by 25 passenger miles per gallon gives 4,550 Btu per passenger mile. If four people were in the car, we would divide by 100 passenger miles (4 people each traveling 25 miles). For the purposes of this example, we'll assume that the distance the car travels on a gallon of gasoline with four people is the same as with one person, although it might be slightly less because of the added weight. The same calculations can be made for the other modes of transportation, including an assumption of the average occupancy for trains, buses, and airplanes. As you can see, modes of transportation that include more people are more efficient—they will take people farther (the work output) for the same amount of energy used.

Finding the Right Energy Source for the Job

When deciding between two energy sources for a given job, or between two different ways to achieve a given task, it is essential to consider the thermal efficiency as well as the overall system efficiency. An excellent illustration of this principle is the home hot water heater. Electric hot water heaters are often described as being 100 percent efficient. Even though the Second Law of Thermodynamics tells us that it is impossible to be 100 percent efficient, electric water heaters come very close. This is because heat, which is usually the waste product that reduces the efficiency of an engine, is the intended product of the electrical energy conversion. If the conversion from electricity to heat occurs inside the tank of water, which is usually the case with electric hot water heaters, so little energy is lost that we can say the thermal efficiency is ~100 percent. (In a hot water heater, there are no accessory functions, such as running the drive train or turning the wheels of the car, so the thermal energy and the machine energy are the same.)

Animal dung can be burned in an open fire and a pot heated directly from the flame.

By ק.עיש - Own work, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=10359518

There are often two or more fuels that can serve the same function. The source that provides the desired work with the fewest energy conversions is the best match, or the most efficient energy source for a given task. Cooking food indoors, for example, can be achieved with a variety of fuels. Animal dung can be burned in an open fire and a pot heated directly from the flame. Wood can be burned under a stove, heating an entire stove-top. Natural gas can be burned directly under the pot. And an electric coil underneath a pan can heat it. Without doing any calculations, we can compare the number of steps involved in cooking with natural gas, wood, or animal dung:

Combust natural gas, wood, or animal dung → heat food

Now, let's consider the steps involved in cooking with electricity:

Combust coal, sustain a nuclear reaction, etc.→→ heat water→ produce steam → turn turbine → generate electricity → transfer to home → electric stove top → heat food

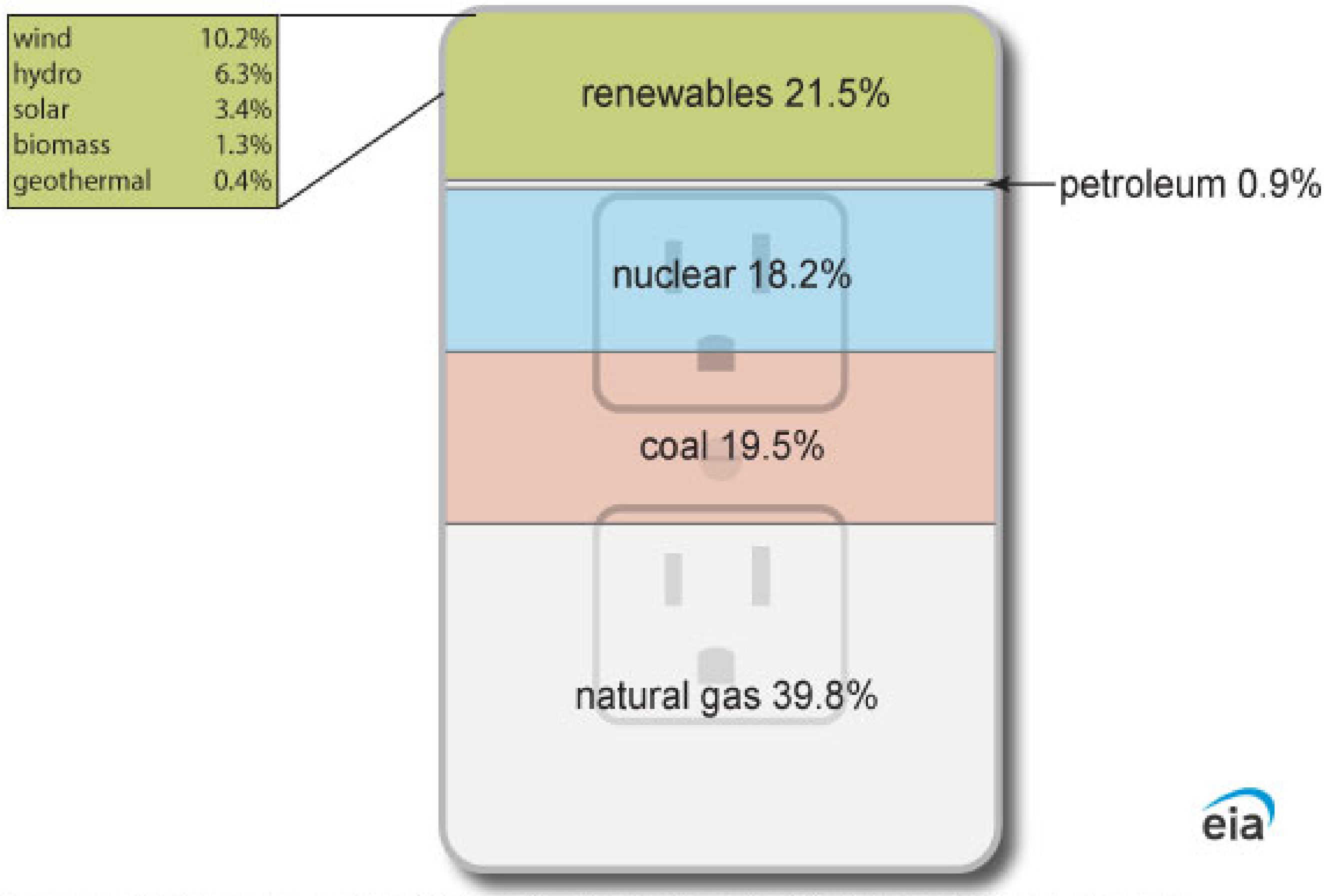
Clearly, with only one energy conversion compared to seven, cooking with gas or biomass is a much more energy-efficient process.

So far, in talking about the various sources of energy that power modern society, we have treated electricity as a part of the mix that is comparable to the other sources. It is important to realize, however, that although electricity does provide energy, it is not the *original* source as biomass or oil are. In other words, electricity is an energy source but not a fuel. We use a variety of fuels to generate electricity.

Generating Electricity

The non-renewable energy sources discussed above—and the renewable energy sources we will discuss later—are *primary* energy sources. However, the electricity that we use to power our lights, EVs, electronics, and much of our modern society is a *secondary* energy source that is converted from a primary source. Electricity-

FIGURE 91



Sources of U.S. electricity generation, 2022

Total = 4.24 trillion kilowatthours

Data source: U.S. Energy Information Administration, *Electric Power Monthly*, February 2023, preliminary data

Note: Includes generation from power plants with at least 1,000 kilowatts of electric generation capacity (utility-scale). Hydro is conventional hydroelectric. Petroleum includes petroleum liquids, petroleum coke, other gases, hydroelectric pumped storage, and other sources.

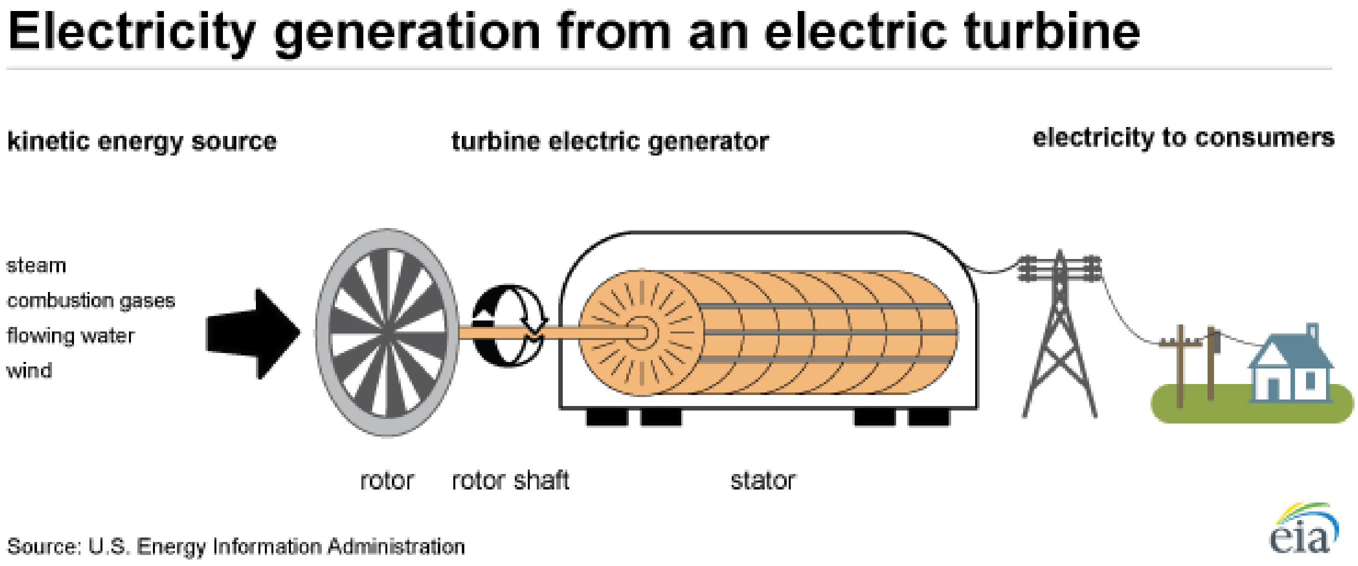
Sources of U.S. electricity generation, 2022.

Source: EIA

generating powerplants convert the chemical **potential energy** of a number of fuels into electrical potential energy (electricity). The basic process is the same, regardless of the fuel. Non-renewable energy source-powered plants use coal, oil, natural gas, or radioactive fuel rods to produce steam, which turns a turbine, which turns a generator. The electricity generated is then transported along power lines and converted to heat energy for cooking, **kinetic energy** for running motors, and radiant energy for powering lights. As we will see later, renewable energy sources—such as wind and the flow of water in a hydroelectric dam—can also be used to drive a turbine.

Most older, conventional electricity-generating plants have an efficiency of about 36 percent. Newer coal-burning plants may have efficiencies of up to 42 percent. Efficiencies of over 50 percent are possible for coal-fired systems but are not commercially feasible at present. An improvement in gas-combustion technology has led to the combined cycle natural gas-fired power plant, which can achieve efficiencies of 60 percent, making this system highly desirable.

FIGURE 92



Electricity generation from an electric turbine.

Source: EIA

The Power Grid

Electricity-generating power plants are located throughout the country in a large, somewhat amorphous delivery system called the electric *power grid*. The grid loosely connects the plants to one another and to all the homes in a given area. For example, the northeastern United States is part of one grid; California, Oregon, Washington, and many of the Rocky Mountain states belong to another grid. When one electric powerplant is operating and generating electricity, it sends its output over the power lines. Most likely, electricity users near the plant utilize the electricity. But if the plant is generating more electricity than local users need, the electricity is transported along the power grid to users farther away. For example, when there is a summer heat wave in Boston, it is likely that powerplants in cooler Maine are sending some electricity south, perhaps preventing blackouts and brownouts that occur when energy consumption is greater than the amount of energy that can be provided. Likewise, a cold spell in Oregon might result in electricity from California being transported northward.

Any number of power plants contribute to the electricity grid. The mix of fuel sources that provide electricity in any given locality varies by region of the country and by country throughout the world. Coal-fired plants were the backbone of electricity generation in the United States, responsible for approximately 50 percent of all electricity produced as recently as 2005. However, that dropped to only 19.5 percent by 2022. Nuclear power plants make up 18 percent of electricity generation in the U.S., while natural gas has gone from contributing only 15 percent of electricity generation in 2000 to almost 40 percent in 2022.

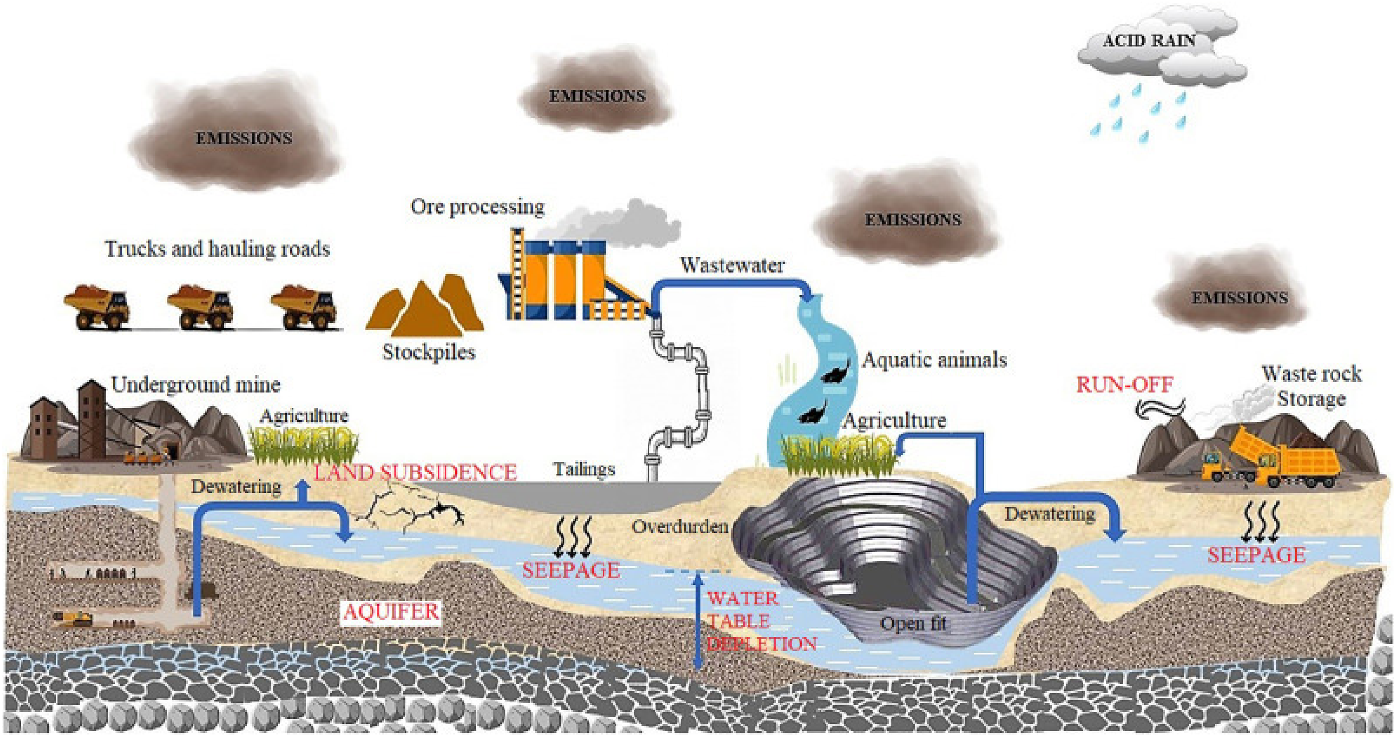
Nonrenewable Energy Sources

Coal

Between 160 million and 400 million years ago, tropical plants growing in swamps and marshes were covered by sediments. Because the rich organic matter was buried, decomposition was limited. High pressure and temperature and eons of time compacted the organic matter into the dense, energy-rich carbon material that we know as coal. Because of this origin, coal is called a fossil fuel. There are several different kinds of coal, representing the different amounts of time and pressure needed for formation; classified from lesser to greater energy content, they are peat, lignite, bituminous coal, and anthracite.

Because coal is very energy dense and plentiful, it is ideal for the generation of electricity and for industrial processes such as making steel. Coal is mined in two general ways: deep shaft mining and surface mining. In deep-shaft mining, tunnels are dug into the Earth, perhaps as deep as 2,000 feet, and people descend into the shafts, dislodge the coal, and bring it to the surface. Surface mining comes in many forms, from digging a pit to removing a mountaintop. Coal extraction can result in major adverse environmental impacts, including the emissions of several harmful air pollutants, including sulfur dioxides, particulate matter, and mercury, and mining degrades water quality of nearby streams, creating an environmental problem called acid mine drainage.

FIGURE 93



Environmental impacts of coal mining.

Petroleum

Petroleum—the mixture of **hydrocarbons**, water and, usually, sulfur that occurs in underground deposits—is also a fossil fuel. In contrast to coal, petroleum formed from the remains of ocean-dwelling plankton that were preserved roughly 65 to 250 million years ago. It occurs in certain locations with porous rocks, such as sandstone, that are capped by nonporous rock. The petroleum filled the pore spaces in the rock, geologic events deformed the rock layers so that they formed a trap, and after millions of years, the petroleum migrated upward toward the highest point in the rock.

Petroleum must be extracted with wells, drilled on land and under water, and pumped from the ground, except in specific locations where it flows out under pressure from drilling. Petroleum contains natural gas as well as oil; when the gas is separated out, the remaining product is known as liquid petroleum or *crude oil*. Crude oil is further refined into a variety of compounds that are separated by weight, including, among others, gasoline, diesel fuel, and kerosene.

Oil

Petroleum is currently the greatest energy source in the United States, although natural gas has closed the gap. It is extremely convenient, relatively energy dense, and clean burning compared to coal. Sulfur and other impurities can be removed from oil before combustion, although the lower-sulfur-content oils are generally more expensive to manufacture and thus more expensive to purchase. Since it is a fossil fuel, oil will release carbon into the atmosphere when burned, although only 85 percent as much as coal when producing the equivalent amount of energy. In addition, as we discussed in Section III, oil spills of all sizes are a significant source of water pollution.

Natural Gas

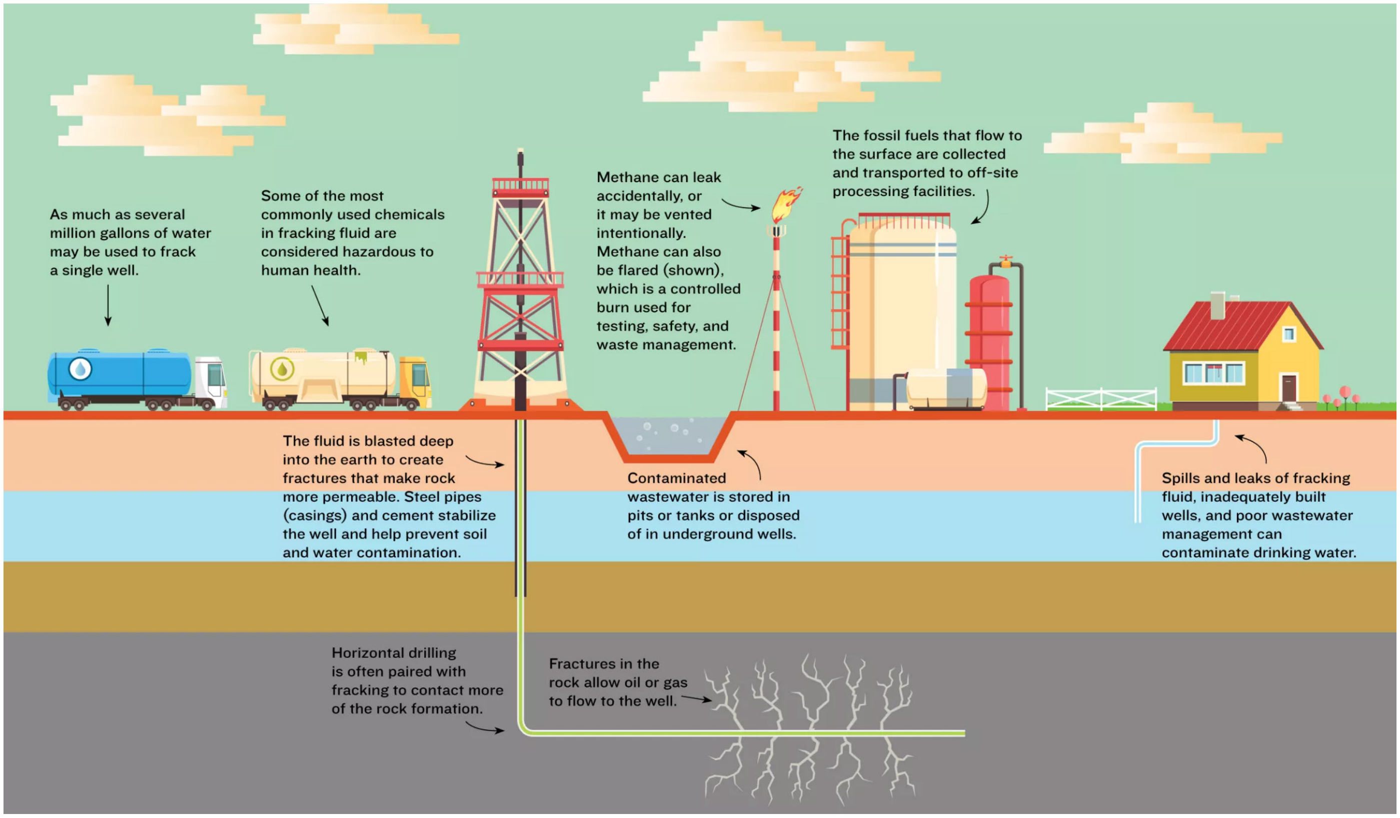
Natural gas, which is 80 to 95 percent methane (CH_4), occurs with oil in the ground. Because it is less dense than oil, it lies above it in the rock strata. Relative to coal and oil, natural gas contains fewer impurities and therefore gives rise to virtually no SO_2 and particulates during combustion. However, CH_4 is a potent greenhouse gas (twenty-five times more efficient at trapping heat from the Earth than CO_2). The leaking of natural gas during extraction is a major cause of CH_4 pollution. However, natural gas only produces 60 percent as much CO_2 as coal for the same amount of energy produced, making it, overall, a lower contributor to greenhouse gas emissions.

Hydraulic Fracturing

Hydraulic fracturing extracts previously untapped oil and natural gas reserves. Hydraulic fracturing (or fracking) involves injecting high-pressure streams of water, sand, and chemicals into bedrock to create fractures in the rock formation to extract trapped oil and gas. This technique, coupled with horizontal drilling, has allowed previously unreachable reservoirs of oil and natural gas to be tapped. Fracking has been the major reason that natural gas has overtaken coal as the second most used energy source in the U.S., behind petroleum.

There are several environmental and human health concerns related to fracking. The fluid used to “frack” the bedrock contains chemicals such as methanol, ethylene glycol, and propargyl alcohol that are hazardous to human health.[33] The extent to which these chemicals are impacting water resources is uncertain. However, it

FIGURE 94



The fracking process.

Source: NRDC

is known that large-scale fracking operations use a tremendous amount of water—about 1.5 trillion gallons of water since 2011, and fracking a single well can use 40 million gallons of water or more.[34] Large-scale fracking projects can dramatically lower key aquifers. And much of this large-scale fracking, and massive use of water, is taking place in areas like Texas, where droughts are becoming more common.

Nuclear Power

Nuclear power is a relatively clean means of electricity generation but produces radioactive waste. Nuclear power does not directly provide energy for consumers but is used to generate electricity. The fuel itself is uranium, a natural element that occurs in relatively small concentrations in a wide variety of rocks, including shale and sandstone. As much as two thousand pounds of uranium must be mined to produce seven pounds of uranium oxide for **nuclear fuel**. Surface mining removes large amounts of the host rock. The uranium is extracted from the rock and concentrated, and the remaining material is left in slag piles. The western U.S. and parts of Canada are two locations where commercial operations mine uranium for nuclear fuel.

After extraction, the uranium ore is enriched, a process that includes, among other things, the removal of naturally occurring impurities so that the ore might contain 2–3 percent uranium oxide. The enriched uranium is processed into pellets, which are then put into hollow fuel rods approximately six feet high. A typical nuclear reactor might contain 75 to 100 bundles of fuel rods. A pellet of uranium oxide undergoes extremely rapid *radioactive decay*, or the splitting of the uranium atoms into more atoms. Each time an atom splits (a **fission reaction**), a small amount of heat is given off. When a number of pellets representing trillions of uranium atoms are bundled together into fuel rods, a great deal of heat is released. In the reactor, the heat warms water, which eventually becomes steam, which turns a turbine just as in any other electricity generating station.

FIGURE 95

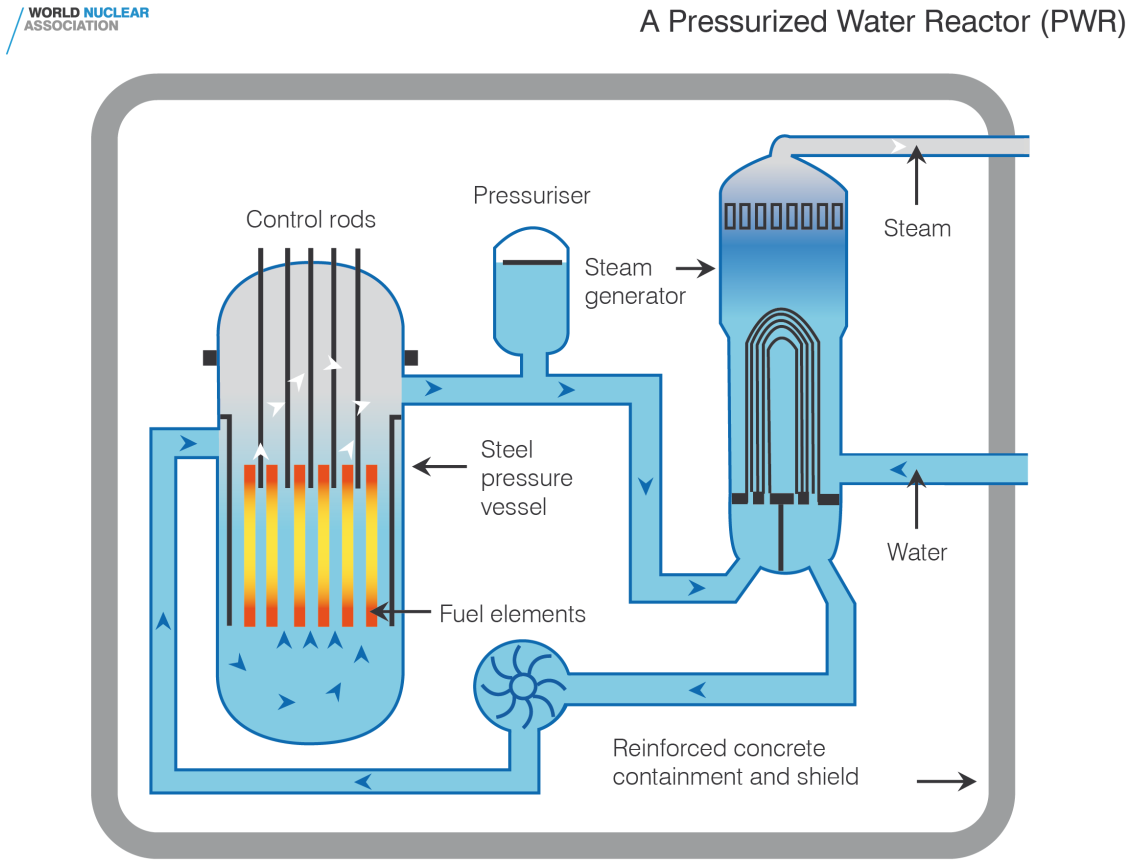


Diagram of a nuclear reactor.

Source: World Nuclear Association

Uranium is the most concentrated of all the energy sources we have considered. A pound of enriched uranium, which is smaller than a baseball, has the energy content of a million gallons of gasoline. Ten tons of enriched uranium oxide contain roughly the same energy as 260,000 tons of coal. We can say that there is 26,000 times more energy in uranium than in coal.

Nuclear power plants do not produce any air pollution when they are operating, so proponents of nuclear power consider it "clean" energy. However, fossil fuels are used during other parts of nuclear power generation, which does produce air pollution—for example when the power plant is constructed, when uranium ore is mined and processed, when used fuel rods are transported from the plant to their ultimate storage location, and when the plant is decommissioned. (Nuclear power plants have a life of approximately fifty years before the level of radioactivity in the plant and obsolescence of the structure require them to be shut down.) Nevertheless, even with all these releases taken into account, emissions of carbon dioxide per kilowatt-hour of electricity generated are at most 60 grams for a nuclear power plant, compared to 800 to 1,100 grams for a modern coal-burning power plant.

A clean-up crew works to remove radioactive contamination at Three Mile Island after the accident there in 1979.

Nuclear Accidents

Three accidents in widely separated parts of the world have contributed to the extensive protests against nuclear power in the United States. On March 28, 1979, at the Three Mile Island plant in Pennsylvania, human error caused a cooling water valve to be closed, which led to a loss of coolant around the nuclear core. The core overheated and suffered damage, and a small amount of radiation was released from the plant. This event, compounded by the coincidental release of the film *The China Syndrome*, in which a nuclear plant suffered a major "meltdown," led to widespread public fear and anger. One result was a huge amount of scrutiny given to the safety of nuclear power plants and some of the early assumptions that had been made about the relative risks of operating them.

An even more serious accident occurred on April 26, 1986, at the nuclear power plant in Chernobyl, Ukraine. An explosion and fire exposed the core of one of the reactors, and at least thirty-one plant workers and firefighters died immediately of acute radiation exposure—with many hundreds, and perhaps thousands, dying over a longer period of time from the radiation exposure. The Chernobyl accident has been intensively studied and has been characterized as a "runaway" reactor incident. The accident occurred during a special test of the plant when, in violation of safety regulations, operators deliberately disconnected emergency cooling systems and removed the control rods. With no control rods and no coolant, the nuclear reactions went out of control, and the plant overheated. Shortly afterward, the plant exploded, and fires began to burn. Because the control rods were made of flammable graphite, the fire was worse than it would have been in a plant with water control rods.

Finally, in March 2011, a major **earthquake** occurred off the coast of Japan that resulted in a tsunami hitting the main island of Honshu, killing over 18,000 people and flooding the reactors of the Fukushima nuclear power plant. This caused radioactive leakage that forced more than 150,000 people to evacuate. The area around the nuclear plant remains off limits, and it is estimated that it will take up to forty years to finish the decontamination work.[35]

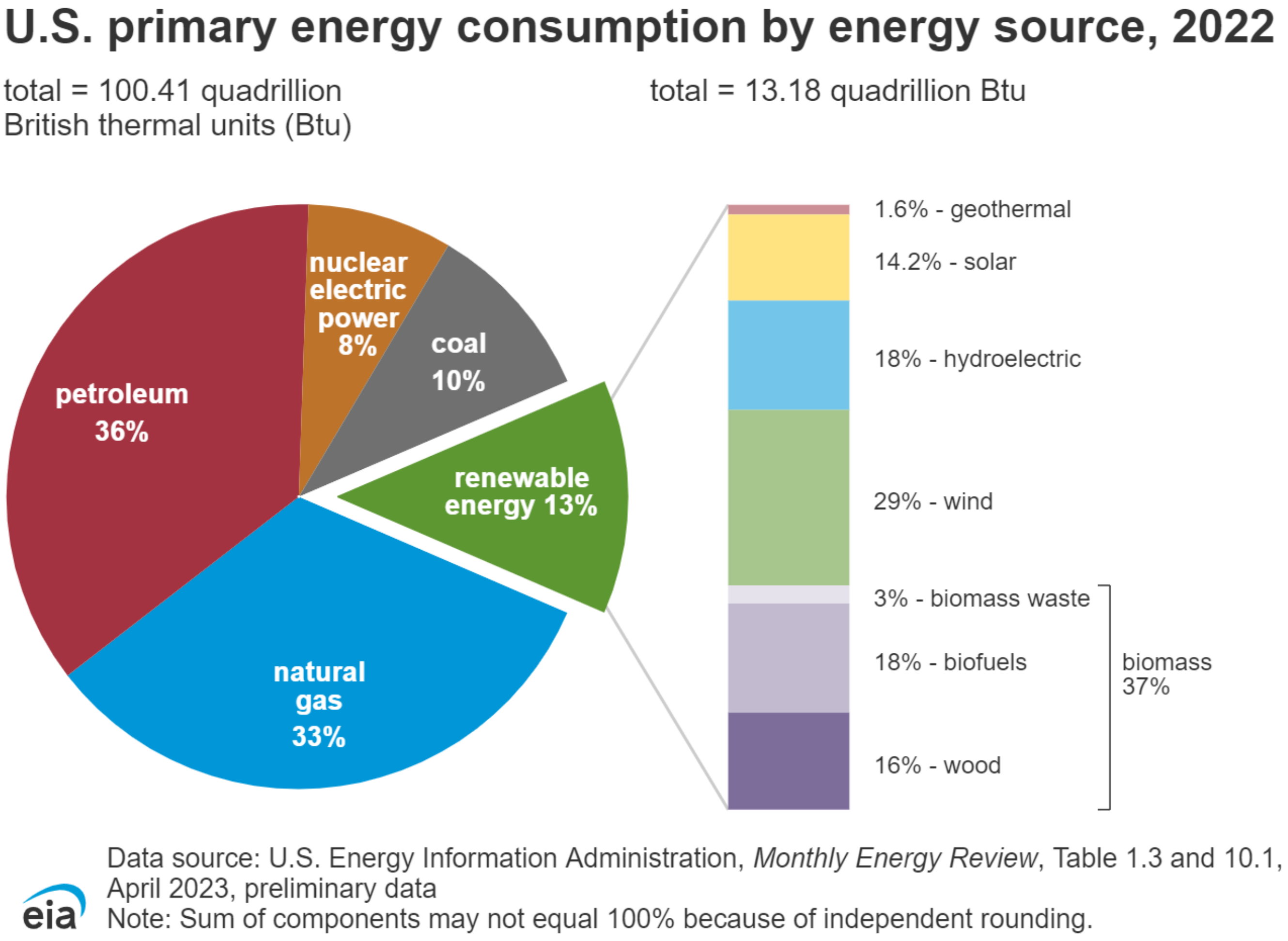
Radioactive Waste

While nuclear power does not produce fossil-fuel emissions, it does produce extremely dangerous radioactive waste that requires special and secure storage. The radioactive waste is classified as: 1) high-level waste from spent fuel rods; 2) low-level waste from contaminated maintenance materials; and 3) the uranium residue that is left over after uranium mining and enrichment. While all three kinds of waste require careful handling, it is the spent fuel rods that are most dangerous and therefore require the most care in disposal.

After a period of time, nuclear fuel rods become “spent,” meaning they do not have enough fuel left to produce enough heat to effectively generate electricity. The rods still contain highly radioactive fission fragments and will remain a threat to humans and other organisms for tens of thousands of years. At present, nuclear power plants are required to store spent fuel rods at the plant itself, in pools of water at least twenty feet deep that act as a shield from the radiation. From the spent fuel pools, rods are moved to onsite cement storage canisters (called dry cask storage), which can fit two to six dozen spent fuel rod assemblies each.

In 1978, the U.S. Department of Energy began examining a site at Yucca Mountain, Nevada, about a hundred miles northwest of Las Vegas, as a possible long-term repository for the country’s spent nuclear fuel and other high-level radioactive waste. In the early 2000s, it seemed almost certain that the repository would

FIGURE 96



Renewable energy currently accounts for 13 percent of U.S. energy consumption.

Source: EIA

be constructed; however, that has not happened. Political pressure from Nevada, protests from the Western Shoshone people living in the area (who also identify Yucca Mountain as a sacred site), and some scientific uncertainty over whether the site was geologically stable enough to house the waste for thousands of years has, as of 2023, seemingly put an end to that plan. If and where radioactive waste will be consolidated into a few or one single storage site is currently uncertain.

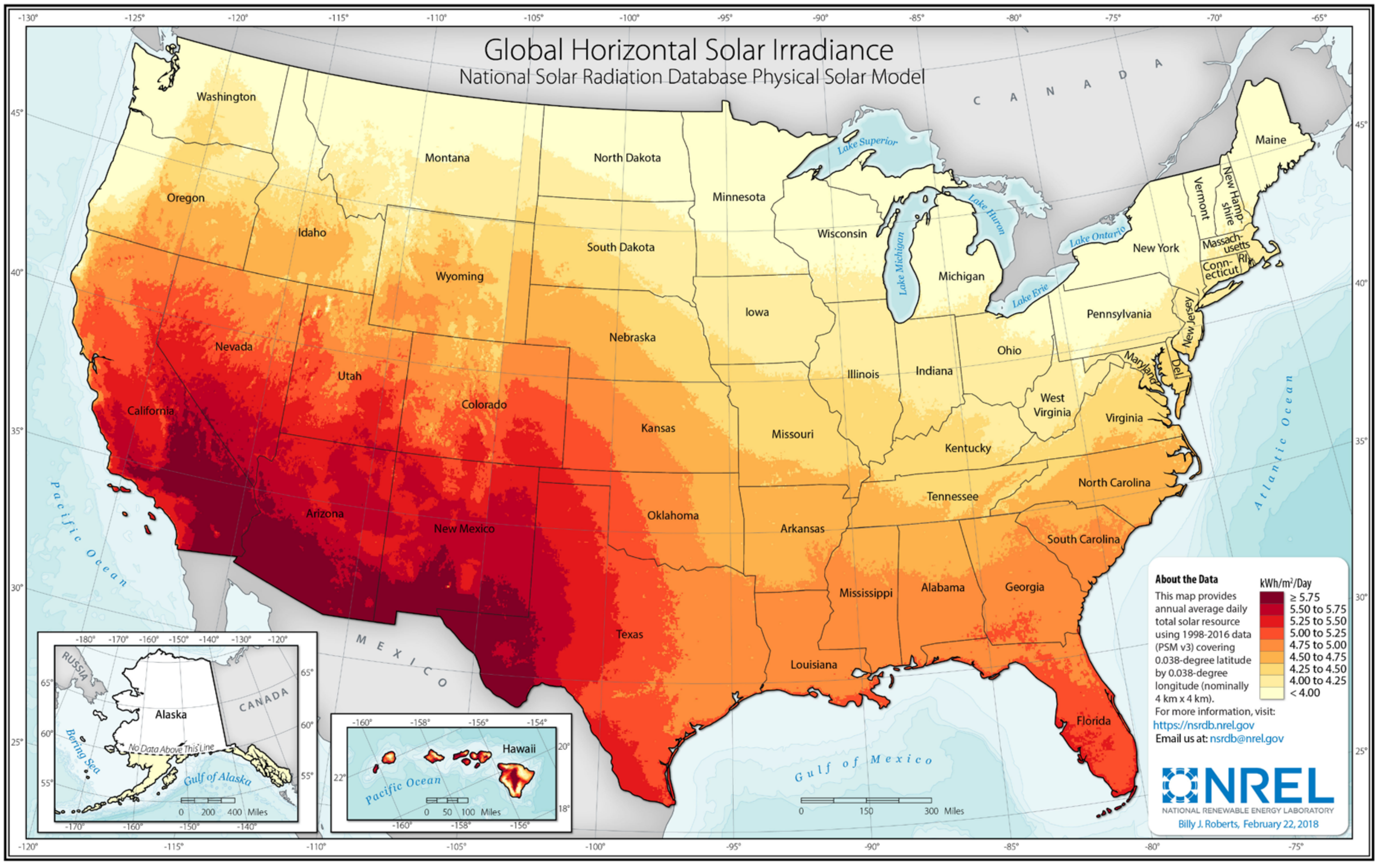
Renewable Energy

From the system analysis perspective introduced in Section I, fossil fuels are a resource pool with many outputs (human energy use), but no real inputs (any "new" coal, oil, or natural gas will not be available to use for many millions of years). So, like a lake that is being drained, but not being replenished, the use of fossil fuels is not sustainable. Instead, sustainable energy use is based on the use of *renewable energy* sources—sources like the Sun and the wind—that cannot be depleted (at least as long as our Sun and Earth survive). Other energy sources, such as biofuels like wood, are *potentially renewable* if they are managed so that their use is balanced by the creation of new resources, e.g., balancing the logging and regrowth of a forest. And the sustainability of energy use, in general, can be improved by using less energy through improving energy efficiency and energy conservation.

Direct and Indirect Solar Energy

Almost all energy on Earth, both conventional and alternative, derives from the Sun. Fossil fuels are the product of plants and animals that were buried millions of years ago. The energy stored in these organisms was gained either directly or indirectly through photosynthesis. The Sun is also responsible for evaporating water, which is an essential aspect of the hydrologic cycle. In the hydrologic cycle, water moves from the oceans to the land,

FIGURE 97



Average annual solar radiation in the U.S. (kilowatt-hours per square meter per day).

Source: NREL

where it falls to the ground as precipitation. This precipitation is the source of all rivers and streams, which provide hydrologic power. And because the Sun heats the Earth unevenly, causing air to move from one location to another, it is responsible for generating wind. Water- and wind-based energy sources can therefore be considered forms of *indirect* solar energy. The only significant sources of energy that are not solar based are nuclear, geothermal, and tidal.


The Andasol solar power station in Spain.

Energy from the Sun also comes to us directly. Every day, the Earth is bathed with solar energy. The amount reaching the top of the Earth's atmosphere—roughly 1,370 watts per square meter each day—is called the *solar constant*. Because the atmosphere reflects and absorbs a good fraction of this energy, only about 200 watts arrive at the Earth's surface near the equator, though this amount may vary between 50 and 300 watts, depending on the location and the time of year. This is the energy that is potentially available for use by people; it is known as the *solar potential*. Of course, solar energy is not available in every location every day. On cloudy days, there is much less solar input to the surface of the Earth than on sunny days; at night solar input is zero. And different regions of the world have different solar potential. In the United States, the Southwest has the greatest solar potential, with solar energy available at least 90 percent of the time.

Passive Solar Energy

Passive solar refers to the collection of solar energy directly from the rays of the Sun without an intermediate technology such as a pump or blower. Passive solar energy has been harnessed for thousands of years for purposes ranging from home heating to cooking. Positioning a house so that it absorbs the most energy and using dark materials on the roof or walls of a building so that more solar energy is absorbed than reflected are passive solar techniques. In the Northern Hemisphere, constructing a house with windows along a south-facing wall will allow the Sun's rays that are close to the horizon for much of the day during the winter months to penetrate and warm the house. Sometimes it is advantageous to install construction material with a great deal of thermal inertia—in other words, material that once heated, remains hot, and once cooled, remains cool. Stone and concrete have thermal inertia; wood and glass do not. A southern exposure room with stone walls and a stone floor will heat up on sunny winter days and retain that heat long after the Sun has set.

Active Solar Energy

Systems that utilize energy from the Sun with the assistance of fans, blowers, and pumps are active solar systems. Active solar energy is used primarily for two main applications: heating hot water and generating electricity.

Solar Water Heating

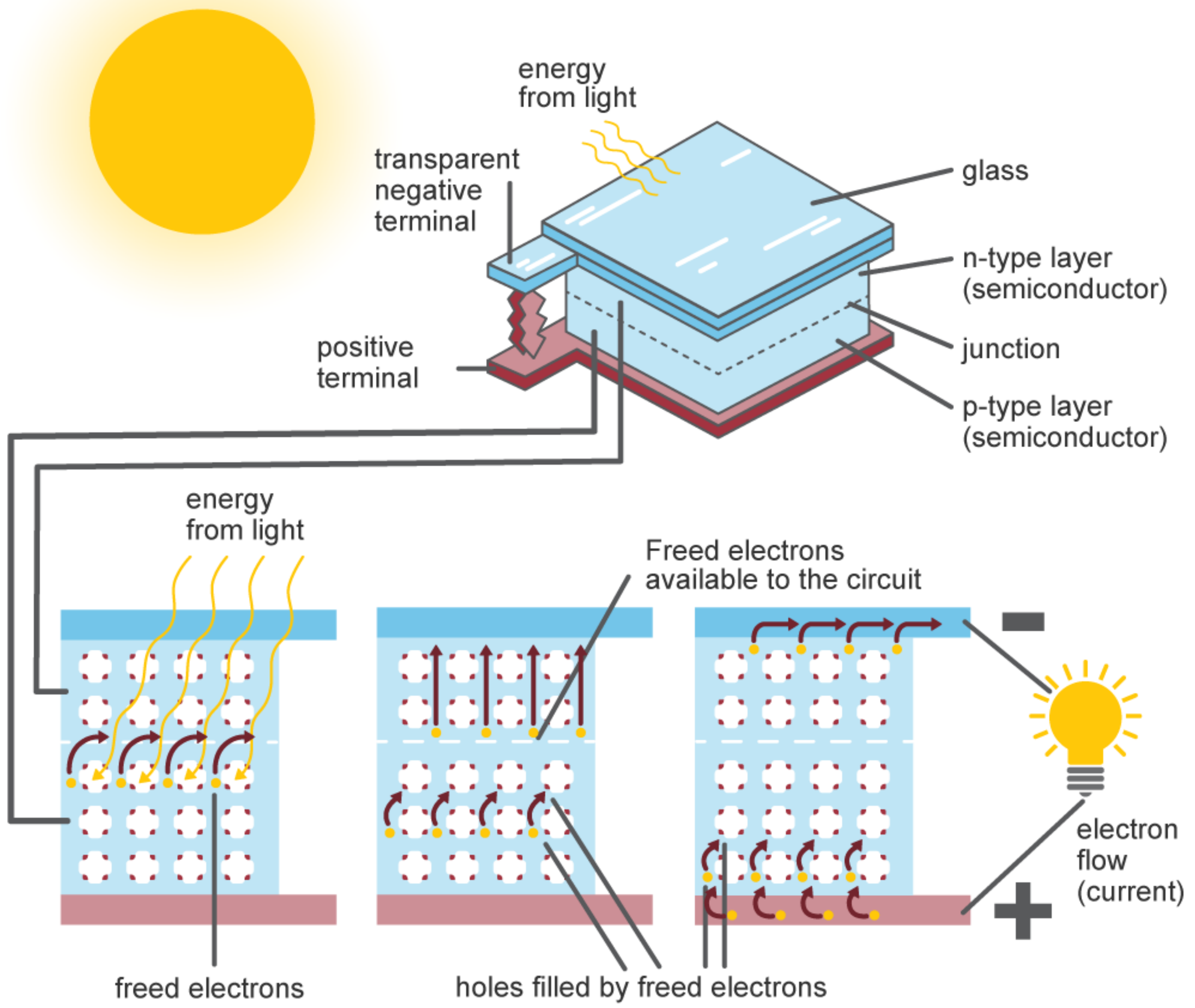
In a house with an active solar water heater, before cold water enters the water heater, a small electric pump pushes water onto the roof, where it circulates in copper tubing. Painted black and sometimes put behind glass, the tubing absorbs energy from the Sun and transfers it to the water. The water then returns to the building, where it enters the hot water heater tank and is heated further or, if it is already hot enough, is available for use.

Solar Generation of Electricity

Energy from the Sun can be converted directly to electrical energy with a *photovoltaic solar cell*. A photovoltaic solar cell makes use of the fact that very thin, ultra-clean layers of silicon dioxide (SiO_2) generate an electrical current when they are exposed to direct sunlight. Contemporary photovoltaic cells are made of SiO_2 combined with a very small amount of a metal, such as arsenic or antimony, to increase the voltage of the output. An

FIGURE 98

Inside a photovoltaic cell



Source: U.S. Energy Information Administration

Diagram of a photovoltaic cell.

Source: EIA

individual photovoltaic cell will produce about one or two watts. Normally twenty-four or more cells are joined together and often mounted on the rooftops of buildings.

The electricity from photovoltaic cells can run directly to an appliance through wires from the roof or can be stored in batteries that are then used for power. The electricity can also be converted to the voltage of the power grid and exported to the grid.

Wind Energy

A wind turbine is a device that converts the kinetic energy of wind to the potential energy of electricity. A contemporary wind turbine may be as tall as ~100 meters, with blades 40 to 75 meters long. The average turbine will generate over 843,000 kWh per month, which is enough energy for over 940 average U.S. homes.[36] The most rapidly growing sites for wind-generated electricity are offshore wind parks that are clusters of windmills within a few miles of the coastline. There are at least forty offshore wind farms in operation in Northern Europe, with over two thousand total wind turbines. However, there are only two offshore wind farms in the U.S. although more have been proposed or are in the permitting or construction process.

A windfarm near Palm Springs, California.

By Conn, Kit at the English-language Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=5395739

Advantages and Disadvantages of Solar and Wind Energy

The use of solar and **wind energy** has the potential to provide heat and/or electricity without producing any air or water pollution or fossil carbon dioxide at the time the energy is harnessed. Solar and wind energy can also provide electricity in remote locations where there are no transmission lines. A correctly constructed and positioned house can take advantage of passive solar energy to produce energy savings and offset pollution and carbon dioxide for decades without any additional energy input. And large wind turbines—especially in agricultural areas—have been found to be compatible with other land uses, such as farming and animal grazing.

Nevertheless, there are disadvantages to both. The Sun doesn't shine, and the wind doesn't blow all the time. That means that some of the energy that is produced when conditions are good will need to be stored for when

FIGURE 99

Solar and Wind—Environmental Impacts

- Utility-scale solar facilities require from 3.5 to 16.5 acres per megawatt output; little opportunity to share land with other uses (e.g., farms)
- Utility-scale wind facilities use 30 to 141 acres per megawatt output; however, less than 1 acre per megawatt is permanently disturbed—the rest can be used for other land uses.
- Bird and bat deaths occur but can be lessened with improved technology and knowledge of animal behavior.

Environmental impacts of solar and wind energy.

conditions are not ideal. Storage requires large-scale battery production, which remains difficult and expensive. Also, as we have discussed previously, energy is lost with each new step added to an energy system—including the storage of energy in a battery and use of the energy from a battery. The batteries used to store the energy are similar to the batteries in smart phones, computers, and electric cars—they require lithium, cobalt, and other minerals that require mining, which leads to environmental harm and environmental health and justice issues for those workers mining the materials.

Once wind turbines are manufactured and installed, the only energy input to them comes from the wind, a sustainable, renewable, and free resource. Some energy is required to maintain the windmill (travel to the wind park and service of the moving parts), but relative to the energy generated, these energy costs are minimal. However, wind farms have an aesthetic disadvantage—many people do not like living in a place where they can see or hear the turbines. For example, in 2003 a proposal to put windmills off the coast of Cape Cod in Nantucket Sound raised questions of both economic equity and aesthetics. Some opponents of the project asked why a private company had the right to profit from wind blowing across the ocean, in a public space. They maintained that wind is public, and no individual or corporation has the right to capture it, convert it, and sell it for profit. Another objection was that the windmills would be unsightly and destroy the view from many towns along Cape Cod and Nantucket. In response, proponents of the project accused the opponents, a number of whom were wealthy celebrities, of NIMBY (not in my backyard) behavior at the expense of much needed clean electricity for many people. They also claimed that the windmill support towers would take up very little space on the ocean floor, look attractive, and appear quite small from the coast.

One environmental objection to wind power has come from the fact that an estimated 10,000 to 40,000 birds die each year in collisions with windmills in the United States. New designs and the purposeful location of towers away from migration paths have reduced bird deaths, but some bird deaths are an inevitable by-product of wind power. For comparison, many millions of birds die in collisions with communication towers, buildings, and windows in both commercial buildings and residences. The number of bird deaths from collisions with wind towers is relatively small. That said, newer objections have been raised about the possibility of off-shore wind farms harming migratory and endangered whales off the New England coast.

Hydroelectric Power

The kinetic energy of water can be used to generate electricity. **Hydroelectric power**, or **hydropower**, the use of river water to generate electricity, is one of two renewable energy sources that are widely used in the United States today. (The other is the combustion of biomass.) Hydropower currently accounts for approximately 28.7 percent of the total renewable electricity, and 6.2 percent of the total electricity generated in the U.S.

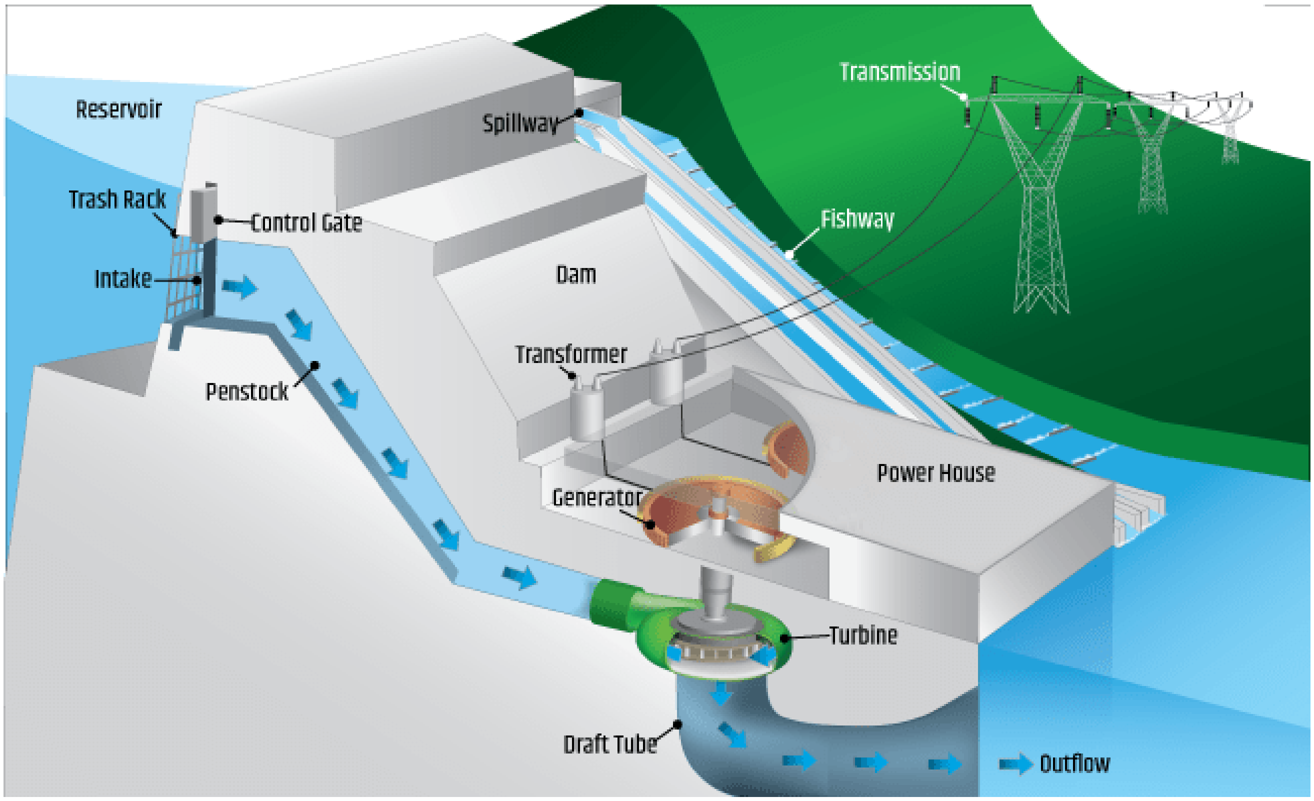
As water falls over a vertical distance, the potential energy stored is released as kinetic energy. A hydroelectric power plant captures this kinetic energy and uses it to turn a turbine, just as the kinetic energy of steam turns a turbine in a coal-fired electricity generating plant. The turbine transforms the kinetic energy into electrical energy. The amount of electricity that can be generated at a particular power plant depends on both the vertical distance through which the water falls and the flow rate, or amount of water that flows past a certain point per unit of time. There are two main types of hydroelectric generation: run-of-the-river and water impoundment.

Run-of-the-River Hydro

In **run-of-the-river** hydro generation, water is diverted from a river, passed through a narrow channel, and directed toward a turbine. After the water goes through the turbine, it is returned to the river. Run-of-the-river hydro plants are mostly small scale, generating around one megawatt at peak capacity, enough to supply electricity to about a thousand homes. Because the water is not stored in a reservoir, run-of-the-river electricity generation is dependent on natural water flow, which means that supply is variable during the year, limiting its usefulness during the dry summer months, when electricity demands are at their highest.

Although run-of-the river hydro has much less impact on aquatic plants and animals than water impoundment because natural high- and low-flow periods continue, species that swim upstream will find at least part of their

FIGURE 100



Water impoundment hydroelectric dam.

Source: U.S. Department of Energy

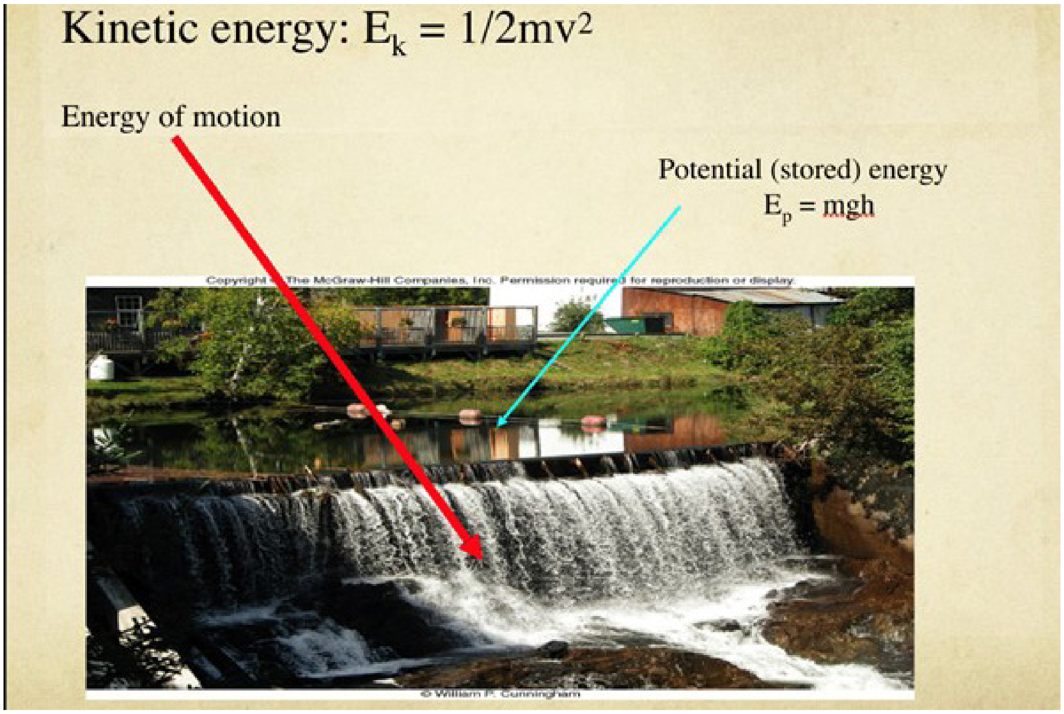
path impeded by the presence of even a run-of-the-river electricity generation facility. Fish ladders, a series of pools and pipes designed like ascending steps that allow fish to travel upstream around a hydro dam are sometimes installed, but some species find it difficult to utilize them, and some predatory species have learned to watch the fish ladders for prey. In addition, the water intake for any dam, run-of-the-river, or water impoundment is a potentially dangerous place for any number of species, including humans.

Water Impoundment

A more reliable source of water for hydropower is water impoundment, or storing water in a reservoir behind a dam. The basic principle of dammed hydropower is similar to that of run-of-the-river, but the flow of water is controlled. Water impoundment is more common than run-of-the-river hydro because it allows for electricity generation on demand, rather than only during periods of heavy rainfall and water flow. In addition, it can produce more power than run-of-the-river generation; the large series of Hydro Quebec dams near James Bay, Canada, for example, can generate 7,300 MW at peak, far more than any run-of-the-river station could produce.

Nevertheless, water impoundment has many negative environmental effects. First, when water that was formerly free flowing in a river is stored, an area of land is flooded. This may entail the loss of hundreds of square miles of forest, rich bottom land ideal for agriculture, canyons that have great aesthetic or archeological value, or wild river recreation. Ecological communities are lost, and people are often displaced from their homes, communities, and livelihoods. The Hydro Quebec dams mentioned above forced the resettlement of a major James Bay Cree community, and the Three Gorges Dam in China forced over 1.3 million people to abandon their home. In addition, anaerobic bacteria that thrive on the flooded vegetation mobilize mercury from the water column and sediment. Hydro dams can create the conditions for the mercury to be converted from elemental mercury, which is relatively harmless in ecosystems, to methyl mercury, which concentrates in fatty tissue and bioaccumulates

FIGURE 101



Kinetic energy: $E_k = 1/2mv^2$

Energy of motion

Potential (stored) energy

$E_p = mgh$

Potential energy (water stored in reservoir)→Kinetic energy (energy of moving water)→electric energy (from hydroelectric turbine).

in fish and ultimately humans, potentially causing serious health problems. This has also impacted the James Bay Cree community near the Hydro Quebec dams; the fish that once formed a major part of their diet now show unhealthy levels of mercury.

Even without the problems noted above, large-scale hydro dam projects alter the ecology of the water and land areas both upstream from the dam, where large areas of a former river have been flooded, and downstream. For example, certain species, such as salmon, steelhead trout, and freshwater clams and mussels, have life cycles that depend on seasonal variations in water flow. Some plant species, such as the cottonwood tree, depend on sand bars created by natural flooding to carry out the reproductive phases of their life cycles. Researchers have documented changes in the abundance of such species that have resulted from interrupted flow, lack of flooding downstream, and other conditions stemming from the creation of a dam.

Biomass Around the World

Biomass energy is the potential energy contained in organic matter. The Earth's organic matter—plants, animals, and other organisms, and their waste products—contains a great deal of energy that originally derived from the Sun and was concentrated in what we know as biomass. The potential energy remaining when these organisms die and decompose, or in their waste products, is available to do useful work. Wood—including charcoal—animal dung, plant remains, and any decomposition products from plants, such as ethanol, are all sources of biomass energy. Municipal solid waste (MSW) **incineration**—burned in **waste-to-energy facilities**—is also a source of energy. Together, the variety of biomass products accounts for roughly 37 percent of all renewable energy consumed in the U.S.

Biomass is burned as wood, charcoal, or dung to heat homes or water or to cook food; combusted in wood-fired power plants to produce electricity; and, after being fermented to ethanol (from corn) and mixed with gasoline, used to power vehicles. Roughly two-thirds of the biomass energy used in the U.S. comes from wood and wood products. Almost one-quarter comes from MSW. Agricultural wastes and methane collected from MSW landfills each comprise 5 percent of biomass energy. In many parts of the world, especially developing countries, animal dung is the most common source of biomass energy.

Modern Carbon vs Fossil Carbon

Biomass is organic matter, and thus it contains a great deal of carbon. You might think, therefore, that burning it would contribute to pollution and global warming in the same way that burning fossil fuel does. However, the age of the carbon in biomass makes its effects different. The carbon in biomass was in the atmosphere until fairly recently (months ago for products like corn, a few hundred years ago for a large tree). This carbon is called *modern carbon*, in contrast to the carbon in fossil fuels, which is called *fossil carbon*.

Roughly two-thirds of the biomass energy used in the U.S. comes from wood and wood products.

Although all carbon is chemically the same and can combine with oxygen to form carbon dioxide, the use of fossil carbon is more deleterious to the environment because its use adds to the amount of carbon in the atmosphere. Modern carbon, on the other hand, was already in the atmosphere until it was removed by plants relatively recently. Moreover, if new vegetation regrows where crops or trees were cut down, the new vegetation will take up a good deal of the carbon dioxide during photosynthesis. (Some older forests actually remove very little carbon from the atmosphere because their primary productivity is not much greater than their respiration.) As long as the amount of biomass removed is replaced by new growth, there is no net effect on the carbon cycle or global CO_2 concentrations from burning biomass. In contrast, any time fossil carbon is burned, there is a net increase in global CO_2 concentrations.

Ethanol

Ethanol is the most common biomass fuel, or *biofuel*. It is made by *fermentation*, the decomposition of the sugars and starches in biomass by yeasts, bacteria, and molds that results in the production of alcohol. More than 1.8 billion gallons of ethanol are made and used in the U.S. each year. Of that, 92 percent is derived from corn and corn by-products. Ethanol is mixed with gasoline, usually at a ratio of 1:10. It boosts the octane of the gasoline and helps oxygenate it, which reduces certain air pollutants. In addition, it has other beneficial effects, such as absorbing moisture in the gasoline to prevent freezing. Finally, it reduces the amount of gasoline used and replaces fossil carbon with modern carbon that was removed from the atmosphere the year the corn was harvested. Some opponents of using ethanol in automobile fuel point out that a 90 percent gasoline/10 percent ethanol mix is two to three percent less efficient than 100 percent gasoline fuel. Furthermore, growing corn specifically for fuel and converting it to ethanol uses fossil fuel energy and reduces the amount of agricultural land for producing food crops.

Geothermal and Tidal Energy

Besides the major renewable energy sources discussed above, other types are of regional and potential importance. We won't discuss these in detail, but you should be aware of their existence and the potential they have to become more important energy sources in the future. **Geothermal energy** is the heat produced from the radioactive decay of elements deep in the Earth. Geothermal energy will not deplete for as long as there is an Earth, and it is relatively inexpensive to tap. The energy can also be used directly to heat water, or it can be used as the primary energy source to produce electricity by creating steam to power turbines, without the greenhouse gases or other pollutants that are produced by burning fossil fuels. However, it can emit other localized dangerous gases, and most importantly, it is geographically limited to those areas that are geologically active. Iceland, a country known for, among other things, active volcanoes gets 100 percent of its electricity from renewable energy sources: 73 percent hydroelectric and 27 percent geothermal.[37]

A geothermal power plant in Iceland. Twenty-seven percent of Iceland's energy comes from geothermal sources.

Tidal generation plants are operating in areas of Maine and Washington state; Brittany, France; Nova Scotia, Canada; and other locations. However, **tidal energy** is not currently a major energy source. One reason is that, in most areas, the difference in water level between high and low tides is not great enough to provide enough kinetic energy to generate a sufficient amount of electricity. In addition, to harness tidal energy and convert it to electricity, power stations must be built directly on the coastline, for example, in an **estuary**, which has a disruptive effect on the ecology of coastal, shoreline, and ocean organisms. Areas used for tidal generating stations are unavailable for recreational and commercial use and contribute to the aesthetic deterioration of the coastline, all of which tend to generate opposition among nearby residents.

Conservation and Efficiency

So far, we have talked about sustainable energy in terms of particular sources or technologies. It may be years before many of these are available or affordable, and often they have disadvantages of their own. Therefore, energy sustainability relies as much on reducing the amount of energy that individuals or nations use as on new sources or technologies for providing energy. Conservation and increased efficiency are necessary aspects of energy sustainability.

Conservation is a consumer-based approach that focuses on reducing energy use by changing users' habits and actions. Conservation measures can be everyday actions as simple as turning off lights when they're not needed, choosing to drive less, combining trips so that overall mileage driven is reduced, wearing warmer clothes rather than turning up a thermostat in winter, taking a shorter shower, and many, many more. This approach is available to anyone; its only drawback is the need to change long-standing habits.

More complex is *increasing energy efficiency*, or using less energy to do the same work. We have previously discussed the concept of energy efficiency and how it is derived; here, let's consider it from the perspective of sustainability. Energy is the ability to do work—say, getting from Point A to Point B, one hundred miles down the road. The quantity of usable work (getting you there) is the same, regardless of the weight of the vehicle in which you travel. In terms of physics, however, traveling in a two-ton car takes more work than traveling in a one-ton car, and therefore uses more energy. If you can get there in a smaller, lighter car, you consume less gasoline in the process and therefore increase energy efficiency.

Uniti, a two-seater micro electric vehicle. Smaller, lighter cars are more energy efficient.

Photo: Uniti

Creating more energy-efficient machines is within the ability of—and some would say is the responsibility of—the manufacturers of vehicles and appliances. However, we can increase energy efficiency individually through the choices we make. Buying a small car rather than a large car or an SUV, insulating a home so that less fuel is required to heat it, using compact fluorescent light bulbs, purchasing EnergyStar appliances, and traveling less all contribute to energy sustainability.

Reducing Peak Demand

There are certain times when demand for electricity is greatest—in the middle of a hot summer day, when people are using more air conditioning than normal; or in the middle of a cold winter night in a region where homes have electric heat. In order to meet *peak demand*—the greatest quantity of electricity that will be needed at any one time—utilities usually build new power plants. However, some utilities have come up with creative ways to reduce peak demand.

One way is to encourage consumers and businesses to conduct optional activities that demand electricity at non-peak times. Usage is monitored by having two electric meters at each location, one recording the electricity used during the peak demand period—usually 8 AM through 8 PM and the other recording the usage during non-peak periods. Peak-demand electricity is billed at a higher rate, so a business or consumer might choose to wait until after 8 PM to conduct certain high-electricity-demand activities. For example, a homeowner might choose to run the dishwasher and electric clothes dryer at 9 PM; a business might use a timer to run energy intensive applications at night or create a second shift for certain activities. If this is done throughout a utility district, it can greatly decrease the peak electrical demand and thereby reduce the need for new power plants.

The Environmental Protection Agency's Energy Star Program designates as Energy Star compliant certain appliances that do their job at a specified level of efficiency. For example, an air conditioner that removes 10,000 Btus of heat per hour while using less than 1,000 watts will receive an Energy Star designation. A non-Energy Star compliant air conditioner might use 1,200 watts to do the same job. The difference of 200 watts for an hour in one household doesn't seem like much; it might be 2 cents worth of electricity. But if 100,000 households in a large city had Energy Star compliant air conditioners, the peak demand during a mid-afternoon summer heat wave could be reduced by 20 megawatts, or 4 percent of a typical power plant's output. If both residential and business customers used a variety of Energy Star appliances regularly, it could make a significant difference in the number of new power plants needed.

HUMAN ENVIRONMENTAL IMPACTS AND HUMAN HEALTH RISKS

All the human activities that we have discussed in this and previous sections modify the environment (the land, water, and the air) and adversely impact humans in some way. In the following section, we will focus on how science is used to determine the risks to human health from those human actions that add chemicals to the environment, whether from emitting or discharging them into the air and water, from spraying them on our crops, or by adding them to products that you buy in a store. And while we will focus on only a few chemicals as examples, the methods discussed are used for the thousands of chemicals released into the environment as part of our modern industrial society, including the "forever chemicals," perfluoroalkyl and polyfluoroalkyl substances (PFAS), that are of growing concern today.[38]

Qualitative and Quantitative Risk Assessment

Risk analysis helps determine the relative costs and benefits of environmental decisions. Let's consider a specific example. Radon, a radioactive gas that results from the breakdown of uranium, occurs naturally in rock and soil in many parts of the world. Humans can be exposed to radon if it seeps into homes or drinking water from underlying rock, soil, or groundwater. The U.S. Environmental Protection Agency (EPA), the federal agency most responsible for identifying, measuring, and dealing with **environmental risks**, estimates that between 6,500 and 31,000 people die each year from radon-induced lung cancer, making radon the second leading cause of lung cancer behind smoking. The range of potential deaths is so broad because, unlike the link between cigarette smoking and lung cancer, the evidence for the cancer-causing effects of radon is much more indirect—it is based primarily on studies of the cancer rates among uranium miners, who are exposed to much higher levels of radon in their work, rather than on studies of the general public.

Ironically, even though airborne radon is responsible for the vast majority of radon-caused cancer deaths, the EPA has the legal authority to regulate only radon in drinking water. Lacking the legal power to require the reduction of airborne radon, the EPA suggests that people test their homes for airborne radon and take relatively inexpensive actions such as sealing basements and improving ventilation to reduce radon levels. The EPA estimates that spending $86 million on a program that combines a *recommended* reduction in airborne radon with a *required*, but minimal, reduction in radon levels in drinking water would significantly reduce the risk of radon-caused cancer.

The EPA could achieve the same level of risk reduction by using their legal authority to require an even lower level of radon in drinking water. However, the necessary improvements in water treatment plants across the nation would cost more than $400 million. An estimated 168 deaths per year are caused by radon in drinking water. Is it worth spending more than $300 million extra to ensure that the radon risk to this group is reduced? Or do we push some of the burden onto individuals to decide whether the risk from radon outweighs the cost of installing radon **mitigation** systems for their air and/or water in their homes? Such questions provide a vivid example of how environmental science, economics, and **ethics** must be balanced in the measurement and management of environmental risks.

A radon mitigation system. Although airborne radon is responsible for the vast majority of radon-caused cancer deaths, the EPA only has authority to regulate radon in drinking water, so it is up to individuals to assess their risk and consider means of mitigating it.

Many of our actions involve some risk from economic, health, or environmental hazards. The hazards we face may be *voluntary*, as when we make a decision to smoke tobacco or take up skydiving, or they may be *involuntary*, such as the unknown risk from radon in our example above. How “risky” a hazard is depends upon both how common it is and how certain it is to cause harm once faced. We can express this relationship mathematically with a simple equation:

Risk = probability of exposure to a hazard × probability of harm once exposed

For example, flying 1,000 miles in a year or eating 40 tablespoons of peanut butter, which contains the naturally occurring aflatoxin fungus, a carcinogen, in a year both give you a 1 in 1 million chance of dying. The risk of dying in a plane crash depends on the probability of your plane crashing (which is very low) multiplied by the probability of dying if the plane does crash (which is relatively high). In contrast, the risk of dying of cancer from eating peanut butter depends upon the near 100 percent chance that you will be exposed to the aflatoxin fungus multiplied by the very small chance that you will die from cancer from eating it. Few of us base our personal activities on such a *quantitative* estimate of the probabilities of the various risks that we face. However, when we choose to slow down on a wet highway and thereby risk missing our job interview or pick a more expensive car for its increased safety, we are making *qualitative* judgments of the relative risks of various decisions.

The peanut butter/plane crash example demonstrates a fundamental rule of risk assessment: the risk of rare events with a high likelihood of causing harm can be equal to the risk of common events with a low likelihood of causing harm. Current studies of risk perception show that most people don’t realize this and see a catastrophic though rare event (a plane crash or nuclear reactor meltdown) as riskier. This misperception is just one way in which individual subjectivity biases the qualitative comparison of different risks. We also tend to downplay the risk of activities that may result in cultural, political, or economic advantages to ourselves. Figure 102 compares the EPA’s assessment of risk of a number of environmental hazards with public perceptions of risky activities, albeit from a few decades ago.

FIGURE 102

EPA's Top Concerns (Not in Rank Order)	Public's Top Concerns (In Rank Order)
Ecological Risks	
Global climate change	Active **hazardous waste** sites
Stratospheric ozone depletion	Abandoned hazardous waste sites
Habitat alteration	Water pollution
Loss of biodiversity	Occupational exposure to toxins
Health Risks	
Criteria air pollutants (smog)	Oil spills
Toxic air pollutants	Destruction of ozone layer
Radon	Nuclear power plant accidents
Indoor air pollution	Industrial accidents
Drinking water contamination	Radioactive waste
Occupational exposure to chemicals	Air pollution from factories
Application of pesticides	Leaking underground storage tanks
Stratospheric ozone depletion	Coastal water contamination
	Solid waste and litter
	Pesticide risk to farmworkers
	Water pollution from agriculture
	Water pollution from sewage plants
	Air pollution from vehicles
	Pesticide residues in food
	Greenhouse effect
	Drinking water contamination
	Destruction of wetlands
	Acid rain
	Water pollution from city runoff
	Nonhazardous waste sites
	Biotechnology
	Indoor air pollution
	Radiation from X-rays
	Radon in homes
	Radiation from microwave ovens

Public Perception versus EPA Assessment of Risks (1990)

Environmental Risk Analysis

Environmental Risk Analysis is based on a quantitative assessment of risks. For environmental scientists, risk is the probability of health, economic, or environmental harm resulting from exposure to some form of environmental hazard. An environmental hazard is anything in our surrounding environment that can potentially cause harm, including *substances*, such as pollutants or other chemical contaminants; *human activities*, such as draining swamps or logging forests; or *natural catastrophes*, such as volcanoes and earthquakes.

International and national agencies do risk analyses routinely. You can see that risk analysis is one place where environmental science intersects with concerns about sustainability, economics, and equity. Environmental scientists and policy makers usually follow three steps in accounting for risks:

- *Risk Assessment*: How much risk is there?
- *Risk Acceptance*: How much risk is acceptable?
- *Risk Management*: How can we manage the risk?

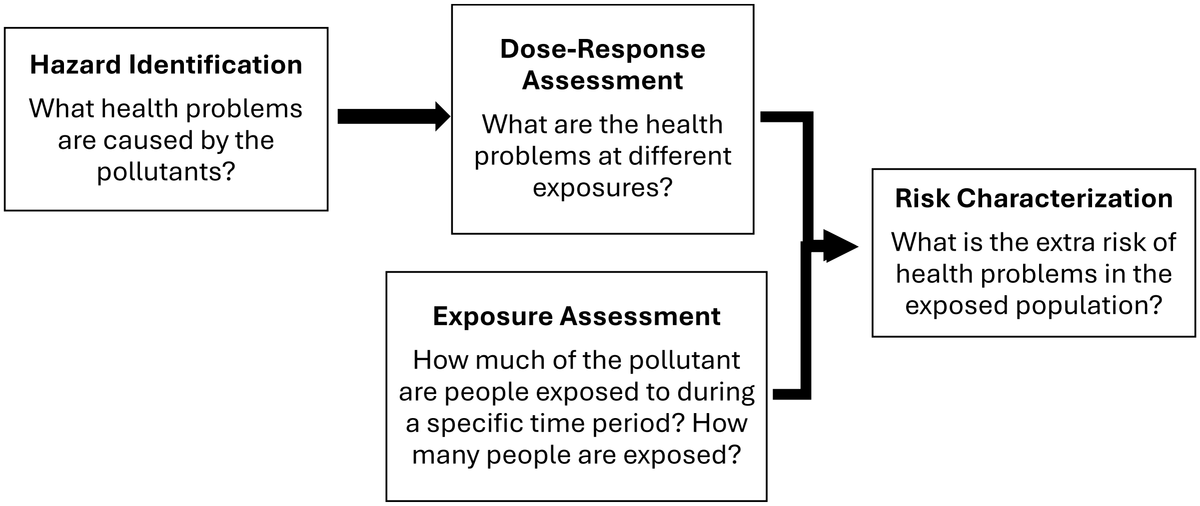
Risk Assessment

The U.S. Environmental Protection Agency has identified four types of risks that need to be assessed: cancer risks, non-cancer health effects, damage to public welfare, and ecological risks. *Ecological risk assessment* refers to the risk to non-human populations and ecosystems that results from our use and manipulation of the environment. The harms identified focus on biodiversity and other ecological and/or ecosystem elements of the environment. Such activities as filling in a swamp to promote urban development or increasing a fishing quota to meet demand for fish sticks may not directly affect human health but may cause harm to specific ecosystems or non-human populations.

After identifying a potential risk, a quantitative risk assessment must estimate how much harm will be caused by various levels of exposure to the risk and how likely these levels of exposure are. (Remember our equation: Risk = probability of exposure to a hazard × the probability of harm once exposed.) Assessments will include such scientific research as laboratory and field studies of health and ecological effects, animal studies for estimating health effects, and epidemiological studies of current or past real effects on human populations. The result of the research is an estimate of how much harm is caused by varying amounts of the hazard under study, known as

FIGURE 103

The Four-Step Risk Assessment Process



The EPA's four-step risk assessment process.

Source: EPA

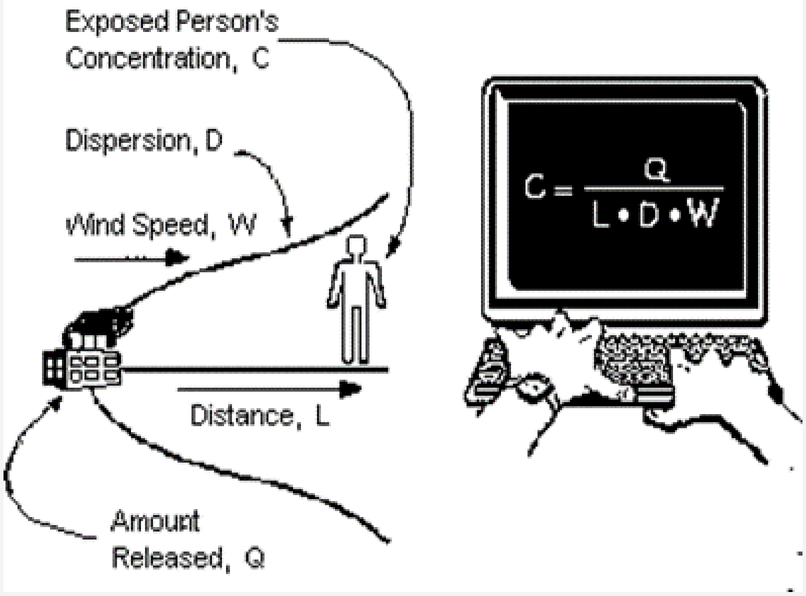
dose-response. All this research is then integrated into a more complete *statistical risk assessment* that results in an estimate of the probability of harm. Figure 103 illustrates the EPA's four-step assessment process.

Risk assessment works only if risks are known. For many of our actions, including environmental decisions, there is uncertainty not only about how much risk is involved, but also about what the risks are. And scientific uncertainty—from the lack of being able to collect perfect data from dose-response or other scientific studies—is the source of many errors in identifying the amount of risk involved in environmental decisions.

ENVIRONMENTAL SCIENCE CASE STUDY: Risk Assessment

The amount of exposure to an environmental hazard is one part of a risk assessment (C in Figure 104). Uncertainty in the measurement of any of the variables in this example will result in uncertainty in the estimation of risk.

FIGURE 104



Determining exposure to risk.

Source: *Risk Assessment for Toxic Air Pollutants—A Citizen's Guide* (EPA, 1991)

PCBs (polychlorinated biphenyls) are mixtures of synthetic organic chemicals that are used in many industrial applications because they are inflammable, chemically stable, and have insulating properties. However, the very stability that makes them commercially useful results in their persistence in the environment. PCBs are known to cause cancer at high doses in laboratory animals. Studies also show that workers in industries that use PCBs have a higher incidence of cancer.

Further, because PCBs are found throughout the environment and can be taken up by humans in multiple ways, the *risk exposure* is relatively high.

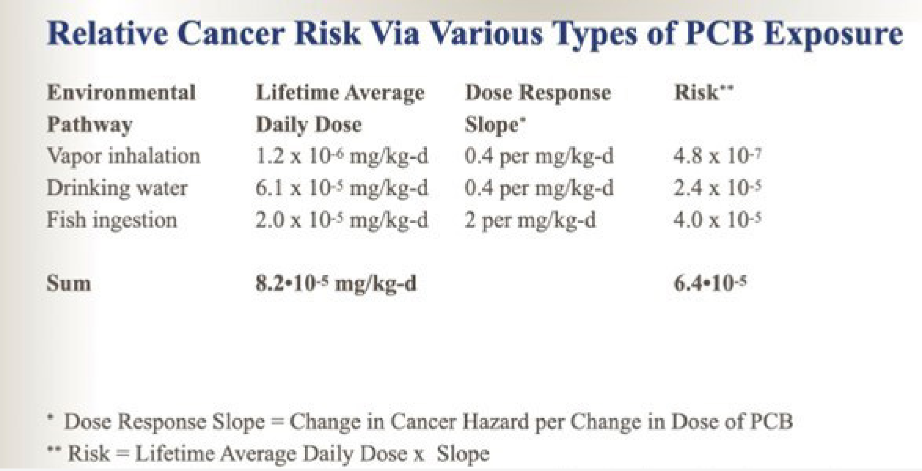
What was not known was how harmful these environmental levels of PCBs were to humans. In 1996 the EPA carried out a dose-response study, which quantified the cancer-causing action of various levels of PCB exposure. This study involved four parts:

1. Epidemiological studies of the effects on humans of occupational doses of PCBs.
2. Dose-response studies of the cancer-causing effects during the lifetime of laboratory rats.

3. Comparative studies of how various environmental pathways (e.g., eating contaminated fish versus breathing contaminated air) will affect PCB exposure levels.
4. Mathematical models using the data from steps 1, 2, and 3 to estimate the increased rate of cancer that would be expected from environmental levels of PCBs.

The EPA attempted to reduce scientific uncertainty as much as possible through a large number of independent research studies (recall our discussion in Section I of the importance of repetition in scientific methodology). The final result was an extrapolation of the relative risk of developing cancer by being exposed to various levels

FIGURE 105



Relative Cancer Risk Via Various Types of PCB Exposure

Environmental Pathway	Lifetime Average Daily Dose	Dose Response Slope*	Risk**
Vapor inhalation	1.2 x 10^{-6} mg/kg-d	0.4 per mg/kg-d	4.8 x 10^{-7}
Drinking water	6.1 x 10^{-5} mg/kg-d	0.4 per mg/kg-d	2.4 x 10^{-5}
Fish ingestion	2.0 x 10^{-5} mg/kg-d	2 per mg/kg-d	4.0 x 10^{-5}
Sum	**8.2•10^{-5} mg/kg-d**		**6.4•10^{-5}**

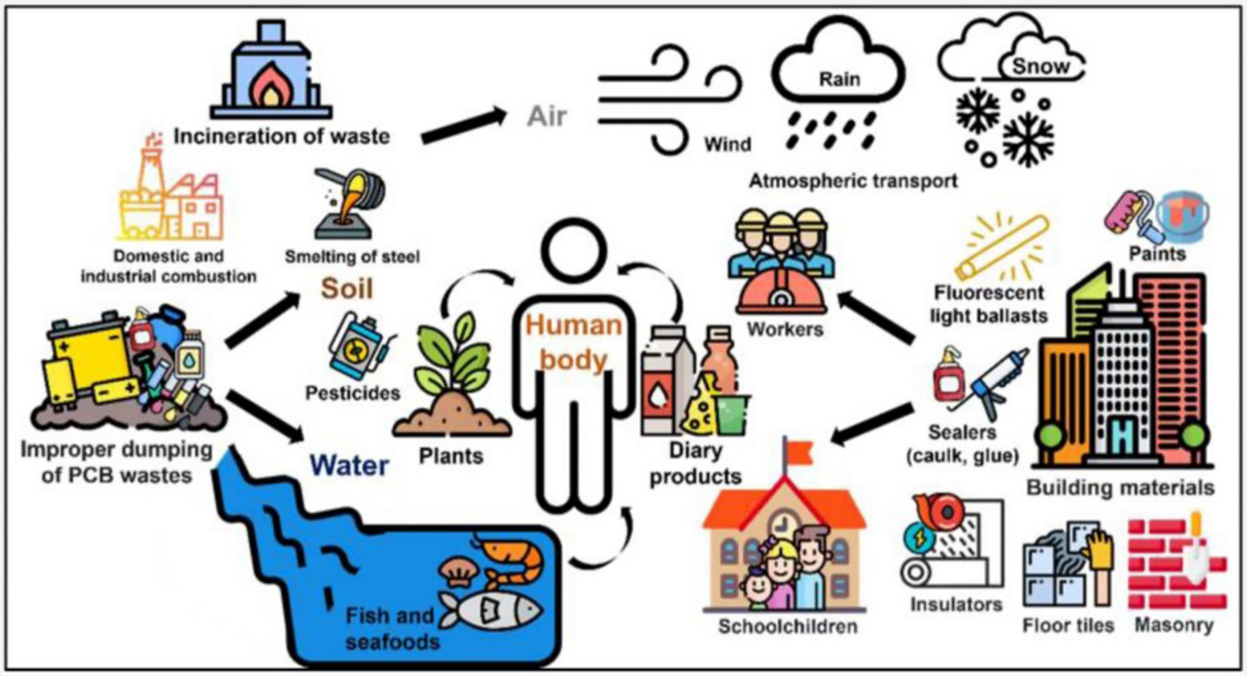
* Dose Response Slope = Change in Cancer Hazard per Change in Dose of PCB

** Risk = Lifetime Average Daily Dose x Slope

PCB risk analysis.

Source: PCBs: *Cancer Dose-Response Assessment and Application to Environmental Mixtures*. EPA Publication. EPA/600/P-96/001F (1996).

FIGURE 106



Pathways of human exposure to PCBs.

Source: NCBI

and environmental sources of PCBs. The findings showed that the risk from eating contaminated fish is higher than from drinking contaminated water and much higher than from breathing contaminated air, but the overall absolute risk of an individual developing cancer from PCB exposure is very low. Nevertheless, the large number of people exposed to PCBs in the environment will result in many new cancer cases.

Old power transformers are a major source of PCBs.

By Sturmovik, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=24404504

Scientific research on the human health impacts of PCBs continues today—adding knowledge of additional human health harms (including dementia, immune system dysfunctions, and cardiovascular disease) and newer sources of exposure (with e-waste **recycling** sites found to be a major contamination source). In addition, there is newer evidence of how ecological processes that we discussed in Section II (the movement of material through trophic food chains in particular) increase the potential risk to humans.[39]

The key ecological processes that increase the harmful impacts of PCBs—and other POPs—are **bioaccumulation** and **biomagnification**, which are two different processes that often occur together. Toxins, like PCBs, that are long lasting can build up in the tissues of organisms (bioaccumulate) as the organism continues to ingest or inhale the toxins over its lifetime. For example, bioaccumulation can occur when fish continue to feed on contaminated food sources and when humans continue to feed on the contaminated fish population. Recent studies have shown that PCB bioaccumulation can increase PCB levels to a point where they may cause both reduced fertility in one generation and harm to the reproductive systems of offspring. In addition, the exposure to PCBs, and concentration levels in the body, will increase through biomagnification as the chemical moves up the food chain, from lower concentrations in prey species to higher concentrations in predator species (including humans).

Risk Acceptance

Risk assessment is only the first part of the decision-making process. Assume that one in one million is a relatively accurate estimate of the chances of dying from radiation-induced cancer by living next to a nuclear power plant for fifty years. Is this risk too high? Our acceptance of risk involves several factors:

- The amount of harm associated with the risk.
- The importance of the activity associated with the risk to us.
- Our confidence in being able to deal with the risk.

While not requiring the marshaling of scientific studies as risk assessment does, risk acceptance can be far more difficult to achieve. Some people are willing to accept various levels of risk, even very high risk, to do things they want—for them, the benefits of the activity outweigh the risks. For other people, the goal of environmental management is to reduce risk to as close to zero as possible—risks will almost always outweigh the benefits. In this case, the disagreement is not over the risk assessment results, but over individual feelings regarding how much risk is acceptable. Further, even among those people who are willing to accept some risk, *how much* risk is open to heated disagreement.

The U.S. Environmental Protection Agency finds that a one in a million risk is acceptable for most environmental hazards. But some people see even this as too high a risk, one that devalues human life. Others see a one in a million chance of death from radiation leaks as a small price to pay for such benefits as the relatively cheap power that we can obtain from nuclear power plants. While personal preferences will always complicate the determination of risk acceptance, environmental scientists, economists, and others can help by providing as accurate estimates as possible of the benefits and costs of environmental activities. And, the more accurate the risk estimates are, the less that uncertainties over scientific findings can be used to reduce the acceptance of managing the risk.

A landfill is unlikely to be built if the benefits obtained from disposing of the wastes do not balance the risk to human health or its acceptance by the public.

Risk Management

The assessment of how much risk is present as well as the determination of how much risk is acceptable are critical parts of the cost-benefit analysis that is used in environmental economics. It is the relative risk of different activities that is the basis of the non-money costs of various environmental decisions. When the decision is made to locate a toxic-waste landfill in a particular place, the costs include the financial cost of building the landfill and transporting the waste. However, it is unlikely that the landfill will be built if the benefits obtained from disposing of the wastes do not balance the risk to human health or its acceptance by the public.

Risk management is the balancing of actual risks and acceptance of those risks with the benefits. Whereas **environmental risk assessment** is the job of environmental scientists, risk management is a regulatory activity that is typically carried out by government (local, national, or international) agencies. Put simply, risk management is the decision to regulate a particular environmental activity (automobile lead emissions, for instance) depending upon whether the risks have been shown to outweigh the social and/or economic benefits. How an agency, or a society, decides to balance these risks and benefits is frequently based on two distinct philosophies: 1) the **precautionary principle** (or, "guilty until proven innocent") in which a substance (e.g., a potential new pesticide, food additive, etc.) is assumed to be unsafe *until* sufficient scientific studies show that the risk is low and acceptable; or 2) the "innocent until proven guilty" approach in which limited testing is done on a substance before consumers become exposed to it. In this case, the substance is not rigorously tested for safety *until* there is evidence that it may be too risky.

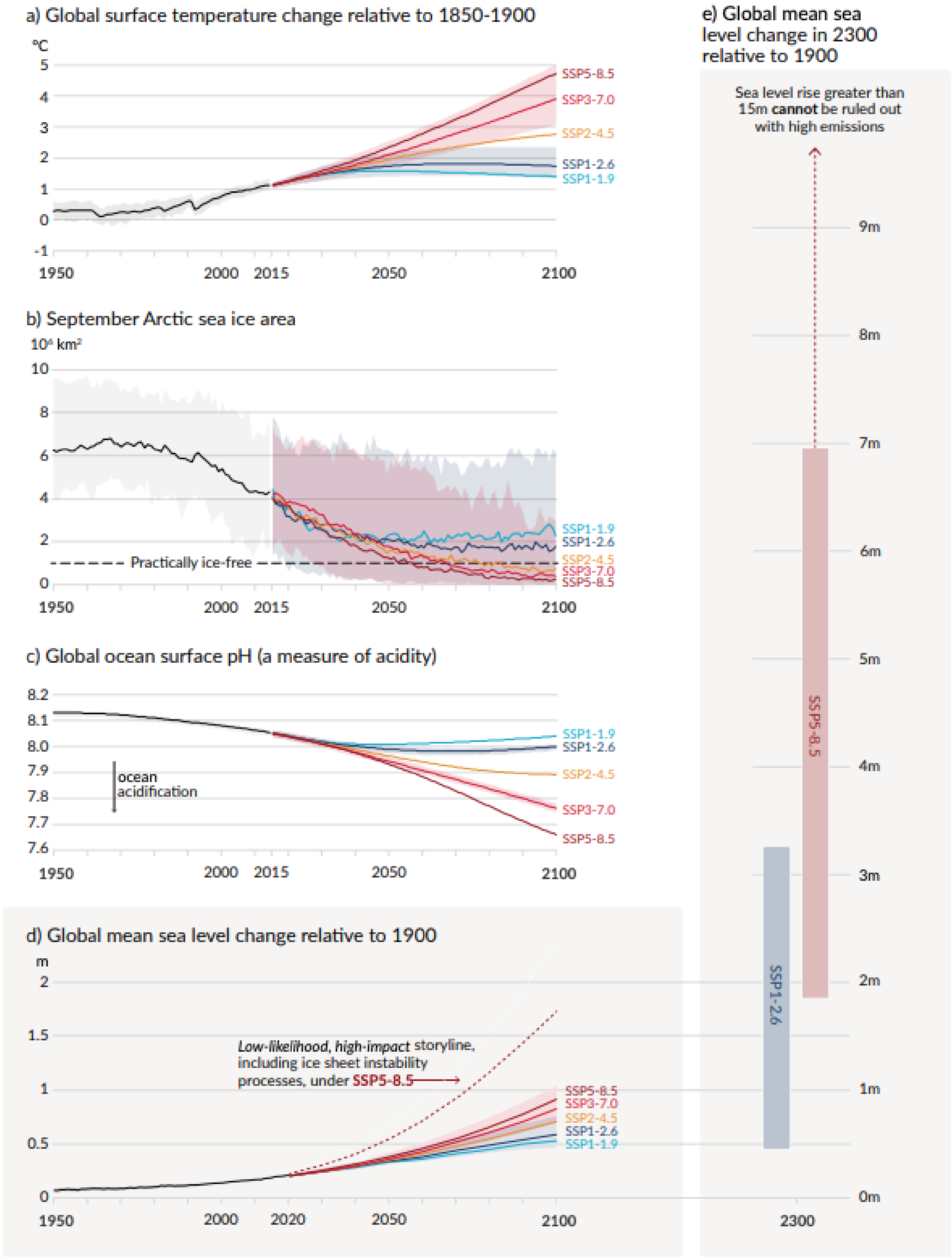
Unfortunately, until recently, much of the U.S. approach in testing new chemicals and other substances used for commercial and other purposes fell into this second approach, unlike the European Union where the precautionary principle tends to dominate. This is why you can see the same pesticide banned in Europe, but allowed in the U.S. However, the federal government in the U.S.—as well as several state governments—has strengthened its pre-commercial testing of many new compounds and is moving toward a precautionary principle approach.

GLOBAL CLIMATE CHANGE

The Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Programme and the World Meteorological Organization in 1988 for the purpose of preparing reviews of the state of knowledge on climate change, including climate change science and climate change impacts today and in the future. From 2021 to 2023, the IPCC published its sixth multi-volume assessment of the changing knowledge regarding climate change. During each assessment, the IPCC has improved and increased the amount of global climate change data it analyzes and the models it uses to make projections. This has enabled the IPCC to decrease the amount of scientific uncertainty in its estimates to the point that, in the latest assessment, it could state that, "It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred."[40]

FIGURE 107

Human activities affect all the major climate system components, with some responding over decades and others over centuries



Human impact on major climate system components.

Source: IPCC

The melting of Arctic and Antarctic ice that shows up in the news with increasing frequency is only one example of physical and biogeochemical change taking place on Earth. Increasing atmospheric concentrations of CO_2 and other atmospheric chemicals, such as compounds of nitrogen and sulfur, and the increase in mercury in fish and mammals are some other significant biogeochemical changes that have occurred over the past fifty years and more. Change that occurs in the chemistry, biology, and physical properties of worldwide systems is referred to as *global change*. Many of these types of changes have occurred over geologic time; for example, concentrations of CO_2 in the atmosphere have ranged from 180 **parts per million** (**ppm**) to almost 280 ppm over the last 800,000 years. However, not only has the pace of change increased dramatically because of recent human activity, but the CO_2 concentrations we see today (420>400 ppm) are the highest they have been for millions of years. Global change incorporates all the previous topics that we have dealt with—the interconnectedness of Earth's systems, the current and future status of Earth and the environmental indicators that enable us to evaluate it, and the interaction of environmental science and policy.

The terms *global change*, *climate change*, and *global warming* are often used synonymously, particularly in the popular press, but they should not be. **Climate change** is variation in the average weather—temperature, precipitation, storm frequency and strength, etc.—over years and decades. Global warming deals with the fact that the Earth's global surface temperature has been increasing relative to pre-industrial temperatures. Global change includes those issues, as well as the other environmental changes that have been largely caused by human activity. This includes large-scale deforestation and other land conversions and the correlated loss of biodiversity, non-greenhouse gas pollution and its impact on human health, and other large-scale changes.

The Sun–Earth Heating System

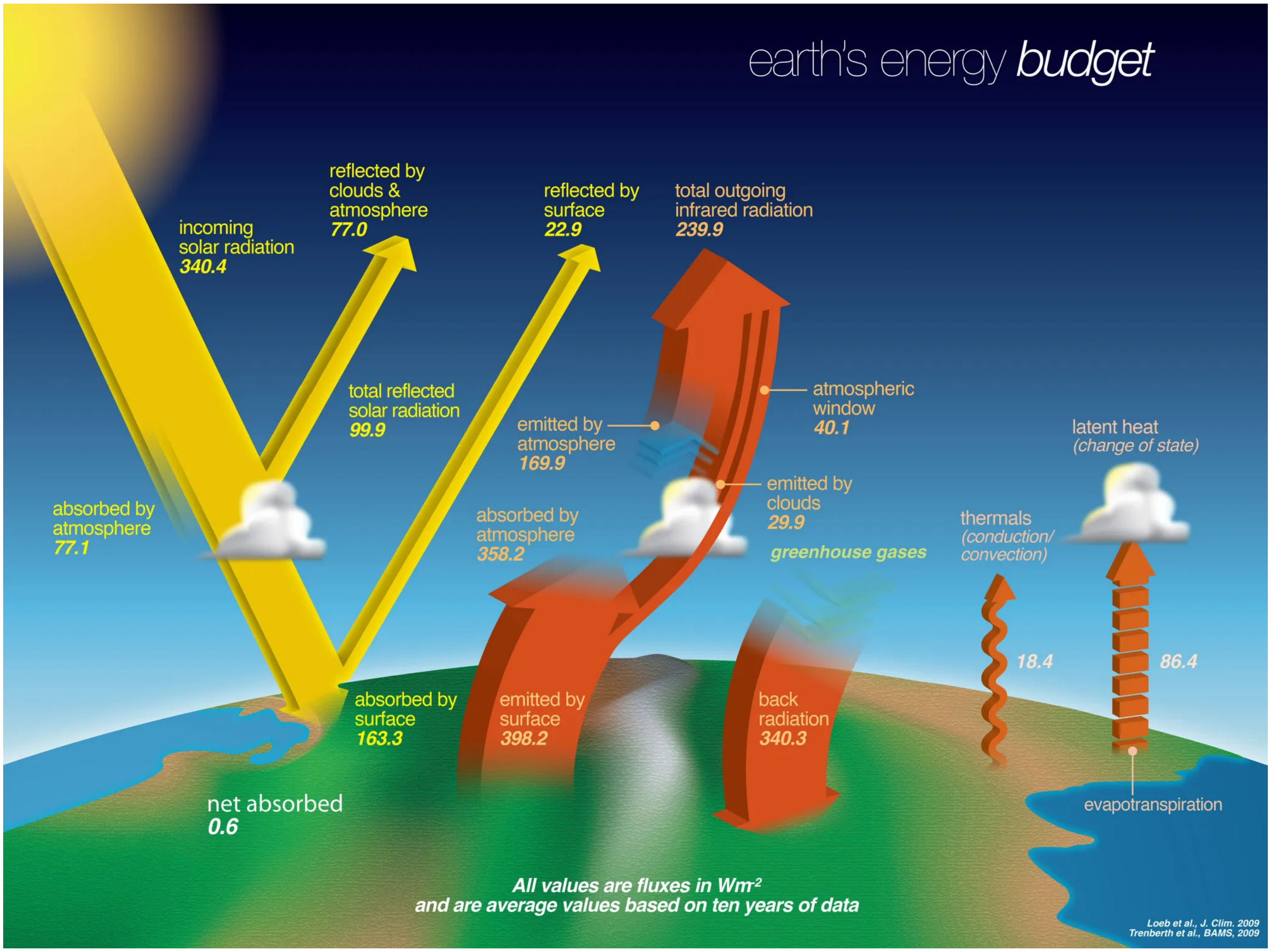
The physical and biogeochemical systems that regulate temperature at the surface of the Earth are essential to life on our planet. These systems derive ultimately from what we can think of as the Sun–Earth system, which—like other systems—can be treated as a series of inputs and outputs, and which involves the interaction between multiple environmental systems.

If you have entered an automobile that has been parked in the sun with its windows closed on a relatively cool day, you have experienced the greenhouse effect. Though the outside temperature may be 10ºC (50ºF), the inside of the car might be 30ºC (86ºF). On a day when the outside temperature is 30ºC, the inside of the car might be 38ºC (100ºF) or even higher. These striking temperature differentials can be explained by the **greenhouse effect**, a natural process that leads to the warming of an area that is underneath something that traps heat—in the case of a greenhouse or the car, the glass of the windows. Most incoming solar energy passes through the windows without being absorbed by the glass, which is transparent to solar radiation in the visible range. The solar energy is absorbed by the upholstery, the dashboard, and the steering wheel, which experience an increase in temperature and then begin to radiate energy outward. Though the windows of the car allowed solar radiation to pass through, they do not allow passage of very much of the outgoing "car" radiation, which is in the infrared range. This energy is absorbed and reradiated back into the car. The inflow of energy into the car is greater than the outflow of energy, so there is a positive net flux of energy into the car, causing the car to become increasingly warmer, even on a relatively cool day.

A very similar process takes place at the surface of Earth. As energy from the Sun travels toward Earth, it is absorbed by the atmosphere or is reflected and scattered back into space. Almost half of this solar energy passes through Earth's atmosphere, much like the solar energy passed through the car windows, and is absorbed by objects at the surface of Earth, such as water, land, vegetation, rocks, and human-made structures, and radiated back out. Since objects at the surface of Earth are roughly the temperature of Earth (15ºC), they radiate in the infrared. Like the car windows, heat-trapping gases make the atmosphere almost opaque to outgoing infrared radiation.

In the Sun–Earth heating system, there is one major energy input—solar radiation—and two major outputs—reflection of solar energy from the atmosphere or from the surface of the Earth and infrared radiation of Earth energy. Over the long term, the net flux of heat is zero; inputs of heat to Earth equal outputs from Earth, and the

FIGURE 108



The Sun–Earth heating system.

Source: NASA

system is in a steady state. However, the input can be greater than the outputs because of an increase in incoming solar radiation (from sunspots, for example) or because of a decrease in outgoing reflected solar radiation either from a change in materials covering the surface of the Earth or from an increase in heat-trapping greenhouse gases. If solar radiation is greater than the sum of reflected solar energy and radiating infrared Earth energy, Earth becomes warmer in response to the input of additional heat energy. If solar radiation is less than the other two fluxes, Earth becomes cooler. This is where the greenhouse effect becomes important.

Greenhouse Gases

The relatively hospitable temperatures on Earth are largely a function of the heat-trapping gases that are present in the atmosphere, commonly called **greenhouse gases (GHGs)**. We discussed the generation of GHGs when discussing pollution and energy production. Nevertheless, you may be surprised to learn that the most common GHG is water: water vapor (H_2O gas) absorbs infrared energy radiating from the Earth. The major, but not the only, heat-trapping gases added to the atmosphere by human activities, such as the combustion of fossil fuels and clearing of land, are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs). In the absence of GHGs, the temperature on Earth would be approximately negative 18ºC (0ºF). Thus, although we commonly think of GHGs—and the global greenhouse effect—as a negative, it is actually necessary for human life on Earth. The problem arises when the natural greenhouse effect is increased by the human addition of GHGs, making for a hotter greenhouse.

While the temperature of Earth has fluctuated over geologic time, most of the temperature changes have been very slow, and in any given decade, century, and sometimes millennium, the Earth's temperature has been relatively constant. Our system analysis makes clear that in order for Earth to stay at a constant temperature, the energy inputs must equal the energy outputs. However, a variety of natural processes and human activities may increase or decrease the concentration of GHGs, and the extent of absorption and radiation of energy will increase or decrease accordingly, resulting in variations in the greenhouse effect. The re-radiation and reabsorption of energy by greenhouse gases is called *radiative forcing* because the gases that are present return energy to Earth, forcing a change in Earth's energy balance.

When assessing the impact of each GHG, we need to consider three environmental parameters: the concentration of the gas in the atmosphere, its global warming potential, and how long the gas molecules will persist in the atmosphere. The global warming potential of a gas is an estimate of how much a molecule of that gas can warm the atmosphere over a hundred years, relative to a molecule of CO_2. Methane, nitrous oxide, and CFCs all have greater warming potential than CO_2. However, it is the much greater concentration of CO_2 in the atmosphere—along with its much longer duration in the atmosphere—that makes it the most important greenhouse gas.

FIGURE 109

Greenhouse gas	**Concentration in 2022 (ppm = parts per million)**	**Global warming potential (based on Carbon Dioxide = 1)**	**Duration in the atmosphere**
Water vapor	Variable with temperature	<1	9 days
Carbon dioxide	417 ppm	1	Highly variable (years to hundreds of years)
Methane	1.9 ppm	25	12 years
Nitrous oxide	0.3 ppm	300	114 years
Chlorofluorocarbons	≈0.8 ppm	1,600 to 13,000	55 to >500 years

Major greenhouse gases and their impacts on warming. The major greenhouse gases differ in their atmospheric concentrations, their ability their global warming potential, and the duration that molecules of the gas will remain in the atmosphere.

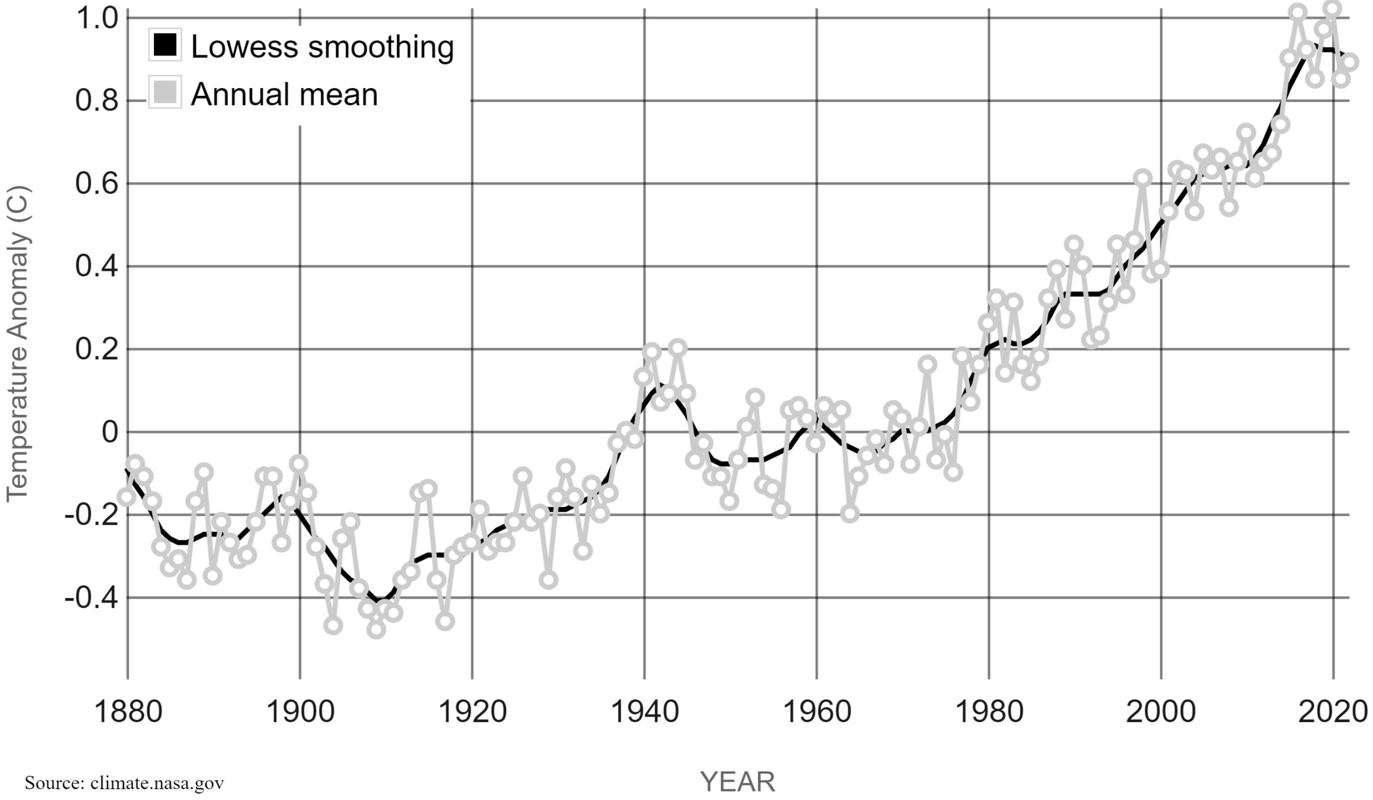
Source: NOAA

At the beginning of our discussion of global change, you saw the current estimates—from the IPCC's 6th Assessment Report—for several climate change indicators, including the increase in global surface temperatures. We will now explore some of the ways that these indictors have been measured.

Evidence of Temperature Change over Time

Global warming refers to the increased warming of Earth's atmosphere and surface due to an increase in gases that trap heat and, in particular, warming caused by human activity. As previously mentioned, global warming is one component of the broader phenomenon of global change. One of the greatest difficulties in determining if global warming is occurring is the difficulty of establishing what, if any, temperature change has occurred in recent decades. Though indirect measurements have made it clear that global temperatures have fluctuated over geologic time, what is needed is precise, widespread measures of temperature from locations around the globe for hundreds and thousands of years. Earth surface and ocean temperatures have been measured directly only since about 1880, with varying, though increasing, degrees of confidence. There is a high degree of confidence in at least one global temperature data set maintained by James Hansen at the NASA Institute for Space Studies in New York City. Hansen and his colleagues have generated a graph of global temperature change that is updated monthly and posted on NASA's website (Figure 110). This graph, which is comprised of thousands of measurements from around the world, clearly shows a steady increase in global temperatures from 1880 through 2020 (although there are yearly variations). Measurements for 2023 are not yet complete; however, we can note that June, July, August, and September of 2023 were the hottest for those months on record. Historical evidence and scientific models suggest that Earth is becoming warmer.

FIGURE 110



Global surface temperature measurements. Lowess smoothing is a method of fitting a smooth curve (the black line in the figure) to data points, such as the yearly temperature variation in the figure.

Source: NASA

Indicators of Climate Change

Indirect measurements that can be obtained through biological and physical parameters suggest that current global temperatures are higher than at any time in at least the last 150,000 years. One such indicator is the sampling of ice cores that we discussed in the first part of Section I. Trees can provide indirect records of temperatures for decades and centuries and on rare occasions for more than a thousand years. Each year, most trees add layers of wood from millimeters to centimeters thick. In middle and high latitudes, these annual rings are quite distinct and allow careful measurement of tree growth and a subsequent estimate of temperature. Wider rings correspond with better temperatures for growth (if there is also enough moisture), which usually means warmer and/or wetter conditions in the year when—or the year before—the rings were added to the tree. Corals are another surrogate indicator. In relatively clean ocean waters in and near the tropics, marine corals add annual bands of calcium carbonate. A number of geochemical signals in the calcium carbonate allow researchers to reconstruct the approximate temperature of the water in which the corals have been growing. Corals can record temperatures for tens and sometimes hundreds of years.

Corals can serve as an indicator of climate change, as they can record temperatures for tens and sometimes hundreds of years.

By Holobionics - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=49070224

Models

We've previously discussed the use of models to predict the environmental effects of various factors such as energy use or pollution. Because direct measurements are scarce, models are particularly important in calculating changes in temperature and other aspects of climate. Environmental scientists use recorded temperatures to construct models that correlate many parameters, including past concentrations of GHGs, with past temperatures. The models are then used to predict future concentrations of greenhouse gases and estimate future temperatures based on the predicted gas concentrations. Based on the projected temperatures, estimates are then made of how another parameter, such as sea level or precipitation patterns, will be affected by the change in temperature.

For example, when Earth becomes one degree warmer, eventually the oceans will become one degree warmer as well. Because of thermal expansion, each degree Centigrade increase in ocean temperature results in approximately a six centimeter rise in the height of the ocean. Sea level change is difficult to measure precisely—although current satellite data is becoming more reliable for recent measurements—but it appears that over the past century, as ocean temperature has risen approximately 1ºC, sea level has risen by approximately 10 cm. Based on these correlations, predictions for the next hundred years suggest that sea level might rise another 10 cm or more.

Other models can be used to predict, for instance, a particular change in ocean or atmospheric circulation patterns resulting from certain air or water temperature changes. The changes in circulation might lead to warmer or cooler temperatures in one region of Earth, in turn influencing the precipitation patterns that occur in this region. Finally, the combined effects of changes in temperature and precipitation may influence a particular species of tree, which may expand or constrict its geographic range. The effect might also include the length of the growing season in a particular area, or increased temperature of water in freshwater lakes, which could lead to a decrease in biodiversity in those lakes.

A variety of models, known collectively as atmosphere/ocean/sea-ice general circulation models (AOGCMs), are used to predict the effects of global climate change. Researchers first characterize past climate based on existing data for air and ocean temperatures, CO_2 concentrations, size of different biological populations, extent of sea ice coverage at the poles, and many other parameters. Characterizing past climate conditions, which can be assessed against the actual climate conditions that were measured by meteorological instruments, is a test of how well the model works and thus how well it will predict future conditions. The model is calibrated and refined to better "predict" what has already happened. Then future parameters, such as the estimated atmospheric CO_2 concentration in 2050, are inserted into the model to predict what the temperature might be at a given location on Earth at a certain time in the future, such as 2050 or 2100.

Feedback in the Global Greenhouse System

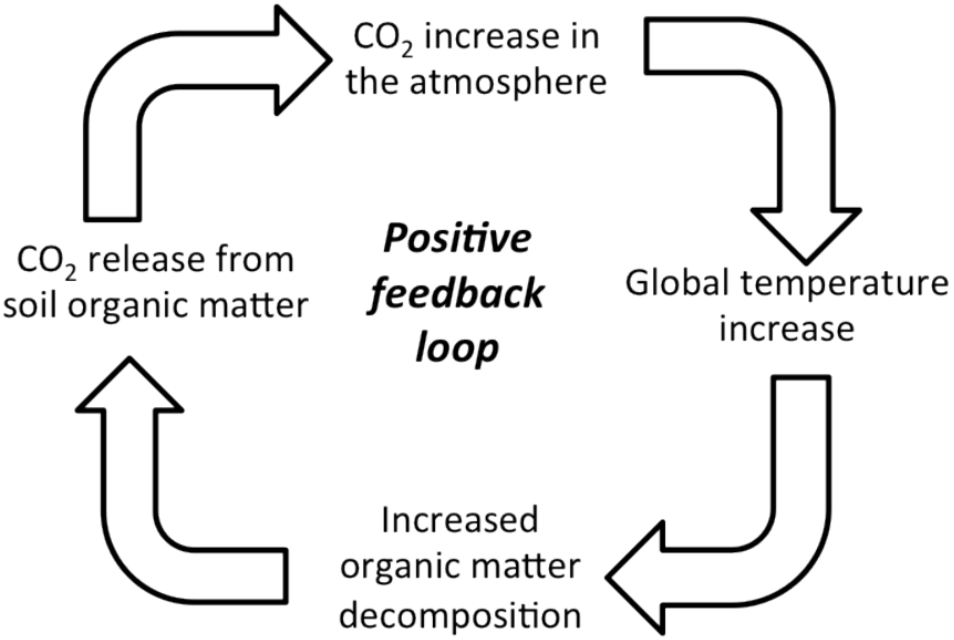
The global greenhouse system is similar to the Mono Lake system we examined in Section I in that it is made up of several interconnected systems. However, both the number of subsystems and the number of different components within each system make the global greenhouse system much more complex. Several important feedback loops contribute both to increased atmospheric concentration of GHGs and to increased global temperatures. Global warming affects all environmental and human systems.

The Temperature–CO_2 Feedback Loop

As you learned in Section II, soils of different kinds cover much of the land surface on Earth, and in many locations the soils contain a significant amount of organic matter. When oxygen is present, the organic matter is broken down by microorganisms, which give off CO_2 as a by-product of this **aerobic** (oxygen-rich) *decomposition*, much as human beings give off CO_2 as a by-product of respiration. In general, organic matter in soils is at steady state: it is decomposed at roughly the same rate at which new organic matter is contributed. However, certain changes can disrupt this steady state.

Decomposition generally occurs more rapidly in warmer environments than in cooler environments. If an increase in CO_2 emissions leads to warmer temperatures, decomposition will increase, giving rise to more CO_2 production. The increase in CO_2 production will increase atmospheric CO_2 concentrations further and enhance the greenhouse effect. This in turn will promote more decomposition, which will lead to more atmospheric CO_2, and so on, in a positive feedback cycle that will continue to move CO_2 toward an exceedingly high concentration. In the real world, something would eventually limit the positive feedback, such as the availability of dead organic matter, but in the meantime the net concentration of CO_2 in the atmosphere would have increased.

FIGURE 111



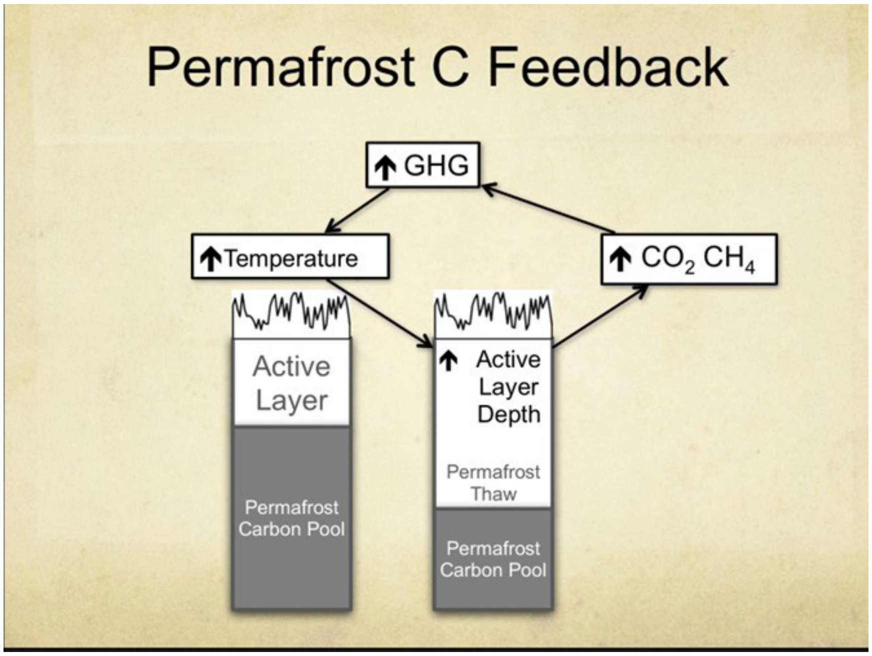
Temperature–CO_2 feedback loop.

The Temperature–Permafrost Feedback Cycle

In the northern latitudes, a large amount of dead organic matter is bound within the arctic tundra, which is frozen much of the year. When the tundra thaws, it is very wet. Extremely wet organic matter contains little oxygen and therefore does not undergo aerobic decomposition. However, the tundra contains organisms that can decompose organic matter anaerobically, which produces methane as well as CO_2. Even a slight warming of temperatures in northern latitudes would increase the number of days each year that the tundra is not frozen, thereby increasing the number of days during which anaerobic decomposition, and hence methane production, would occur.

Since the greenhouse gas efficiency of methane is twenty-five times that of CO_2, a positive feedback cycle could easily result. An increase in methane in the atmosphere would lead to more radiative forcing, which would lead to slightly warmer temperatures, which would lead to more days with unfrozen tundra and increased anaerobic decomposition. Like the temperature–CO_2 feedback cycle, the temperature–permafrost feedback cycle will create a net increase of greenhouse gas in the atmosphere, which will have an impact everywhere in the world, not simply in the arctic.

FIGURE 112



Permafrost C Feedback

↑ GHG

↑ Temperature

↑ CO_2 CH_4

Active Layer

Permafrost Carbon Pool

↑ Active Layer Depth

Permafrost Thaw

Permafrost Carbon Pool

Temperature–permafrost feedback loop.

Source: Professor Ross Virginia, Environmental Studies Department, Dartmouth College.

The Ice–Albedo Feedback Loop

One last feedback loop to consider is of particular importance in ice- and snow-covered areas: the ice–albedo feedback loop. Sea ice and snow-covered ground are solar reflectors, sending solar energy from the Earth's surface back to the atmosphere, with some escaping back into space. The overall effect is to cool global surface temperatures. However, as global warming decreases the amount of sea ice and snowpack, the albedo decreases since the ocean and uncovered ground have lower albedo and absorb more of the solar energy.

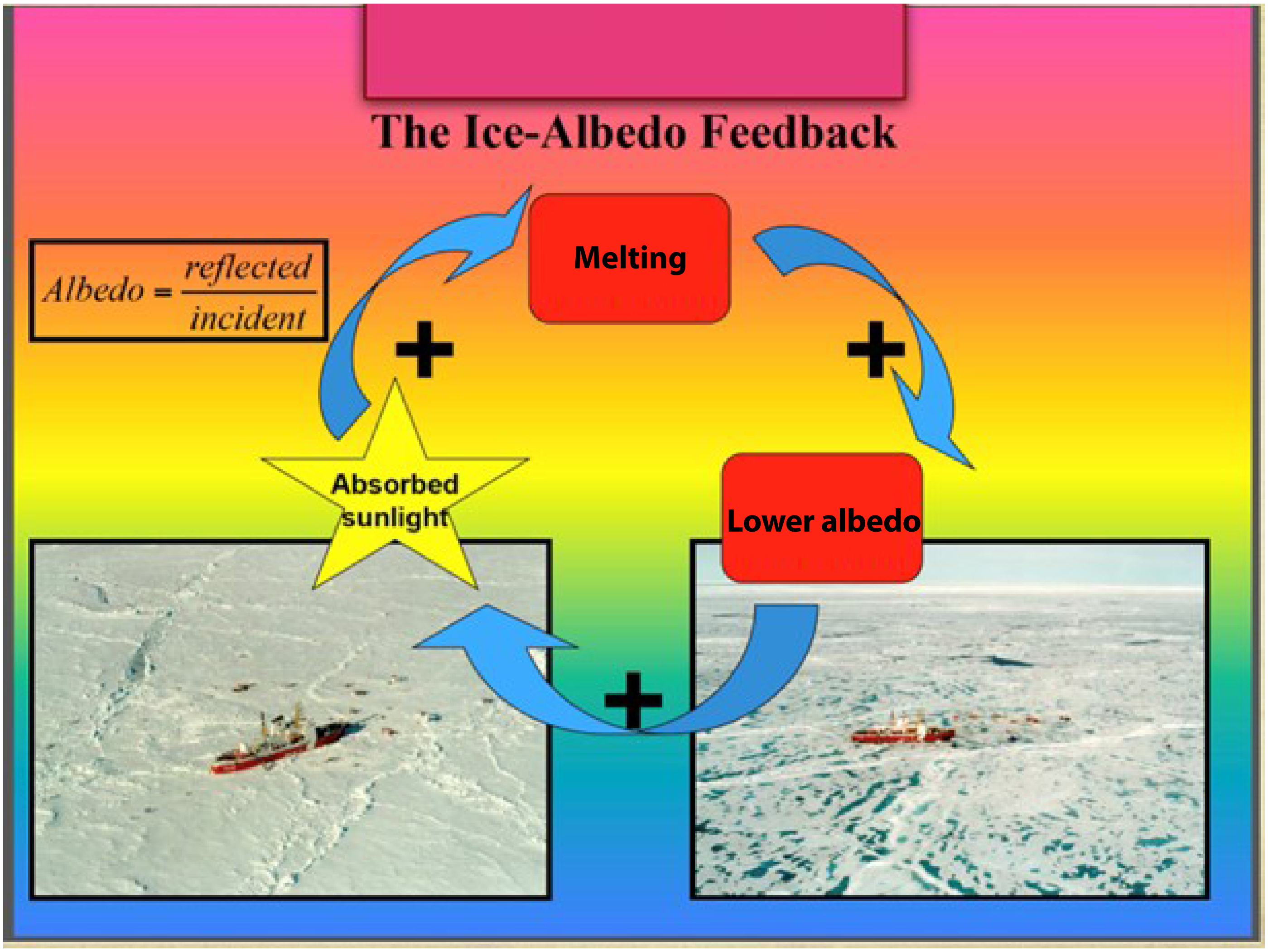
A young male polar bear found a remaining iceberg, clawed out a bed, and drifted off to sleep in Norway's Svalbard archipelago. The impacts of climate change are significant, and environmental scientists foresee still more extensive changes throughout all of Earth's systems in the future.

Photo by Nima Sarikhani/Wildlife Photographer of the Year

Effects of Global Warming

Global warming is already contributing to overall global change. Atmospheric CO_2 has increased 50 percent since 1750[41], and global average temperature has increased by about 2ºF since 1880. Although a temperature increase of 2 degrees may seem small, it is enough to affect global processes significantly, as suggested by many environmental indicators, including the amount of arctic ice. Snow cover has decreased by at least 10 percent since observations were first conducted in the 1960s. Permafrost has thawed, warmed, and degraded in polar, sub-polar, and some mountainous regions. The growing season has lengthened by one to four days per decade since the 1960s in the Northern Hemisphere.

FIGURE 113



The ice–albedo feedback loop.

Source: Professor Ross Virginia, Environmental Studies Department, Dartmouth College.

The geographic range for many plants, insects, and birds has shifted northward in the Northern Hemisphere and on some occasions has moved up in altitude on mountains. In some cases, species that have increased the northern extent of their range in the Northern Hemisphere have constricted their southern range because conditions are less favorable for them further south. Flowering plants have been blooming earlier, birds arrive earlier at their spring nesting grounds, and insects are emerging earlier in the Northern Hemisphere.

"The tip of the iceberg" is an almost literal description of the changes that have already occurred. Environmental scientists foresee extensive changes throughout all of Earth's systems in the future.

Predicted Future Effects of Global Warming

A number of global changes have been predicted to occur by the end of the twenty-first century as a result of global warming, a few of which we have already mentioned. Here we outline some other projections based on available data and the models we described earlier. Though these occurrences represent moderate to worst-case scenarios, many of them are nevertheless considered likely.

- Continental glaciers and the Greenland ice sheet are expected to continue to retreat. Global mean sea level, in part as a result of the melting of glaciers, is expected to rise by 0.1 to 0.9 m by 2100.

- Maximum temperatures will be higher, and more heat waves will occur across virtually all land areas. There will be a potential for heat and drought damage to crops or greater irrigation requirements for crops. Demand for energy for cooling of living spaces and food will increase.
- Minimum temperatures will increase over most land areas, with fewer extremely cold days and fewer days below freezing in certain locations. Such conditions will result in fewer cold-temperature deaths among humans and a decrease in the risk of crop damage. A decrease in killing frosts that limit the geographic extent of pest species will lead to an increase in the range of pest and disease **vectors**. Demand for heating of living spaces should decrease, which will decrease the demand for energy.
- Precipitation patterns will change. Higher rainfall amounts over certain land areas are projected, although models differ on which areas of the globe will receive the greatest rainfall. Increased precipitation is expected to result in increased flooding, landslides, and mudslides, as well as increased soil erosion. Benefits may include increased recharge to aquifers and in some cases increased crop yields. At the same time, changes in regional climates may either increase or decrease precipitation and storm frequency; how regional climates will change is not well understood.

U.S. Secretary of State John Kerry, with his two-year-old granddaughter Isabelle Dobbs-Higginson on his lap and United Nations Secretary-General Ban ki-Moon looking on, signs the COP21 Climate Change Agreement on behalf of the United States during a ceremony on Earth Day, April 22, 2016, at the U.N. General Assembly Hall in New York.

- Global ocean currents may shift, which would dramatically disrupt the distribution of heat on the planet (remember that the unequal distribution of heat is the basis for the circulation currents present on Earth).
- The natural processes of ecosystems, especially those that have already been fragmented by human development, will change. Anticipated changes in ecosystems in the northeastern and north-central U.S., for instance, suggest that spruce-fir, aspen-birch, and maple-beech-birch stands of forest will move significantly northward, greatly decreasing their abundance in existing locations. This change in the makeup of vegetation will have profound impacts on the wildlife that depends on these particular types of trees. Many other species may be threatened by extinction, as rapid temperature change does not allow every population of organisms time to adapt. As the productivity of an ecosystem and the ecological services it provides are generally a result of the variety of species that are present in the ecosystem, a reduction in species may mean that overall ecosystem function and productivity will be reduced.
- Global warming and the resulting changes will dramatically affect human populations. As sea levels rise, coastal communities and certain open ocean islands will be threatened by inundation and, even before that, contamination of their drinking water and erosion of their coastal areas. In the South Pacific, a number of islands and island nations have already been threatened with flooding from rising sea levels. High tides and rough seas have led to short-term inundation of areas in the Marshall Islands, Cook Island, Tuvalu, and lower lying areas of Papua New Guinea.
- A general decrease in water availability in landlocked regions is also predicted. As the planet warms, disease vectors, such as the mosquitoes carrying West Nile virus and malaria, will extend over greater areas, bringing disease to areas that were once relatively untouched. Heat waves will cause more deaths among the very young, the very old, and those without access to air conditioning. Infectious diseases and bacterial and fungal illnesses will extend over a wider range than at present.

Climate change is already having economic and **environmental justice** consequences. In northern locations, warmer average temperatures and shorter winters may sound appealing at first but would drastically alter the character of northern communities that depend on snow for the tourism industry. The damage to marine corals will have an impact on eco-tourism. Poorer communities close to or along coastlines will not have the resources to rebuild on higher ground. In general, the poor will bear the greatest costs of global change because they have the fewest resources to deal with the changes.

While environmental science, in general, and climate change science in particular, can provide important data on the current and potential future states of our Earth, the issues summarized above cannot be solved by science. Reducing GHG levels in the atmosphere—as well as funding and building the necessary infrastructures required to deal with the climate change impacts that we are facing—require global policy agreements, such as the 2015 Paris Agreement that provides a framework for every country to do what it can to reduce GHG emissions and provide the help necessary to those countries that are on the frontlines of climate change.

SECTION IV SUMMARY

Atmospheric Science and Air Pollution

- Air pollution includes the compounds present in the troposphere at levels high enough to cause damage to human beings, animals, plants, and structures or to alter ecosystems. The six U.S. criteria air pollutants are sulfur dioxide, nitrogen oxides, carbon monoxide, lead, particulate matter, and ozone. Primary pollutants—compounds that are pollutants in the form that comes directly out of a smokestack, exhaust pipe, or natural emission source—include CO, CO_2, SO_2, NO_X, most suspended particulate matter, and many VOCs. In the atmosphere, primary pollutants are transformed through complex chemical reactions into secondary pollutants. Ozone and components of acidic deposition are some of the secondary pollutants of greatest concern.
- A large percentage of air pollution comes from natural sources such as volcanoes, fires, and plants. Anthropogenic sources are transportation, industrial processes, and other fuel combustion, primarily electricity generation. Transportation is responsible for more than half of outdoor air pollution.
- Through a series of reactions, SO_2 and NO_x form into the secondary pollutants nitric acid and sulfuric acid, which produce acid rain.
- Photochemical smog forms when oxides such as NO_X combine with oxygen and VOCs in the presence of sunlight to produce photochemical air pollutants, particularly ozone. Human activity is an important contributor to smog because it supplies the VOCs without which ozone would be destroyed. Smog is common in urban areas, particularly if a thermal inversion traps pollutants at ground level, but it also occurs in nonurban settings. Photochemical smog is detrimental to both human health and ecosystems.
- Particulates can be removed from industrial emissions by a number of technological devices. Primary pollutants are harder to control, and photochemical smog is particularly difficult because of the complex of primary pollutants involved. Predictive models help environmental scientists and governments determine where and when pollution might be a problem.

Nonrenewable Energy Sources

- Energy use has changed over time with the appearance of different technologies. The United States and the rest of the developed world have moved from a heavy reliance on wood and coal to mostly fossil fuels and nuclear power, whereas the developing world still relies largely on biomass. Different sources of energy are suited for different activities.
- Energy efficiency, the amount of usable work that can be obtained from a given input of energy, can be broken down into three different types. To determine how efficient a particular device is, we must compare its thermal, machine, and system efficiencies. In general, the energy source that entails the fewest conversions from its original form to the end use will likely be the most efficient. Though multi-

passenger transportation is the most energy-efficient way to travel, in the United States the single-passenger vehicle is most popular.

- Electricity-generating power plants convert the chemical potential energy of fuel into electrical potential energy (electricity). Coal, oil, natural gas, and nuclear power are the most common energy sources for generating electricity. The power grid ties electricity-generating plants together over defined regions.
- Coal is a very dense fossil fuel that is a good source for efficient electricity generation. Deep-shaft coal mining has serious health and safety consequences and leaves toxic slag piles in the environment. Surface mining can remove whole mountain tops and contaminate nearby waterways. Coal combustion is a major source of air pollution.
- Petroleum includes both crude oil and natural gas. Oil is currently the greatest energy source in the United States, used primarily for transportation. It produces significant air pollution as well as greenhouse gas, and oil spills are a major hazard to organisms and habitats. Oil extraction in various parts of the world has led to environmental justice issues. Natural gas (methane), the fuel of choice for cooking and heating, does not produce particulate air pollution, but it is a major GHG.
- Nuclear power is a relatively clean means of electricity generation, though fossil fuels are used in constructing nuclear power plants and mining uranium. The major environmental hazards of nuclear power are accidents and radioactive waste. The fuel used in a nuclear plant will remain radioactive for as long as 100,000 years; disposing of it is currently a political as well as environmental issue.
- Total energy consumption in the United States is projected to increase in the future, while the country's fossil fuel reserves are shrinking, indicating that the existing energy program in the U.S. is not sustainable.

Renewable Energy Sources

- Sustainable energy is energy consumed at a level that will allow an adequate supply to remain for future generations and at the same time does as little direct damage to the environment as possible. Renewable energy is created continuously from perpetual sources such as the Sun and wind and will always be available.
- The Sun is the ultimate source of most energy on Earth. Direct solar energy is the energy from the Sun's rays striking the Earth directly, or the solar constant. The Sun is also responsible for causing winds and promoting the hydrologic cycle, which are thus indirect forms of solar energy. Passive solar refers to the collection of solar energy without an intermediate technology such as a pump or blower, as in a solar cooker. Active solar utilizes mechanical devices, such as photovoltaic cells, to harness or transfer the energy to useable forms of heat or electricity.
- The kinetic energy of wind is converted to potential energy in electricity. Wind power is the fastest growing source of electricity in the world. Large wind turbines are frequently grouped in wind farms or offshore wind parks. Wind is a very clean form of energy, though some people object to wind turbines largely on aesthetic grounds.
- Biomass energy, the potential energy contained in organic matter, is one of the major forms of energy in the developing world but is also used in developed countries. The carbon produced by the burning of biomass does not add appreciably to atmospheric CO_2 levels because it is modern, rather than fossil, carbon. Wood and wood byproducts, dung, municipal solid waste, ethanol, and biodiesel are all biomass energy sources. Wood is potentially renewable because if managed correctly, it can be a continuous source of biomass energy.
- The kinetic energy of water can be harnessed to generate electricity. Run-of-the-river hydroelectric power uses little or no water impoundment. More common are larger dammed hydro systems.
- Heat from deep in the Earth produces geothermal energy. This energy is used to generate electricity. Hydropower is one of the cleanest forms of energy, as fossil fuels are used only in construction and

maintenance of the facilities; but hydropower facilities impact the environment by flooding or otherwise disrupting ecosystems. Tidal energy is derived from the twice-daily movement of water along coastlines.

- Though many scenarios have been predicted for the world's energy future, conservation—the reduction in energy demand—and increasing energy efficiency—the use of less energy to do the same amount of work—as well as new technologies will be necessary for energy sustainability.

Global Climate Change

- Changes to Earth's biogeochemical, climatic, and biological systems are interconnected. Global warming and climate change are subsets of overall global change.
- Radiant solar energy of differing wavelengths reaches Earth, where energy is absorbed and radiated back. In the Sun–Earth heating system, if the solar radiation reaching Earth is greater than the sum of the solar energy reflected back and the energy radiated by Earth, Earth becomes warmer. The greenhouse effect is a natural process that leads to the warming of an area underneath something that traps heat. On Earth, heat can be trapped by a number of greenhouse gases, the most common of which is water vapor. Radiative forcing—the radiation and absorption of energy by greenhouse gases—forces a change in Earth's energy balance. The impact of each GHG is measured by its relative GHG efficiency, which depends in part on the concentration of other GHGs in the atmosphere. CO_2 is the greatest contributor to total anthropogenic radiative forcing because of its high concentration in the atmosphere.
- Global warming is the increased warming of Earth's atmosphere due to an increase in gases that trap heat—in particular, warming caused by human activity. Because of the scarcity of direct temperature measurements over historical time (more than 140 years), evidence of the warming of Earth is based largely on surrogate indicators. Models are used to predict future warming on the basis of past trends.
- Natural causes of global warming include volcanoes, denitrification, and evaporation from all sources of water on Earth. Currently, anthropogenic causes of global warming are of more concern than natural causes because they are increasing over a much shorter time scale and are of a greater magnitude.
- Burning of fossil fuels is the greatest anthropogenic source of global warming, adding new carbon to the carbon cycle and thus increasing the amount of CO_2 in the atmosphere. Other anthropogenic causes include deforestation that is not balanced by replanting and, to a lesser extent, certain agricultural practices and biomass burning. Developed countries are by far the largest contributors to global warming.
- Global warming affects all environmental and human systems through three interconnected feedback cycles. Global average temperature has increased over the past hundred years to a level which is enough to affect natural processes significantly. Predicted future effects include weather and climate changes; disruption of natural ecosystem processes; loss of biodiversity; and health, social, and economic problems for humans.

Conclusion

Earth is made up of many interconnected systems of different sizes and complexities. Systems can be natural (e.g., a lake), human-made (e.g., a city), or a combination (e.g., a farm). Systems can also vary in scale, from a small pond to the largest system that we dealt with—the entire Earth. What all systems have in common is that they consist of interacting components in which changes in one component affect other parts of the system. Environmental science studies those systems, how they change when impacted, and how we can better manage them for the future.

Environmental indicators are one of the main tools relied on by environmental scientists; these indicators include changes in species number, global temperature and atmospheric carbon dioxide levels, and food production and land use. From following these indicators over time, environmental scientists have been able to show, with variable levels of scientific certainty, how the growth of the human population and industrialization have negatively impacted these environmental indicators. Their work shows that species loss is currently so great that we are likely heading toward a sixth mass extinction event. Deforestation and other human land use is eliminating much of our natural world. Furthermore, atmospheric greenhouse gas levels are a major cause of rising temperatures, droughts, increasing intensity of storms and wildfires, and rising sea levels.

Despite all these negative consequences of human activities, there is hope—quite a bit of it actually. Environmental scientists, working with policymakers, are developing strategies to protect large parts of the wilderness and the species that live there. Holistic approaches to natural resource management that focus on entire ecosystems are demonstrating that the sustainable management of natural resources is possible. Stricter standards for the release of human-generated chemicals into the environment are the result of scientists studying the human health impacts of air and water pollutants, pesticides, and other substances. And the many decades of work by those environmental scientists working on global climate change has resulted in new international agreements to reduce greenhouse gas emissions and thereby slow and, maybe in the future, reverse the large-scale impacts we are already beginning to experience.

Glossary[42]

acid rain – acid deposition that results when rain combines with the air pollutants sulfur dioxide and nitrogen oxides to produce rain with a pH value of 4.0, instead of the pH of 5.0 to 5.5 of normal rain

aerobic – refers to an environment in which oxygen (O_2) is readily available; compare with *anaerobic.*

age-structure diagram – a diagram that shows the proportions of individuals in various age classes of a population

agroforestry – the cultivation of trees in plantations, typically using relatively intensive management practices

algal bloom – an event of high phytoplankton biomass

ammonification – the oxidation of the organically bound nitrogen of dead biomass into ammonium (NH_4^+).

anaerobic – refers to an environment in which there is no free oxygen (O_2); compare with *aerobic*.

anthropogenic – occurring as a result of a human influence

aquifer – groundwater resources in some defined area

artificial selection – the deliberate breeding of species to enhance traits that are viewed as desirable by humans

atmosphere – the gaseous envelope surrounding the Earth, held in place by gravity

atmospheric inversion (temperature inversion) – a relatively stable atmospheric condition in which cool air is trapped beneath a layer of warmer air

atmospheric water – water occurring in the atmosphere in vapor, liquid, or solid forms

bioaccumulation – the occurrence of chemicals in much higher concentrations in organisms than in the ambient environment; compare with *biomagnification*.

biodiversity (biological diversity) – the richness of biological variation, including genetic variability as well as species and community richness

biodiversity crisis – the present era of high rates of species extinction and reduction in multiple levels of biodiversity, from genetic diversity to ecosystems

biochemical oxygen demand (BOD) – the capacity of organic matter and other substances in water to consume oxygen during decomposition

biomagnification – the tendency for top predators in a food web to have the highest residues of chemicals that persist and move through the food chain; compare with *bioaccumulation*.

biomass energy – the chemical potential energy of plant biomass, which can be combusted to provide thermal energy

biome – a geographically extensive ecosystem, occurring throughout the world wherever environmental conditions are suitable

biosphere – all life on Earth, plus their ecosystems and environments

bog – a freshwater wetland of soft, spongy ground consisting mainly of partially decayed plant matter, called peat, that usually develops in cool but wet climates

boreal coniferous forest – a northern forest dominated by coniferous trees, usually species of fir, larch, pine, or spruce

by-catch – inadvertent harvesting of a non-target species

calorie – a standard unit of energy, defined as the amount of energy needed to raise the temperature of one gram of pure water from 15°C to 16°C; compare with *joule*.

carnivore (secondary consumer) – an animal that hunts and eats other animals

carrying capacity – the number of organisms that can be sustained indefinitely without the habitat becoming degraded

chaparral – a shrub-dominated ecosystem that occurs in south-temperate environments with winter rains and summer drought

chromosome – subcellular unit composed of DNA and containing the genetic information of eukaryotic organisms

clear-cutting – the harvesting of all economically useful trees from an area at the same time

climate – the prevailing, long-term, meteorological conditions of a place or region, including temperature, precipitation, wind speed, and other factors; compare with *weather*.

climate change – long-term changes in air, soil, or water temperature; precipitation regimes; wind speed; or other climate-related factors

coal – a carbon-rich, solid fossil fuel mined from sedimentary geological formations

community – In ecology, this refers to populations of various species that are co-occurring at the same time and place.

compaction – a decrease in the pore space of soil or sediment (or increased bulk density) caused by the passage of heavy machinery

competition – a biological interaction occurring when the demand for an ecological resource exceeds its limited supply, causing organisms to interfere with each other

competitor – a species that is dominant in a habitat in which disturbance is rare and environmental stresses are unimportant, so competition is the major influence on evolution and community organization

compost – partially decomposed, well-humified organic material

composting – the process of encouraging decomposition of discarded organic matter under warm, moist, oxygen-rich conditions; the product, known as compost, is a useful fertilizer and soil conditioner.

conservation – wise use of natural resources; conservation of renewable resources includes recycling and ensuring that harvesting does not exceed the rate of regeneration of the stock.

contamination – the presence of potentially damaging chemicals in the environment

control (control treatment) – an experimental treatment that was not manipulated and is intended for comparison with manipulated treatments

core – Earth's massive interior, made up of hot molten metals

Coriolis effect – an influence of Earth's west-to-east rotation, which makes winds in the Northern Hemisphere deflect to the right and those in the Southern Hemisphere deflect to the left

crust – the outermost layer of Earth's sphere, overlying the lithosphere and composed mostly of crystalline rocks

decay – the decomposition or oxidation of dead biomass, mostly through the actions of microorganisms

decomposer – a heterotroph that feeds on dead organic matter

deforestation – a permanent conversion of forest into some other kind of ecosystem, such as agriculture or urbanized land use

denitrification – the microbial reduction of nitrate (NO_3^-) into gaseous N_2O or N_2

desert – a temperate or tropical biome characterized by low yearly precipitation, usually receiving less than 25 cm of precipitation per year

desertification – the increasing aridity of drylands; an environmental change that can make agriculture difficult or impossible

developed countries – countries with a relatively well-organized economic infrastructure and a high average per-capita income

development (economic development) – an economic term that implies improving efficiency in the use of materials and energy in an economy and progress toward a sustainable economic system

discipline – a specific area of study, such as mathematics or music

disturbance – an episode of destruction of some part of a community or ecosystem

DNA – the biochemical deoxyribonucleic acid, the main constituent of the chromosomes of eukaryotic organisms

domesticate – to genetically, anatomically, and physiologically modify crops and other species from their wild progenitor species through the selective breeding of preferred individuals

doubling time – the time it takes for something to increase by a factor of two (as in population growth)

dumping – the inappropriate disposal of disused material, for example, by placing solid waste into a sanitary landfill or by discarding liquid waste into a waterbody

earthquake – a trembling or movement of the earth, caused by a sudden release of geological stresses at some place within the crust

ecological footprint – the area of ecoscape (i.e., landscape and seascape) required to supply a human population with the necessary food, materials, energy, waste disposal, and other crucial goods and services

ecological pyramid – a model of the trophic structure of an ecosystem, organized with plant productivity on the bottom, that of herbivores above, and carnivores above the herbivores; see also *trophic level.*

ecology – the study of the relationships between organisms and their environment

ecosystem – a general term used to describe one or more communities that are interacting with their environment as a defined unit; ecosystems range from small units occurring in microhabitats to larger units such as landscapes and seascapes, and even the biosphere.

ecosystem approach – a holistic interpretation of the natural world that considers the web-like interconnections among the many components of ecosystems

ecosystem service – an ecological function that is useful to humans and to ecosystem stability and integrity, such as nutrient cycling, productivity, and control of erosion

endangered – In the U.S., this specifically refers to a species listed as endangered under the Endangered Species Act because of its high risk of extinction.

energy – the capacity of a body or system to accomplish work; divided among electromagnetic, kinetic, and potential energies

environment (the) – (1) refers to influences on organisms and ecosystems, including both non-living (abiotic) and biological factors; (2) an indeterminate word for issues associated with the causes and consequences of environmental damage or with the larger environmental crisis

environmental degradation – commonly refers to pollution, disturbance, resource depletion, lost biodiversity, and other kinds of human-caused environmental damage but can also be caused by natural environmental stressors

environmental indicators – relatively simple measurements that are sensitive to changes in the intensity of stressors and are useful for the monitoring of human and nonhuman impacts on the environment

environmental justice – the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation and enforcement of environmental laws, regulations, and policies

environmental quality – a notion related to the amounts of toxic chemicals and other stressors in the environment, to the frequency and intensity of disturbances, and to their effects on humans, other species, ecosystems, and economies

environmental risk – a hazard or probability of suffering damage or misfortune because of exposure to some environmental circumstance

environmental risk assessment − a quantitative evaluation of the risks associated with an environmental hazard

environmental science − an interdisciplinary branch of science that studies the impacts of human activities on environmental systems

erosion − the physical removal of rocks and soil through the combined actions of flowing water, wind, ice, and gravity

estuary − a coastal ecosystem that is open to the sea and has habitats transitional between purely marine and freshwater ecosystems

ethics − norms of conduct that distinguish between acceptable and unacceptable behavior

eutrophication − increased primary productivity of an aquatic ecosystem resulting from nutrient inputs

evaporation − the change of water from a liquid to a gas

evapotranspiration − water losses from a landscape due to evaporation and transpiration

evolution − genetically based changes in populations of organisms occurring over successive generations

experiment − a controlled test or investigation designed to provide evidence for, or preferably against, a hypothesis about the natural or physical world

exposure − the interaction of organisms with an environmental stressor at a particular place and time; often used in environmental health as a measure of the amount of contact of an individual with a specific health risk

extinct (extinction) − a condition in which a species or other taxon no longer occurs anywhere on Earth

First Law of Thermodynamics − a physical principle stating that energy can undergo transformations among its various states, but it is never created or destroyed; thus, the energy content of the universe remains constant; see also *Second Law of Thermodynamics.*

fission reaction − nuclear reaction involving the splitting of heavier, radioactive atoms into lighter ones, with the release of large quantities of energy

fitness − the proportional contribution of an individual to the progeny of its population

flux − a movement of mass or energy between compartments of a material or energy cycle

food chain − a hierarchical model of feeding relationships among species in an ecosystem

food web − a complex model of feeding relationships, describing the connections among all food chains within an ecosystem

forestry − the harvesting of trees and management of post-harvest succession to foster the regeneration of another forest

fossil fuels − geological materials, such as coal, petroleum, and natural gas, made from decomposing plants and animals that contain carbon and hydrogen that can be burned for energy

gene − a region of a chromosome containing a length of DNA that behaves as a specific unit in inheritance and determines the development of a specific trait

genotype − the genetic complement of an individual organism; see also *phenotype.*

geothermal energy − heat in Earth's crust, which can sometimes be used to provide energy for heating or generation of electricity

glacier − a persistent sheet of ice, occurring in the Arctic and Antarctic and at high altitude on mountains

Green Revolution − intensive agricultural systems involving the cultivation of improved crop varieties in monoculture and increased use of mechanization, fertilizers, and pesticides

greenhouse effect − the physical process by which infrared-absorbing gases (such as CO_2) warm the atmosphere

greenhouses gases (GHGs) − atmospheric gases that efficiently absorb infrared radiation and then dissipate some of the thermal energy gain by re-radiation

gross primary productivity (GPP) − the fixation of energy by primary producers within an ecosystem; see also *respiration* and *net primary productivity.*

groundwater – water stored underground in soil and rocks

habitat – the place or "home" where a plant or animal lives, including the specific environmental factors required for its survival

hazardous waste – wastes that are flammable, explosive, toxic, or otherwise dangerous

herbicide – a pesticide used to kill unwanted plants

herbivore (primary consumer) – an animal that feeds on plants

higher-income countries – countries with a relatively high average per-capita income

humus – amorphous, partially decomposed organic matter; an important and persistent type of soil organic matter, it is very important in soil tilth and fertility.

hydrocarbons – molecules composed of hydrogen and carbon only

hydroelectric power (hydropower) – electricity generated using the kinetic energy of moving water

hydrologic (water) cycle – the movement between and storage of water in various compartments of the hydrosphere

hypothesis – a proposed explanation for the occurrence or causes of natural phenomena; scientists formulate hypotheses as statements and test them through experiments and other forms of research.

impoundment – an area of formerly terrestrial landscape that is flooded behind a dam

incineration – the combustion of mixed solid wastes to reduce the amount of organic material present

individual organism – a genetically and physically discrete living entity

insecticide – a pesticide used to kill insects that are considered pests; see also *pesticide* and *pest*.

instrumental value – the usefulness of a thing or function to humans

integrated pest management (IPM) – the use of a variety of complementary tactics toward pest control, with the aim of having fewer environmental and health risks

interdisciplinary – encompassing a wide diversity of kinds of knowledge

intrinsic value – value that exists regardless of any direct or indirect value in terms of the needs or welfare of humans

invertebrate – any animal that lacks an internal skeleton, in particular a backbone

joule – a standard unit of energy, defined as the energy needed to accelerate 1 kg of mass at 1 m/s^2 for a distance of 1 meter

keystone species – a dominant species in a community, usually a predator, with an influence on structure and function that is highly disproportionate to its biomass

kinetic energy – energy associated with motion, including mechanical and thermal types

laws of thermodynamics – physical principles that govern all transformations of energy; see also *First Law of Thermodynamics* and *Second Law of Thermodynamics.*

leaching – the movement of dissolved substances through the soil via the flow of water

less-developed countries – countries with a relatively less developed economic infrastructure and a lower average per-capita income

limiting resource – an environmental resource that is the primary restriction on the productivity of autotrophs in an ecosystem

lithosphere – an approximately 100-km thick region of rigid, relatively light rocks that surround Earth's mantle and core

lower-income counties – countries with a relatively small average per-capita income

mantle – Earth's thickest layer that encloses Earth's core and is below the crust; composed of minerals in a hot, plastic state known as magma

marsh – a productive wetland, typically dominated by species of monocotyledonous angiosperm plants that grow as tall as several meters above the water surface

mass extinction – an event of synchronous extinction of many species, occurring over a relatively short period of time, that significantly reduces biodiversity; there are five mass extinction events documented in the geological record, and there may be a sixth human-caused mass extinction occurring now.

maximum sustainable yield (MSY) − the largest amount of harvesting that can occur without degrading the productivity of the stock

mitigation − an action that repairs or offsets environmental damages to some degree

monoculture − the cultivation of only one species while attempting to exclude others from the agroecosystem

mutualism (mutualistic symbiosis) − a symbiosis in which both partners benefit

natural gas − a gaseous, hydrocarbon-rich mixture mined from certain geological formations

natural mortality − mortality due to natural causes

natural resource − a source of material or energy that is extracted or harvested from the environment

natural selection − a mechanism of evolution, favoring individuals with genotypes that produce phenotypes that are better adapted to existing environmental factors; these more fit individuals have an improved probability of leaving descendants, ultimately leading to genetically based changes in populations, or evolution.

net primary productivity (NPP) − primary production that remains as biomass after primary producers have accounted for their respiratory needs; see also *respiration* and *gross primary production*.

niche − the role of a species within its biological community

nitrification − the bacterial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-)

nitrogen fixation − the oxidation of nitrogen gas (N_2) to ammonia (NH_3) or nitric oxide (NO)

nonrenewable fuel − a fuel resource present on Earth in finite quantities, so as it is used, its future stocks are diminished; examples are metals and fossil fuels.

nuclear fuel − unstable isotopes of uranium (235U) and plutonium (239Pu) that decay through fission, releasing large amounts of energy that can be used to generate electricity

nutrient − any chemical required for the proper metabolism of organisms

nutrient cycle − the transfer and chemical transformation of nutrients in ecosystems, including recycling through decomposition

old-growth forest − a late-successional forest characterized by the presence of old trees, an uneven-aged population structure, and a complex physical structure

organic agriculture − systems by which crops are grown using natural methods of maintaining soil fertility and pest-control methods that do not involve synthetic pesticides

overexploitation − unsustainable harvesting of a potentially renewable resource, leading to a decline of its stocks

parameter − one or more constants that determine the form of a mathematical equation; in the linear equation $Y = aX + b$, a and b are parameters, and Y and X are variables; see also *variable*.

parasitism − a biological relationship involving one species obtaining nourishment from a host, usually without causing its death

parts per million (ppm) − unit of concentration, equivalent to 1 milligram per kilogram (mg/kg), or in aqueous solution, 1 mg per liter (mg/L)

persistence − the nature of chemicals, especially pesticides, to remain in the environment before eventually being degraded by microorganisms or physical agents such as sunlight and heat

pest − any organism judged to be significantly interfering with some human purpose

pesticide − a substance used to poison pests

petroleum (crude oil) − a fluid, hydrocarbon-rich mixture mined from certain geological formations

phenotype − the set of traits expressed by individuals that result from the interaction of genotype and environment; see also *genotype*.

photochemical air pollutants − ozone, peroxy acetyl nitrate, and other strongly oxidizing gases that form in the atmosphere through complex reactions involving sunlight, hydrocarbons, oxides of nitrogen, and other chemicals

photosynthesis − the process by which producers use solar energy to convert carbon dioxide and water into glucose.

plantation − In forestry, these are tree farms managed for high productivity of wood fibre.

poaching − the illegal harvesting of wildlife (plants or animals)

point source − a location where large quantities of pollutants are emitted into the environment, such as a smokestack or sewer outfall

pollution − the exposure of organisms to chemicals or energy in quantities that exceed their tolerance, causing toxicity or other ecological damages

population − In ecology, this refers to individuals of the same species that occur together in time and space.

potential energy − the stored ability to perform work, capable of being transformed into electromagnetic or kinetic energies; potential energy is associated with gravity, chemicals, compressed gases, electrical potential, magnetism, and the nuclear structure of matter.

prairie − grassland ecosystems occurring in temperate regions

precautionary principle − an approach to environmental management, adopted by many countries at the 1992 Earth Summit, which essentially states that scientific uncertainty is not a sufficient reason to postpone control measures when there is a threat of harm to human health or the environment

precipitation − deposition of water from the atmosphere as liquid rain or as solid snow or hail

primary consumer − an herbivore, or a heterotrophic organism that feeds on plants or algae

primary pollutants − chemicals that are emitted into the environment; compare with *secondary pollutants*.

primary producer − an organism that uses the energy of the Sun to produce usable forms of energy

primary productivity − productivity by primary producers, such as plants or algae; often measured as biomass accumulated over a unit of time, or sometimes by the amount of carbon fixed

productivity − an ecological term for production standardized per unit area and time

recycling − the processing of discarded materials into useful products

replacement fertility rate − the fertility rate that results in the numbers of progeny replacing their parents, with no change in size of the equilibrium population

residence time − (1) the time required for the disappearance of an initial amount; (2) the length of time that a stressor or other environmental influence remains active

resilience − the ability of a system to recover from disturbance

respiration − physiological processes needed to keep organisms alive and healthy

restoration − establishment of a self-maintaining copy of a natural ecosystem on degraded land, as when abandoned farmland is converted to a native prairie or forest

restoration ecology − activities undertaken by ecologists to repair ecological damage, such as establishing vegetation on degraded habitat, increasing the populations of endangered species, and decreasing the area of threatened ecosystems

run-of-the-river − a hydroelectric development that directly harnesses the flow of a river to drive turbines, without creating a substantial impoundment for water storage

salinization − the buildup of soluble salts in the soil surface, an important agricultural problem in drier regions

scientific method − an objective method to explore the natural world, draw inferences from it, and predict the outcome of certain events, processes, or changes

Second Law of Thermodynamics − the law stating that when energy is transformed, the quantity of energy remains the same, but its ability to do work diminishes; see also *First Law of Thermodynamics*

secondary consumer – a carnivore that feeds on primary consumers (or herbivores)

secondary pollutants – pollutants that are not emitted (primary pollutants), but form in the environment by chemical reactions involving primary pollutants; compare with *primary pollutants*.

sedimentary rock – rock formed from precipitated minerals such as calcite, or from lithified particles weathered and eroded from other rocks

selective cutting – harvesting of only some trees from a stand, leaving others behind and the forest substantially intact

sewage treatment – the use of physical filters, chemical treatment, and/or biological treatment to reduce pathogens, organic matter, and nutrients in waste waters, containing sewage

slash-and-burn agriculture – an agricultural system that results in a permanent conversion of a forest into crop production, involving cutting and burning the forest followed by continuous use of the land for crops

sludge – a solid or semi-solid precipitate that settles from polluted water during treatment; sludge is produced during the treatment of sewage and also in pulp mills and some other industrial facilities. It may be disposed of in a landfill, but if it is organic, it can be used as a beneficial soil amendment.

smog – an event of ground-level air pollution

soil – a complex mixture of fragmented rock, organic matter, moisture, gases, and living organisms that covers almost all of Earth's terrestrial landscapes

solar energy – electromagnetic energy radiated by the Sun

solid wastes – extremely variable municipal wastes that include discarded food, garden discards, newspapers, bottles, cans, construction debris, old cars, and disused furniture

species – an aggregation of individuals and populations that can potentially interbreed and produce fertile offspring and is reproductively isolated from other such groups

species richness – the number of species in some area or place

stratosphere – the upper atmosphere, extending from 8–17 km to as high as about 50 km; see also *troposphere*.

succession – a process of community-level recovery following disturbance

surface water – water that occurs in glaciers, lakes, ponds, rivers, streams, and other surface bodies of water

swamp – a forested wetland, flooded seasonally or permanently

symbiosis – an intimate relationship between different species; see also *mutualism*.

system – a set of living and/or nonliving components connected in such a way that changes in one part of the system affect other parts; a group or combination of regularly interacting and interdependent elements, which form a collective entity, but one that is more than the sum of its constituents; see also *ecosystem*.

temperate grassland – grass-dominated ecosystems occurring in temperate regions with an annual precipitation of 25–60 cm per year; sufficient to prevent desert from developing but insufficient to support forest

temperate rainforest – a forest developing in a temperate climate in which winters are mild and precipitation is abundant year-round; because wildfire is rare, old-growth forests may be common.

theory – a general term that refers to a set of scientific laws, rules, and explanations supported by a large body of experimental and observational evidence, all leading to robust, internally consistent conclusions

thermal pollution – an increase in environmental temperature sufficient to result in ecological change

threatened – in the U.S., a species that is listed as threatened under the Endangered Species Act because it is at risk of becoming endangered; see *endangered.*

tidal energy − energy that results from the change in water level due to tides in oceanic surface waters and can potentially be used to generate electricity

tolerance − In environmental health, this refers to a genetically based ability of organisms or species to not suffer toxicity when exposed to chemicals or other stressors.

transpiration − the evaporation of water from plants; compare with *evapotranspiration*.

trophic level − a level in the feeding structure of organisms; the higher trophic levels consume organisms from lower levels, and together these levels form a trophic structure.

troposphere − the lower atmosphere, extending to 8–17 km

tundra − a treeless biome occurring in environments with long, cold winters and short, cool growing seasons

variable − a changeable factor believed to influence a natural phenomenon of interest or that can be manipulated during an experiment

vector − species of insects and ticks that transmit pathogens from alternate hosts to people or animals

vertebrates − animals with a backbone

volatile organic compounds − organic compounds that evaporate to the atmosphere at typical environmental temperatures, so they are present in gaseous or vapor forms

waste − any discarded materials

waste-to-energy facility − an incinerator that burns organic waste and uses the heat generated to produce commercial energy

water cycle − See *hydrologic cycle.*

watershed − an area of land from which surface water and groundwater flow into a stream, river, or lake

weather − the short-term, day-to-day or instantaneous meteorological conditions at a place or region; compare with *climate.*

weathering − physical and chemical processes by which rocks and minerals are broken down by such environmental agents as rain, wind, temperature changes, and biological influences

wetland − an area that is wet constantly or seasonally and is intermediate between aquatic and terrestrial ecosystems, such as a bog, fen, marsh, and swamp

wind − an air mass moving in Earth's atmosphere

wind energy − the kinetic energy of moving air masses, which can be tapped and utilized in various ways, including the generation of electricity

Notes

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30 Source: "Guideline on Air Quality Models" (Appendix W to Part 51), EPA regulations, 40 CFR Ch. I.

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40 IPCC 6th Assessment: Climate Change 2021: The Physical Science Basis, Summary for Policymakers, page 4.

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42 Definitions of glossary terms were modified, in part, from *Environmental Science: A Canadian Perspective* 6th edition, Bill Freedman. Creative Commons Attribution-NonCommercial 4.0 International License: https://ecampusontario.pressbooks.pub/environmentalscience/.

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