Introduction to Environmental Sciences and Sustainability

Introduction to Environmental Sciences and Sustainability

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Introduction to Environmental Science and Sustainability is a free and open textbook that enables students to develop a nuanced understanding of today's most pressing environmental issues while also discussing the essentials of sustainability and best practices to incorporate ways we can incorporate socially and environmentally sustainable communities. This text helps students grasp the scientific foundation of environmental topics so they can better understand the world around them and their impact upon it. This book collaborates with various authors and organizations committed to providing students with high-quality and affordable textbooks. Mainly, this text draws from the following open sources, in addition to new content from the editor:

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Special Note to Instructors:

Publication and ongoing maintenance of this textbook are possible due to grant support from the University of West Florida's Library and the Faculty Open Education Resources (OER) award. Whenever you use this textbook, please email the editor (eharris@uwf.edu) and provide the number of courses and students involved. This allows for the impact of this open textbook to be monitored, and hopefully, it justifies continued financial support for it.

Also, please check with the editor before adopting this textbook to see if any substantial revisions or additions are pending.

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Chapter 1: Introduction to Environmental Science and Sustainability

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Learning Outcomes

After studying this chapter, you should be able to:

- Describe what the environment is and some of its major components.
- Identify the shared characteristics of the natural sciences
- Understand the process of scientific inquiry
- Compare inductive reasoning with deductive reasoning
- Describe the goals of basic science and applied science
- Define environmental science
- Understand why it is important to study environmental science
- Explain the concept of sustainability and its social, political, and cultural challenges
- Evaluate the main points of environmental ethics
- Describe the concept of environmental justice
- Differentiate between developed and developing countries

Chapter Outline

What is Environmental Science?

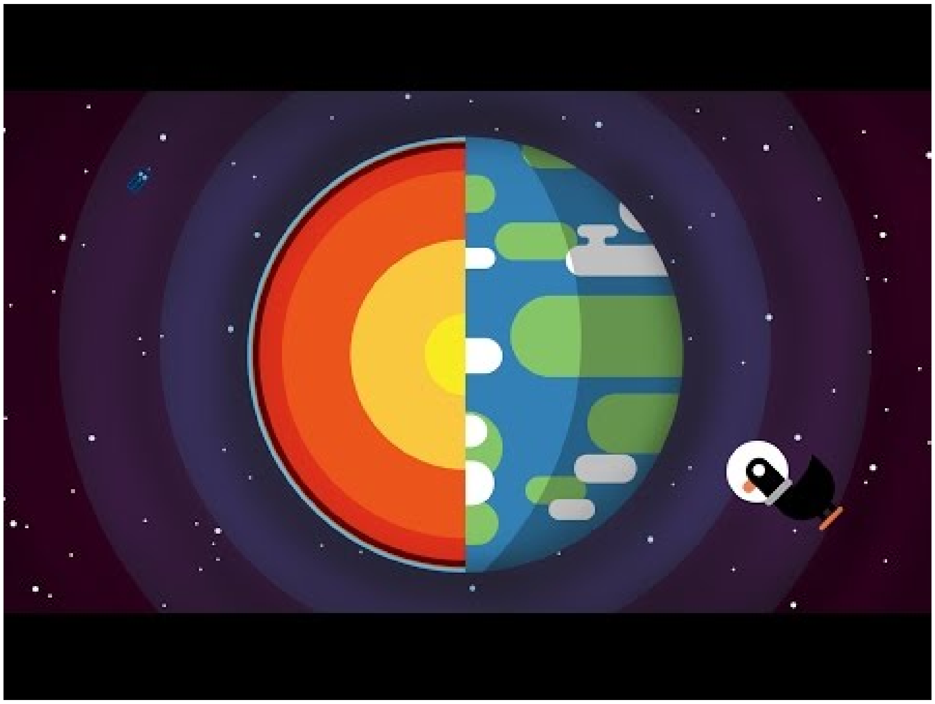
Environmental science is the dynamic, interdisciplinary study of the interaction of living and non-living parts of the environment, with a special focus on the impact of humans on the environment. Environmental science studies include circumstances, objects, or conditions surrounding an organism or community and their complex interactions.

Why Study Environmental Science?

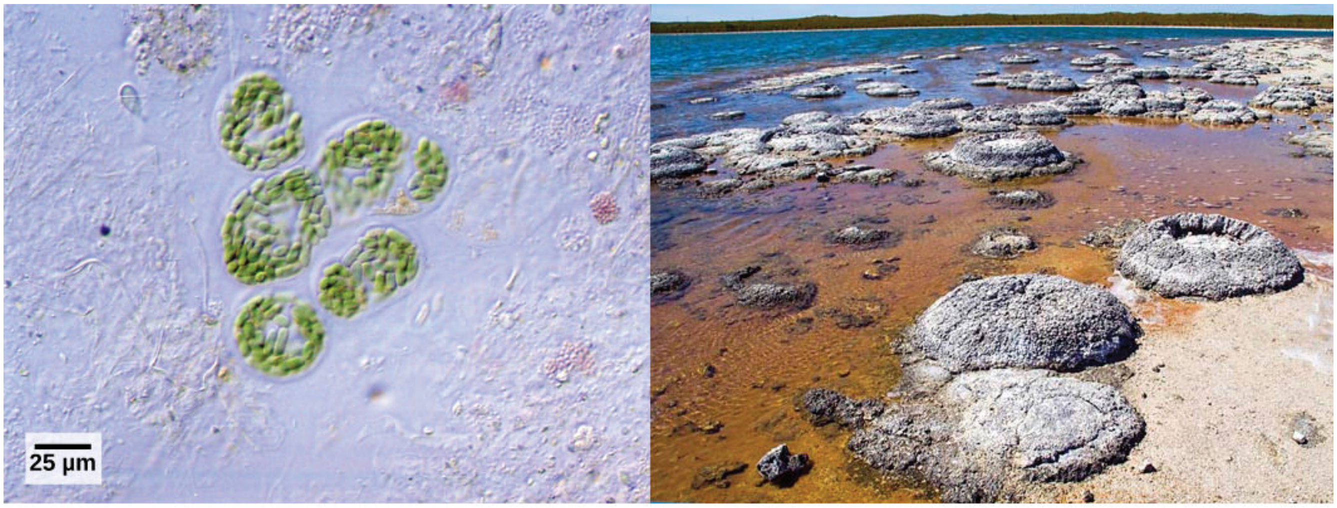
The need for equitable, ethical, and sustainable use of Earth's resources by a global population that nears the planet's carrying capacity requires us not only to understand how human behaviors affect the environment but also the scientific principles that govern interactions between living and non-living. Our future depends on our ability to understand and evaluate evidence-based arguments about the environmental consequences of human actions and technologies and to make informed decisions based on those arguments.

From global climate change to habitat loss driven by human population growth and development, Earth is becoming a different planet—right before our eyes. The global scale and rate of environmental change are beyond anything in recorded human history. Our challenge is to understand better Earth's complex environmental systems, systems characterized by interactions within and among their natural and human components that link local to global and short-term to long-term phenomena, and individual behavior to collective action. The complexity of environmental challenges demands that we all participate in finding and implementing solutions leading to long-term environmental sustainability.

Everything You Need to Know About Planet Earth video:



Kurzgesagt-In a Nutshell. (2018). Everything You Need to Know about Planet Earth. https://youtu.be/JGXi_9A__Vc



(a) (b)

Figure 1. (a) The cyanobacteria seen through a light microscope are some of Earth's oldest life forms. These (b) stromatolites along the shores of Lake Thetis in Western Australia are ancient structures formed by the layering of cyanobacteria in shallow waters. (Credit a: modification of work by NASA; scale-bar data from Matt Russell; credit b: modification of work by Ruth Ellison)

Like other natural sciences, environmental science is a science that gathers knowledge about the natural world. The scientific methods include careful observation, record keeping, logical and mathematical reasoning, experimentation, and submitting conclusions to the scrutiny of others. Science also requires considerable imagination and creativity; a well-designed experiment is commonly described as elegant or beautiful. Science has considerable practical implications; some are dedicated to practical applications, such as disease prevention (figure 2). Other science proceeds largely motivated by curiosity. Whatever its goal, there is no doubt that science has transformed human existence and will continue to do so.

The Nature of Science

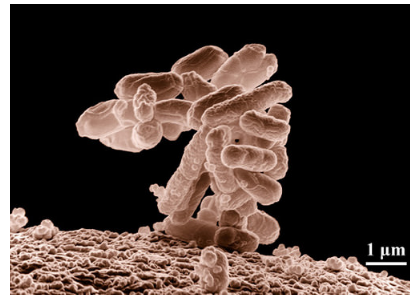


Figure 2. Scientists may choose to study Escherichia coli (E. coli), a bacterium that is a normal resident of our digestive tracts but which is also sometimes responsible for disease outbreaks. This micrograph visualizes the bacterium using a scanning electron microscope and digital colorization. (Credit: Eric Erbe; digital colorization by Christopher Pooley, USDA-ARS)

What exactly is science? **Science** (from the Latin *scientia*, meaning "knowledge") can be defined as a process of gaining knowledge about the natural world.

Science is a very specific way of learning about the world. The history of the past 500 years demonstrates that science is a very powerful way of gaining knowledge about the world; it is largely responsible for the technological revolutions that have occurred during this time. There are areas of knowledge, however, that the methods of science cannot be applied to. These include such things as morality, aesthetics, or spirituality. Science cannot investigate these areas because they are outside the realm of material phenomena, the phenomena of matter and energy, and cannot be observed and measured.

The **scientific method** is research with defined steps that include experiments and careful observation. The steps of the scientific method will be examined in detail later, but one of the most important aspects of this method is the testing of hypotheses. A **hypothesis** is a proposed explanatory statement for a given natural phenomenon that can be tested. Hypotheses, or tentative explanations, are different than a **scientific theory**. A scientific theory is a widely accepted, thoroughly tested, and confirmed explanation for a set of observations or phenomena. A scientific theory is the foundation of scientific knowledge. In addition, in many scientific disciplines, there are **scientific laws**, often expressed in mathematical formulas, describing how elements of nature will behave under certain conditions. Still, they do not offer explanations for why they occur.

Natural Sciences

What would you expect to see in a museum of natural sciences? Frogs? Plants? Dinosaur skeletons? Exhibits about how the brain functions? A planetarium? Gems and minerals? Or maybe all of the above? Science includes such diverse fields as astronomy, computer sciences, psychology, biology, and mathematics. However, those fields of science related to the physical world and its phenomena and processes are considered **natural sciences** and include the disciplines of physics, geology, biology, and chemistry. Environmental science is a cross-disciplinary natural science because it relies on the disciplines of chemistry, biology, and geology.

Scientific Inquiry

One thing is common to all forms of science: an ultimate goal to know. Curiosity and inquiry are the driving forces for the development of science. Scientists seek to understand the world and the way it operates. Two methods of logical thinking are used: inductive reasoning and deductive reasoning.

Inductive reasoning is a form of logical thinking that uses related observations to arrive at a general conclusion. This type of reasoning is common in descriptive science. A life scientist, such as an environmental scientist, records observations. These data can be qualitative (descriptive) or quantitative (consisting of numbers), and the raw data can be supplemented with drawings, pictures, photos, or videos. The scientist can infer conclusions (inductions) based on evidence from many observations. Inductive reasoning involves formulating generalizations inferred from careful observation and analyzing a large amount of data. Brain studies often work this way. Many brains are observed while people are doing a task. The part of the brain that lights up (indicating activity) is then demonstrated to be the part controlling the response to that task.

Deductive reasoning or deduction is the type of logic used in hypothesis-based science. In deductive reasoning, the thinking pattern moves in the opposite direction compared to inductive reasoning. Deductive reasoning is a form of logical thinking that uses a general principle or law to forecast specific results. From those general principles, a scientist can extrapolate and predict the specific results that would be valid as long as the general principles are valid. For example, a prediction would be that if the climate is becoming warmer in a region, the distribution of plants and animals should change. Comparisons have been made between distributions in the past, and the present, and the many changes that have been found are consistent with a warming climate. Finding the change in distribution proves the climate change conclusion is valid.

Both types of logical thinking are related to the two main pathways of scientific study: descriptive science and hypothesis-based science. **Descriptive** (or discovery) **science** aims to observe, explore, and discover. In contrast, **hypothesis-based science** begins with a specific question or problem and a potential answer or solution that can be tested. The boundary between these two study forms is often blurred because most scientific endeavors combine both approaches. Observations lead to questions, questions lead to forming a hypothesis as a possible answer to those questions, and then the hypothesis is tested. Thus, descriptive science and hypothesis-based science are in continuous dialogue.

"Scientists have become the bearers of the torch of discovery in our quest for knowledge." – *Stephen Hawking and Leonard Mlodinov, in* The Grand Design *(2010), Bantam Books*

Hypothesis Testing

Environmental scientists study the natural world by posing questions about it and seeking science-based responses. This approach is also common to other sciences and is often referred to as the scientific method. The scientific method was used even in ancient times, but it was first documented by England's Sir Francis Bacon (1561–1626), who set up inductive methods for scientific inquiry. Environmental scientists do not exclusively use the scientific method, but it can be applied to almost anything as a logical problem-solving method.

The scientific process typically starts with an observation (often a problem to be solved) that leads to a question. Let's think about a simple problem that starts with an observation and apply the scientific method to solve the problem. On Monday morning, a student arrives and quickly discovers that the classroom is too warm. That observation also describes a problem: the classroom is too warm. The student then asks, "Why is the classroom so warm?"

Figure 3. Sir Francis Bacon is credited with being the first to document the scientific method.

Recall that a hypothesis is a suggested explanation that can be tested. To solve a problem, several hypotheses may be proposed. For example, one hypothesis might be, "The classroom is warm because no one turned on the air conditioning." But there could be other responses to the question, so other hypotheses may be proposed. A second hypothesis might be, "The classroom is warm because there is a power failure, so the air conditioning doesn't work."

Once a hypothesis has been selected, a prediction may be made. A prediction is similar to a hypothesis, but it typically has the format "If . . . then . . . ." For example, the prediction for the first hypothesis might be, "*If* the student turns on the air conditioning, *then* the classroom will no longer be too warm."

A hypothesis must be testable to ensure that it is valid. For example, a hypothesis that depends on what a bear thinks is not testable because it can never be known what a bear thinks. It should also be **falsifiable**, meaning that it can be disproven by experimental results. An example of an unfalsifiable hypothesis is "Botticelli's *Birth of Venus* is beautiful." No experiment might show this statement to be false. To test a hypothesis, a researcher will conduct one or more experiments designed to eliminate one or more of the hypotheses. This is important. A hypothesis can be disproven or eliminated, but it can never be proven. Science does not deal with proofs like mathematics. Suppose an experiment fails to disprove a hypothesis. In that case, we find support for that explanation, but this is not to say that a better explanation will not be found down the road, or a more carefully designed experiment will be found to falsify the hypothesis.

Each experiment will have one or more variables and one or more controls. **Experimental variables** are any part of the experiment that can vary or change during the experiment. **Controlled variables** are parts of the experiment that do not change. Lastly, experiments might have a **control group**: a group of test subjects that are as similar as possible to all other test subjects, except that they don't receive the experimental treatment (those that do receive it are known as the **experimental group**). For example, in a study testing a weight-loss drug, the control group would be test subjects who don't receive the drug (but might receive a placebo, such as a sugar pill, instead). Look for these various things in the example that follows:

An experiment might be conducted to test the hypothesis that phosphate (a nutrient) promotes algae growth in freshwater ponds. A series of artificial ponds are filled with water, and half are treated by adding phosphate each week, while the other half are treated by adding a non-nutritional mineral not used by algae. The experimental variable here is the presence/absence of a nutrient (phosphate). One potential controlled variable would be the volume of water in each tank. The amount of water algae have access to may influence the results; thus, researchers want to control its influence on the results by ensuring all test subjects get the same amount. The control group consisted of the tanks that received a placebo (non-nutritional mineral) instead of the phosphate. If the ponds with phosphate show more algal growth, then we have found support for the hypothesis. If they do not, then we reject our hypothesis.

Be aware that rejecting one hypothesis does not determine whether or not the other hypotheses can be accepted; it simply eliminates one hypothesis that is not valid (Figure 3). Using the scientific method, the hypotheses that are inconsistent with experimental data are rejected.

The example below uses the scientific method to solve an everyday problem. Which part in the example below is the hypothesis? Which is the prediction? Based on the results of the experiment, is the hypothesis supported? If it is not supported, propose some alternative hypotheses.

1. My toaster doesn't toast my bread.
2. Why doesn't my toaster work?
3. There is something wrong with the electrical outlet.
4. If something is wrong with the outlet, my coffeemaker also won't work when plugged into it.
5. I plug my coffeemaker into the outlet.
6. My coffeemaker works.

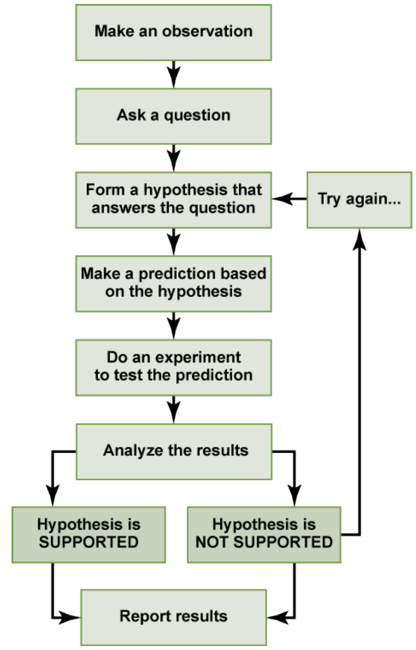


Figure 4. The scientific method is a series of defined steps that include experiments and careful observation. If data does not support a hypothesis, a new hypothesis can be proposed.

In practice, the scientific method is not as rigid and structured as it might at first appear. Sometimes an experiment leads to conclusions that favor a change in approach; often, an experiment brings entirely new scientific questions to the puzzle. Science often does not operate linearly; scientists continually draw inferences and make generalizations, finding patterns as their research proceeds. Scientific reasoning is more complex than the scientific method alone suggests.

Basic and Applied Science

Is it valuable to pursue science to gain knowledge simply, or does scientific knowledge only have worth if we can apply it to solving a specific problem or bettering our lives? This question focuses on the differences between two types of science: basic science and applied science.

Basic science or "pure" science seeks to expand knowledge regardless of the short-term application of that knowledge. It is not focused on developing a product or a service of immediate public or commercial value. The immediate goal of basic science is knowledge for knowledge's sake, though this does not mean that, in the end, it may not result in an application.

In contrast, **applied science** aims to use science to solve real-world problems, such as improving crop yield, finding a cure for a particular disease, or saving animals threatened by a natural disaster. In applied science, the problem is usually defined for the researcher.

Some may perceive applied science as "useful" and basic science as "useless." A question these people might pose to a scientist advocating knowledge acquisition would be, "What for?" However, a careful look at the history of science reveals that basic knowledge has resulted in many remarkable applications of great value. Many scientists think that a basic understanding of science is necessary before an application is developed; therefore, applied science relies on the results generated through basic science. Other scientists think it is time to move on from basic science and instead find solutions to actual problems. Both approaches are valid. Some problems demand immediate attention; however, few solutions would be found without the help of the knowledge generated through basic science.

One example of how basic and applied science can work together to solve practical problems occurred after discovering DNA structure led to an understanding of the molecular mechanisms governing DNA replication. Strands of DNA, unique in every human, are found in our cells, providing the instructions for life. During DNA replication, new copies of DNA are made shortly before a cell divides to form new cells. Understanding DNA replication mechanisms (through basic science) enabled scientists to develop laboratory techniques that are now used to identify genetic diseases, pinpoint individuals at a crime scene, and determine paternity (all examples of applied science). Without basic science, it is unlikely that applied science would exist.

Another example of the link between basic and applied research is the Human Genome Project, a study in which each human chromosome was analyzed and mapped to determine the precise sequence of the DNA code and the exact location of each gene. (The gene is the basic unit of heredity; an individual's complete collection of genes is his or her genome.) Other organisms have also been studied as part of this project to gain a better understanding of human chromosomes. The Human Genome Project (Figure 5) relied on basic research carried out with non-human organisms and, later, with the human genome. An important end goal eventually became using the data for applied research seeking cures for genetic diseases.

Scientific Work is Transparent and Open to Critique

Figure 5. The Human Genome Project was a 13-year collaborative effort among researchers working in several different fields of science. The project was completed in 2003. (credit: the U.S. Department of Energy Genome Programs)

Whether scientific research is basic science or applied science, scientists must share their findings for other researchers to expand and build upon their discoveries. For this reason, an important aspect of a scientist's work is disseminating results and communicating with peers. Scientists can share results by presenting them at a scientific meeting or conference, but this approach can reach only a few present. Instead, most scientists present their results in peer-reviewed articles published in scientific journals. **Peer-reviewed articles** are scientific papers that are reviewed, usually anonymously, by a scientist's colleagues or peers. These colleagues are qualified individuals, often experts in the same research area, who judge whether or not the scientist's work is suitable for publication. The peer review process helps ensure that the research described in a scientific paper or grant proposal is original, significant, logical, ethical, and thorough. Scientists publish their work so other scientists can reproduce their experiments under similar or different conditions to expand on the findings. The experimental results must be consistent with the findings of other scientists.

As you review scientific information, whether in an academic setting or as part of your day-to-day life, it is important to think about the credibility of that information. You might ask yourself: has this scientific information been through the rigorous peer review process? Are the conclusions based on available data and accepted by the larger scientific community? Scientists are inherently skeptical, especially if conclusions are not supported by evidence (and you should be too).

Suggested Supplementary Reading:

Sundermier, A. 2016. "These 5 mind-melting thought experiments helped Albert Einstein come up

with his most revolutionary scientific ideas." *Business Insider*. <https://www.businessinsider.com/5-of-albert-einsteins-thought-experiments-that-revolutionized-science-2016-7>

Introduction to Sustainability

This section introduces the concept of **sustainability,** which refers to the sociopolitical, scientific, and cultural challenges of living within the means of the Earth without significantly impairing its function.

Taking The Long View: Sustainability in Evolutionary and Ecological Perspective

Of the different forms of life that have inhabited the Earth in its three to four-billion-year history, 99.9% are now extinct. Against this backdrop, the human enterprise barely merits attention with its roughly 200,000-year history. As the American novelist Mark Twain once remarked, if our planet's history were compared to the Eiffel Tower, human history would be a mere smear on the very tip of the tower. But while modern humans (*Homo sapiens*) might be insignificant in geologic time, we are by no means insignificant regarding our recent planetary impact. For example, a 1986 study estimated that 40% of the product of terrestrial plant photosynthesis — the basis of the food chain for most animal and bird life — was being appropriated by humans for their use. More recent studies estimate that 25% of photosynthesis on continental shelves (coastal areas) is ultimately used to satisfy human demand. Human appropriation of such natural resources profoundly impacts the wide diversity of other species that depend on them.

Evolution normally results in the generation of new lifeforms at a rate that outstrips the extinction of other species; this results in strong biological diversity. However, scientists have evidence that, for the first observable time in evolutionary history, another species — *Homo sapiens* — has upset this balance to the degree that the rate of species extinction is now estimated at 10,000 times the rate of species renewal. Human beings, just one species among millions, are crowding out the other species we share the planet with. Evidence of human interference with the natural world is visible in practically every ecosystem, from the presence of pollutants in the stratosphere to the artificially changed courses of the majority of river systems on the planet. It is argued that humans have continually manipulated their natural world to meet their needs ever since we abandoned nomadic, gatherer-hunter ways of life for settled societies some 12,000 years ago. While this observation is correct, the rate, scale, and the nature of human-induced global change — particularly in the post-industrial period — is unprecedented in the history of life on Earth.

There are three primary reasons for this:

Firstly, the mechanization of industry and agriculture in the last century resulted in vastly improved labor productivity, enabling the creation of goods and services. Since then, scientific advances and technological innovations — powered by ever-increasing inputs of fossil fuels and their derivatives — have revolutionized every industry and created many new ones. The subsequent development of Western consumer culture, and the satisfaction of the accompanying disposable mentality, have generated material flows of an unprecedented scale. Professor Friedrich Schmidt-Bleek (1932 – 2019), founder and Director of the Factor 10 Institute and Honorary President of the World Resources Forum, estimates that humans are now responsible for moving greater amounts of matter across the planet than all natural occurrences (earthquakes, storms, etc.) put together (Schmidt-Bleek, 1994).

Secondly, the sheer size of the human population is unprecedented. Every passing year adds another 90 million people to the planet. Even though the environmental impact varies significantly between countries (and within them), the exponential growth in human numbers and rising material expectations in a world of limited resources have catapulted the distribution issue to prominence. Global inequalities in resource consumption and purchasing power mark the clearest dividing line between the haves and the have-nots. It has become apparent that present production and consumption patterns are unsustainable for a global population projected to reach between 12 billion by the year 2050. Suppose ecological crises and rising social conflict are to counter. In that case, the present rates of over-consumption by a rich minority and under-consumption by a large majority will have to be balanced.

Thirdly, it is not only the rate and the scale of change but the nature of that change that is unprecedented. Human inventiveness has introduced chemicals and materials into the environment, which either does not occur naturally at all or do not occur in the ratios in which we have introduced them. These persistent chemical pollutants are believed to be causing environmental alterations, the effects of which are only slowly manifesting themselves and the full scale of which is beyond calculation. CFCs and PCBs are only two examples of the approximately 100,000 chemicals currently circulating globally (between 500 and 1,000 new chemicals are being added to this list annually). Most of these chemicals have not been tested for their toxicity on humans and other life forms, let alone tested for their effects in combination with other chemicals. These issues are now the subject of special UN and other intergovernmental working groups.

The Evolution of Sustainability Itself

Our Common Future (1987), the World Commission on Environment and Development report, is widely credited with popularizing the concept of **sustainable development.** It defines sustainable development in the following ways…

- …development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
- … sustainable development is not a fixed state of harmony but rather a process of change in which the exploitation of resources, the orientation of technological development, and institutional change are consistent with future and present needs.

The concept of sustainability, however, can be traced to the oral histories of indigenous cultures. For example, the principle of inter-generational equity is captured in the Inuit saying, 'We do not inherit the Earth from our parents, we borrow it from our children.' The Native American' Law of the Seventh Generation' is another illustration. According to this, before any major action was undertaken, its potential consequences on the seventh generation had to be considered. For a species that at present is only 6,000 generations old and whose current political decision-makers operate on time scales of months or a few years at most, the thought that other human cultures have based their decision-making systems on time scales of many decades seems wise but unfortunately inconceivable in the current political climate.

Environmental Equity

While much progress is being made to improve resource efficiency, far less progress has been made to improve resource distribution. Just one-fifth of the global population currently consumes three-quarters of the Earth's resources (Figure 1). If the remaining four-fifths were to exercise their right to grow to the level of the rich minority, it would result in ecological devastation. So far, global income inequalities and lack of purchasing power have prevented poorer countries from reaching industrialized countries' standard of living (and also resource consumption/waste emission).

However, countries like China, Brazil, India, and Malaysia are catching up quickly. In such a situation, global consumption of resources and energy needs to be drastically reduced to a point where future generations can repeat it. But who will make the reduction? Poorer nations want to produce and consume more. Yet so do richer countries: their economies demand ever greater consumption-based expansion. Such stalemates have prevented any meaningful progress toward equitable and sustainable resource distribution at the international level. Moreover, these issues of fairness and distributional justice remain unresolved.

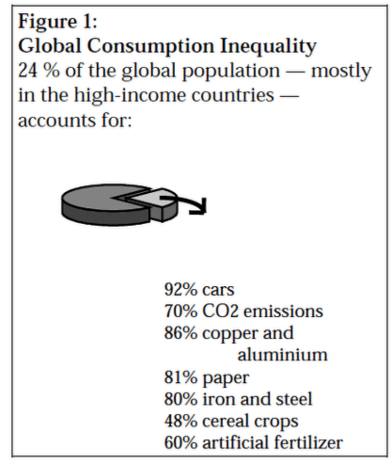


Figure 1. Global consumption inequality – accounting for consumption

Concepts in Environmental Science

The **ecological footprint** (EF), developed by Canadian ecologist and planner William Rees, is an accounting tool that uses the land as the unit of measurement to assess per capita consumption, production, and discharge needs. It starts from the assumption that every category of energy, material consumption, and waste discharge requires the productive or absorptive capacity of a finite area of land or water. If we (add up) all the land requirements for all categories of consumption and waste discharge by a defined population, the total area represents the Ecological footprint of that population on Earth, whether or not this area coincides with the population's home region.

Land is used as the unit of measurement for the simple reason that, according to Rees, "Land area not only captures planet Earth's finiteness, it can also be seen as a proxy for numerous essential life support functions from gas exchange to nutrient recycling … land supports photosynthesis, the energy conduit for the web of life. Photosynthesis sustains all-important food chains and maintains the structural integrity of ecosystems."

What does the ecological footprint tell us? Ecological footprint analysis can tell us in a vivid, ready-to-grasp manner how much of the Earth's environmental functions are needed to support human activities. It also makes visible the extent to which consumer lifestyles and behaviors are ecologically sustainable, calculating that the ecological footprint of the average American is – conservatively – 5.1 hectares per capita of productive land. With roughly 7.4 billion hectares of the planet's total surface area of 51 billion hectares available for human consumption, if the current global population were to adopt American consumer lifestyles, we would need two additional planets to produce the resources, absorb the wastes, and provide general life-support functions.

The **precautionary principle** is an important concept in environmental sustainability. A 1998 consensus statement characterized the precautionary principle: "When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically." For example, if a new pesticide chemical is created, the precautionary principle would dictate that we presume, for safety, that the chemical may have potentially negative consequences for the environment and/or human health, even if such consequences have not been proven yet. In other words, it is best to proceed cautiously in the face of incomplete knowledge about something's potential harm.

Some Indicators of Global Environmental Stress

Forests — Deforestation remains a main issue. One million hectares of forest were lost annually in 1980-1990. The largest losses of forest area are in the tropical moist deciduous forests, the zone best suited to human settlement and agriculture. Recent estimates suggest that nearly two-thirds of tropical deforestation is due to farmers clearing land for agriculture. In addition, there is increasing concern about the decline in forest quality associated with the intensive use of forests and unregulated access.

Soil — As much as 10% of the Earth's vegetated surface is now at least moderately degraded. Trends in soil quality and management of irrigated land raise serious questions about longer-term sustainability. It is estimated that about 20% of the world's 250 million hectares of irrigated land are already degraded to the point where crop production is seriously reduced.

Fresh Water — Some 20% of the world's population lacks access to safe water, and 50% lacks access to safe sanitation. If current trends in water use persist, two-thirds of the world's population could be living in countries experiencing moderate or high water stress by 2025.

Marine fisheries — 25% of the world's marine fisheries are being fished at their maximum level of productivity, and 35% are overfished (yields are declining). To maintain the current per capita fish consumption, global fish harvests must be increased; much of the increase might come through aquaculture, a known source of water pollution, wetland loss, and mangrove swamp destruction.

Biodiversity — Biodiversity is increasingly threatened by development, which destroys or degrades natural habitats and pollution from various sources. The first comprehensive global biodiversity assessment put the total number of species at close to 14 million and found that between 1% and 11% of the world's species may be threatened by extinction every decade. Coastal ecosystems, which host a very large proportion of marine species, are at great risk, with perhaps one-third of the world's coasts at high potential risk of degradation and another 17% at moderate risk.

Atmosphere — The Intergovernmental Panel on Climate Change has established that human activities have a discernible influence on global climate. CO_2 emissions in most industrialized countries have risen during the past few years. Countries generally failed to stabilize their greenhouse gas emissions at 1990 levels by 2000 as the Climate Change Convention required.

Toxic chemicals — About 100,000 chemicals are now in commercial use, and their potential impacts on human health and ecological function represent largely unknown risks. Persistent organic pollutants are now so widely distributed by air and ocean currents that they are found in the tissues of people and wildlife everywhere; they are of particular concern because of their high toxicity levels and environmental persistence.

Hazardous wastes — Pollution from heavy metals, especially from their use in industry and mining, also creates serious health consequences in many parts of the world. In addition, incidents and accidents involving uncontrolled radioactive sources continue to increase, and particular risks are posed by the legacy of contaminated areas left by military activities involving nuclear materials.

Waste — Domestic and industrial waste production continues to increase in both absolute and per capita terms worldwide. In the developed world, per capita waste generation has increased threefold over the past 20 years; in developing countries, waste generation will likely double during the next decade.

However, the level of awareness regarding the health and environmental impacts of inadequate waste disposal remains relatively poor; poor sanitation and waste management infrastructure are still one of the principal causes of death and disability for the urban poor.

Frontier Ethic

Ethical attitudes and behaviors determine how humans interact with the land and its natural resources. Early European settlers in North America rapidly consumed the land's natural resources. After they depleted one area, they moved westward to new frontiers. Their attitude towards the land was that of a **frontier ethic**. A frontier ethic assumes that the earth has an unlimited supply of resources. If resources run out in one area, more can be found elsewhere, or alternatively, human ingenuity will find substitutes. This attitude sees humans as masters who manage the planet. The frontier ethic is completely anthropocentric (human-centered), for only the needs of humans are considered.

Most industrialized societies experience population and economic growth based upon this frontier ethic, assuming that infinite resources exist to support continued growth indefinitely. Economic growth is considered a measure of how well a society is doing. The late economist Julian Simon pointed out that life on earth has never been better and that population growth means more creative minds to solve future problems and give us an even better standard of living. However, now that the human population has passed seven billion and few frontiers are left, many are beginning to question the frontier ethic. Such people are moving toward an environmental ethic, which includes humans as part of the natural community rather than managers. Such an ethic limits human activities (e.g., uncontrolled resource use) that may adversely affect the natural community.

Some of those still subscribing to the frontier ethic suggest that outer space may be the new frontier. They argue that if we run out of resources (or space) on Earth, we can simply populate other planets. This seems an unlikely solution, as even the most aggressive colonization plan would be incapable of transferring people to extraterrestrial colonies at a significant rate. Natural population growth on Earth would outpace the colonization effort. A more likely scenario would be that space could provide the resources (e.g., from asteroid mining) that might help to sustain human existence on Earth.

Sustainable Ethic

A **sustainable ethic** is an environmental ethic by which people treat the earth as if its resources are limited. This ethic assumes that the earth's resources are not unlimited and that humans must use and conserve resources to allow their continued use in the future. A sustainable ethic also assumes that humans are a part of the natural environment and that we suffer when the health of a natural ecosystem is impaired. A sustainable ethic includes the following tenets:

- The earth has a limited supply of resources.
- Humans must conserve resources.
- Humans share the earth's resources with other living things.
- Growth is not sustainable.
- Humans are a part of nature.
- Humans are affected by natural laws.
- Humans succeed best when they maintain the integrity of natural processes and cooperate

with nature.

For example, if a fuel shortage occurs, how can the problem be solved consistently with a sustainable ethic? The solutions might include finding new ways to conserve oil or developing renewable energy alternatives. A sustainable, ethical attitude in the face of such a problem would be that if drilling for oil damages the ecosystem, that damage will also affect the human population. A sustainable ethic can be either anthropocentric or biocentric (life-centered). For example, an advocate for conserving oil resources may consider all oil resources as the property of humans. Using oil resources wisely so that future generations can access them is an attitude consistent with an anthropocentric ethic. Using resources wisely to prevent ecological damage follows a biocentric ethic.

Land Ethic

In his book, A Sand County Almanac, Aldo Leopold, an American wildlife natural historian and philosopher, advocated a biocentric ethic. He suggested that humans had always considered land property, just as ancient Greeks considered enslaved people property. He believed that mistreatment of land (or of enslaved people) makes little economic or moral sense, much as today, the concept of slavery is considered immoral. All humans are merely one component of an ethical framework. Leopold suggested that land be included in an ethical framework, calling this the land ethic.

"The **land ethic** simply enlarges the boundary of the community to include soils, waters, plants, and animals; or collectively, the land. In short, a land ethic changes the role of *Homo sapiens* from conqueror of the land community to plain member and citizen. It implies respect for his fellow members, and also respect for the community as such." (Aldo Leopold, 1949)

Leopold divided conservationists into two groups: one that regards the soil as a commodity and the other that regards the land as a biota, with a broad interpretation of its function. If we apply this idea to the field of forestry, the first group of conservationists will grow trees like cabbages. In contrast, the second group will strive to maintain a natural ecosystem. Leopold claimed that the conservation movement must be based upon more than just economic necessity. Species without discernible economic value to humans may be integral to a functioning ecosystem. The land ethic respects all parts of the natural world regardless of their utility, and decisions based upon that ethic result in more stable biological communities.

"Anything is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends to do otherwise." (Aldo Leopold, 1949)

Hetch Hetchy Valley

In 1913, the Hetch Hetchy Valley – located in Yosemite National Park in California – was the site of a conflict between two factions, one with an anthropocentric ethic and the other with a biocentric ethic. As the last American frontiers were settled, the rate of forest destruction started to concern the public.

Figure 1. Yosemite Valley, California, USA.

The conservation movement gained momentum but quickly broke into two factions. One faction, led by Gifford Pinchot, Chief Forester under Teddy Roosevelt, advocated utilitarian conservation (i.e., conservation of resources for the public's good). The other faction, led by John Muir, advocated the preservation of forests and other wilderness for their inherent value. Both groups rejected the first tenet of frontier ethics, the assumption that resources are limitless. However, the conservationists agreed with the rest of the tenets of frontier ethics, while the preservationists agreed with the tenets of the sustainable ethic.

The Hetch Hetchy Valley was part of a protected National Park. Still, after the devastating fires of the 1906 San Francisco earthquake, residents of San Francisco wanted to dam the valley to provide their city with a stable water supply. Gifford Pinchot favored the dam.

"As to my attitude regarding the proposed use of Hetch Hetchy by the city of San Francisco…I am fully persuaded that… the injury…by substituting a lake for the present swampy floor of the valley…is altogether unimportant compared with the benefits derived from its use as a reservoir.

"The fundamental principle of the whole conservation policy is that of use, to take every part of the land and its resources and put it to that use in which it will serve the most people" (Gifford Pinchot, 1913).

John Muir, the founder of the Sierra Club and a great lover of wilderness, led the fight against the dam. He saw wilderness as having an intrinsic value, separate from its utilitarian value to people. He advocated the preservation of wild places for their inherent beauty and for the sake of the creatures that live there. The issue aroused the American public, who were becoming increasingly alarmed at the growth of cities and the destruction of the landscape for commercial enterprises. Key senators received thousands of letters of protest.

"These temple destroyers, devotees of ravaging commercialism, seem to have a perfect contempt for Nature, and instead of lifting their eyes to the God of the Mountains, lift them to the Almighty Dollar" (John Muir, 1912).

Despite public protest, Congress voted to dam the valley. The preservationists lost the fight for the Hetch Hetchy Valley, but their questioning of traditional American values had some lasting effects. In

1916, Congress passed the “National Park System Organic Act,” which declared that parks were to be maintained in a manner that left them unimpaired for future generations. As we use our public lands, we debate whether we should be guided by preservationism or conservationism.

The Tragedy of the Commons

In his essay, The Tragedy of the Commons, Garrett Hardin (1968) looked at what happens when humans do not limit their actions by including the land in their ethics. The **tragedy of the commons** develops in the following way: Imagine a pasture open to all (the ‘commons’). Each herder is expected to keep as many cattle as possible on the commons. As rational beings, each herder seeks to maximize their gain. Adding more cattle increases their profit, and they do not suffer any immediate negative consequences because all share the commons. Therefore, the rational herdsman concludes that the only sensible course is to add another animal to their herd, another, and so forth. However, this same conclusion is reached by every rational herder sharing the commons. Therein lies the tragedy: each person is locked into a system that compels them to increase their herd, without limit, in a limited world. Eventually, this leads to the ruination of the commons. In a society that believes in the freedom of the commons, freedom brings ruin to everyone because everyone acts selfishly.

Hardin applied the situation to modern commons: overgrazing of public lands, overuse of public forests and parks, depletion of fish populations in the ocean, use of rivers as a common dumping ground for sewage, and fouling the air with pollution.

The “Tragedy of the Commons” applies to what is arguably the most consequential environmental problem: global climate change. The atmosphere is a commons into which countries dump carbon dioxide from burning fossil fuels. Although we know that the generation of greenhouse gases will damage the globe, we continue to burn fossil fuels. As a country, the immediate benefit from the continued use of fossil fuels is seen as a positive component (because of economic growth). All countries, however, will share the negative long-term effects.

Suggested Supplementary Reading

Blankenbuehler, P. 2016. Why Hetch Hetchy is staying under water. *High Country News*. <https://www.hcn.org/issues/48.9/why-hetch-hetchy-is-staying-under-water>

Environmental Justice

Environmental Justice is defined as the fair treatment and meaningful involvement of all people, regardless of race, color, national origin, or income, concerning the development, implementation, and enforcement of environmental laws, regulations, and policies. It will be achieved when everyone enjoys the same degree of protection from environmental and health hazards and equal access to the decision-making process to have a healthy environment to live, learn, and work.

During the 1980s, minority groups protested that hazardous waste sites were preferentially in minority neighborhoods. In 1987, Benjamin Chavis of the United Church of Christ Commission for Racism and Justice coined **environmental racism** to describe such a practice. The charges generally failed to consider whether the facility or the area's demography came first. Most hazardous waste sites are located on a property used as disposal sites long before modern facilities and disposal methods were available. Areas around such sites are typically depressed economically, often due to past disposal activities. Low-income people are often constrained to live in undesirable but affordable areas. The problem more likely resulted from insensitivity rather than racism. Indeed, the ethnic makeup of potential disposal facilities was most likely not considered when the sites were chosen.

Decisions in citing hazardous waste facilities are generally made based on economics, geological suitability, and the political climate. For example, a site must have a soil type and geological profile that prevents hazardous materials from moving into local aquifers. The cost of land is also an important consideration. The high cost of buying land would make it economically unfeasible to build a hazardous waste site in Beverly Hills. Some communities have seen hazardous waste facilities as a way of improving their local economy and quality of life. Emelle County, Alabama, had illiteracy and infant mortality rates that were among the highest in the nation. A landfill constructed there provided jobs and revenue that ultimately helped to reduce both figures.

There would be no hazardous waste facilities in an ideal world, but we do not live in an ideal world. Unfortunately, we live in a world plagued by rampant pollution and the dumping of hazardous waste. Our industrialized society has necessarily produced waste while manufacturing products for our basic needs. Until technology can find a way to manage (or eliminate) hazardous waste, disposal facilities will be necessary to protect both humans and the environment. By the same token, this problem must be addressed. Industry and society must become more socially sensitive in selecting future hazardous waste sites. All humans who help produce hazardous wastes must share the burden of dealing with those wastes, not just people experiencing poverty and minorities.

Indigenous People

Since the end of the 15th century, established nations have claimed and colonized most of the world's frontiers. Invariably, these conquered frontiers were home to people indigenous to those regions. Unfortunately, indigenous people were wiped out or assimilated by the invaders, while others survived while trying to maintain their unique cultures and way of life. As a result, the United Nations officially classifies **indigenous people** as "having a historical continuity with pre-invasion and pre-colonial societies" and "consider themselves distinct from other sectors of the societies now prevailing in those territories or parts of them." Furthermore, indigenous people are "determined to preserve, develop and transmit to future generations, their ancestral territories, and their ethnic identity, as the basis of their continued existence as peoples in accordance with their own cultural patterns, social institutions, and legal systems." A few of the many groups of indigenous people around the world are the many tribes of Native Americans (i.e., Navajo, Sioux) in the contiguous 48 states, the Inuit of the arctic region from Siberia to Canada, the rainforest tribes in Brazil, and the Ainu of northern Japan.

Many problems face indigenous people, including the lack of human rights, exploitation of their traditional lands and themselves, and degradation of their culture. In response to the problems faced by these people, the United Nations proclaimed an "International Decade of the World's Indigenous People" beginning in 1994. According to the United Nations, this proclamation's main objective is "the strengthening of international cooperation for the solution of problems faced by indigenous people in such areas as human rights, the environment, development, health, culture, and education." Its major goal is to protect the rights of indigenous people. Such protection would enable them to retain their cultural identities, such as their language and social customs, while participating in the political, economic, and social activities of the region in which they reside.

Despite the lofty U.N. goals, the rights and feelings of indigenous people are often ignored or minimized, even by supposedly culturally sensitive developed countries. For example, in the United States, many of those in the federal government are pushing to exploit oil resources in the Arctic National Wildlife Refuge on the northern coast of Alaska. The "Gwich'in," an indigenous people who rely culturally and spiritually on the herds of caribou that live in the region, claims that drilling in the area would devastate their way of life. Thousands of years of culture would be destroyed for a few months' oil supply. Drilling efforts have been stymied in the past, but mostly out of concern for environmental factors and not necessarily the needs of the indigenous people. Curiously, another group of indigenous people, the "Inupiat Eskimo," favor oil drilling in the Arctic National Wildlife Refuge. They would potentially reap economic benefits from the region's development because they own considerable amounts of land adjacent to the refuge.

Figure 1. An Inupiaq woman, Nome, Alaska, c. 1907. Credit: This work is in the Public Domain, CC0

The heart of most environmental conflicts governments face usually involves what constitutes proper and sustainable levels of development. For many indigenous peoples, sustainable development includes an integrated wholeness, where no single action is separate from others. They believe that sustainable development requires the maintenance and continuity of life from generation to generation and that humans are not isolated entities but are part of larger communities, which include the seas, rivers, mountains, trees, fish, animals, and ancestral spirits. These, along with the sun, moon, and cosmos, constitute a whole. From the point of view of indigenous people, sustainable development is a process that must integrate spiritual, cultural, economic, social, political, territorial, and philosophical ideals.

Suggested Supplementary Reading

Miller, E. “Flint Water Crisis: A Turning Point For Environmental Justice.” *WOSU Public Media*.<http://radio.wosu.org/post/flint-water-crisis-\ turning-point-environmental-justice#stream/0>

Summary

Science attempts to describe and understand the nature of the universe in whole or in part. Science has many fields related to the physical world and its phenomena, considered natural sciences. A hypothesis is a tentative explanation for an observation. A scientific theory is a well-tested and consistently verified explanation for a set of observations or phenomena. A scientific law is a description, often in the form of a mathematical formula, of the behavior of an aspect of nature under certain circumstances. Two types of logical reasoning are used in science. Inductive reasoning uses results to produce general scientific principles. Deductive reasoning is a form of logical thinking that predicts results by applying general principles. The common thread throughout scientific research is the use of the scientific method. Scientists present their results in peer-reviewed scientific papers published in scientific journals. Science can be basic or applied. The main goal of basic science is to expand knowledge without any expectation of short-term practical application of that knowledge. However, applied research's primary goal is to solve practical problems.

Sustainability refers to three simple concerns: the need to arrest environmental degradation and ecological imbalance, the need not to impoverish future generations, and the need for quality of life and equity between current generations. Added up, these core concerns are an unmistakable call for transformation. Business-as-usual is no longer an option. The concept of ethics involves standards of conduct. These standards help to distinguish between behavior that is considered right and that which is considered wrong. Ethical attitudes and behaviors determine how humans interact with the land and its natural resources. A frontier ethic assumes that the Earth has an unlimited supply of resources. Environmental ethics includes humans as part of the natural community rather than managers of it. Sustainable ethics assumes that the Earth's resources are not unlimited and that humans must use and conserve resources to allow their continued use in the future. A variety of methods categorize countries. During the Cold War, the United States government categorized countries according to each government's ideology and capitalistic development. Current classification models utilize economic (and sometimes other) factors in their determination. Environmental justice is achieved when everyone enjoys the same degree of protection from environmental and health hazards and equal access to the decision-making process to have a healthy environment. Many problems face indigenous people, including lack of human rights, exploitation of their traditional lands and themselves, and degradation of their culture. Despite the lofty U.N. goals, the rights and feelings of indigenous people are often ignored or minimized, even by supposedly culturally sensitive developed countries.

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Chapter attributions:

Chapter 2: Matter, Energy, and Life

Like almost all organisms, this sage thrasher's diet depends on photosynthesis.

Learning Outcomes

After studying this chapter, you should be able to:

- Describe matter and elements
- Describe the ways in which carbon is critical to life
- Describe the roles of cells in organisms
- Compare and contrast prokaryotic cells and eukaryotic cells
- Summarize the process of photosynthesis and explain its relevance to other living things

Chapter Outline

- 2.1 Matter
- 2.2 Energy
- 2.3 A Cell is the Smallest Unit of Life
- 2.4 Energy Enters Ecosystems Through Photosynthesis
- 2.5 Chapter Resources

Atoms, Molecules, and Compounds

At its most fundamental level, life is made of **matter**. Matter is something that occupies space and has mass. All matter is composed of **elements**, substances that cannot be broken down or transformed chemically into other substances. Each element is made of atoms, each with a constant number of protons and unique properties. A total of 118 elements have been defined; however, only 92 occur naturally, and fewer than 30 are found in living cells. The remaining 26 elements are unstable and therefore do not exist for very long or are theoretical and have yet to be detected. Each element is designated by its chemical symbol (such as H, N, O, C, and Na) and possesses unique properties. These unique properties allow elements to combine and bond with each other in specific ways.

An **atom** is the smallest component of an element that retains all of the chemical properties of that element. For example, one hydrogen atom has all of the properties of the element hydrogen, such as it exists as a gas at room temperature and bonds with oxygen to create a water molecule. Hydrogen atoms cannot be broken down into anything smaller while still retaining the properties of hydrogen. If a hydrogen atom were broken down into subatomic particles, it would no longer have the properties of hydrogen. At the most basic level, all organisms are made of a combination of elements. They contain atoms that combine to form molecules. In multicellular organisms, such as animals, molecules can interact to form cells that combine to form tissues, which make up organs. These combinations continue until entire multicellular organisms are composed.

All matter is made of atoms, whether a rock or an organism. Often, these atoms combine to form **molecules**. Molecules are chemicals made from two or more atoms bonded together. Some molecules are very simple, like O2, which comprises just two oxygen atoms. Some molecules used by organisms, such as DNA, are made of many millions of atoms. All atoms contain protons, electrons, and neutrons (Figure 1 below). The only exception is hydrogen (H), made of one proton and one electron. A **proton** is a positively charged particle that resides in the nucleus (the core of the atom) of an atom and has a mass of 1 and a charge of +1. An **electron** is a negatively charged particle that travels in the space around the nucleus. In other words, it resides outside of the nucleus. It has a negligible mass and a charge of –1. **Neutrons**, like protons, reside in the nucleus of an atom. They have a mass of 1 and no charge. The positive (protons) and negative (electrons) charges balance each other in a neutral atom with a net zero charge.

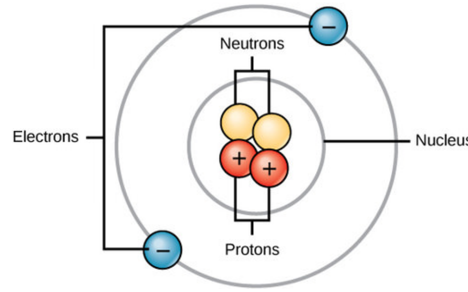


Figure 1. Atoms are comprised of protons and neutrons located within the nucleus and electrons surrounding the nucleus. The nucleus of an atom should not be confused with the nucleus of a cell.

Each element contains a different number of protons and neutrons, giving it its atomic and mass numbers. An element's **atomic number** equals the number of protons that an element contains. The **mass number** is the number of protons plus the number of neutrons of that element. Therefore, it is possible to determine the number of neutrons by subtracting the atomic number from the mass number.

Isotopes are different forms of the same element with the same number of protons but a different number of neutrons. Some elements, such as carbon, potassium, and uranium, have naturally occurring isotopes. Carbon 12, the most common carbon isotope, contains six protons and six neutrons. Therefore, it has a mass number of 12 (six protons and six neutrons) and an atomic number of 6 (which makes it carbon). Carbon 14 contains six protons and eight neutrons. Therefore, it has a mass number of 14 (six protons and eight neutrons) and an atomic number of 6, meaning it is still the element carbon. These two alternate forms of carbon are isotopes. Some isotopes are unstable and will lose protons, other subatomic particles, or energy to form more stable elements. These are called **radioactive isotopes** or radioisotopes.

EVOLUTION IN ACTION

Carbon dating

Carbon-14 (14C) is a naturally occurring radioisotope created in the atmosphere by cosmic rays. This is a continuous process, so more 14C is always being created. As a living organism develops, its body's relative level of 14C is equal to the concentration of 14C in the atmosphere. When an organism dies, it no longer ingests 14C, so the ratio will decline. 14C decays to 14N by a process called beta decay; it gives off energy in this slow process. After approximately 5,730 years, only one-half of the starting concentration of 14C will have been converted to 14N. The time it takes for half of the original concentration of an isotope to decay to its more stable form is called its half-life.

Because the half-life of 14C is long, it is used to age formerly living objects, such as fossils. Using the ratio of the 14C concentration found in an object to the amount of 14C detected in the atmosphere, the amount of the isotope that has not yet decayed can be determined. Based on this amount, the age of the fossil can be calculated to be about 50,000 years (Figure 2 below). Isotopes with longer half-lives, such as potassium-40, are used to calculate the ages of older fossils. Using carbon dating, scientists can reconstruct the ecology and biogeography of organisms living within the past 50,000 years.

Figure 2. The age of remains that contain carbon and are less than about 50,000 years old, such as this pygmy mammoth, can be determined using carbon dating. (credit: Bill Faulkner/ NPS)

Chemical Bonds

How elements interact with one another depends on the number of electrons and how they are arranged. When an atom does not contain equal numbers of protons and electrons, it is called an **ion**. Because the number of electrons does not equal the number of protons, each ion has a net **charge**. For example, if sodium loses an electron, it now has 11 protons and only 10 electrons, leaving it with an overall charge of +1. Positive ions are formed by losing electrons and are called **cations**. Negative ions are formed by gaining electrons and are called **anions**. Elemental anionic names are changed to end in -ide. For example, when chlorine becomes an ion, it is called chloride.

Ionic and covalent bonds are strong bonds formed between two atoms. These bonds hold atoms together in a relatively stable state. **Ionic bonds** are formed between two oppositely charged ions (an anion and a cation). Because positive and negative charges attract, these ions are held together much like two oppositely charged magnets would stick together. **Covalent bonds** form when electrons are shared between two atoms. Each atom shares one of its electrons, which then orbits the nuclei of both atoms, holding the two atoms together. Covalent bonds are the strongest and most common form of chemical bond in organisms. Unlike most ionic bonds, covalent bonds do not dissociate in water.

Covalent bonds come in two varieties: polar and non-polar. A **non-polar covalent bond** occurs when electrons are shared equally between the two atoms. **Polar covalent bonds** form when the electrons are shared unequally. Why does this happen? Each element has a known **electronegativity**: a measure of its affinity for electrons. Some elements, such as oxygen, are very electronegative because they strongly attract electrons from other atoms. Hydrogen, meanwhile, has low electronegativity and thus weakly attracts electrons in comparison. Polar covalent bonds form when the two atoms involved have significantly different electronegativities. In biological systems, this occurs when oxygen bonds with hydrogen and when nitrogen (also quite electronegative) bonds with hydrogen.

When oxygen and hydrogen bond, for example, the shared electrons are pulled more strongly toward oxygen and thus farther away from hydrogen's nucleus. Because the electrons move farther away from hydrogen, it becomes slightly positively charged (δ+). The oxygen becomes slightly negatively charged as the electrons become closer to it (δ–). If two molecules with polar covalent bonds approach one another, they can interact due to the attraction of opposite electrical charges. For example, the slight positive charge of hydrogen in a water molecule can be attracted to the slight negative charge of oxygen in a different water molecule (Figure 3). This interaction between two polar molecules is called a **hydrogen bond**. This type of bond is very common in organisms. Notably, hydrogen bonds give water the unique properties that sustain life. If not for hydrogen bonding, water would be a gas rather than a liquid at room temperature.

Water is Crucial to Maintaining Life

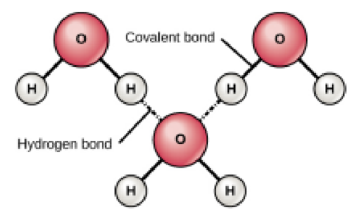


Figure 3. Hydrogen bonds form between slightly positive (δ+) and slightly negative (δ–) charges of polar covalent molecules, such as water.

Do you ever wonder why scientists spend time looking for water on other planets? Water is essential to life; even minute traces of it on another planet can indicate that life could or did exist on that planet. Water is one of the more abundant molecules in living cells and the one most critical to life as we know it. Approximately 60–70 percent of your body is made up of water. Without it, life would not exist.

- **Water is polar.** The hydrogen and oxygen atoms within water molecules form polar covalent bonds. The shared electrons spend more time associated with the oxygen atom than with hydrogen atoms. There is no overall charge to a water molecule, but there is a slight positive charge on each hydrogen atom and a slight negative charge on the oxygen atom. Because of these charges, the slightly positive hydrogen atoms repel each other and form a unique shape. Each water molecule attracts other water molecules because of the positive and negative charges in the different parts of the molecule. Water also attracts other polar molecules (such as sugars) that can dissolve in water and are referred to as hydrophilic ("water-loving").
- **Water stabilizes temperature.** The hydrogen bonds in water allow it to absorb and release heat energy more slowly than many other substances. Temperature is a measure of the motion (kinetic energy) of molecules. As the motion increases, energy is higher, and thus temperature is higher. Water absorbs a great deal of energy before its temperature rises. Increased energy disrupts the hydrogen bonds between water molecules. Because these bonds can be created and disrupted rapidly, water absorbs an increase in energy, and temperature

changes only minimally. This means that water moderates temperature changes within organisms and in their environments.

- **Water is an excellent solvent.** Because water is polar, with slightly positive and negative charges, ionic compounds and polar molecules can readily dissolve in it. Therefore, water is referred to as a solvent—a substance capable of dissolving another substance. The charged particles will form hydrogen bonds with a surrounding layer of water molecules.
- **Water is cohesive.** Have you ever filled a glass of water to the top and slowly added a few more drops? Before it overflows, the water forms a dome-like shape above the rim of the glass. This water can stay above the glass because of the property of cohesion. In cohesion, water molecules are attracted to each other (because of hydrogen bonding), keeping the molecules together at the liquid-air (gas) interface, although there is no more room in the glass. Cohesion gives rise to surface tension, the capacity of a substance to withstand rupture when placed under tension or stress. For example, when you drop a small scrap of paper onto a droplet of water, the paper floats on top of the water droplet, although the object is denser (heavier) than the water. This occurs because of the surface tension created by the water molecules. Cohesion and surface tension keep the water molecules intact and the item floating on top. If you place it gently without breaking the surface tension, it is possible to "float" a steel needle on top of a glass of water. These cohesive forces are also related to the water's adhesion property or the attraction between water molecules and other molecules. This is observed when water "climbs" up a straw placed in a glass of water. You will notice that the water appears higher on the sides of the straw than in the middle. This is because the water molecules are attracted to the straw and adhere to it. Cohesive and adhesive forces are important for sustaining life. For example, because of these forces, water can flow from the roots to the tops of plants to feed the plant.

Buffers, pH, Acids, and Bases

The **pH** of a solution is a measure of its **acidity** or **alkalinity**. The pH scale ranges from 0 to 14. A change of one unit on the pH scale represents a change in the concentration of hydrogen ions by a factor of 10, and a change in two units represents a change in the concentration of hydrogen ions by a factor of 100. Thus, small changes in pH represent large changes in the concentrations of hydrogen ions. Pure water is neutral. It is neither acidic nor basic and has a pH of 7.0. Anything below 7.0 (ranging from 0.0 to 6.9) is acidic, and anything above 7.0 (7.1 to 14.0) is alkaline. The blood in your veins is slightly alkaline (pH = 7.4). The environment in your stomach is highly acidic (pH = 1 to 2). Orange juice is mildly acidic (pH = approximately 3.5), whereas baking soda is basic (pH = 9.0).

Acids are substances that provide hydrogen ions (H+) and lower pH, whereas **bases** provide hydroxide ions (OH–) and raise pH. The stronger the acid, the more readily it donates H+. For example, hydrochloric acid and lemon juice are very acidic and readily give up H+ when added to water. Conversely, bases are those substances that readily donate OH–. The OH– ions combine with H+ to produce water, which raises a substance's pH. Sodium hydroxide and many household cleaners are very alkaline and give up OH– rapidly when placed in water, thereby raising the pH.

How can we ingest or inhale acidic or basic substances and not die? **Buffers** are the key. Buffers readily absorb excess H+ or OH–, keeping the body's pH carefully maintained in the aforementioned narrow range. Carbon dioxide is part of a prominent buffer system in the human body; it keeps the pH within the proper range. This buffer system involves carbonic acid (H_2CO_3) and bicarbonate (HCO_3^-) anion. If too much H+ enters the body, bicarbonate will combine with the H+ to create carbonic acid and limit the decrease in pH. Likewise, if too much OH– is introduced into the system, carbonic acid will combine with it to create bicarbonate and limit the increase in pH. While carbonic acid is an important product in this reaction, its presence is fleeting because carbonic acid is released from the body as carbon dioxide gas each time we breathe. Without this buffer system, the pH in our bodies would fluctuate too much, and we would fail to survive.

Figure 4. The pH scale measures the concentration of hydrogen ions (H+) in a substance. (credit: modification of work by Edward Stevens)

Biological Molecules

Besides water, the molecules necessary for life are organic. **Organic molecules** are those that contain carbon covalently bonded to hydrogen. In addition, they may contain oxygen, nitrogen, phosphorus, sulfur, and additional elements. There are four major classes of organic molecules: **carbohydrates**, **lipids**, **proteins**, and **nucleic acids.** Each is an important component of the cell and performs a wide array of functions.

It is often said that life is "carbon-based." This means that carbon atoms, bonded to other carbon atoms or other elements, form the fundamental components of many molecules found uniquely in living things. Other elements play important roles in biological molecules, but carbon certainly qualifies as the "foundation" element for molecules in living things. The bonding properties of carbon atoms are responsible for their important role.

Carbon can form four covalent bonds with other atoms or molecules. The simplest organic carbon molecule is methane (CH_4), in which four hydrogen atoms bind to a carbon atom (Figure 5). **Carbohydrates** include what is commonly referred to as simple sugars, like glucose, and complex carbohydrates, such as starch. While many types of carbohydrates are used for energy, some are used for structure by most organisms, including plants and animals. For example, cellulose is a complex carbohydrate that adds rigidity and strength to the cell walls of plants. The suffix "-ose" denotes a carbohydrate, but note that not all carbohydrates were given that suffix when named (e.g., starch).

Lipids are a diverse group of compounds united by a common feature. Lipids are hydrophobic ("water-fearing") or insoluble in water because they are non-polar molecules (molecules that contain non-polar covalent bonds). Lipids perform many different functions in a cell. For example, cells store energy for long-term use in the form of lipids called fats. Lipids also provide insulation from the environment for plants and animals. For example, they help keep aquatic birds and mammals dry because of their water-repelling nature. Lipids are also the building blocks of many hormones and are an important constituent of cellular membranes. Lipids include fats, oils, waxes, phospholipids, and steroids.

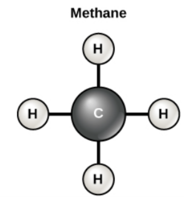


Figure 5. Carbon can form four covalent bonds to create an organic molecule. The simplest carbon molecule is methane (CH4), depicted here.

Proteins are one of the most abundant organic molecules in living systems and have the most diverse range of functions of all macromolecules. They are all polymers of amino acids. The functions of proteins are very diverse because 20 different chemically distinct amino acids form long chains, and the amino acids can be in any order. Proteins can function as enzymes, hormones, contractile fibers, cytoskeleton rods, and more. **Enzymes** are vital to life because they catalyze biochemical reactions (like digestion). Each enzyme is specific for the substrate (a reactant that binds to an enzyme) upon which it acts. In addition, enzymes can function to break molecular bonds, rearrange bonds, or form new bonds.

Nucleic acids are very large molecules important to life's continuity. They carry the genetic blueprint of a cell and, thus, the instructions for its functionality. The two main types of nucleic acids are deoxyribonucleic acid (**DNA**) and ribonucleic acid (RNA). DNA is the genetic material found in all organisms, ranging from single-celled bacteria to multicellular mammals. The other type of nucleic acid, **RNA**, is mostly involved in protein synthesis. The DNA molecules never leave the nucleus but instead use an RNA intermediary to communicate with the rest of the cell. Other types of RNA are also involved in protein synthesis and its regulation. DNA and RNA are made up of small building blocks known as **nucleotides**. The nucleotides combine with each other to form a polynucleotide: DNA or RNA. Each nucleotide comprises three components: a nitrogenous base, a pentose (five-carbon) sugar, and a phosphate. DNA has a beautiful double-helical structure (Figure 6).

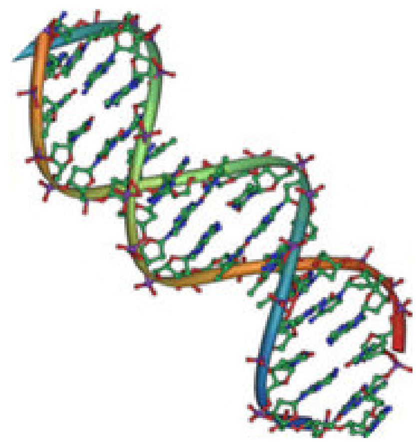
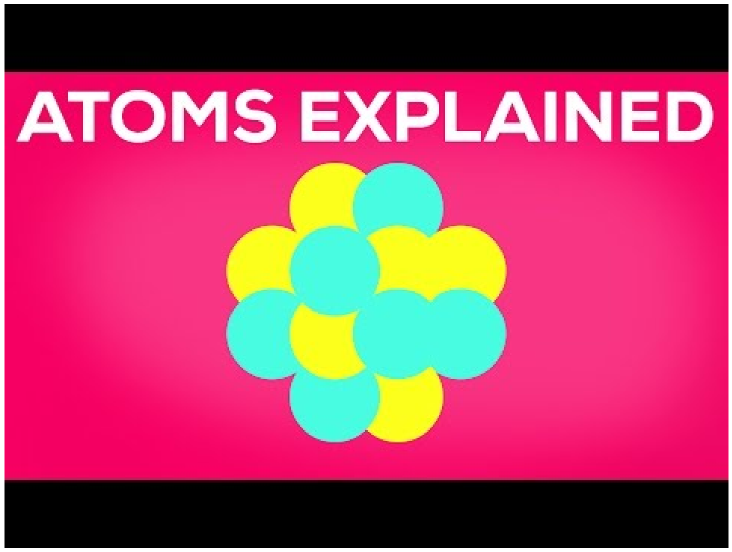


Figure 6. The double-helix model shows DNA as two parallel strands of intertwining molecules.

Additional Resources:



Kurzgesagt-In a Nutshell. (2014). How Small is an Atom? Spoiler: Very Small. https://youtu.be/_lNF3_30lUE

Virtually every task performed by living organisms requires energy. Nutrients and other molecules are imported into the cell to meet these energy demands. For example, energy is required to synthesize and break down molecules and transport molecules into and out of cells. In addition, ingesting and breaking down food, exporting wastes and toxins, and cell movement requires energy.

Scientists use the term **bioenergetics** to describe the concept of energy flow through living systems, such as cells. Cellular processes, such as the building and breaking down complex molecules, occur through step-wise chemical reactions. Some of these chemical reactions are spontaneous and release energy, whereas others require energy to proceed. Together, all of the chemical reactions that take place inside cells, including those that consume or generate energy, are referred to as the cell's **metabolism**.

From where and in what form does this energy come? How do living cells obtain energy, and how do they use it? This section will discuss different forms of energy and the physical laws that govern energy transfer.

Energy

Thermodynamics refers to the study of energy and energy transfer involving physical matter. The matter relevant to a particular case of energy transfer is called a system, and everything outside of that matter is called the surroundings. For instance, when heating a pot of water on the stove, the system includes the stove, the pot, and the water. Energy is transferred within the system (between the stove, pot, and water). There are two types of systems: open and closed. In an **open system**, energy can be exchanged with its surroundings. For example, the stovetop system is open because heat can be lost to the air. A **closed system** cannot exchange energy with its surroundings.

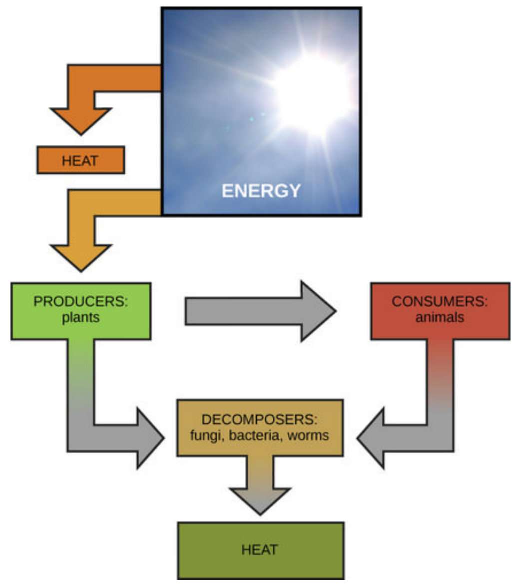


Figure 1. Ultimately, most life forms get their energy from the sun. Plants use photosynthesis to capture sunlight, and herbivores eat plants for energy. Carnivores eat the herbivores, and the eventual decomposition of plant and animal material contributes to the nutrient pool.

Biological organisms are open systems. Energy is exchanged between them and their surroundings as they use energy from the sun to perform photosynthesis or consume energy-storing molecules and release energy to the environment by doing work and releasing heat. Like all things in the physical world, energy is subject to physical laws. The laws of thermodynamics govern the transfer of energy in and among all systems in the universe. In general, **energy** is defined as the ability to do work or to create some kind of change. Energy exists in different forms: electrical energy, light energy, mechanical energy, and heat energy are all different types of energy. To appreciate how energy flows into and out of biological systems, it is important to understand two physical laws governing energy.

The **first law of thermodynamics** states that the total amount of energy in the universe is constant and conserved. In other words, there has always been and always will be, exactly the same amount of energy in the universe. Energy exists in many different forms. According to the first law of thermodynamics, energy may be transferred from place to place or transformed into different forms, but it cannot be created or destroyed. The transfers and transformations of energy take place around us all the time. Light bulbs transform electrical energy into light and heat energy. Gas stoves transform chemical energy from natural gas into heat energy. Plants perform one of Earth's most biologically useful energy transformations: converting sunlight to chemical energy stored within organic molecules (Figure 2 below).

The challenge for all living organisms is obtaining energy from their surroundings in forms usable to perform cellular work. Cells have evolved to meet this challenge. Chemical energy stored within organic molecules such as sugars and fats is transferred and transformed through cellular chemical reactions into energy within molecules of ATP (adenosine triphosphate). Energy in ATP molecules is easily accessible to do work. Examples of the types of work that cells need to do include building complex molecules, transporting materials, powering the motion of cilia or flagella, and contracting muscles to create movement.

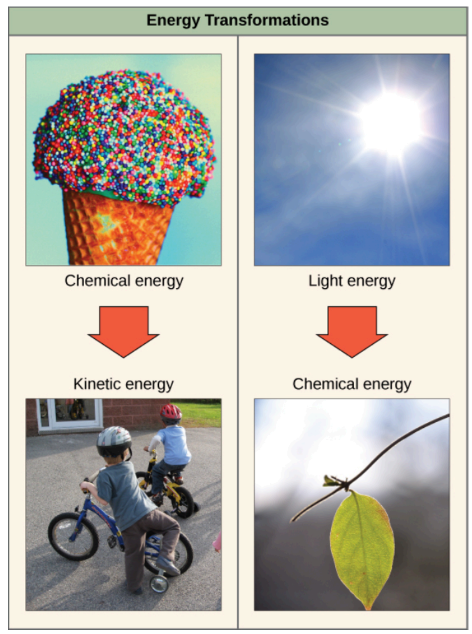


Figure 2. Shown are some examples of energy transferred and transformed from one system to another and from one form to another. The food we consume provides our cells with the energy required to carry out bodily functions, just as light energy provides plants with the means to create the chemical energy they need. (credit "ice cream": modification of work by D. Sharon Pruitt; credit "kids": modification of work by Max from Providence; credit "leaf": modification of work by Cory Zanker)

A living cell's primary tasks of obtaining, transforming, and using energy to do work may seem simple. However, the **second law of thermodynamics** explains why these tasks are harder than they appear. All energy transfers and transformations are never completely efficient. In every energy transfer, some amount of energy is lost in an unusable form. In most cases, this form is heat energy.

Thermodynamically, **heat energy** is defined as the energy transferred from one system to another that is not work. For example, when a light bulb is turned on, some energy converted from electrical to light energy is lost as heat energy. Likewise, some energy is lost as heat energy during cellular metabolic reactions.

An important concept in physical systems is that of order and disorder. The more energy that is lost by a system to its surroundings, the less ordered and more random the system is. Scientists refer to the measure of randomness or disorder within a system as **entropy**. High entropy means high disorder and low energy. Molecules and chemical reactions have varying entropy as well. For example, entropy increases as molecules at a high concentration in one place diffuse and spread out. The second law of thermodynamics says that energy will always be lost as heat in energy transfers or transformations. Therefore, living things are highly ordered, requiring constant energy input to be maintained in a low entropy state.

Potential and Kinetic Energy

When an object is in motion, there is energy associated with that object. Think of a wrecking ball. Even a slow-moving wrecking ball can do a great deal of damage to other objects. Energy associated with objects in motion is called **kinetic energy**. For example, a speeding bullet, a walking person, and the rapid movement of molecules in the air all have kinetic energy. What if that same motionless wrecking ball is lifted two stories above ground with a crane? If the suspended wrecking ball is not moving, is there energy associated with it? The answer is yes. The energy required to lift the wrecking ball did not disappear but is now stored in the wrecking ball by its position and the force of gravity acting on it. This type of energy is called **potential energy** (Figure 3 below). If the ball were to fall, the potential energy would be transformed into kinetic energy until all of the potential energy was exhausted when the ball rested on the ground. Wrecking balls also swing like a pendulum; through the swing, there is a constant change of potential energy (highest at the top of the swing) to kinetic energy (highest at the bottom of the swing). Other potential energy examples include the energy of water held behind a dam or a person about to skydive out of an airplane.

Figure 3. Still water has potential energy; moving water, such as in a waterfall or a rapidly flowing river, has kinetic energy. (credit "dam": modification of work by "Pascal"/Flickr; credit "waterfall": modification of work by Frank Gualtieri)

Potential energy is not only associated with matter's location but also with matter's structure. Even a spring on the ground has potential energy if it is compressed; so does a rubber band that is pulled taut. On a molecular level, the bonds that hold the atoms of molecules together exist in a particular structure with potential energy. The fact that energy can be released by breaking certain chemical bonds implies that those bonds have potential energy. Potential energy is stored within the bonds of all the food molecules we eat, which is harnessed for use. The type of potential energy that exists within chemical bonds, and is released when those bonds are broken, is called **chemical energy**. Chemical energy is responsible for providing living cells with energy from food. The release of energy occurs when the molecular bonds within food molecules are broken.

Levels of Biological Organization

Living things are highly organized and structured, following a scale hierarchy from small to large (Figure 1). The atom is the smallest and most fundamental unit of matter. It consists of a nucleus surrounded by electrons. Atoms combine to form molecules, which are chemical structures consisting of at least two atoms held together by a chemical bond. In plants, animals, and many other types of organisms, molecules come together in specific ways to create structures called organelles. Organelles are small structures that exist within cells and perform specialized functions. As discussed below, all living things are made of one or more cells.

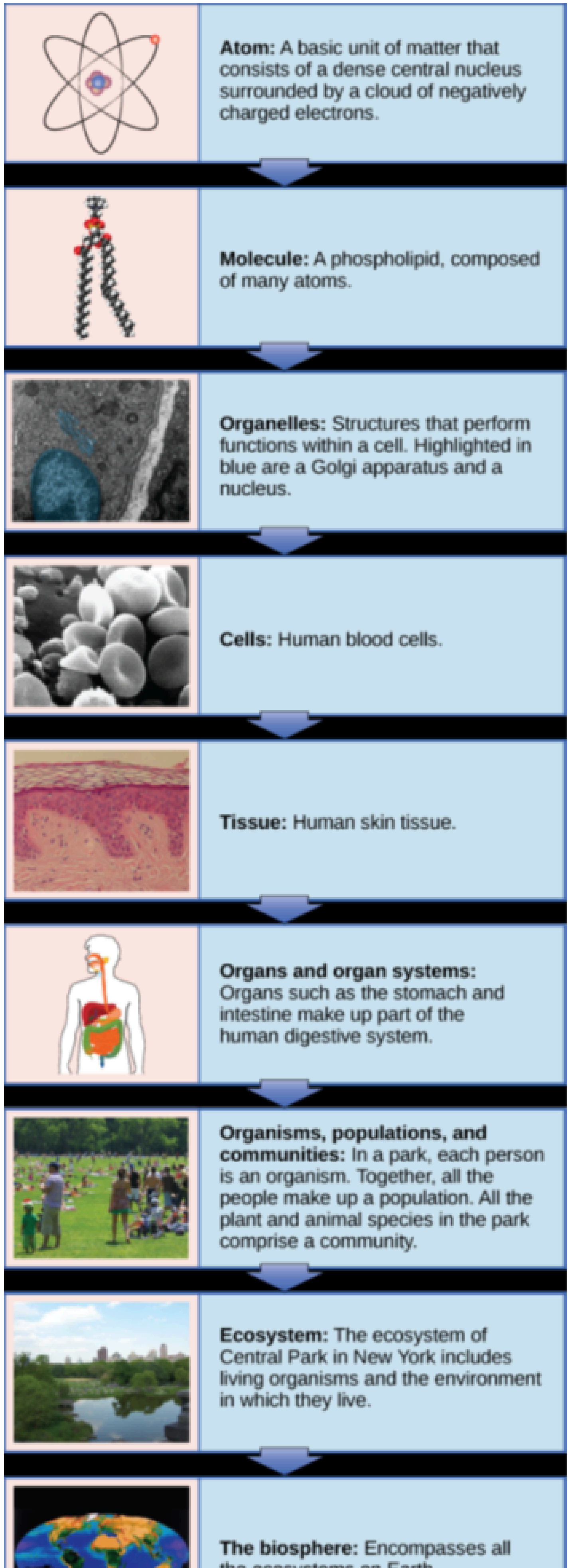

Atom: A basic unit of matter that consists of a dense central nucleus surrounded by a cloud of negatively charged electrons.
Molecule: A phospholipid, composed of many atoms.
Organelles: Structures that perform functions within a cell. Highlighted in blue are a Golgi apparatus and a nucleus.
Cells: Human blood cells.
Tissue: Human skin tissue.
Organs and organ systems: Organs such as the stomach and intestine make up part of the human digestive system.
Organisms, populations, and communities: In a park, each person is an organism. Together, all the people make up a population. All the plant and animal species in the park comprise a community.
Ecosystem: The ecosystem of Central Park in New York includes living organisms and the environment in which they live.
The biosphere: Encompasses all

Figure 1. Biology examines all aspects of life from an atom to the entire Earth. (credit "molecule": modification of work by Jane Whitney; credit "organelles": modification of work by Louisa Howard; credit "cells": modification of work by Bruce Wetzel, Harry Schaefer, National Cancer Institute; credit "tissue": modification of work by "Kilbad"/Wikimedia Commons; credit "organs": modification of work by Mariana Ruiz Villareal, Joaquim Alves Gaspar; credit "organisms": modification of work by Peter Dutton; credit "ecosystem": modification of work by "gigi4791"/Flickr; credit "biosphere": modification of work by NASA)

In most multicellular organisms, cells combine to make tissues, which are groups of similar cells carrying out the same function. Organs are collections of tissues grouped together based on a common function. Organs are present not only in animals but also in plants. An organ system is a higher level of organization that consists of functionally related organs. For example, vertebrate animals have many organ systems, such as the circulatory system, that transports blood throughout the body and to and from the lungs; it includes organs such as the heart and blood vessels. Organisms are individual living entities. For example, each tree in a forest is an organism.

All the individuals of a species living within a specific area are collectively called a population. A community is a set of different populations inhabiting a common area. For instance, all of the forest's trees, flowers, insects, and other populations form the forest's community. The forest itself is an ecosystem. An ecosystem consists of all the living things in a particular area together with the abiotic or non-living parts of that environment, such as nitrogen in the soil or rainwater. At the highest level of organization, the biosphere is the collection of all ecosystems, representing the life zones on Earth. It includes land, water, and portions of the atmosphere.

Cell Theory

Close your eyes and picture a brick wall. What is the basic building block of that wall? It is a single brick, of course. Like a brick wall, your body is composed of basic building blocks, and the building blocks of your body are cells. Your body has many cells, each specialized for a specific purpose. Just as a home is made from various building materials, the human body is constructed from many cell types. For example, bone cells help to support and protect the body. Cells of the immune system fight invading bacteria. And red blood cells carry oxygen throughout the body. Each cell type plays a vital role during the body's growth, development, and day-to-day maintenance. Despite their enormous variety, however, all cells share certain fundamental characteristics.

The microscopes we use today are far more complex than those used in the 1600s by Antony van Leeuwenhoek, a Dutch shopkeeper with great skill in crafting lenses. Despite the limitations of his now-ancient lenses, van Leeuwenhoek observed the movements of single-celled organisms and sperm, which he collectively termed "animalcules." In a 1665 publication called *Micrographia*, experimental scientist Robert Hooke coined the term "cell" (from the Latin *cella*, meaning "small room") for the box-like structures he observed when viewing cork tissue through a lens. In the 1670s, van Leeuwenhoek discovered bacteria and protozoa. Later advances in lenses and microscope construction enabled other scientists to see different components inside cells.

By the late 1830s, botanist Matthias Schleiden and zoologist Theodor Schwann were studying tissues and proposed the unified **cell theory**, which states that all living things are composed of one or more cells, that the cell is the basic unit of life and that all new cells arise from existing cells.

These principles still stand today. There are many types of cells, and all are grouped into one of two broad categories: prokaryotic and eukaryotic. Animal, plant, fungal, and protist cells are classified as eukaryotic, whereas bacteria and archaea cells are classified as prokaryotic.

All cells share four common components: 1) a plasma membrane, an outer covering that separates the cell's interior from its surrounding environment; 2) cytoplasm, consisting of a jelly-like region within the cell in which other cellular components are found; 3) DNA, the genetic material of the cell; and 4) ribosomes, particles that synthesize proteins. However, prokaryotes differ from eukaryotic cells in several ways.

Components of Prokaryotic Cells

A **prokaryotic cell** is a simple, single-celled (unicellular) organism without a nucleus or any other membrane-bound organelle. We will shortly come to see that this is significantly different in eukaryotes. Prokaryotic DNA is found in the central part of the cell: a darkened region called the nucleoid (Figure 2).

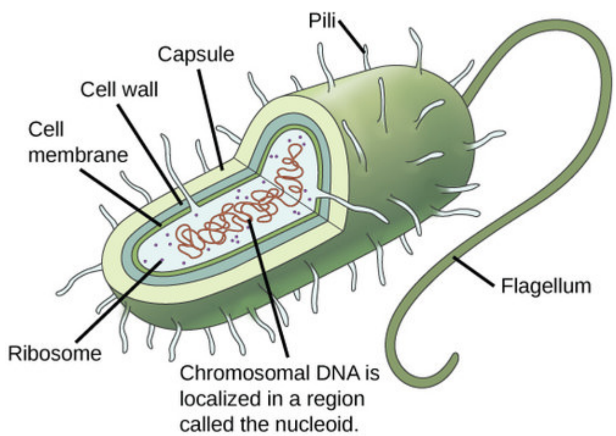


Figure 2. This figure shows the generalized structure of a prokaryotic cell.

Unlike Archaea and eukaryotes, bacteria have a cell wall made of peptidoglycan (molecules comprised of sugars and amino acids), and many have a polysaccharide capsule. The cell wall acts as an extra layer of protection, helps the cell maintain its shape, and prevents dehydration. The capsule enables the cell to attach to surfaces in its environment. Some prokaryotes have flagella, pili, or fimbriae. Flagella are used for locomotion. Pili are used to exchange genetic material during a type of reproduction called conjugation. Fimbriae are protein appendages used by bacteria to attach to other cells.

Eukaryotic Cells

A **eukaryotic cell** is a cell that has a membrane-bound nucleus and other membrane-bound compartments called **organelles.** There are many different types of organelles, each with a highly specialized function (see Figure 3). The word eukaryotic means "true kernel" or "true nucleus," alluding to the presence of the membrane-bound nucleus in these cells. The word "organelle" means "little organ," as already mentioned, organelles have specialized cellular functions, just as the organs of your body have specialized functions.

Cell Size

At 0.1–5.0 µm in diameter, most prokaryotic cells are significantly smaller than eukaryotic cells, with diameters ranging from 10–100 µm (Figure 3). The small size of prokaryotes allows ions and organic molecules that enter them to spread quickly to other parts of the cell. Similarly, any waste produced within a prokaryotic cell can quickly move out. However, larger eukaryotic cells have evolved different structural adaptations to enhance cellular transport. Indeed, the large size of these cells would not be possible without these adaptations. Cell size is generally limited because volume increases much more quickly than cell surface area. As a cell grows, it becomes more and more difficult for the cell to acquire sufficient materials to support the processes inside the cell because the relative size of the surface area through which materials must be transported declines.

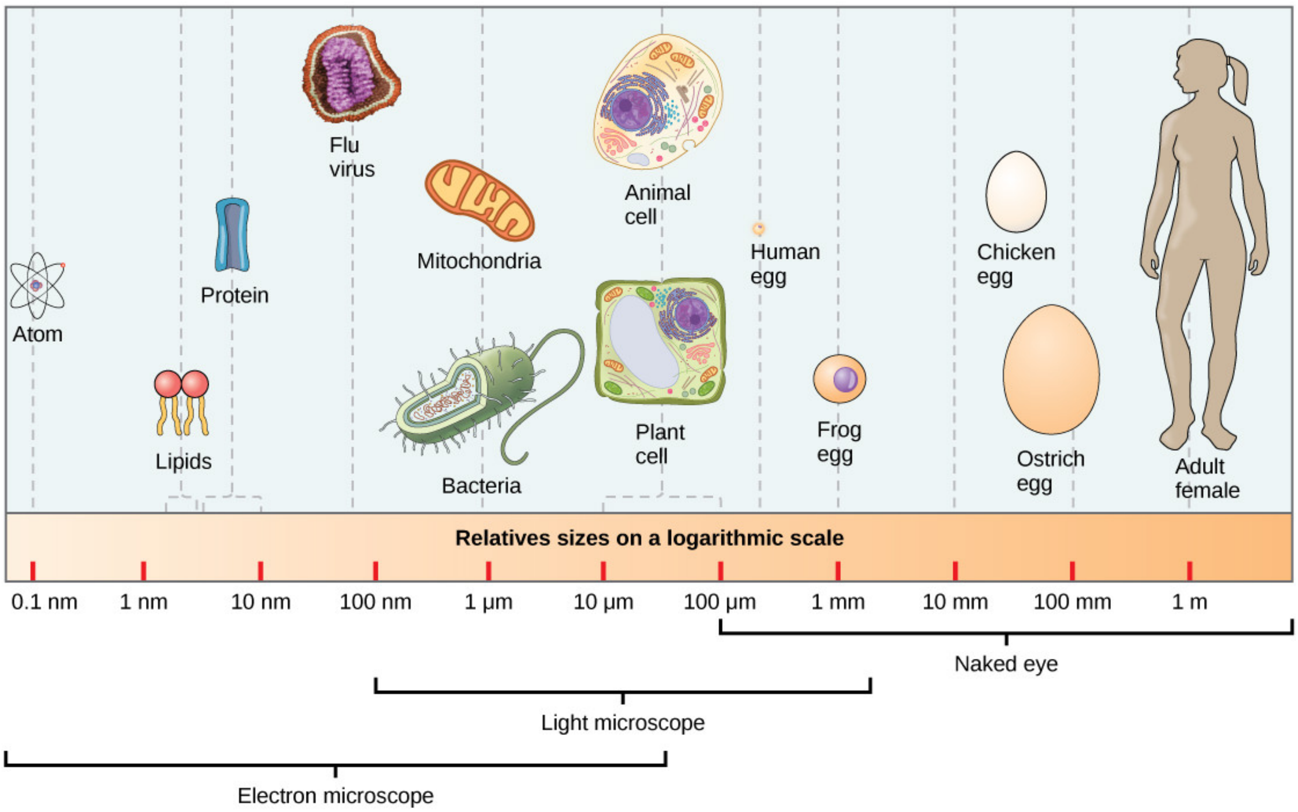


Figure 3. This figure shows the relative sizes of different kinds of cells and cellular components. An adult human is shown for comparison.

Animal Cells versus Plant Cells

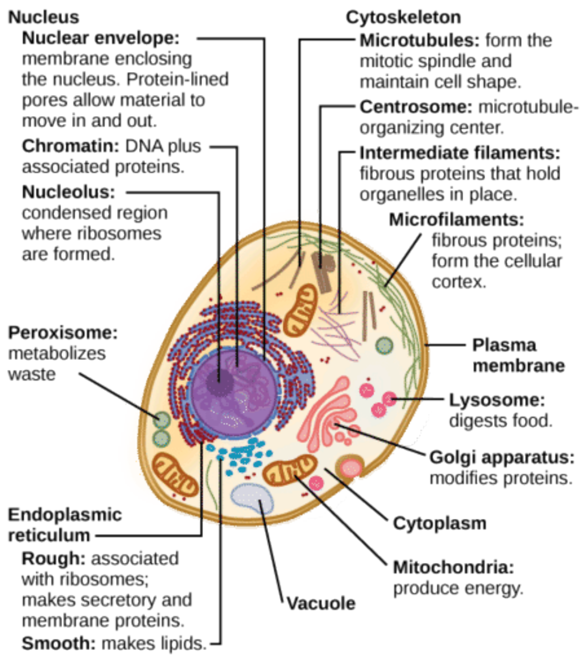


Figure 4. An example of a typical animal cell.

Despite their fundamental similarities, there are some striking differences between animal and plant cells (Figure 4 and 5). Animal cells have centrioles, centrosomes, and lysosomes, whereas plant cells do not. Plant cells have a rigid cell wall that is external to the plasma membrane, chloroplasts, plasmodesmata, and plastids used for storage, and a large central vacuole, whereas animal cells do not.

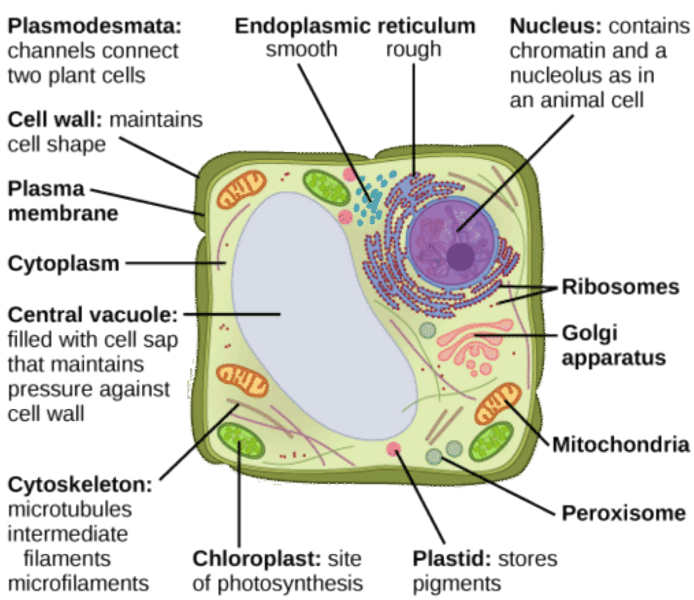


Figure 5. An example of a typical plant cell.

Chloroplasts

From an ecological perspective, **chloroplasts** are a particularly important type of organelle because they perform photosynthesis. Photosynthesis forms the foundation of food chains in most ecosystems. Chloroplasts are only found in eukaryotic cells such as plants and algae. Carbon dioxide, water, and light energy make glucose and molecular oxygen during photosynthesis. One major difference between algae/plants and animals is that plants/algae can make their own food, like glucose, whereas animals must obtain food by consuming other organisms.

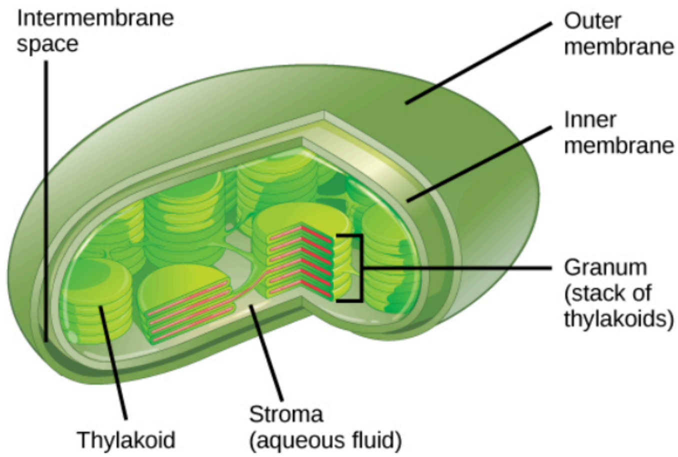


Figure 6. This simplified diagram of a chloroplast shows its structure.

Chloroplasts have outer and inner membranes, but within the space enclosed by a chloroplast's inner membrane is a set of interconnected, stacked, fluid-filled membrane sacs called thylakoids (Figure 6). Each stack of thylakoids is called a granum (plural = grana). The fluid enclosed by the inner membrane and surrounding the grana is called the stroma. Each structure within the chloroplast has an important function enabled by its particular shape. A common theme in biology is that form and function are interrelated. For example, the membrane-rich stacks of the thylakoids provide ample surface area to embed the proteins and pigments vital to photosynthesis.

Cells run on the chemical energy found mainly in carbohydrate molecules, and the majority of these molecules are produced by one process: photosynthesis. Through photosynthesis, certain organisms convert solar energy (sunlight) into chemical energy, which is then used to build carbohydrate molecules. The energy stored in the bonds to hold these molecules together is released when an organism breaks down food. Cells then use this energy to perform work, such as movement. The energy harnessed from photosynthesis enters our planet's ecosystems continuously and is transferred from one organism to another. Therefore, directly or indirectly, photosynthesis provides most of the energy required by living things on Earth. Photosynthesis also results in the release of oxygen into the atmosphere. In short, humans depend almost entirely on the organisms that carry out photosynthesis to eat and breathe.

Solar Dependence and Food Production

Figure 1. (a) Plants, (b) algae, and (c) certain bacteria, called cyanobacteria, are photoautotrophs that can carry out photosynthesis. Algae can grow over enormous areas in water, at times completely covering the surface. (credit a: Steve Hillebrand, U.S. Fish, and Wildlife Service; credit b: "eutrophication&hypoxia"/Flickr; credit c: NASA; scale-bar data from Matt Russell)

Some organisms can carry out photosynthesis, whereas others cannot. An **autotroph** is an organism that can produce its own food. The Greek roots of the word autotroph mean "self" (auto) or "feeder" (troph). Plants are the best-known autotrophs, but others exist, including certain types of bacteria and algae (Figure 1). Marine algae contribute enormous quantities of food and oxygen to global food chains. More specifically, plants are **photoautotrophs**, a type of autotroph that uses sunlight and carbon from carbon dioxide to synthesize chemical energy in the form of carbohydrates. All organisms carrying out photosynthesis require sunlight.

Figure 2. The energy stored in carbohydrate molecules from photosynthesis passes through the food chain. The predator that eats these deer is getting energy from the photosynthetic vegetation consumed by the deer. (credit: Steve VanRiper, U.S. Fish and Wildlife Service)

Heterotrophs are organisms incapable of photosynthesis that must obtain energy and carbon from food by consuming other organisms. The Greek roots of the word *heterotroph* mean "other" (*hetero*) "feeder" (*troph*), meaning that their food comes from other organisms. Even if the organism being consumed is another animal, it traces its stored energy back to autotrophs and photosynthesis. Humans are heterotrophs, as are all animals and fungi. Heterotrophs depend on autotrophs, either directly or indirectly. For example, a deer obtains energy by eating plants. A wolf eating a deer obtains energy that originally came from the plants eaten by that deer (Figure 2). Using this reasoning, all food eaten by humans can be traced back to autotrophs that carry out photosynthesis.

Summary of Photosynthesis

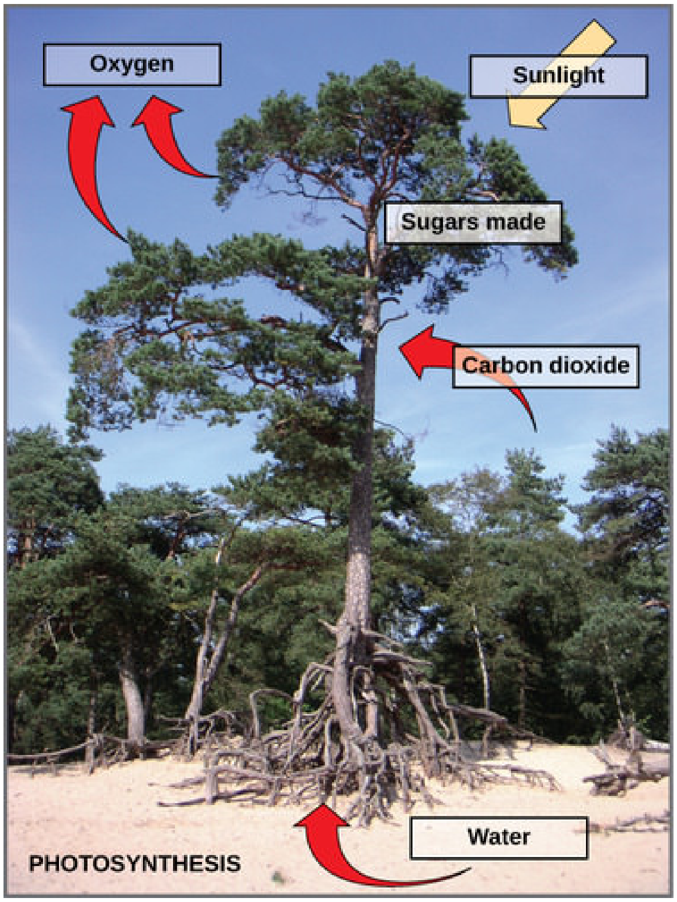


Figure 3. Photosynthesis uses solar energy, carbon dioxide, and water to release oxygen and to produce energy-storing sugar molecules.

Photosynthesis requires sunlight, carbon dioxide, and water as starting reactants (Figure 3). After the process is complete, photosynthesis releases oxygen and produces carbohydrate molecules, most commonly glucose. These sugar molecules contain the energy that living things need to survive. The chemical equation shown in Figure 4 below summarizes the complex reactions of photosynthesis.

Although the equation looks simple, the many steps during photosynthesis are quite complex. In plants, photosynthesis takes place primarily in the chloroplasts of leaves. Chloroplasts have a double (inner and outer) membrane. Within the chloroplast is a third membrane that forms stacked, disc-shaped structures called thylakoids. Embedded in the thylakoid membrane are molecules of **chlorophyll**, a pigment (a molecule that absorbs light) through which the entire process of photosynthesis begins.

Photosynthesis Equation			
Carbon dioxide +	Water $\xrightarrow{\text{SUNLIGHT}}$	Sugar +	Oxygen
$6CO_2$	$6H_2O$	$C_6H_{12}O_6$	$6O_2$

Figure 4. This equation means that six molecules of carbon dioxide (CO2) combine with six molecules of water (H2O) in the presence of sunlight. This produces one molecule of glucose.

The Two Parts of Photosynthesis

Photosynthesis occurs in two stages: the light-dependent reactions and the Calvin cycle**.** In **light-dependent reactions**, chlorophyll absorbs energy from sunlight and then converts it into chemical energy with the aid of water. The light-dependent reactions release **oxygen** as a byproduct of the splitting of water. In the **Calvin cycle**, the chemical energy derived from the light-dependent reactions drives carbon capture in **carbon dioxide** molecules and the subsequent assembly of sugar molecules.

The Global Significance of Photosynthesis

The process of photosynthesis is crucially important to the biosphere for the following reasons:

1. It creates O_2, which is important for two reasons. The molecular oxygen in Earth's atmosphere was created by photosynthetic organisms; without photosynthesis, there would be no O_2 to support cellular respiration (see chapter 3.2) needed by complex, multicellular life. Photosynthetic bacteria were likely the first organisms to perform photosynthesis, dating back 2-3 billion years ago. Thanks to their activity and diversity of present-day photosynthesizing organisms, Earth's atmosphere is currently about 21% O_2. Also, this O_2 is vital for creating the ozone layer (see chapter 10.2), which protects life from harmful ultraviolet radiation emitted by the sun. Ozone (O_3) is created from the breakdown and reassembly of O_2.
2. It provides energy for nearly all ecosystems. By transforming light energy into chemical energy, photosynthesis provides the energy used by organisms, whether those organisms are plants, grasshoppers, wolves, or fungi. The only exceptions are found in very rare and isolated ecosystems, such as near deep-sea hydrothermal vents where organisms get energy that originally came from minerals, not the sun.
3. It provides the carbon needed for organic molecules. Organisms are primarily made of two things: water and organic molecules, the latter being carbon-based. Through the process of **carbon fixation,** photosynthesis takes carbon from CO_2 and converts it into sugars (which are organic). Carbon in these sugars can be re-purposed to create the other types of organic molecules that organisms need, such as lipids, proteins, and nucleic acids. For example, the carbon used to make your DNA was once CO_2 used by photosynthetic organisms (see section 3.1 for more information on food webs).

Summary

Matter is anything that occupies space and has mass. It is made up of atoms of different elements. Elements that occur naturally have unique qualities that allow them to combine in various ways to create compounds or molecules. Atoms, which consist of protons, neutrons, and electrons, are the smallest units of an element that retain all of the properties of that element. Electrons can be donated or shared between atoms to create bonds, including ionic, covalent, and hydrogen bonds. The pH of a solution is a measure of the concentration of hydrogen ions in the solution. Living things are carbon-based because carbon plays a prominent role in the chemistry of living things.

A cell is the smallest unit of life. Most cells are so small that they cannot be viewed with the naked eye. The unified cell theory states that all organisms are composed of one or more cells, the cell is the basic unit of life, and new cells arise from existing cells. Each cell runs on the chemical energy found mainly in carbohydrate molecules (food), and the majority of these molecules are produced by one process: photosynthesis. Through photosynthesis, certain organisms convert solar energy (sunlight) into chemical energy, which is then used to build carbohydrate molecules. Directly or indirectly, photosynthesis provides most of the energy required by living things on Earth. Photosynthesis also results in the release of oxygen into the atmosphere. In short, humans depend almost entirely on the organisms that carry out photosynthesis to eat and breathe.

Additional Materials:

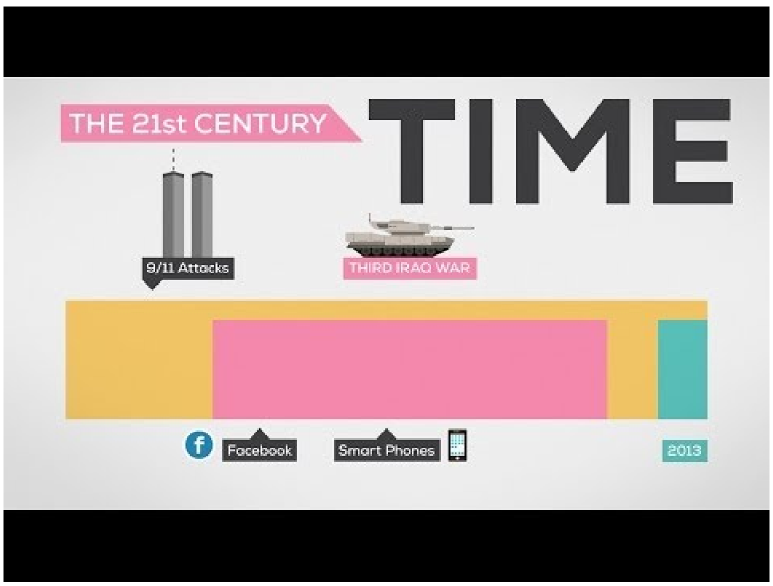


Figure 1. Click on this video link (https://youtu.be/2XkV6IpV2Y0) which provides some perspective about time, history, life, the universe, and everything.

References:

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Chapter attributions:

Chapter 3: Ecosystems and the Biosphere

(a) (b)

The (a) Karner blue butterfly and (b) wild lupine live in oak-pine barren habitats in North America. This habitat is characterized by natural disturbance in the form of fire and nutrient-poor soils that are low in nitrogen—important factors in the distribution of the plants that live in this habitat. Researchers interested in ecosystem ecology study the importance of limited resources in this ecosystem and the movement of resources (such as nutrients) through the biotic and abiotic portions of the ecosystem. Researchers also examine how organisms have adapted to their ecosystem. (credit: USFWS)

Learning Outcomes

After studying this chapter, you should be able to:

- Describe the basic types of ecosystems on Earth
- Differentiate between food chains and food webs and recognize the importance of each
- Describe how organisms acquire energy in a food web and associated food chains
- Discuss the biogeochemical cycles of water, carbon, nitrogen, phosphorus, and sulfur
- Explain how human activities have impacted these cycles

Chapter Outline

- 3.1 Energy Flow through Ecosystems

(a) (b)

Figure 1. A (a) tidal pool ecosystem in Matinicus Island, Maine, is a small ecosystem, while the (b) Amazon rainforest in Brazil is a large ecosystem. (credit a: modification of work by Jim Kuhn; credit b: modification of work by Ivan Mlinaric)

An **ecosystem** is a community of organisms and their abiotic (non-living) environment. Ecosystems can be small, such as the tide pools found near the rocky shores of many oceans, or large, such as those found in the tropical rainforest of the Amazon in Brazil (Figure 1).

There are three broad categories of ecosystems based on their general environment: freshwater, marine, and terrestrial. These three categories are individual ecosystem types based on the environmental habitat and organisms present.

Freshwater ecosystems are the least common, occurring on only 1.8 percent of Earth's surface. These systems comprise lakes, rivers, streams, and springs; they are quite diverse and support a variety of animals, plants, fungi, protists, and prokaryotes.

Marine ecosystems are the most common, comprising 75 percent of Earth's surface and consisting of three basic types: shallow ocean, deep ocean water, and deep ocean bottom. Shallow ocean ecosystems include extremely biodiverse coral reef ecosystems. Small photosynthetic organisms suspended in ocean waters, collectively known as **phytoplankton,** perform 40 percent of all photosynthesis on Earth. Deep ocean bottom ecosystems contain a wide variety of marine organisms. These ecosystems are so deep that light is unable to reach them.

Terrestrial ecosystems, also known for their diversity, are grouped into large categories called biomes. A **biome** is a large-scale community of organisms primarily defined on land by the dominant plant types that exist in geographic regions of the planet with similar climatic conditions. Examples of biomes include tropical rainforests, savannas, deserts, grasslands, temperate forests, and tundras. Grouping these ecosystems into just a few biome categories obscures the great diversity of the individual ecosystems within them. For example, the saguaro cacti (*Carnegiea gigantean*) and other plant life in the Sonoran Desert in the United States are relatively diverse compared with the desolate rocky desert of Boa Vista, an island off the coast of Western Africa (Figure 2).

Ecosystem Services

An ecosystem is a dynamic complex of plant, animal, and microorganism communities and the nonliving environment interacting as a functional unit, while **ecosystem services** are the benefits people obtain from ecosystems. Ecosystem services are critical to human well-being and sufficiently diverse and numerous to justify classification into four major categories.

Figure 2. Desert ecosystems, like all ecosystems, can vary greatly. The desert in (a) Saguaro National Park, Arizona, has abundant plant life, while the rocky desert of (b) Boa Vista island, Cape Verde, Africa, is devoid of plant life. (credit a: modification of work by Jay Galvin; credit b: modification of work by Ingo Wölbern)

1. Provisioning ecosystem services are actively harvested by us from the natural world to meet our resource needs, e.g., food, water, timber, and fiber.
2. Regulating ecosystem services are processes in the Earth system that control key physical and biological elements of our environment, e.g., climate regulation, food regulation, disease regulation, and water purification.
3. Cultural ecosystem services reflect the aesthetic and spiritual values we place on nature, as well as the educational and recreational activities dependent on ecosystems.
4. Supporting ecosystem services are the biogeochemical cycles and biological and physical processes that drive ecosystem function, e.g., soil formation, nutrient cycling, and photosynthesis.

We benefit from the services associated with both pristine, natural ecosystems, such as tropical rain forests or arctic tundra, and highly managed ecosystems, such as crop fields or urban landscapes. In all cases, ecosystems contribute to human well-being by influencing the attainability of basic material needs (e.g., food and shelter), health (e.g., clean air and water), good social relations and security (i.e., sufficient resources to avoid conflict, tolerate natural and man-made disasters, provide for children, and maintain social cohesion), as well as freedom of choice and action (an inherent component of the other elements of well-being is the right to live as one chooses). Linkages between some ecosystem services and human well-being vary in strength depending on socio-economic status. For example, many people in developed countries can always afford to buy imported food without dependence on the yields of locally grown crops, thereby avoiding shortages when yields are low because of bad weather. However, in other cases, our ability to control the impact of losing an ecosystem service on human well-being is limited. For example, despite major engineering efforts, flooding still causes considerable human and economic damage in developed countries. The challenge of sustainable development stems from the need to benefit from and manage ecosystem services without causing damage to the ecosystems and Earth system that will reduce their value in the longer term. People have long recognized that some ways of using natural resources are unsustainable, especially where ecosystems are rapidly exploited to the maximum extent possible and further access to the ecosystem services can be achieved only by moving on to previously unexploited areas, as in the case of slash and burn agriculture. Only more recently have we come to appreciate that human activity is altering global-scale phenomena, such as climate regulation, and this understanding raises a host of difficult questions. That is because people in one locale may realize the benefits of an ecosystem service, while the costs (in the form of negative environmental consequences) are imposed on people who live elsewhere and may be less equipped to withstand them.

Food Chains and Food Webs

A **food chain** is a linear sequence of organisms through which nutrients and energy pass as one organism eats another. The levels in the food chain are producers, primary consumers, higher-level consumers, and, finally, decomposers. These levels are used to describe ecosystem structure and dynamics. There is a single path through a food chain. Each organism in a food chain occupies a specific trophic level (energy level), its position in the food chain or food web.

In many ecosystems, the food chain's base, or foundation, consists of photosynthetic organisms (plants or phytoplankton), which are called **producers**. The organisms that consume the producers are herbivores called **primary consumers**. **Secondary consumers** are usually carnivores that eat the primary consumers. **Tertiary consumers** are carnivores that eat other carnivores. Higher-level consumers feed on the next lower trophic levels, and so on, up to the organisms at the top of the food chain. In the Lake Ontario food chain, shown in Figure 3, the Chinook salmon is the apex consumer at the top of this food chain.

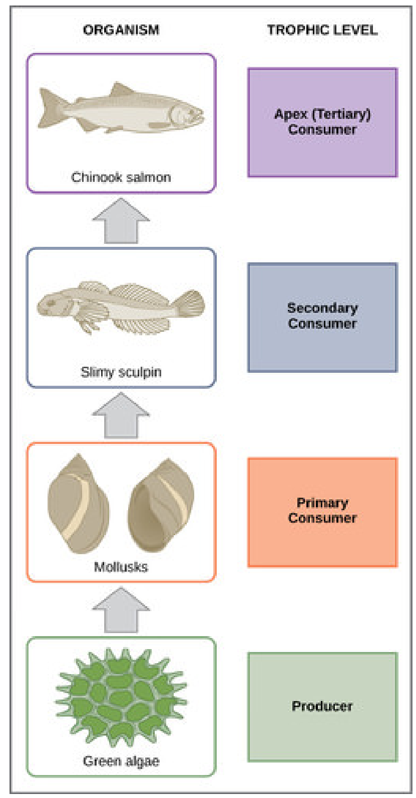

Figure 3. These are the trophic levels of a food chain in Lake Ontario at the United States–Canada border. Energy and nutrients flow from photosynthetic green algae at the base to the top of the food chain: the Chinook salmon. (credit: modification of work by National Oceanic and Atmospheric Administration/ NOAA)

Energy is one major factor limiting the number of steps in a food chain. Energy is lost at each trophic level and between trophic levels as heat and in the transfer to decomposers (Figure 4 . Thus, after a limited number of trophic energy transfers, the amount of energy remaining in the food chain may not be great enough to support viable populations at higher trophic levels.

There is one problem when using food chains to describe most ecosystems. Even when all organisms are grouped into appropriate trophic levels, some of these organisms can feed at more than one trophic level. In addition, species feed on and are eaten by more than one species. In other words, the linear model of ecosystems, the food chain, is a hypothetical and overly simplistic representation of ecosystem structure. A holistic model—including all the interactions between different species and their complex interconnected relationships with each other and the environment—is a more accurate and descriptive model for ecosystems. A **food web** is a concept that accounts for the multiple trophic (feeding) interactions between each species (Figure 5 below).

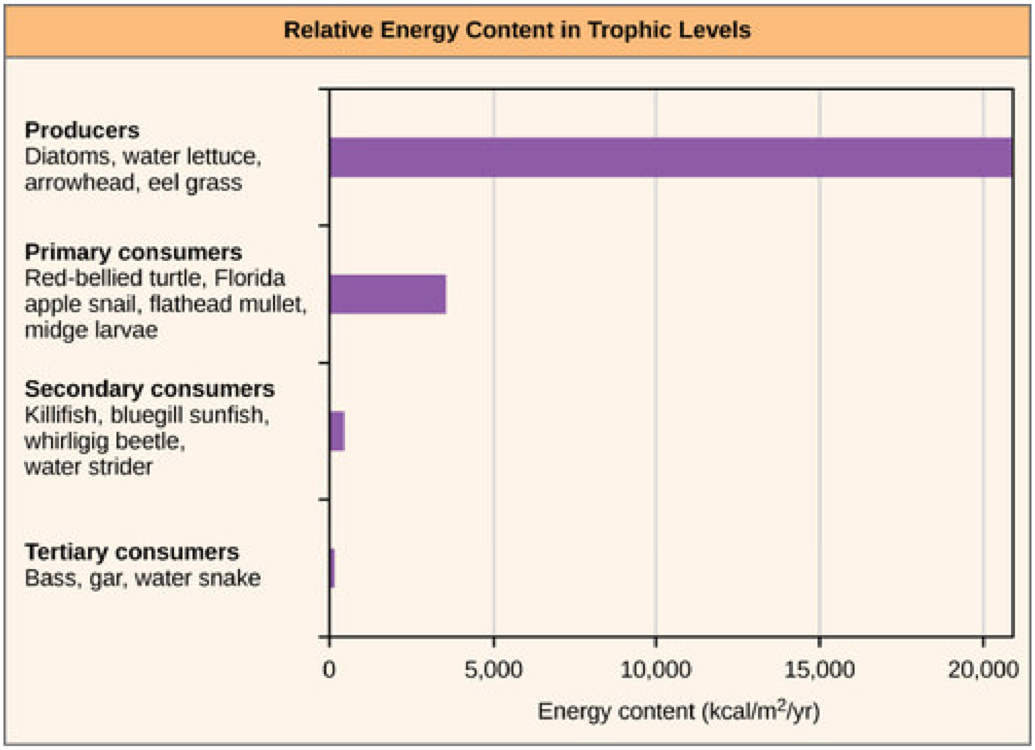

Figure 4. The relative energy in trophic levels in a Silver Springs, Florida, ecosystem is shown. Each trophic level has less energy available and usually, but not always, supports a smaller mass of organisms at the next level.

Two general types of food webs are often shown interacting within a single ecosystem. A grazing food web has plants or other photosynthetic organisms at its base, followed by herbivores and various carnivores. A detrital food web consists of a base of organisms that feed on decaying organic matter (dead organisms), including **decomposers** (which break down dead and decaying organisms) and **detritivores** (which consume organic detritus). These organisms are usually bacteria, fungi, and invertebrate animals that recycle organic material back into the biotic part of the ecosystem as other organisms consume them themselves.

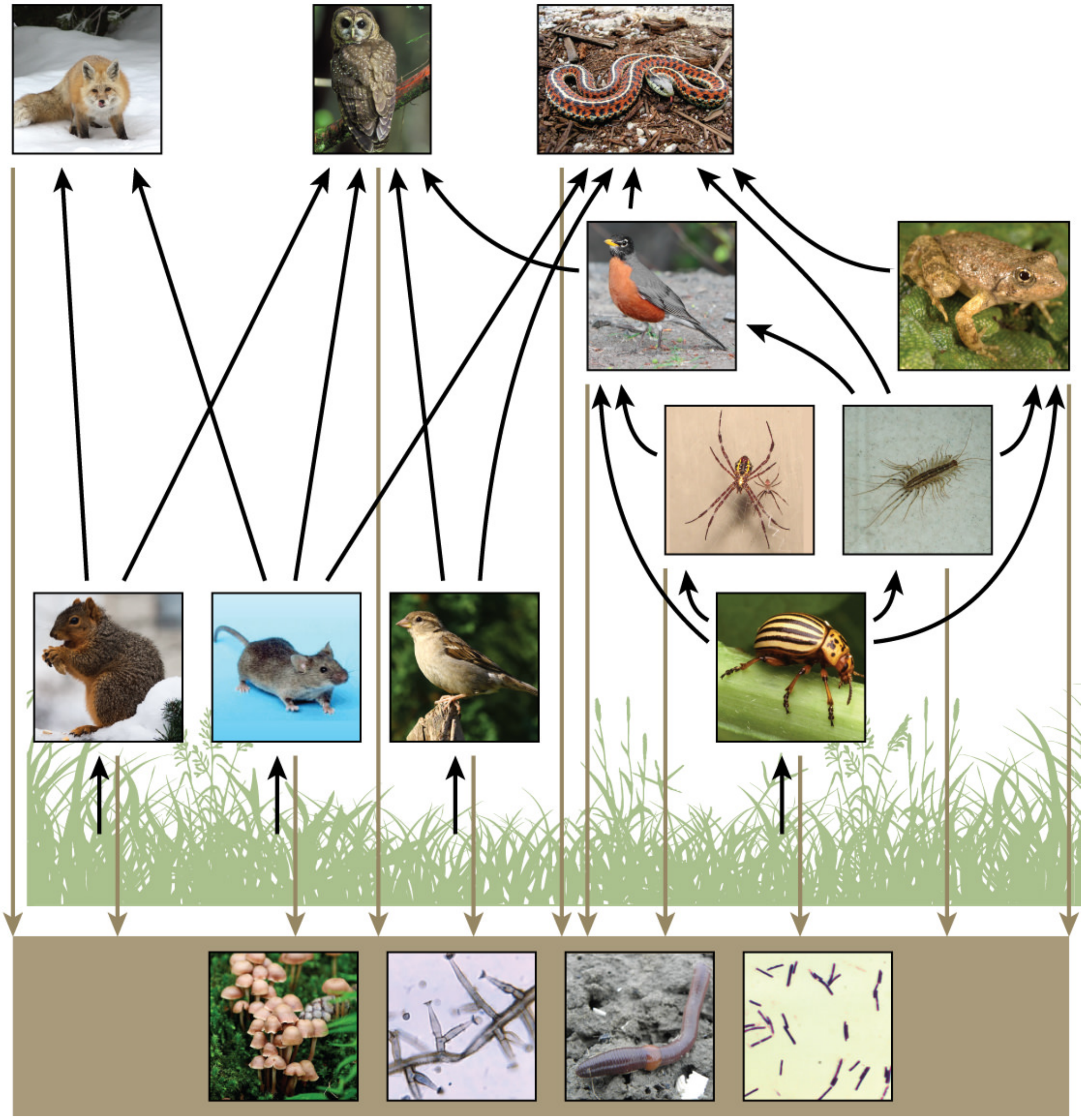

Figure 5. This food web shows the interactions between organisms across trophic levels. Arrows point from an organism that is consumed to the organism that consumes it. All the producers and consumers eventually become nourishment for the decomposers (fungi, mold, earthworms, and bacteria in the soil). (credit "fox": modification of work by Kevin Bacher, NPS; credit "owl": modification of work by John and Karen Hollingsworth, USFWS; credit "snake": modification of work by Steve Jurvetson; credit "robin": modification of work by Alan Vernon; credit "frog": modification of work by Alessandro Catenazzi; credit "spider": modification of work by "Sanba38"/Wikimedia Commons; credit "centipede": modification of work by "Bauerph"/Wikimedia Commons; credit "squirrel": modification of work by Dawn Huczek; credit "mouse": modification of work by NIGMS, NIH; credit "sparrow": modification of work by David Friel; credit "beetle": modification of work by Scott Bauer, USDA Agricultural Research Service; credit "mushrooms": modification of work by Chris Wee; credit "mold": modification of work by Dr. Lucille Georg, CDC; credit "earthworm": modification of work by Rob Hille; credit "bacteria": modification of work by Don Stalons, CDC)

How Organisms Acquire Energy in a Food Web

All living things require energy in one form or another. At the cellular level, energy is used in most metabolic pathways (usually ATP), especially those responsible for building large molecules from smaller compounds. Living organisms would not be able to assemble complex organic molecules (proteins, lipids, nucleic acids, and carbohydrates) without constant energy input.

Food-web diagrams illustrate how energy flows directionally through ecosystems. They can also indicate how efficiently organisms acquire energy and use it and how much remains for use by other food web organisms. In two ways, energy is acquired by living things: autotrophs harness light or chemical energy, and heterotrophs acquire energy through the consumption and digestion of other living or previously living organisms.

Photosynthetic and chemosynthetic organisms are autotrophs capable of synthesizing their own food (specifically, using inorganic carbon as a carbon source). Photosynthetic autotrophs (**photoautotrophs**) use sunlight as an energy source, and chemosynthetic autotrophs (**chemoautotrophs**) use inorganic molecules as an energy source. Autotrophs are critical for ecosystems because they occupy the trophic level containing producers. Without these organisms, energy would not be available to other living organisms, and life would not be possible.

Photoautotrophs, such as plants, algae, and photosynthetic bacteria, are the energy source for a majority of the world's ecosystems. Photoautotrophs harness the Sun's solar energy by converting it to chemical energy. The rate at which photosynthetic producers incorporate energy from the Sun is called **gross primary productivity**. However, not all of the energy incorporated by producers is available to the other organisms in the food web because producers must also grow and reproduce, which consumes energy. **Net primary productivity** is the energy that remains in the producers after accounting for these organisms' metabolism and heat loss. The net productivity is then available to the primary consumers at the next trophic level.

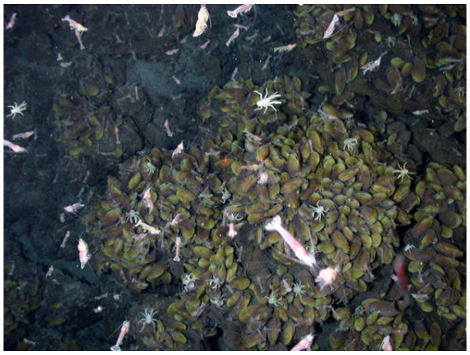

Figure 6. Swimming shrimp, a few squat lobsters, and hundreds of vent mussels are seen at a hydrothermal vent at the bottom of the ocean. As no sunlight penetrates this depth, the ecosystem is supported by chemoautotrophic bacteria and organic material that sinks from the ocean's surface. This picture was taken in 2006 at the submerged NW Eifuku volcano off the coast of Japan by the National Oceanic and Atmospheric Administration (NOAA). The summit of this highly active volcano lies 1535 m below the surface.

Chemoautotrophs are primarily bacteria and archaea found in rare ecosystems where sunlight is unavailable, such as those associated with dark caves or hydrothermal vents at the bottom of the ocean (Figure 6). Many chemoautotrophs in hydrothermal vents use hydrogen sulfide (H_2S), released from the vents, as a source of chemical energy. This allows them to synthesize complex organic molecules, such as glucose, for their own energy and, in turn, supplies energy to the rest of the ecosystem.

Biomagnification is one of the most important consequences of ecosystem dynamics in terms of human impact. **Biomagnification** is the increasing concentration of persistent, toxic substances in organisms at each successive trophic level. These are substances that are lipid soluble and are stored in the fat reserves of each organism. Many substances have been shown to biomagnify, including classical studies with the pesticide dichlorodiphenyltrichloroethane (DDT), which was described in the 1960s bestseller *Silent Spring* by Rachel Carson. DDT was a commonly used pesticide before its dangers to apex consumers, such as the bald eagle, became known. DDT and other toxins are taken in by producers and passed on to successive levels of consumers at increasingly higher rates. As bald eagles feed on contaminated fish, their DDT levels rise. It was discovered that DDT caused the eggshells of birds to become fragile, which contributed to the bald eagle being listed as an endangered species under U.S. law. The use of DDT was banned in the United States in the 1970s.

Another biomagnified substance is polychlorinated biphenyl (PCB), used as a coolant liquid in the United States until its use was banned in 1979. PCB was best studied in aquatic ecosystems where predatory fish species accumulated very high concentrations of the toxin that otherwise exists at low environmental concentrations. As illustrated in a study performed by the NOAA in the Saginaw Bay of Lake Huron of the North American Great Lakes (Figure 7 below), PCB concentrations increased from the producers of the ecosystem (phytoplankton) through the different trophic levels of fish species. The apex consumer, the walleye, has more than four times the amount of PCBs compared to phytoplankton. Also, research found that birds that eat these fish may have PCB levels at least ten times higher than those in lake fish.

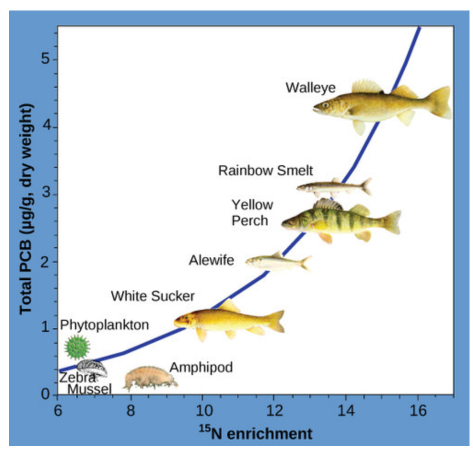

Figure 7. This chart shows the PCB concentrations found at the various trophic levels in the Saginaw Bay ecosystem of Lake Huron. Notice that the fish in higher trophic levels accumulate more PCBs than those in lower trophic levels. (credit: Patricia Van Hoof, NOAA)

Other concerns have been raised by the biomagnification of heavy metals, such as mercury and cadmium, in certain types of seafood. The United States Environmental Protection Agency recommends that pregnant women and young children should not consume any swordfish, shark, king mackerel, or tilefish because of their high mercury content. These individuals are advised to eat fish low in mercury: salmon, shrimp, pollock, and catfish. Biomagnification is a good example of how ecosystem dynamics can affect our everyday lives, even influencing our food.

Energy flows directionally through ecosystems, entering as sunlight (or inorganic molecules for chemoautotrophs) and leaving as heat during energy transformation between trophic levels. Rather than flowing through an ecosystem, the matter that makes up organisms is conserved and recycled. The six most common elements associated with organic molecules—carbon, nitrogen, hydrogen, oxygen, phosphorus, and sulfur—take various chemical forms and may exist for long periods in the atmosphere, on land, in water, or beneath Earth's surface. Geologic processes, such as weathering, erosion, water drainage, and the subduction of continental plates, all play a role in the cycling of elements on Earth. Because geology and chemistry have major roles in studying these processes, recycling inorganic matter between living organisms and their nonliving environment is called **biogeochemical cycles**.

Organisms use the six aforementioned elements in a variety of ways. Hydrogen and oxygen are found in water and organic molecules, both essential to life. Carbon is found in all organic molecules, whereas nitrogen is an important component of nucleic acids and proteins. Phosphorus is used to make nucleic acids and the phospholipids that comprise biological membranes. Lastly, sulfur is critical to the three-dimensional shape of proteins.

The cycling of these elements is interconnected. For example, water movement is critical for leaching sulfur and phosphorus into rivers, lakes, and oceans. Minerals cycle through the biosphere between the biotic and abiotic components and from one organism to another.

The Water Cycle

The **hydrosphere** is the area of Earth where water movement and storage occurs: as liquid water on the surface (rivers, lakes, oceans) and beneath the surface (groundwater) or ice (polar ice caps and glaciers), and as water vapor in the atmosphere. The human body is about 60 percent water, and human cells are more than 70 percent water. Of the stores of water on Earth, 97.5 percent is salt water (see Figure 1 below). Of the remaining water, more than 99 percent is groundwater or ice. Thus, less than one percent of freshwater is present in lakes and rivers. Many organisms depend on this small percentage, a lack of which can negatively affect ecosystems. Humans have developed technologies to increase water availability, such as digging wells to harvest groundwater, storing rainwater, and using desalination to obtain drinkable water from the ocean. Although this pursuit of drinkable water has been ongoing throughout human history, freshwater supply remains a major issue. The various processes that occur during the cycling of water are illustrated in Figure 2 below.

The processes include the following:

- evaporation and sublimation
- condensation and precipitation
- subsurface water flow
- surface runoff and snowmelt
- streamflow

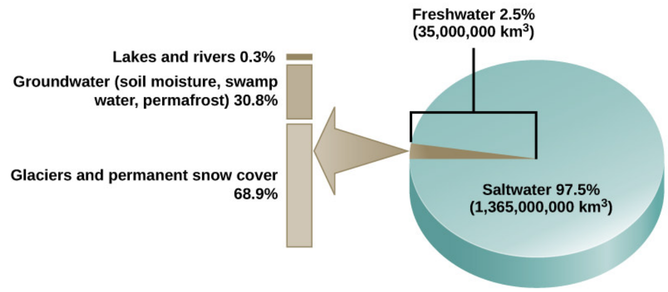

Figure 1. Only 2.5 percent of water on Earth is freshwater, and less than 1 percent of fresh water is easily accessible to living things.

The Sun's energy drives the **water cycle** as it warms the oceans and other surface waters. This leads to **evaporation** (liquid water to water vapor) of liquid surface water and **sublimation** (ice to water vapor) of frozen water, thus moving large amounts of water into the atmosphere as water vapor. Over time, this water vapor condenses into clouds as liquid or frozen droplets, eventually leading to precipitation (rain, snow, hail), returning water to Earth's surface. Rain reaching Earth's surface may evaporate again, flow over the surface, or percolate into the ground. Most easily observed is **surface runoff**: the flow of freshwater over land either from rain or melting ice. Runoff can make its way through streams and lakes to the oceans.

In most natural terrestrial environments, rain encounters vegetation before it reaches the soil surface. A significant percentage of water evaporates immediately from the surfaces of plants. What is left reaches the soil and begins to move down. Surface runoff will occur only if the soil becomes saturated with water in heavy rainfall. Plant roots can take up water in the soil. The plant will use some of this water for its own metabolism, and some of that will find its way into animals that eat the plants. Still, much of it will be lost back to the atmosphere through a process known as **transpiration:** water enters the vascular system of plants through the roots. It evaporates, or transpires, through the leaves' stomata (small microscope openings). Ecologists combine transpiration and evaporation into a single term that describes water returned to the atmosphere: **evapotranspiration**. Water in the soil not taken up by a plant that does not evaporate can percolate into the subsoil and bedrock, forming groundwater.

Groundwater is a significant subsurface reservoir of fresh water. It exists in the pores between particles in dirt, sand, and gravel or in the fissures in rocks. Groundwater can flow slowly through these pores and fissures and eventually finds its way to a stream or lake, where it becomes part of the surface water again. Many streams flow not because they are replenished from rainwater directly but because they receive a constant inflow from the groundwater below. Some groundwater is found very deep in the bedrock and can persist there for millennia. Most groundwater reservoirs, or **aquifers**, are the source of drinking or irrigation water drawn up through wells. In many cases, these aquifers are being depleted faster than replenished by water percolating down from above.

Rain and surface runoff are major ways minerals, including phosphorus and sulfur, are cycled from land to water. The environmental effects of runoff will be discussed later as these cycles are described.

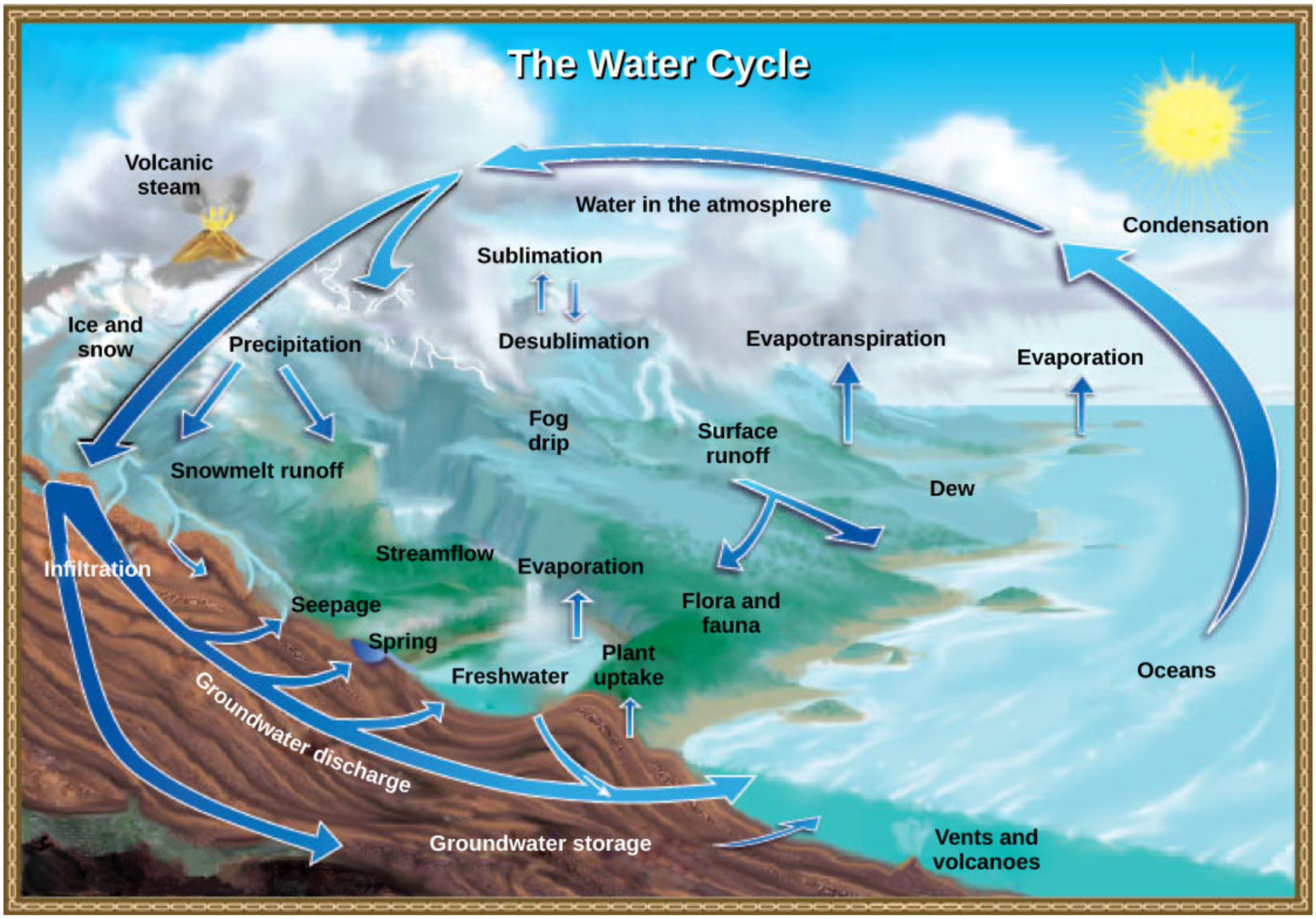

Figure 2. Water from the land and oceans enters the atmosphere by evaporation or sublimation, condensing into clouds and falling as rain or snow. Precipitated water may enter freshwater bodies or infiltrate the soil. The cycle is complete when surface or groundwater reenters the ocean. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

The Carbon Cycle

Carbon is the second most abundant element in organisms by mass. Carbon is present in all organic molecules (and some molecules that are not organic such as CO_2), and its role in the structure of biomolecules is of primary importance. Carbon compounds contain energy, and many of these compounds from dead plants and algae have fossilized over millions of years and are known as **fossil fuels**. Since the 1800s, the use of fossil fuels has accelerated. Since the beginning of the Industrial Revolution, the demand for Earth's limited fossil fuel supplies has risen, causing the amount of carbon dioxide in our atmosphere to increase drastically. This increase in carbon dioxide is associated with climate change and is a major environmental concern worldwide.

The **carbon cycle** is most easily studied as two interconnected subcycles: one dealing with rapid carbon exchange among living organisms and the other dealing with the long-term cycling of carbon through geologic processes. The entire carbon cycle is shown in Figure 3 below.

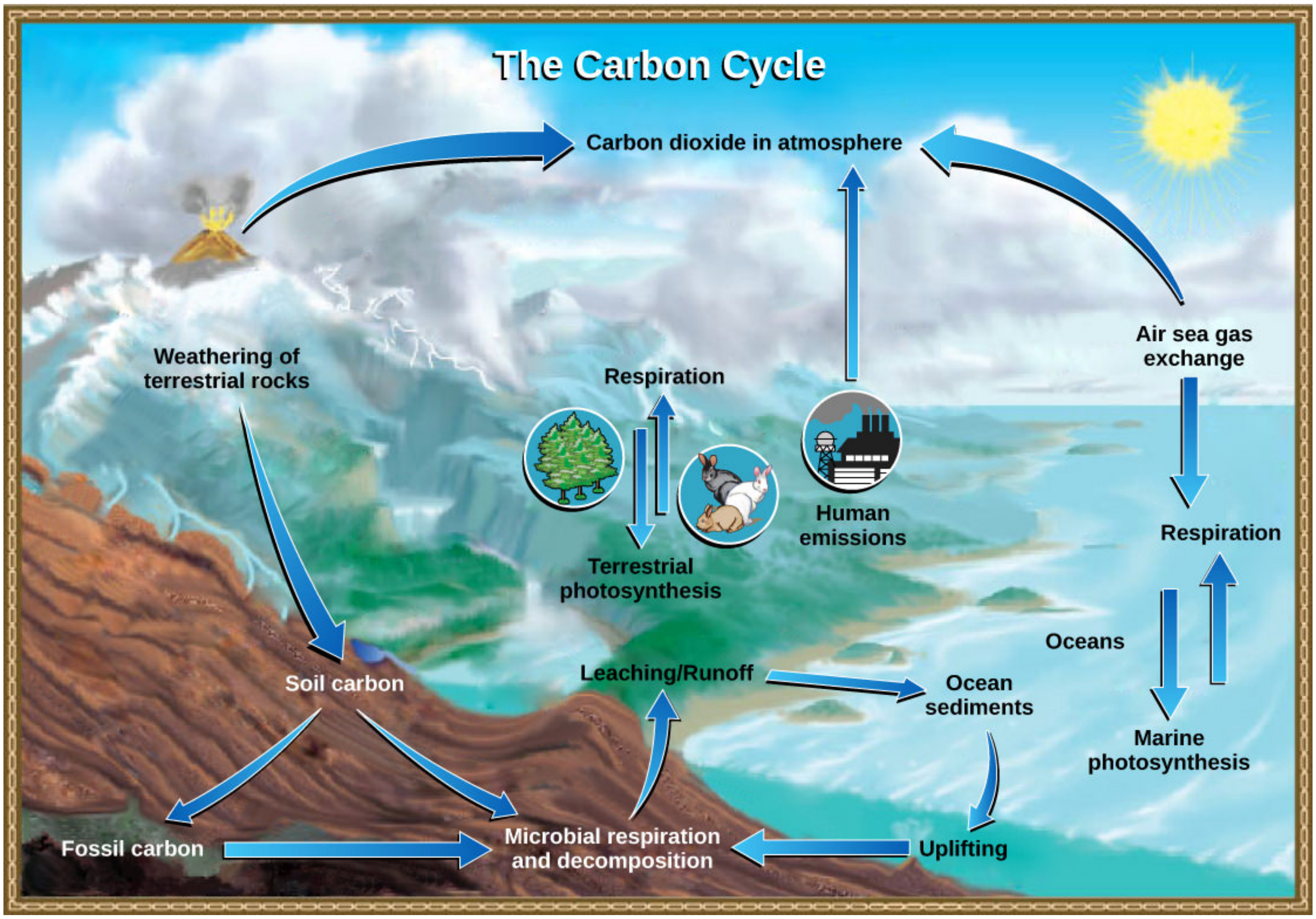

Figure 3. Carbon dioxide gas exists in the atmosphere and is dissolved in water. Photosynthesis converts carbon dioxide gas to organic carbon, and respiration cycles the organic carbon back into carbon dioxide gas. Long-term organic carbon storage occurs when matter from living organisms is buried deep underground and fossilized. Volcanic activity and, more recently, human emissions bring this stored carbon back into the carbon cycle. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

The Biological Carbon Cycle

Organisms are connected in many ways, even among different ecosystems. An example of this connection is the carbon exchange between heterotrophs and autotrophs through atmospheric carbon dioxide. Carbon dioxide (CO_2) is the basic building block autotrophs use to build high-energy compounds such as glucose. These organisms use the energy harnessed from the Sun to form the covalent bonds that link carbon atoms together. These chemical bonds store this energy for later use in the process of respiration. Most terrestrial autotrophs obtain their carbon dioxide directly from the atmosphere, while marine autotrophs acquire it in the dissolved form (bicarbonate, HCO_3^-).

Carbon is passed from producers to higher trophic levels through consumption. For example, when a cow (primary consumer) eats grass (producer), it obtains some of the organic molecules originally made by the plant's photosynthesis. Those organic compounds can then be passed to higher trophic levels, such as humans, when we eat the cow. At each level, however, organisms perform **respiration**, a process in which organic molecules are broken down to release energy. As these organic molecules are broken down, carbon is removed from food molecules to form CO_2, a gas that enters the atmosphere. Thus, CO_2 is a byproduct of respiration. Recall that producers consume CO_2 during photosynthesis to make organic molecules. As these molecules are broken down during respiration, the carbon again enters the atmosphere as CO_2. Carbon exchange like this potentially connects all organisms on Earth. Think about this: the carbon in your DNA was once part of a plant; millions of years ago, perhaps it was part of a dinosaur.

The Biogeochemical Carbon Cycle

The movement of carbon through land, water, and air is complex, and, in many cases, it occurs much more slowly than the movement between organisms. Carbon is stored for long periods in what are known as carbon reservoirs, which include the atmosphere, bodies of liquid water (mostly oceans), ocean sediment, soil, rocks (including fossil fuels), and Earth's interior.

As stated, the atmosphere is a major carbon reservoir in the form of carbon dioxide, which is essential to photosynthesis. The level of carbon dioxide in the atmosphere is greatly influenced by the reservoir of carbon in the oceans. The carbon exchange between the atmosphere and water reservoirs influences how much carbon is found in each. Carbon dioxide (CO_2) from the atmosphere dissolves in water and reacts with water molecules to form ionic compounds. Some of these ions combine with calcium ions in the seawater to form calcium carbonate ($CaCO_3$), a major component of the shells of marine organisms. These organisms eventually die, and their shells form sediments on the ocean floor. Over geologic time, the calcium carbonate forms limestone, which comprises the largest carbon reservoir on Earth.

On land, carbon is stored in soil as organic carbon due to the decomposition of organisms or from weathering of terrestrial rock and minerals (the world's soils hold significantly more carbon than the atmosphere, for comparison). Deeper underground are fossil fuels, the anaerobically decomposed remains of plants and algae that lived millions of years ago. Fossil fuels are considered a non-renewable resource because their use far exceeds their formation rate. A **non-renewable resource** is either regenerated very slowly or not at all. Another way for carbon to enter the atmosphere is from land (including land beneath the ocean's surface) by the eruption of volcanoes and other geothermal systems. Carbon sediments from the ocean floor are taken deep within Earth by the process of **subduction**: the movement of one tectonic plate beneath another. Carbon is released as carbon dioxide when a volcano erupts from volcanic hydrothermal vents.

The Nitrogen Cycle

Getting nitrogen into living organisms is difficult. Plants and phytoplankton are not equipped to incorporate nitrogen from the atmosphere (where it exists as tightly bonded, triple covalent N_2), even though this molecule comprises approximately 78 percent of the atmosphere. Nitrogen enters the living world through free-living and symbiotic bacteria, which incorporate nitrogen into organic molecules through specialized biochemical processes. Certain species of bacteria can perform **nitrogen fixation**, the process of converting nitrogen gas into ammonia (NH_3), which spontaneously becomes ammonium (NH_4^+). Bacteria convert ammonium into nitrites (NO_2^-) and then nitrates (NO_3^-). At this point, the nitrogen-containing molecules are used by plants and other producers to make organic molecules such as DNA and proteins. This nitrogen is now available to consumers.

Organic nitrogen is especially important to the study of ecosystem dynamics because many ecosystem processes, such as primary production, are limited by the available supply of nitrogen. As shown in Figure 4 below, bacteria eventually convert the nitrogen that enters living systems from organic nitrogen back into nitrogen gas (Figure 4). The process of **denitrification** is when bacteria convert the nitrates into nitrogen gas, thus allowing it to re-enter the atmosphere.

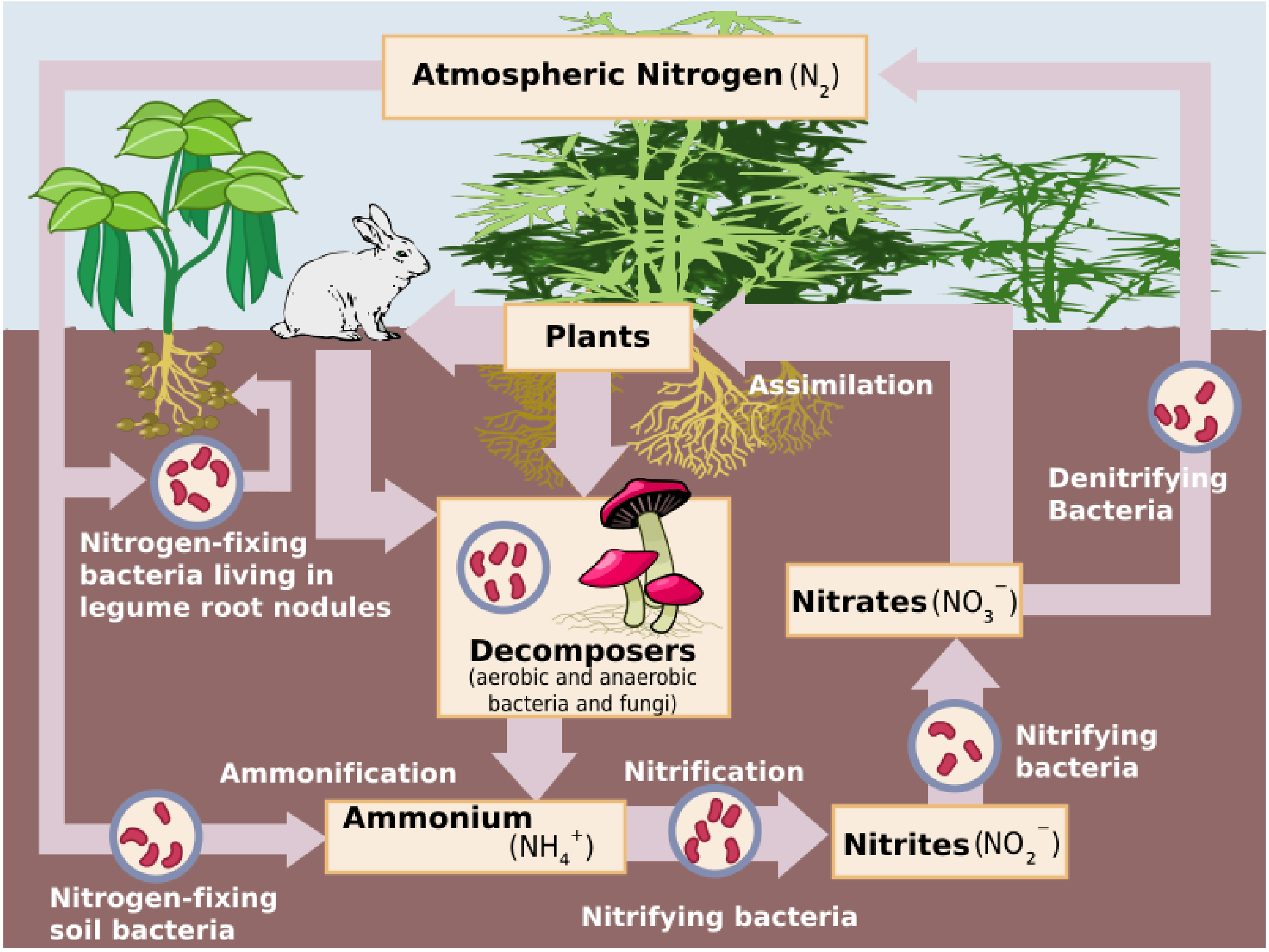

Figure 4. Nitrogen enters the living world from the atmosphere via nitrogen-fixing bacteria. This nitrogen and nitrogenous waste from animals is then processed back into gaseous nitrogen by soil bacteria, which also supply terrestrial food webs with the organic nitrogen they need. (credit: "Nitrogen cycle" by Johann Dréo & Raeky is licensed under CC BY-SA 3.0)

Human activity can alter the nitrogen cycle by two primary means: the combustion of fossil fuels, which releases different nitrogen oxides, and the use of artificial fertilizers (which contain nitrogen and phosphorus compounds) in agriculture, which are then washed into lakes, streams, and rivers by surface runoff. Atmospheric nitrogen (other than N_2) is associated with several effects on Earth's ecosystems, including the production of acid rain (as nitric acid, HNO_3) and greenhouse gas effects (as nitrous oxide, N_2O), potentially causing climate change. A major effect of fertilizer runoff is saltwater and freshwater **eutrophication**, a process whereby nutrient runoff causes the overgrowth of algae, the depletion of oxygen, and the death of aquatic fauna.

In marine ecosystems, nitrogen compounds created by bacteria, or through decomposition, collects in ocean floor sediments. It can then be moved to land in geologic time by uplifting Earth's crust and thereby incorporated into terrestrial rock. Although the movement of nitrogen from rock directly into living systems has been traditionally seen as insignificant compared with nitrogen fixed in the atmosphere, a recent study showed that this process might indeed be significant and should be included in any study of the global nitrogen cycle.

The Phosphorus Cycle

Phosphorus is an essential nutrient for living processes. It is a major component of nucleic acids and phospholipids, and, as calcium phosphate, it makes up the supportive components of our bones. Phosphorus is often the limiting nutrient (necessary for growth) in aquatic, particularly freshwater, ecosystems.

Phosphorus occurs in nature as the phosphate ion (PO_4^{3-}). In addition to phosphate runoff due to human activity, natural surface runoff occurs when it is leached from phosphate-containing rock by weathering, thus sending phosphates into rivers, lakes, and the ocean. This rock has its origins in the ocean. Phosphate-containing ocean sediments form primarily from the bodies of ocean organisms and from their excretions. However, volcanic ash, aerosols, and mineral dust may also be significant phosphate sources. This sediment then is moved to land over geologic time by the uplifting of Earth's surface (see Figure 5 below).

Phosphorus is also reciprocally exchanged between phosphate dissolved in the ocean and marine organisms. The movement of phosphate from the ocean to the land and through the soil is extremely slow, with the average phosphate ion having an oceanic residence time between 20,000 and 100,000 years.

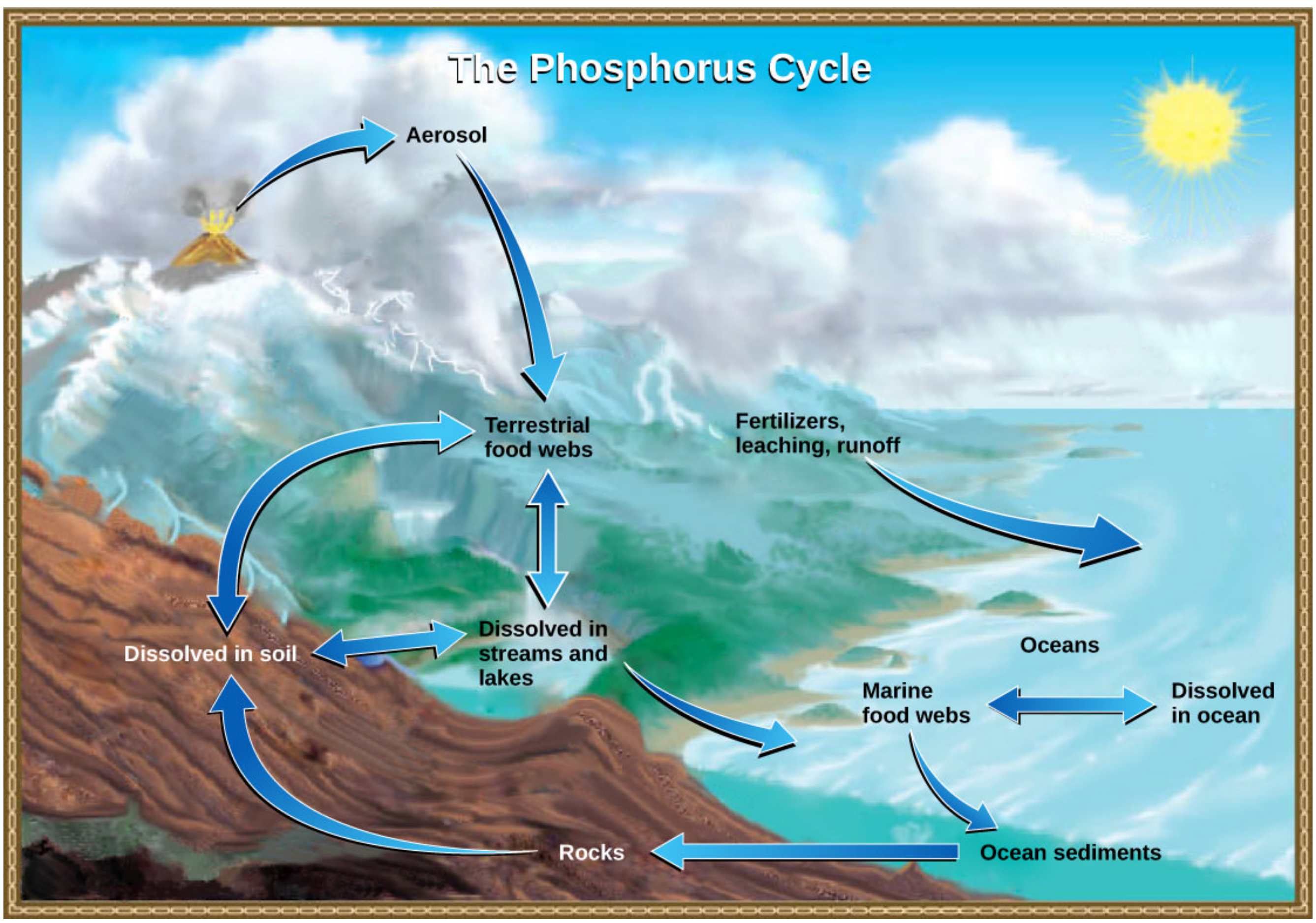

Figure 5. In nature, phosphorus exists as the phosphate ion (PO43-). Weathering of rocks and volcanic activity releases phosphate into the soil, water, and air, where it becomes available to terrestrial food webs. Phosphate enters the oceans through surface runoff, groundwater, and river flow. Phosphate dissolved in ocean water cycles into marine food webs. Some phosphate from the marine food webs falls to the ocean floor, forming sediment. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

Excess phosphorus and nitrogen entering these ecosystems from fertilizer runoff and sewage cause excessive algae growth. The subsequent death and decay of these organisms deplete dissolved oxygen, which leads to the death of aquatic organisms such as shellfish and fish. This process is responsible for dead zones in lakes and at the mouths of many major rivers and for massive fish kills, often during summer (see Figure 6 below).

A **dead zone** is an area in lakes and oceans near the mouths of rivers where large areas are periodically depleted of their normal flora and fauna. These zones are caused by eutrophication coupled with other factors, including oil spills, the dumping of toxic chemicals, and other human activities. The number of dead zones has increased for several years, and more than 400 of these zones were present as of 2008. One of the worst dead zones is off the coast of the United States in the Gulf of Mexico: fertilizer runoff from the Mississippi River basin created a dead zone of over 8,463 square miles. Phosphate and nitrate runoff from fertilizers also negatively affect several lake and bay ecosystems, including the Chesapeake Bay in the eastern United States.

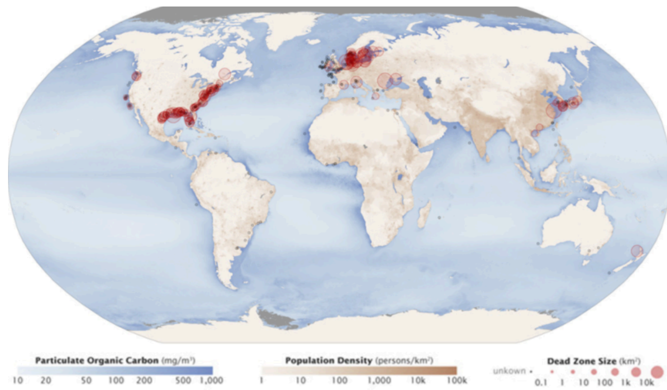

Figure 6. Dead zones occur when phosphorus and nitrogen from fertilizers cause excessive growth of microorganisms, which depletes oxygen and kills fauna. Worldwide, large dead zones are found in coastal areas of high population density (credit: NASA Earth Observatory).

The Sulfur Cycle

Sulfur is an essential element for the molecules of living things. As part of the amino acid cysteine, it is involved in forming proteins. Figure 7 below shows sulfur cycles between the oceans, land, and atmosphere. Atmospheric sulfur is found in the form of sulfur dioxide (SO_2), which enters the atmosphere in three ways: first, from the decomposition of organic molecules; second, from volcanic activity and geothermal vents; and third, from the burning of fossil fuels by humans.

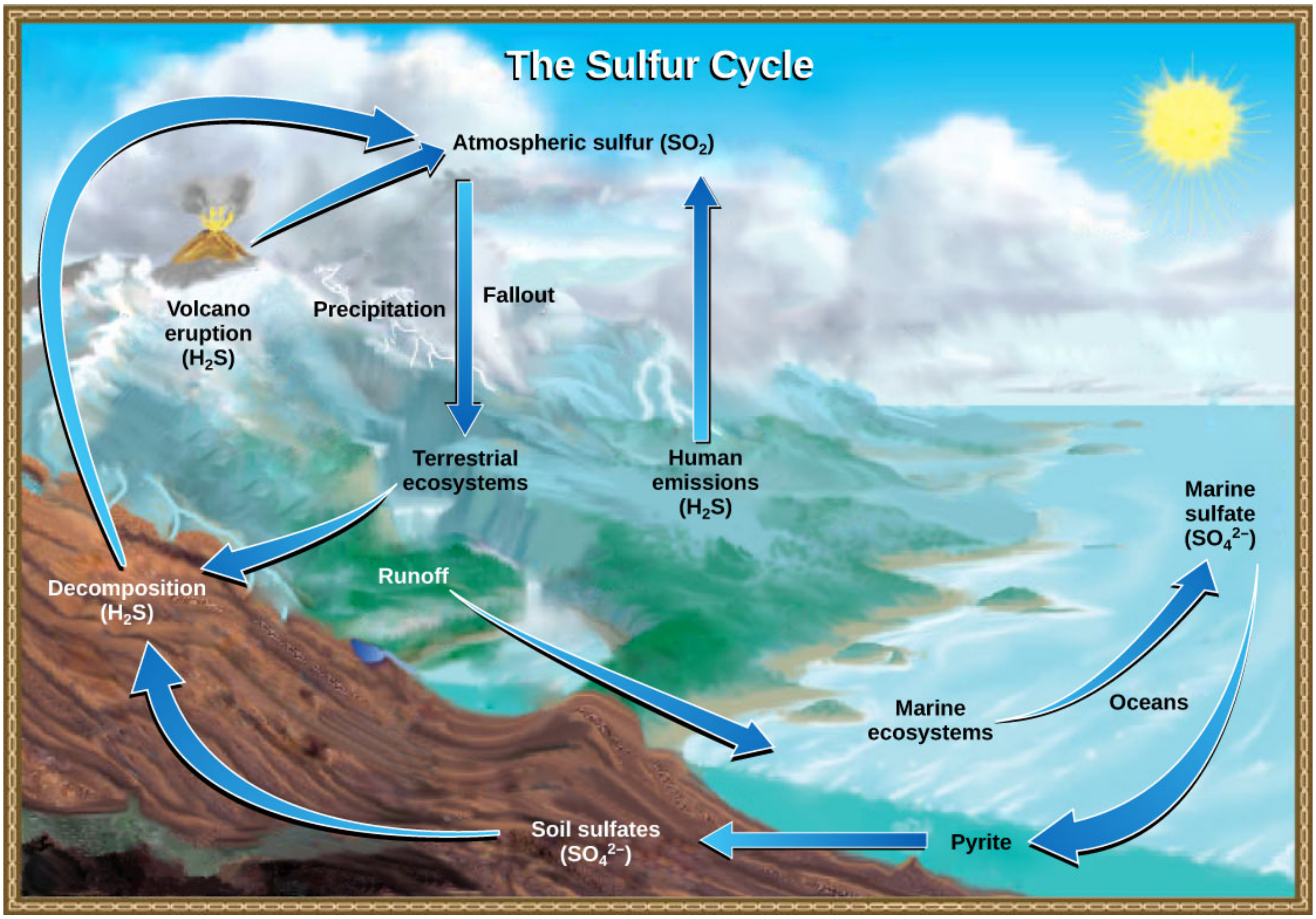

Figure 7. Sulfur dioxide from the atmosphere becomes available to terrestrial and marine ecosystems when it is dissolved in precipitation as weak sulfuric acid or when it falls directly to Earth as fallout. Weathering of rocks also makes sulfates available to terrestrial ecosystems. Decomposition of living organisms returns sulfates to the ocean, soil, and atmosphere. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

On land, sulfur is deposited in four major ways: precipitation, direct fallout from the atmosphere, rock weathering, and geothermal vents. Atmospheric sulfur is found in the form of sulfur dioxide (SO_2), and as rain falls through the atmosphere, sulfur is dissolved in the form of weak sulfuric acid (H_2SO_4). Sulfur can also fall directly from the atmosphere in a process called fallout. Also, as sulfur-containing rocks weather, sulfur is released into the soil. These rocks originate from ocean sediments that are moved to land by the geologic uplifting of ocean sediments. Terrestrial ecosystems can then use these soil sulfates (SO_4^{2-}), which enter the food web by being taken up by plant roots. When these plants decompose and die, sulfur is released into the atmosphere as hydrogen sulfide (H_2S) gas.

Sulfur enters the ocean in runoff from land, atmospheric fallout, and underwater geothermal vents. Some ecosystems rely on chemoautotrophs using sulfur as a biological energy source. This sulfur then supports marine ecosystems in the form of sulfates.

Human activities have played a major role in altering the balance of the global sulfur cycle. Burning large quantities of fossil fuels, especially coal, releases more hydrogen sulfide gas into the atmosphere. As rain falls through this gas, it creates the phenomenon known as acid rain, which damages the natural environment by lowering the pH of lakes, thus killing many resident plants and animals. **Acid rain** is corrosive rain caused by rainwater falling to the ground through sulfur dioxide gas, turning it into weak sulfuric acid, which causes damage to aquatic ecosystems. Acid rain also affects the man-made environment through the chemical degradation of buildings. For example, many marble monuments, such as the Lincoln Memorial in Washington, DC, have suffered significant damage from acid rain. These examples show the wide-ranging effects of human activities on our environment and the challenges that remain for our future.

Suggested Supplementary Reading

Bruckner, M. 2018. The Gulf of Mexico Dead Zone. [Website] <https://serc.carleton.edu/microbelife/topics/deadzone/index.html>

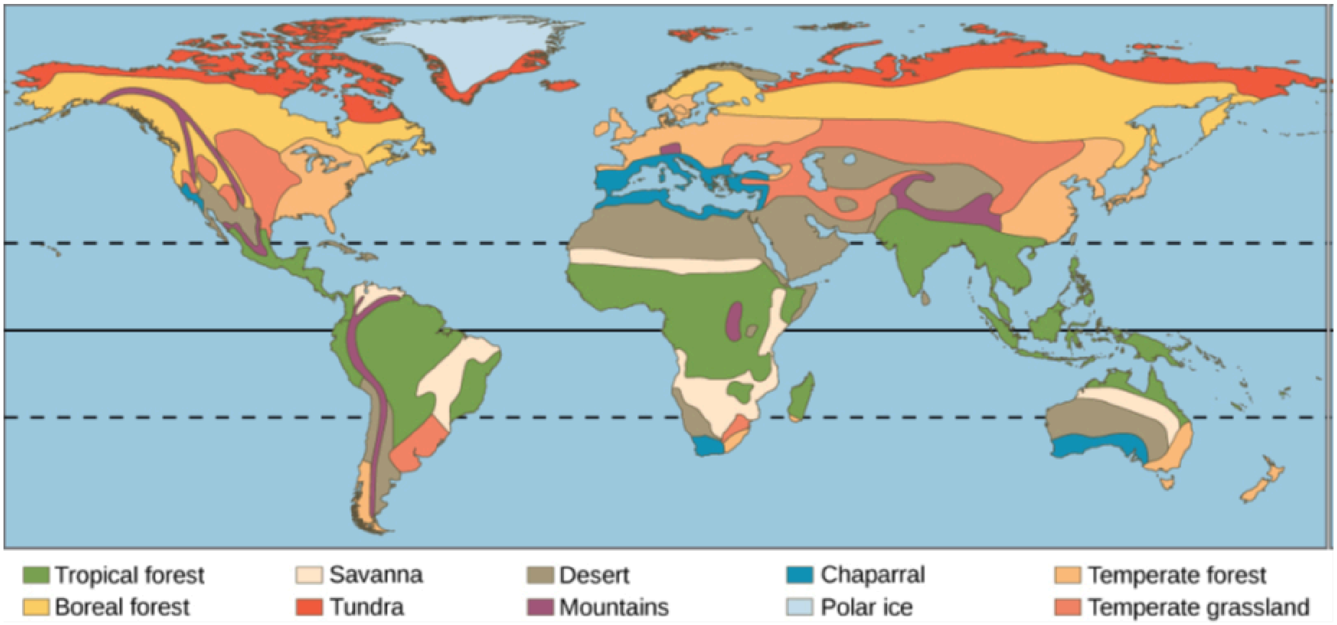

Figure 1. Each of the world's eight major biomes is distinguished by characteristic temperatures and amount of precipitation. Polar ice caps and mountains are also shown.

There are eight major terrestrial biomes: tropical rainforests, savannas, subtropical deserts, chaparral, temperate grasslands, temperate forests, boreal forests, and Arctic tundra. **Biomes** are large-scale environments distinguished by characteristic temperature ranges and precipitation amounts. These two variables affect the vegetation and animal life types in those areas. Because each biome is defined by climate, the same biome can occur in geographically distinct areas with similar climates (Figures 1 and 2).

Tropical rainforests are found in equatorial regions (Figure 1) are the most biodiverse terrestrial biome. This biodiversity is under extraordinary threat, primarily through logging and deforestation for agriculture. Tropical rainforests have also been described as nature's pharmacy because of the potential for new drugs largely hidden in the chemicals produced by the huge diversity of plants, animals, and other organisms. The vegetation is characterized by plants with spreading roots and broad leaves that fall off throughout the year, unlike the trees of deciduous forests that lose their leaves in one season.

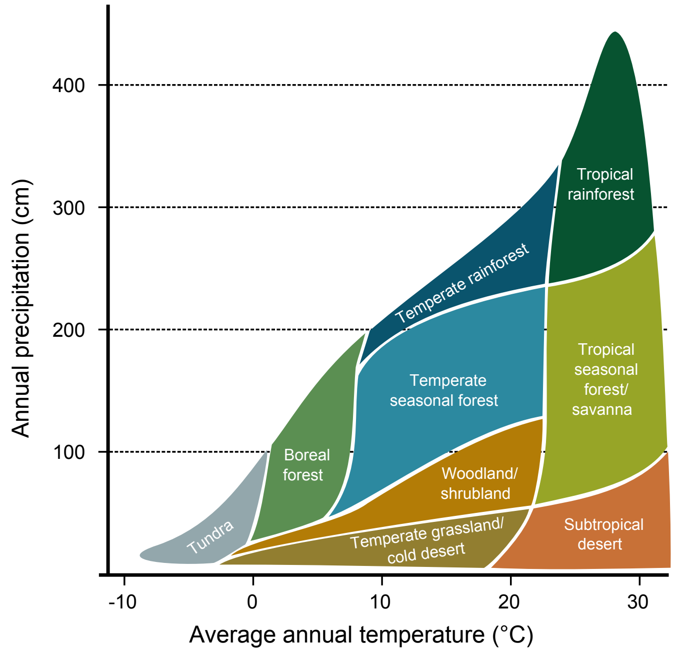

Figure 2. Precipitation and temperature are the two most important climatic variables determining the biome type in a particular location. Credit: "Climate influence on terrestrial biome" by Navarras is in the Public Domain, CC0.

The temperature and sunlight profiles of tropical rainforests are stable compared to other terrestrial biomes, with average temperatures ranging from 20°C to 34°C (68°F to 93°F). Unlike forests farther from the equator, tropical rainforests' monthly temperatures are relatively constant. This lack of temperature seasonality leads to year-round plant growth rather than just seasonal growth. In contrast to other ecosystems, a consistent daily amount of sunlight (11–12 hours per day year-round) provides more solar radiation and, therefore, more opportunity for primary productivity.

The annual rainfall in tropical rainforests ranges from 125 to 660 cm (50–200 in) with considerable seasonal variation. Tropical rainforests have wet months in which there can be more than 30 cm (11–12 in) of precipitation and dry months in which there is less than 10 cm (3.5 in) of rainfall. However, the driest month of a tropical rainforest can still exceed the *annual* rainfall of some other biomes, such as deserts. Tropical rainforests have high net primary productivity because the annual temperatures and precipitation values support rapid plant growth. However, the high amounts of rainfall leach nutrients from the soils of these forests.

Figure 3. Species diversity is very high in tropical wet forests, such as these forests of Madre de Dios, Peru, near the Amazon River. (credit: Roosevelt Garcia)

Tropical rainforests are characterized by vertical vegetation layering and distinct animal habitats within each layer. A sparse layer of plants and decaying plant matter is on the forest floor. Above that is an understory of short, shrubby foliage. A layer of trees rises above this understory and is topped by a closed upper canopy—the uppermost overhead layer of branches and leaves. Some additional trees emerge through this closed upper canopy. These layers provide diverse and complex habitats for various plants, animals, and other organisms. Many species of animals use the variety of plants and the complex structure of tropical wet forests for food and shelter. Some organisms live several meters above ground, rarely descending to the forest floor.

Savannas are grasslands with scattered trees in Africa, South America, and northern Australia (Figure 4). Savannas are hot, tropical areas with temperatures averaging 24^{o}C –29^{o}C (75^{o}F –84^{o}F) and an annual rainfall of 51–127 cm (20–50 in). Savannas have an extensive dry season and consequent fires. As a result, relatively few trees are scattered in the grasses and forbs (herbaceous flowering plants) that dominate the savanna. Because fire is an important source of disturbance in this biome, plants have evolved well-developed root systems that allow them to quickly re-sprout after a fire.

Figure 4. A MinuteEarth video about how trees create rainfall and vice versa. Click on the video link (https://youtu.be/Y3OWgb0Bv-A) to play.

Figure 5. Although savannas are dominated by grasses, small woodlands, such as this one in Mount Archer National Park in Queensland, Australia, may dot the landscape. (credit: "Ethel Aardvark"/Wikimedia Commons)

Subtropical deserts exist between 15^{o} and 30^{o} north and south latitude and are centered on the Tropic of Cancer and the Tropic of Capricorn (Figure 6 below). Deserts are frequently located on the downwind or lee side of mountain ranges, which create a rain shadow after prevailing winds drop their water content on the mountains. This is typical of the North American deserts, such as the Mohave and Sonoran deserts. Deserts in other regions, such as the Sahara Desert in northern Africa or the Namib Desert in southwestern Africa, are dry because of the high-pressure, dry air descending at those latitudes. Subtropical deserts are very dry; evaporation typically exceeds precipitation. Subtropical hot deserts can have daytime soil surface temperatures above $60^{o}C$ ($140^{o}F$) and nighttime temperatures approaching $0^{o}C$ ($32^{o}F$). Subtropical deserts are characterized by low annual precipitation of fewer than 30 cm (12 in) with little monthly variation and a lack of predictability in rainfall. Some years may receive tiny amounts of rainfall, while others receive more. In some cases, the annual rainfall can be as low as 2 cm (0.8 in) in subtropical deserts located in central Australia ("the Outback") and northern Africa.

The low species diversity of this biome is closely related to its low and unpredictable precipitation. Despite the relatively low diversity, desert species exhibit fascinating adaptations to the harshness of their environment. Very dry deserts lack perennial vegetation that lives from one year to the next; instead, many plants are annuals that grow quickly and reproduce when rainfall does occur, then die. Perennial plants in deserts are characterized by adaptations that conserve water: deep roots, reduced foliage, and water-storing stems (Figure 6). Seed plants in the desert produce seeds that can lie dormant for extended periods between rains. Most animal life in subtropical deserts has adapted to a nocturnal life, spending the hot daytime hours beneath the ground. The Namib Desert is the oldest on the planet and has probably been dry for more than 55 million years. It supports a number of endemic species (species found only there) because of this great age. For example, the unusual gymnosperm *Welwitschia mirabilis* is the only extant species of an entire order of plants. There are also five species of reptiles considered endemic to the Namib.

Figure 6. Minute Earth. (2013). Why Does Earth Have Deserts? https://youtu.be/T6Us1sPXBfA

In addition to subtropical deserts, some cold deserts experience freezing temperatures during the winter, and any precipitation is in the form of snowfall. The largest of these deserts are the Gobi Desert in northern China and southern Mongolia, the Taklimakan Desert in western China, the Turkestan Desert, and the Great Basin Desert of the United States.

Figure 7. Many desert plants have tiny leaves or no leaves at all to reduce water loss. The leaves of ocotillo, shown here in the Chihuahuan Desert in Big Bend National Park, Texas, appear only after rainfall and then are shed. (credit "bare ocotillo": "Leaflet"/Wikimedia Commons)

Figure 8. The chaparral is dominated by shrubs (credit: Miguel Vieira).

The **chaparral** is also called scrub forest and is found in California, along the Mediterranean Sea, and along the southern coast of Australia (Figure 7). The annual rainfall in this biome ranges from 65 cm to 75 cm (25.6–29.5 in), and most of the rain falls in the winter. Summers are very dry, and many chaparral plants are dormant during the summertime. The chaparral vegetation is dominated by shrubs and is adapted to periodic fires, with some plants producing seeds that germinate only after a hot fire. The ashes left after a fire are rich in nutrients like nitrogen and fertilize the soil, promoting plant regrowth. Fire is a natural part of the maintenance of this biome.

Temperate grasslands are found throughout central North America, also known as prairies, and in Eurasia, where they are known as steppes (Figure 8 below). Temperate grasslands have pronounced annual fluctuations in temperature, with hot summers and cold winters. The annual temperature variation produces specific growing seasons for plants. Plant growth is possible when temperatures are warm enough to sustain plant growth, which occurs in the spring, summer, and fall.

Annual precipitation ranges from 25.4 cm to 88.9 cm (10–35 in). Temperate grasslands have few trees except those found growing along rivers or streams. The dominant vegetation tends to consist of grasses. Low precipitation, frequent fires, and grazing maintain the treeless condition. The vegetation is very dense, and the soils are fertile because the soil subsurface is packed with these grasses' roots and rhizomes (underground stems). The roots and rhizomes anchor plants into the ground and replenish the soil's organic material (humus) when they die and decay.

Fires, a natural disturbance in temperate grasslands, can be ignited by lightning strikes. It also appears that the lightning-caused fire regime in North American grasslands was enhanced by intentional burning by humans. When a fire is suppressed in temperate grasslands, the vegetation becomes scrub and dense forests. Often, the restoration or management of temperate grasslands requires controlled burns to suppress the growth of trees and maintain the grasses.

Figure 9. The American bison, more commonly called the buffalo, is a grazing mammal that once populated American prairies in huge numbers. (credit: Jack Dykinga, USDA ARS)

Temperate forests are the most common biome in eastern North America, Western Europe, Eastern Asia, Chile, and New Zealand (Figure 9 below). This biome is found throughout mid-latitude regions. Temperatures range between –30^{o}C and 30^{o}C (–22^{o}F to 86^{o}F) and drop below freezing annually. These temperatures mean that temperate forests have defined growing seasons during the spring, summer, and early fall. Precipitation is relatively constant throughout the year and ranges between 75 cm and 150 cm (29.5–59 in).

Deciduous trees are the dominant plant in this biome, with fewer evergreen conifers. Deciduous trees lose their leaves each fall and remain leafless in the winter. Thus, little photosynthesis occurs during the dormant winter period. Each spring, new leaves appear as temperature increases. Because of the dormant period, the net primary productivity of temperate forests is less than that of tropical rainforests. In addition, temperate forests show far less diversity of tree species than tropical rainforest biomes.

The trees of the temperate forests leaf out and shade much of the ground. However, more sunlight reaches the ground in this biome than in tropical rainforests because trees in temperate forests do not grow as tall as trees in tropical rainforests. The soils of the temperate forests are rich in inorganic and organic nutrients compared to tropical rainforests. This is because of the thick layer of leaf litter on forest floors and rainfall's reduced leaching of nutrients. As this leaf litter decays, nutrients are returned to the soil. The leaf litter also protects soil from erosion, insulates the ground, and provides habitats for invertebrates and predators.

Figure 10. Deciduous trees are the dominant plant in the temperate forest.

The **boreal forest,** also known as **taiga** or **coniferous forest**, is roughly between 50^{o} and 60^{o} north latitude across most of Canada, Alaska, Russia, and northern Europe (Figure 10 below). Boreal forests are also found above a certain elevation (and below high elevations where trees cannot grow) in mountain ranges throughout the Northern Hemisphere. This biome has cold, dry winters and short, cool, wet summers. The annual precipitation is from 40 cm to 100 cm (15.7–39 in) and usually forms snow; relatively little evaporation occurs because of the cool temperatures.

The long and cold winters in the boreal forest have led to the predominance of cold-tolerant cone-bearing plants. These are evergreen coniferous trees like pines, spruce, and fir that retain their needle-shaped leaves year-round. Evergreen trees can photosynthesize earlier in the spring than deciduous trees because less energy from the Sun is required to warm a needle-like leaf than a broad leaf. Evergreen trees grow faster than deciduous trees in the boreal forest. In addition, soils in boreal forest regions tend to be acidic, with little available nitrogen. Leaves are a nitrogen-rich structure, and deciduous trees must produce a new set of these nitrogen-rich structures each year. Therefore, coniferous trees that retain nitrogen-rich needles in a nitrogen-limiting environment may have had a competitive advantage over the broad-leafed deciduous trees.

The net primary productivity of boreal forests is lower than that of temperate forests and tropical wet forests. The aboveground biomass of boreal forests is high because these slow-growing tree species are long-lived and accumulate standing biomass over time. Species diversity is less than that seen in temperate forests and tropical rainforests. Boreal forests lack the layered forest structure seen in tropical rainforests or, to a lesser degree, temperate forests. The structure of a boreal forest is often only a tree layer and a ground layer. When conifer needles are dropped, they decompose more slowly than broad leaves; therefore, fewer nutrients are returned to the soil to fuel plant growth.

Figure 11. The boreal forest (taiga) has low-lying plants and conifer trees. (credit: L.B. Brubaker, NOAA)

The Arctic **tundra** lies north of the subarctic boreal forests and is located throughout the Arctic regions of the Northern Hemisphere. Tundra also exists at elevations above the tree line on mountains. The average winter temperature is –34°C (–29.2°F) and the average summer temperature is 3°C–12°C (37°F –52°F). Plants in the Arctic tundra have a short growing season of approximately 50–60 days. However, there are almost 24 hours of daylight during this time, and plant growth is rapid. The annual precipitation of the Arctic tundra is low (15–25 cm or 6–10 in), with little annual variation in precipitation. And, as in the boreal forests, there is little evaporation because of the cold temperatures.

Figure 12. Low-growing plants such as lichen and grasses are common in tundra. Credit: Nunavut tundra by Flickr: My Nunavut is licensed under CC BY 2.0

Plants in the Arctic tundra are generally low to the ground and include low shrubs, grasses, lichens, and small flowering plants (Figure 11 below). There is little species diversity, low net primary productivity, and low above-ground biomass. The Arctic tundra soils may remain in a perennially frozen state called permafrost. The permafrost makes it impossible for roots to penetrate far into the soil and slows the decay of organic matter, which inhibits the release of nutrients from organic matter. The melting of the permafrost in the brief summer provides water for a burst of productivity while temperatures and long days permit it. During the growing season, the ground of the Arctic tundra can be completely covered with plants or lichens.

Suggested Supplementary Reading

HHMI. 2018. *Biome Viewer*. [Interactive Website]. Howard Hughes Medical Institute. <https://www.hhmi.org/biointeractive/biomeviewer>

Abiotic Factors Influencing Aquatic Biomes

Like terrestrial biomes, **aquatic biomes** are influenced by a series of abiotic factors. The aquatic medium—water— has different physical and chemical properties than air. Even if the water in a pond or other body of water is perfectly clear (no suspended particles), water still absorbs light. As one descends into a deep body of water, there will eventually be a depth the sunlight cannot reach. While some abiotic and biotic factors in a terrestrial ecosystem might obscure light (like fog, dust, or insect swarms), usually, these are not permanent features of the environment. The importance of light in aquatic biomes is central to the communities of organisms found in freshwater and marine ecosystems. In freshwater systems, stratification due to differences in density is perhaps the most critical abiotic factor and is related to the energy aspects of light. The thermal properties of water (heating and cooling rates) are significant to the function of marine systems and have major impacts on global climate and weather patterns. Marine systems are also influenced by large-scale physical water movements, such as currents; these are less important in most freshwater lakes.

The ocean is categorized into several areas or zones (Figure 1). All of the ocean's open water is referred to as the **pelagic zone**. The benthic zone extends along the ocean bottom from the shoreline to the deepest parts of the ocean floor. Within the pelagic realm is the **photic zone**, the ocean's portion that light can penetrate (approximately 200 m or 650 ft). At depths greater than 200 m, light cannot penetrate; thus, this is referred to as the **aphotic zone**. The majority of the ocean is aphotic and lacks sufficient light for photosynthesis. The deepest part of the ocean, the Challenger Deep (in the Mariana Trench, located in the western Pacific Ocean), is about 11,000 m (about 6.8 mi) deep. To give some perspective on the depth of this trench, the ocean is, on average, 4267 m. These zones are relevant to freshwater lakes as well.

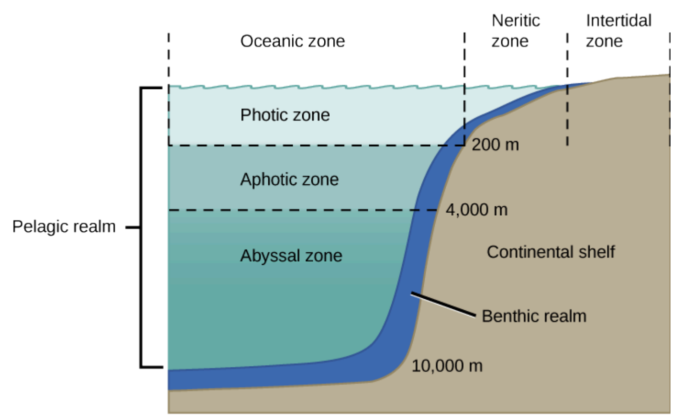

Figure 1. The ocean is divided into different zones based on water depth and distance from the shoreline.

Marine Biomes

The ocean is the largest **marine biome**. It is a continuous body of salt water that is relatively uniform in chemical composition; it is a weak solution of mineral salts and decayed biological matter. Within the ocean, coral reefs are a second kind of marine biome. Estuaries, coastal areas where salt water and fresh water mix, form a third unique marine biome.

Ocean

The physical diversity of the ocean is a significant influence on plants, animals, and other organisms.

The ocean is categorized into different zones based on how far light reaches into the water. Each zone has a distinct group of species adapted to the biotic and abiotic conditions particular to that zone.

The **intertidal zone**, the zone between high and low tide, is the oceanic region closest to land (Figure 2). Generally, most people consider this ocean portion as a sandy beach. In some cases, the intertidal zone is indeed a sandy beach, but it can also be rocky or muddy. Organisms are exposed to air and sunlight at low tide and are mostly underwater, especially during high tide. Therefore, living things that thrive in the intertidal zone are adapted to being dry for long periods of time. The shore of the intertidal zone is also repeatedly struck by waves, and the organisms found there are adapted to withstand damage from the pounding action of the waves (Figure 2). The exoskeletons of shoreline crustaceans (such as the shore crab, *Carcinus maenas*) are tough and protect them from desiccation (drying out) and wave damage. Another consequence of the pounding waves is that few algae and plants establish themselves in the constantly moving rocks, sand, or mud.

Figure 2. Sea urchins, mussel shells, and starfish are often found in the intertidal zone, shown here in Kachemak Bay, Alaska. (credit: NOAA)

The **neritic zone** (Figure 1) extends from the intertidal zone to depths of about 200 m (or 650 ft) at the edge of the continental shelf. Because light can penetrate this depth, photosynthesis can occur. The water here contains silt and is well-oxygenated, low in pressure, and stable in temperature. Phytoplankton and floating *Sargassum* (a free-floating marine seaweed) provide a habitat for some sea life in the neritic zone. Zooplankton, protists, small fishes, and shrimp are found in the neritic zone and are the base of the food chain for most of the world's fisheries.

Beyond the neritic zone is the open ocean area known as the **oceanic zone** (Figure 1). Within the oceanic zone, there is thermal stratification, where warm and cold waters mix because of ocean currents. Abundant plankton serves as the base of the food chain for larger animals such as whales and dolphins. Nutrients are scarce, and this is a relatively less productive part of the marine biome. When photosynthetic organisms and the protists and animals that feed on them die, their bodies fall to the bottom of the ocean, where they remain. The majority of organisms in the aphotic zone include sea cucumbers (phylum Echinodermata) and other organisms that survive on the nutrients contained in the dead bodies of organisms in the photic zone.

The deepest part of the ocean is the **abyssal zone**, at depths of 4000 m or greater. The abyssal zone (Figure 1) is very cold and has very high pressure, high oxygen content, and low nutrient content. A variety of invertebrates and fishes are found in this zone, but the abyssal zone does not have plants because of the lack of light. Cracks in the Earth's crust called hydrothermal vents are found primarily in the abyssal zone. Around these vents, chemosynthetic bacteria utilize the hydrogen sulfide and other minerals emitted as an energy source and serve as the base of the food chain found in the abyssal zone.

Beneath the water is the **benthic zone** (Figure 1), comprised of sand, silt, and dead organisms. This is a nutrient-rich portion of the ocean because of the dead organisms that fall from the ocean's upper layers. Because of this high level of nutrients, a diversity of sponges, sea anemones, marine worms, sea stars, fishes, and bacteria exist.

Coral Reefs

Figure 3. Coral reefs are formed by the calcium carbonate skeletons of coral organisms, which are marine invertebrates in the phylum Cnidaria. (credit: Terry Hughes)

Coral reefs are characterized by high biodiversity and the structures created by invertebrates living in warm, shallow waters within the ocean's photic zone. They are mostly found within 30 degrees north and south of the equator. The Great Barrier Reef is a well-known reef system located several miles off the northeastern coast of Australia. The coral organisms (members of phylum Cnidaria) are colonies of saltwater polyps that secrete a calcium carbonate skeleton. These calcium-rich skeletons slowly accumulate, forming the underwater reef (Figure 3). Corals found in shallower waters (at a depth of approximately 60 m or about 200 ft) have a mutualistic relationship with photosynthetic unicellular algae. The relationship provides corals with the majority of the nutrition and energy they require. The waters in which these corals live are nutritionally poor; without this mutualism, it would not be possible for large corals to grow. Some corals living in deeper and colder water do not have a mutualistic relationship with algae; these corals attain energy and nutrients using stinging cells on their tentacles to capture prey. It is estimated that more than 4,000 fish species inhabit coral reefs. These fishes can feed on coral, other invertebrates, or the seaweed and algae that are associated with the coral.

Watch this National Oceanic and Atmospheric Administration (NOAA) video to see marine ecologist Dr. Peter Etnoyer discusses his research on coral organisms.

EVOLUTION CONNECTION: Global Decline of Coral Reefs

It takes a long time to build a coral reef. The animals that create coral reefs have evolved over millions of years, continuing to slowly deposit the calcium carbonate that forms their characteristic ocean homes. Bathed in warm tropical waters, the coral animals and their symbiotic algal partners evolved to survive at the upper limit of ocean water temperature.

Together, climate change and human activity pose dual threats to the long-term survival of the world's coral reefs. Coral reefs suffer as global warming due to fossil fuel emissions raises ocean temperatures. The excessive warmth causes the reefs to expel their symbiotic, food-producing algae, resulting in a phenomenon known as bleaching. When bleaching occurs, the reefs lose much of their characteristic color as the algae, and the coral animals die if the loss of the symbiotic zooxanthellae is prolonged.

Rising atmospheric carbon dioxide levels further threaten the corals in other ways; as CO_2 dissolves in ocean waters, it lowers the pH and increases ocean acidity. As acidity increases, it interferes with the calcification that normally occurs as coral animals build their calcium carbonate homes.

When a coral reef begins to die, species diversity plummets as animals lose food and shelter. Coral reefs are also economically important tourist destinations, so the decline of coral reefs poses a serious threat to coastal economies.

Human population growth has damaged corals in other ways, too. As human coastal populations increase, the runoff of sediment and agricultural chemicals has increased, too, causing some of the once-clear tropical waters to become cloudy. At the same time, overfishing of popular fish species has allowed the predator species that eat corals to go unchecked.

Although a rise in global temperatures of 1–2˚C (a conservative scientific projection) in the coming decades may not seem large, it is very significant to this biome. When change occurs rapidly, species can become extinct before evolution leads to new adaptations. Many scientists believe that global warming, with its rapid (in terms of evolutionary time) and inexorable increases in temperature, is tipping the balance beyond the point at which many of the world's coral reefs can recover.

Estuaries: Where the Ocean Meets Fresh Water

Estuaries are biomes where a source of fresh water, such as a river, meets the ocean. Therefore, both fresh water and salt water are found in the same vicinity; mixing results in diluted (brackish) saltwater. Estuaries form protected areas where many of the young offspring of crustaceans, mollusks, and fish begin their lives. Salinity is a very important factor that influences the organisms and the adaptations of the organisms found in estuaries. The salinity of estuaries varies and is based on the flow rate of their freshwater sources. Once or twice a day, high tides bring salt water into the estuary. Low tides occurring at the same frequency reverse the current of salt water.

The short-term and rapid variation in salinity due to the mixing of fresh water and salt water is a difficult physiological challenge for the plants and animals that inhabit estuaries. Many estuarine plant species are **halophytes**: plants that can tolerate salty conditions. Halophytic plants are adapted to deal with the salinity resulting from saltwater on their roots or from sea spray. In some halophytes, filters in the roots remove the salt from the water the plant absorbs. Other plants can pump oxygen into their roots. Animals, such as mussels and clams (phylum Mollusca), have developed behavioral adaptations that expend a lot of energy to function in this rapidly changing environment. When these animals are exposed to low salinity, they stop feeding, close their shells, and switch from aerobic respiration (using gills) to anaerobic respiration (a process that does not require oxygen). When high tide returns to the estuary, the salinity and oxygen content of the water increases, and these animals open their shells, begin feeding, and return to aerobic respiration.

Freshwater Biomes

Freshwater biomes include lakes and ponds (standing water) as well as rivers and streams (flowing water). They also include wetlands, which will be discussed later. Humans rely on freshwater biomes to provide aquatic resources for drinking water, crop irrigation, sanitation, and industry. These various roles and human benefits are referred to as ecosystem services. Lakes and ponds are found in terrestrial landscapes and are connected with abiotic and biotic factors influencing these terrestrial biomes.

Lakes and Ponds

Lakes and ponds can range from a few square meters to thousands of square kilometers. Temperature is an important abiotic factor affecting living things in lakes and ponds. In the summer, thermal stratification of lakes and ponds occurs when the upper layer of water is warmed by the sun and does not mix with deeper, cooler water. Light can penetrate within the photic zone of the lake or pond. **Phytoplankton** (small photosynthetic organisms such as algae and cyanobacteria that float in the water) are found here and carry out photosynthesis, providing the base of the food web of lakes and ponds. **Zooplankton** (very small animals that float in the water), such as rotifers and small crustaceans, consume these phytoplankton. At the bottom of lakes and ponds, bacteria in the aphotic zone break down dead organisms that sink to the bottom.

Figure 4. The uncontrolled growth of algae in this lake has resulted in an algal bloom.

Nitrogen and phosphorus are important limiting nutrients in lakes and ponds. Because of this, they are determining factors in the amount of phytoplankton growth in lakes and ponds. When there is a large input of nitrogen and phosphorus (from sewage and runoff from fertilized lawns and farms, for example), algae growth skyrockets, resulting in a large accumulation of algae called an **algal bloom**. Algal blooms (Figure 4) can become so extensive that they reduce light penetration in water. As a result, the lake or pond becomes aphotic, and photosynthetic plants rooted in the lake bottom cannot survive. When the algae die and decompose, severe oxygen depletion of the water occurs. Fishes and other organisms that require oxygen are more likely to die, resulting in dead zones across the globe. Lake Erie and the Gulf of Mexico represent freshwater and marine habitats where phosphorus control and stormwater runoff pose significant environmental challenges.

Rivers and Streams

Rivers and streams are continuously moving bodies of water carrying large amounts from the source, or headwater, to a lake or ocean. The largest rivers include the Nile River in Africa, the Amazon River in South America, and the Mississippi River in North America.

Abiotic features of rivers and streams vary along the length of the river or stream. Streams begin at a point of origin referred to as source water. The source water is usually cold, low in nutrients, and clear. The channel (the width of the river or stream) is narrower than any other place along the length of the river or stream. Because of this, the current is often faster here than at any other point of the river or stream.

The fast-moving water results in minimal silt accumulation at the bottom of the river or stream; therefore, the water is clear. Photosynthesis here is mostly attributed to algae growing on rocks; the swift current inhibits the growth of phytoplankton. Additional energy input can come from leaves or other organic material that falls into the river or stream from trees and other plants that border the water. The organic material and nutrients are returned to the water when the leaves decompose. Plants and animals have adapted to this fast-moving water. For instance, leeches (phylum Annelida) have elongated bodies and suckers on both ends. These suckers attach to the substrate, keeping the leech anchored in place. Freshwater trout species (phylum Chordata) are an important predator in these fast-moving rivers and streams.

As the river or stream flows away from the source, the width of the channel gradually widens, and the current slows. This slow-moving water, caused by the gradient decrease and the volume increase as tributaries unite, has more sedimentation. Phytoplankton can also be suspended in slow-moving water. Therefore, the water will not be as clear as it is near the source. The water is also warmer. Worms (phylum Annelida) and insects (phylum Arthropoda) can burrow into the mud. The higher-order predator vertebrates (phylum Chordata) include waterfowl, frogs, and fishes. These predators must find food in these slow-moving, sometimes murky, waters, and unlike the trout in the waters at the source, these vertebrates may not be able to use vision as their primary sense to find food. Instead, they are more likely to use taste or chemical cues to find prey.

Wetlands

Wetlands are environments where the soil is permanently or periodically saturated with water. Wetlands are different from lakes because wetlands are shallow bodies of water that may periodically dry out. Emergent vegetation consists of wetland plants rooted in the soil but with portions of leaves, stems, and flowers extending above the water's surface. Several types of wetlands include marshes, swamps, bogs, mudflats, and salt marshes (Figure 5).

Figure 5. Located in southern Florida, Everglades National Park is vast array of wetland environments, including sawgrass marshes, cypress swamps, and estuarine mangrove forests. Here, a great egret walks among cypress trees. (credit: NPS)

Summary

Ecosystems exist underground, on land, at sea, and in the air. Organisms in an ecosystem acquire energy in various ways, which is transferred between trophic levels as the energy flows from the base to the top of the food web, with energy being lost at each transfer. Mineral nutrients are cycled through ecosystems and their environment. Water, carbon, nitrogen, phosphorus, and sulfur are particularly important. All of these cycles have major impacts on ecosystem structure and function. Ecosystems have been damaged by various human activities that alter the natural biogeochemical cycles due to pollution, oil spills, and events causing global climate change. The biosphere’s health depends on understanding these cycles and how to protect the environment from irreversible damage. Earth has terrestrial and aquatic biomes. There are eight major terrestrial biomes: tropical rainforests, savannas, subtropical deserts, chaparral, temperate grasslands, temperate forests, boreal forests, and Arctic tundra. Temperature, precipitation, and variations in both are key abiotic factors shaping the composition of animal and plant communities in terrestrial biomes. Sunlight is an important factor in bodies of water, especially very deep ones, because of photosynthesis’s role in sustaining certain organisms. Other important factors include temperature, water movement, and salt content. Aquatic biomes include both freshwater and marine environments. Like terrestrial biomes, aquatic biomes are influenced by abiotic factors. In the case of aquatic biomes, the abiotic factors include light, temperature, flow regime, and dissolved solids.

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Chapter 4: Community and Population Ecology

Learning Outcomes

Asian carp jump out of the water in response to electrofishing. The Asian carp in the inset photograph were harvested from the Little Calumet River in Illinois in May 2010, using rotenone, a toxin often used as an insecticide, to learn more about the species' population. (credit main image: modification of work by USGS; credit inset: modification of work by Lt. David French, USCG)

After studying this chapter, you should be able to:

- Describe how ecologists measure population size and density
- Describe three different patterns of population distribution
- Give examples of how the carrying capacity of a habitat may change
- Explain how humans have expanded the carrying capacity of their habitat
- Discuss the long-term implications of unchecked human population growth

Chapter Outline

- 4.1 Population Dynamics and Demographics
- 4.2 Population Growth & Regulation
- 4.3 The Human Population
- 4.4 Community Ecology
- 4.5 Chapter Resources

Imagine sailing down a river in a small motorboat on a weekend afternoon; the water is smooth, and you are enjoying the sunshine and cool breeze when suddenly you are hit in the head by a 20-pound silver carp. This is a risk now on many rivers and canal systems in Illinois and Missouri because of Asian carp. This fish—a group of species including the silver, black, grass, and big-head carp—has been farmed and eaten in China for over 1,000 years. It is one of the most important aquaculture food resources worldwide. In the United States, however, Asian carp is considered a dangerous invasive species that disrupt ecological community structure to threaten native species. The effects of invasive species (such as the Asian carp, kudzu vine, predatory snakehead fish, and zebra mussel) are just one aspect of what ecologists study to understand how populations interact within ecological communities and what impact natural and human-induced disturbances have on the characteristics of communities.

Populations are dynamic entities. Their size and composition fluctuate due to numerous factors, including seasonal and yearly environmental changes, natural disasters such as forest fires and volcanic eruptions, and competition for resources between and within species. The study of populations is called **demography.**

Population Size and Density

Populations are characterized by population size (total number of individuals) and population density (number of individuals per unit area). A population may have a large number of individuals that are distributed densely or sparsely. There are also populations with small numbers of individuals that may be dense or very sparsely distributed in a local area. Population size can affect the potential for adaptation because it affects the amount of genetic variation present in the population. Density can affect interactions within a population, such as competition for food and the ability of individuals to find a mate. Smaller organisms are more densely distributed than larger ones (Figure 1).

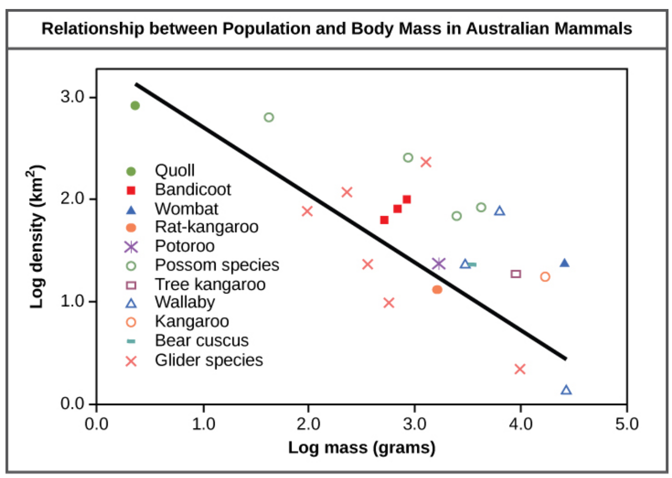


Figure 1. Australian mammals show a typical inverse relationship between population density and body size. As this graph shows, population density typically decreases with increasing body size. Why do you think this is the case?

Estimating Population Size

The most accurate way to determine population size is to count all individuals within the area. However, this method is usually not logistically or economically feasible, especially when studying large areas. Thus, scientists usually study populations by sampling a representative portion of each habitat and use this sample to make inferences about the population as a whole. The methods used to sample populations to determine their size and density are typically tailored to the characteristics of the organism being studied. A quadrat may be used for immobile organisms such as plants or very small and slow-moving organisms. A **quadrat** is a square structure that is randomly located on the ground and used to count the number of individuals that lie within its boundaries. To obtain an accurate count using this method, the square must be placed at random locations within the habitat enough times to produce an accurate estimate.

For smaller mobile organisms, such as mammals, a technique called **mark and recapture** is often used. This method involves marking captured animals and releasing them back into the environment to mix with the rest of the population. Later, a new sample is captured, and scientists determine how many marked animals are in the new sample. This method assumes that the larger the population, the lower the percentage of marked organisms that will be recaptured since they will have mixed with more unmarked individuals. For example, if 80 field mice are captured, marked, and released into the forest, then a second trapping 100 field mice are captured, and 20 of them are marked, the population size (*N*) can be determined using the following equation:

N = (number marked first catch x total number of second catch)/number marked second catch

Using our example, the equation would be:

(80 x 100) / 20 = 400

These results give us an estimate of 400 total individuals in the original population. The true number usually will be a bit different from this because of chance errors and possible bias caused by the sampling methods.

Species Distribution

In addition to measuring size and density, further information about a population can be obtained by looking at the distribution of the individuals throughout their range. A species distribution pattern is the distribution of individuals within a habitat at a particular time—broad categories of patterns are used to describe them.

Individuals within a population can be distributed randomly, in groups, or equally spaced apart (more or less). These are known as **random, clumped, and uniform distribution patterns** (Figure 2). Different distributions reflect important aspects of the biology of the species. They also affect the mathematical methods required to estimate population sizes. An example of random distribution occurs with dandelion and other plants with wind-dispersed seeds germinating wherever they fall in favorable environments. A clumped distribution may be seen in plants that drop their seeds straight to the ground, such as oak trees; it can also be seen in animals that live in social groups (schools of fish or herds of elephants). Uniform distribution is observed in plants that secrete substances inhibiting the growth of nearby individuals (such as the release of toxic chemicals by sage plants). It is also seen in territorial animal species, such as penguins, that maintain a defined territory for nesting. Each individual's territorial defensive behaviors create a regular distribution pattern of similar-sized territories and individuals within those territories. Thus, the distribution of the individuals within a population provides more information about how they interact with each other than a simple density measurement. Just as lower-density species might have more difficulty finding a mate, solitary species with a random distribution might have a similar difficulty when compared to social species clumped together in groups.

Life tables provide important information about the life history of an organism and the life expectancy of individuals at each age. They are modeled after actuarial tables used by the insurance industry for estimating human life expectancy. Life tables may include the probability of each age group dying before their next birthday, the percentage of surviving individuals dying at a particular age interval, their mortality rate, and their life expectancy at each interval. An example of a life table is shown in Table 1 from a study of Dall mountain sheep, a species native to northwestern North America. Notice that the population is divided into age intervals (column A).

As can be seen from the mortality rate data (column D), a high death rate occurred when the sheep were between six months and a year old and then increased even more from 8 to 12 years old, after which there were few survivors. The data indicate that if a sheep in this population survived to age one, it could be expected to live another 7.7 years on average, as shown by the life-expectancy numbers in column E.

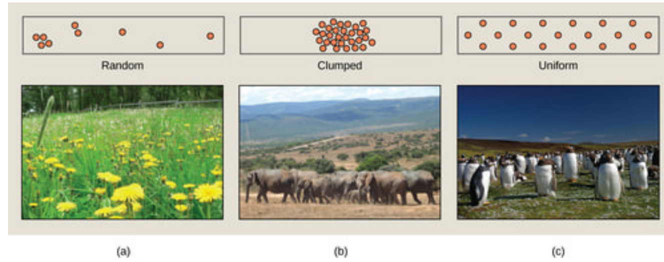


Figure 2. Species may have a random, clumped, or uniform distribution. Plants such as (a) dandelions with wind-dispersed seeds tend to be randomly distributed. Animals such as (b) elephants that travel in groups exhibit a clumped distribution. Territorial birds such as (c) penguins tend to have a uniform distribution. (credit a: modification of work by Rosendahl; credit b: modification of work by Rebecca Wood; credit c: modification of work by Ben Tubby)

Table 1. This life table of *Ovis dalli* shows the number of deaths, number of survivors, mortality rate, and life expectancy at each age interval for Dall mountain sheep.

Life Table of Dall Mountain Sheep[1]				
Age interval (years)	**Number dying in age interval out of 1000 born**	**Number surviving at beginning of age interval out of 1000 born**	**Mortality rate per 1000 alive at beginning of age interval**	**Life expectancy or mean lifetime remaining to those attaining age interval**
0–0.5	**54**	**1000**	**54.0**	**7.06**
0.5–1	**145**	**946**	**153.3**	**—**
1–2	**12**	**801**	**15.0**	**7.7**
2–3	**13**	**789**	**16.5**	**6.8**
3–4	**12**	**776**	**15.5**	**5.9**
4–5	**30**	**764**	**39.3**	**5.0**
5–6	**46**	**734**	**62.7**	**4.2**
6–7	**48**	**688**	**69.8**	**3.4**
7–8	**69**	**640**	**107.8**	**2.6**
8–9	**132**	**571**	**231.2**	**1.9**
9–10	**187**	**439**	**426.0**	**1.3**
10–11	**156**	**252**	**619.0**	**0.9**
11–12	**90**	**96**	**937.5**	**0.6**
12–13	**3**	**6**	**500.0**	**1.2**
13–14	**3**	**3**	**1000**	**0.7**

Another tool population ecologists use is a **survivorship curve**, a graph of the number of individuals surviving at each age interval versus time. These curves allow us to compare the life histories of different populations (Figure 3). There are three types of survivorship curves. In a type I curve, mortality is low in the early and middle years and occurs mostly in older individuals. Organisms exhibiting a type I survivorship typically produce few offspring and provide good care to the offspring, increasing their likelihood of survival. Humans and most mammals exhibit a type I survivorship curve. In type II curves, mortality is relatively constant throughout the entire lifespan, and mortality is equally likely to occur at any point in the life span. Many bird populations provide examples of an intermediate or type II survivorship curve. In type III survivorship curves, early ages experience the highest mortality with much lower mortality rates for organisms that make it to advanced years. Type III organisms typically produce large numbers of offspring but provide very little or no care for them. Trees and marine invertebrates exhibit a type III survivorship curve because very few of these organisms survive their younger years. Still, those that do make it to old age are more likely to survive for a relatively long period of time.

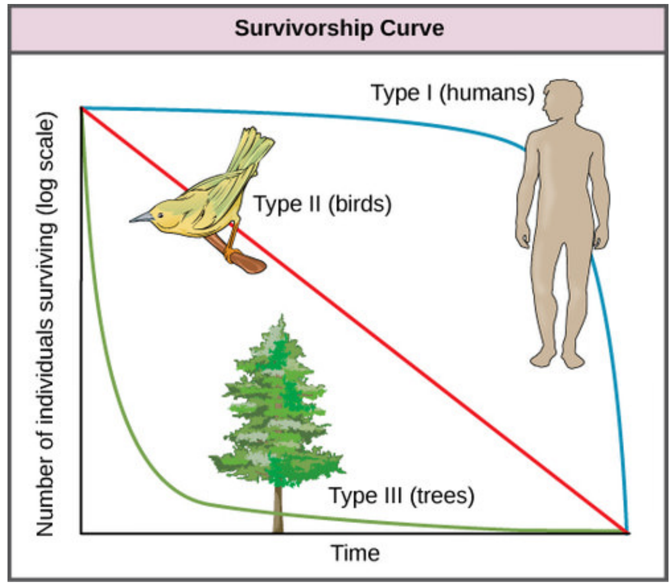


Figure 3. Survivorship curves show the distribution of individuals in a population according to age. Humans and most mammals have a Type I survivorship curve because death primarily occurs in the older years. Birds have a Type II survivorship curve, as death at any age is equally probable. Trees have a Type III survivorship curve because very few survive the younger years, but individuals are much more likely to survive after a certain age.

Population ecologists make use of a variety of methods to model population dynamics. An accurate model should be able to describe the changes occurring in a population and predict future changes.

Population Growth

The two simplest models of population growth use deterministic equations (equations that do not account for random events) to describe the rate of change in the size of a population over time. The first of these models, **exponential growth**, describe populations that increase in numbers without any limits to their growth. The second model, **logistic growth**, introduces limits to reproductive growth that become more intense as the population size increases. Neither model adequately describes natural populations, but they provide points of comparison.

Exponential Growth

In developing his theory of natural selection, Charles Darwin was influenced by the English clergyman Thomas Malthus. Malthus published his book in 1798, stating that populations with abundant natural resources grow very rapidly. However, they limit further growth by depleting their resources. The early pattern of accelerating population size is called exponential growth (Figure 1).

The best example of exponential growth in organisms is seen in bacteria. Bacteria are prokaryotes that reproduce quickly, about an hour for many species. If 1000 bacteria are placed in a large flask with an abundant supply of nutrients (so the nutrients will not become quickly depleted), the number of bacteria will have doubled from 1000 to 2000 after just an hour. Each of the 2000 bacteria will divide in another hour, producing 4000 bacteria. After the third hour, there should be 8000 bacteria in the flask. The important concept of exponential growth is that the growth rate—the number of organisms added in each reproductive generation—is itself increasing; that is, the population size is increasing at a greater and greater rate. After 24 cycles, the population would have increased from 1000 to more than 16 billion bacteria. A J-shaped growth curve is produced when the population size, N, is plotted over time (Figure 1).

The bacteria-in-a-flask example does not truly represent the real world, where resources are usually limited. However, when a species is introduced into a new habitat that it finds suitable, it may show exponential growth for a while. In the case of the bacteria in the flask, some bacteria will die during the experiment and thus not reproduce; therefore, the growth rate is lowered from a maximal rate in which there is no mortality.

Logistic Growth

Extended exponential growth is possible only when infinite natural resources are available; this is not true in the real world. Charles Darwin recognized this fact in his description of the "struggle for existence," which states that individuals will compete, with members of their own or other species, for limited resources. The successful ones are more likely to survive and pass on the traits that made them successful to the next generation at a greater rate (natural selection). Population ecologists developed the logistic growth model to model the reality of limited resources.

Carrying Capacity and the Logistic Model

With limited resources, exponential growth cannot continue indefinitely in the real world. Exponential growth may occur in environments with few individuals and plentiful resources. However, when the number of individuals gets large enough, resources will be depleted, and the growth rate will slow down. Eventually, the growth rate will plateau or level off (Figure 1). This population size, which is determined by the maximum population size that a particular environment can sustain, is called the **carrying capacity**, symbolized as K. In real populations, a growing population often overshoots its carrying capacity, and the death rate increases beyond the birth rate, causing the population size to decline back to the carrying capacity or below it. Most populations usually fluctuate around the carrying capacity in an undulating fashion rather than existing right at it. A graph of logistic growth yields the S-shaped curve (Figure 1). It is a more realistic model of population growth than exponential growth. There are three different sections to an S-shaped curve. Initially, growth is exponential because few individuals and ample resources are available. Then, as resources begin to become limited, the growth rate decreases. Finally, the growth rate levels off at the environment's carrying capacity, with little change in population number over time.

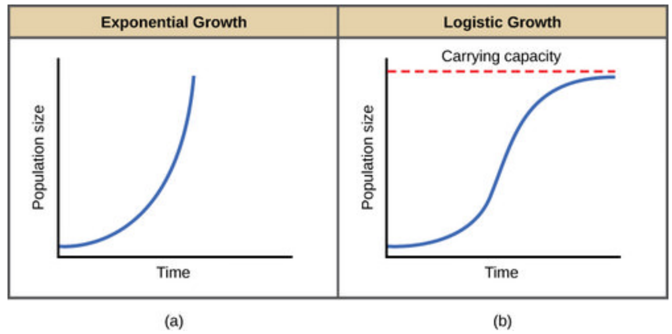


Figure 1. When resources are unlimited, populations exhibit (a) exponential growth, shown in a J-shaped curve. When resources are limited, populations exhibit (b) logistic growth. In logistic growth, population expansion decreases as resources become scarce and levels off when the environment's carrying capacity is reached. The logistic growth curve is S-shaped.

Examples of Logistic Growth

Yeast, a unicellular fungus used to make bread and alcoholic beverages, exhibits the classical S-shaped curve when grown in a test tube (Figure 2a). Its growth levels off as the population depletes the nutrients necessary. In the real world, however, there are variations to this idealized curve. Examples of wild populations include sheep and harbor seals (Figure 2b). In both examples, the population size exceeds the carrying capacity for short periods of time and then falls below the carrying capacity afterward. This fluctuation in population size continues to occur as the population oscillates around its carrying capacity. Still, even with this oscillation, the logistic model is confirmed.

Population Dynamics and Regulation

While valid in many natural populations and useful, the logistic model of population growth simplifies real-world population dynamics. Implicit in the model is that the environment's carrying capacity does not change, which is not the case. The carrying capacity varies annually. For example, some summers are hot and dry, whereas others are cold and wet; in many areas, the carrying capacity during winter is much lower than during summer. Also, natural events such as earthquakes, volcanoes, and fires can alter an environment and its carrying capacity. Additionally, populations do not usually exist in isolation. They share the environment with other species, competing with them for the same resources (interspecific competition). These factors are also important to understanding how a specific population will grow.

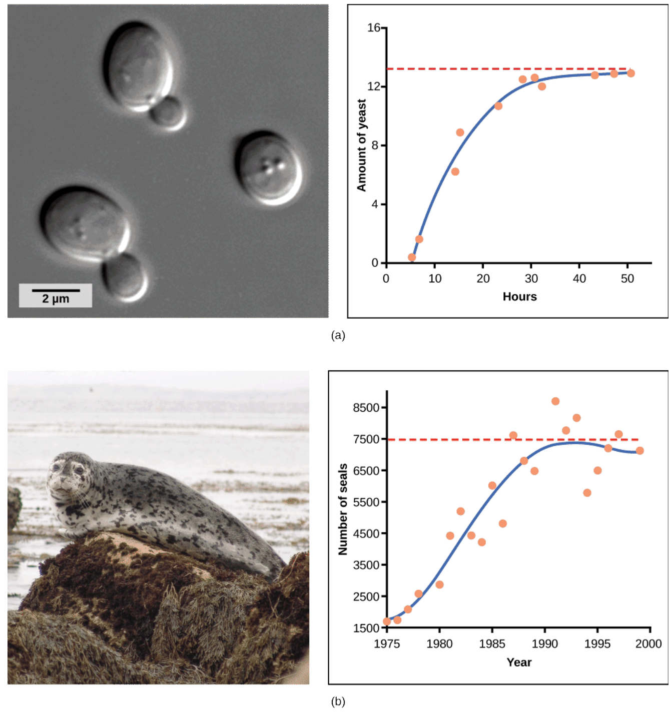


Figure 2. (a) Yeast grown in ideal conditions in a test tube shows a classical S-shaped logistic growth curve, whereas (b) a natural population of seals shows real-world fluctuation. The yeast is visualized using differential interference contrast light micrography. (credit a: scale-bar data from Matt Russell)

Why Did the Woolly Mammoth Go Extinct?

Most populations of woolly mammoths went extinct about 10,000 years ago, soon after paleontologists believe humans began to colonize North America and northern Eurasia (Figure 3). A mammoth population survived on Wrangel Island in the East Siberian Sea and was isolated from human contact until as recently as 1700 BC. We know a lot about these animals from carcasses found frozen in the ice of Siberia and other northern regions. It is commonly thought that climate change and human hunting led to their extinction. A 2008 study estimated climate change reduced the mammoth's range from 3,000,000 square miles 42,000 years ago to 310,000 square miles 6,000 years ago.[2] Through archaeological evidence of kill sites, it is well documented that humans hunted these animals. A 2012 study concluded that no single factor was exclusively responsible for the extinction of these magnificent creatures.[3] In addition to climate change and habitat reduction, scientists demonstrated another important factor in the mammoth's extinction was the migration of human hunters across the Bering Strait to North America during the last ice age 20,000 years ago. Maintaining stable populations was and is very complex, with many interacting factors determining the outcome. It is important to remember that humans are also part of nature. Once, we contributed to a species' decline using primitive hunting technology only.

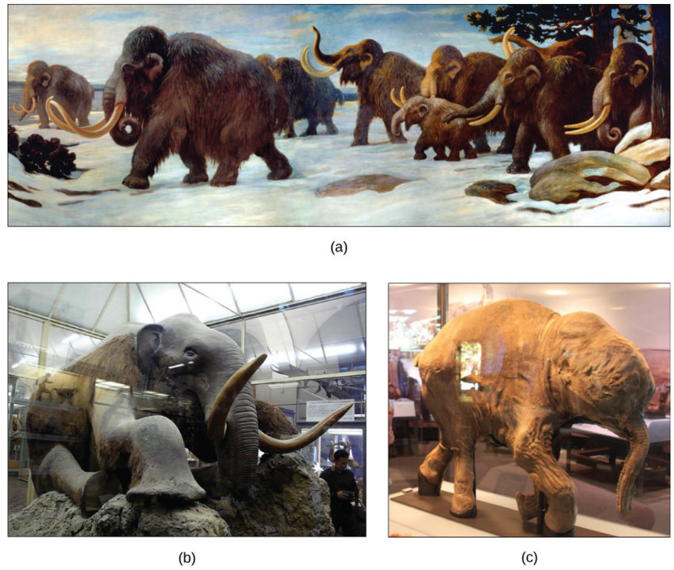


Figure 3. The three images include (a) a 1916 mural of a mammoth herd from the American Museum of Natural History, (b) the only stuffed mammoth in the world is in the Museum of Zoology located in St. Petersburg, Russia, and (c) a one-month-old baby mammoth, named Lyuba, discovered in Siberia in 2007. (credit a: modification of work by Charles R. Knight; credit b: modification of work by "Tanapon"/Flickr; credit c: modification of work by Matt Howry)

Demographic-Based Population Models

Population ecologists have hypothesized that suites of characteristics may evolve in species that lead to particular adaptations to their environments. These adaptations impact the kind of population growth their species experience. Life history characteristics such as birth rates, age at first reproduction, the numbers of offspring, and even death rates evolve like anatomy or behavior, leading to adaptations that affect population growth. Population ecologists have described a continuum of life-history "strategies" with *K*-selected species on one end and *r*-selected species on the other. ***K*-selected species** are adapted to stable, predictable environments. Populations of *K*-selected species tend to exist close to their carrying capacity. These species tend to have larger but fewer offspring and contribute large amounts of resources to each offspring. Elephants would be an example of a *K*-selected species. ***r*-selected species** are adapted to unstable and unpredictable environments. They have large numbers of small offspring. R-selected animals do not provide many resources or parental care to offspring; the offspring are relatively self-sufficient at birth. Examples of *r*-selected species are marine invertebrates such as jellyfish and plants such as the dandelion. The two extreme strategies are at two ends of a continuum on which real species life histories will exist. In addition, life history strategies do not need to evolve as suites. Still, they can evolve independently, so each species may have some characteristics that trend toward one extreme or the other.

Concepts of animal population dynamics can be applied to human population growth. Humans are not unique in their ability to alter their environment. For example, beaver dams alter the stream environment where they are built. Humans, however, can alter their environment to increase their carrying capacity, sometimes to the detriment of other species. Earth's human population and its use of resources are growing rapidly, to the extent that some worry about the ability of Earth's environment to sustain its human population. Long-term exponential growth carries with it the potential risks of famine, disease, and large-scale death, as well as social consequences of crowding, such as increased crime.

Human technology, particularly our harnessing of the energy contained in fossil fuels, has caused unprecedented changes to Earth's environment, altering ecosystems to the point where some may be in danger of collapse. Changes on a global scale, including depletion of the ozone layer, desertification and topsoil loss, and global climate change, are caused by human activities.

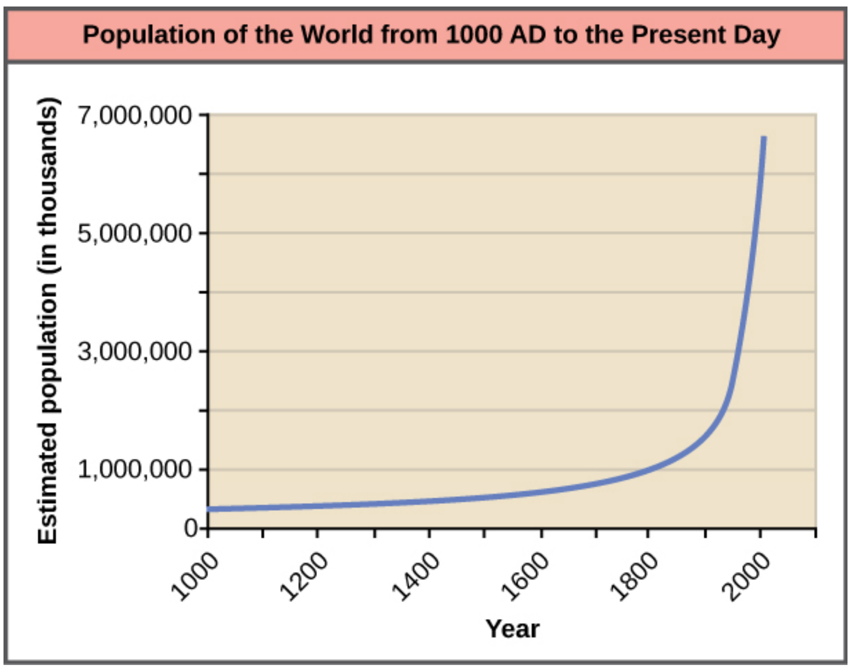


Figure 1. Human population growth since 1000 AD is exponential.

Human population Growth

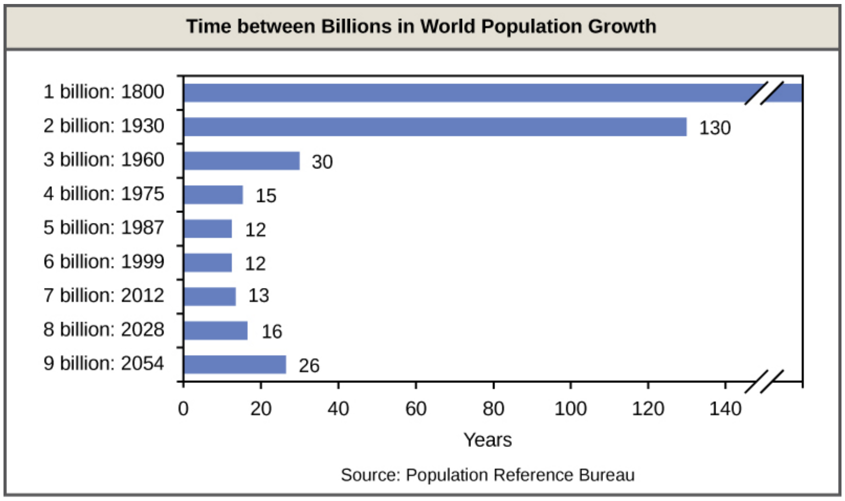


Figure 2. The time between the addition of each billion human beings to Earth decreases over time. (credit: modification of work by Ryan T. Cragun)

The fundamental cause of the acceleration of the human growth rate in the past 200 years has been the reduced death rate due to changes in public health and sanitation. Clean drinking water and proper disposal of sewage have drastically improved health in developed nations. Also, medical innovations such as the use of antibiotics and vaccines have decreased the ability of infectious diseases to limit human population growth. In the past, diseases such as the bubonic plague of the fourteenth century killed between 30 and 60 percent of Europe's population. They reduced the world population by as many as one hundred million. Naturally, infectious disease continues to impact human population growth, especially in poorer nations. For example, life expectancy in sub-Saharan Africa, which increased from 1950 to 1990, began declining after 1985, largely due to HIV/AIDS mortality. The reduction in life expectancy caused by HIV/AIDS was estimated to be seven years in 2005. Technological advances of the industrial age have also supported population growth through urbanization and advances in agriculture. These advances in technology were possible, in part, due to the exploitation of fossil fuels.

Click through this interactive view of how human populations have changed over time.

Age Structure, Population Growth, and Economic Development

The age structure of a population is an important factor in population dynamics. **Age structure** is the proportion of a population in different age classes. Models incorporating age structure allow better prediction of population growth and the ability to associate this growth with a region's economic development level. Countries with rapid growth have a pyramidal shape in their age structure diagrams, showing a preponderance of younger individuals, many of whom are of reproductive age (Figure 3). This pattern is most often observed in underdeveloped countries where individuals do not live to old age because of less-than-optimal living conditions and a high birth rate. Age structures of areas with slow growth, including developed countries such as the United States, still have a pyramidal structure, but with many fewer young and reproductive-aged individuals and a greater proportion of older individuals.

Other developed countries, such as Italy, have zero population growth. The age structure of these populations is more conical, with an even greater percentage of middle-aged and older individuals. The actual growth rates in different countries are shown in Figure 4, with the highest rates tending to be in Africa and Asia's less economically developed countries.

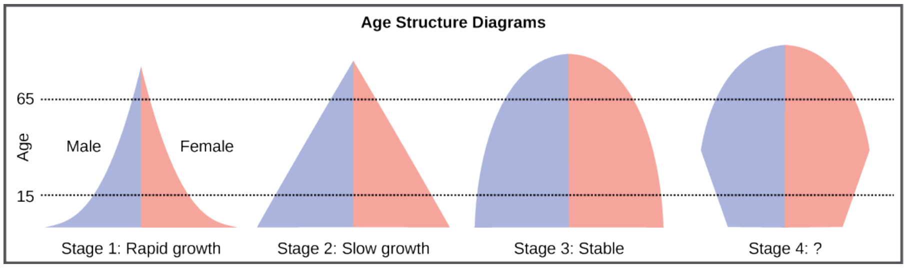


Figure 3. Typical age structure diagrams are shown. The rapid growth diagram narrows to a point, indicating that the number of individuals decreases rapidly with age. In the slow growth model, the number of individuals decreases steadily with age. Stable population diagrams are rounded on the top, showing that the number of individuals per age group decreases gradually and then increases for the older part of the population.

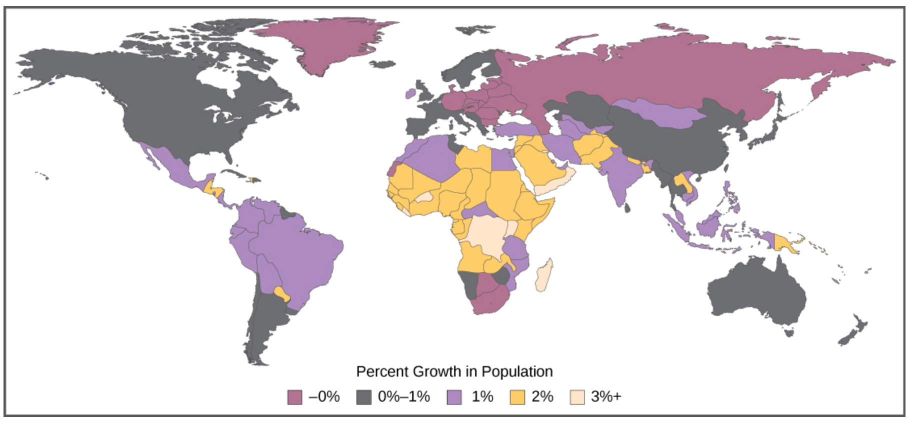


Figure 4. The percent growth rate of the population in different countries is shown. Notice that the highest growth occurs in less economically developed countries in Africa and Asia.

Long-Term Consequences of Exponential Human Population Growth

Many dire predictions have been made about the world's population leading to a major crisis called the "population explosion." In the 1968 book *The Population Bomb*, biologist Paul R. Ehrlich wrote, "The battle to feed all of humanity is over. In the 1970s, hundreds of millions of people starved to death despite any crash programs embarked upon now. Nothing can prevent a substantial increase in the world death rate at this late date."

While these predictions obviously didn't bear fruit, the laws of exponential population growth are still in effect, and unchecked human population growth cannot continue indefinitely. Efforts to moderate population control led to the **one-child policy** in China, which imposes fines on urban couples with more than one child. Because some couples wish to have a male heir, many Chinese couples continue to have more than one child. The effectiveness of the policy in limiting overall population growth is controversial, as is the policy itself. Moreover, there are stories of female infanticide in some of the country's more rural areas. Family planning education programs in other countries have positively affected limiting population growth rates and increasing living standards.

Despite population control policies, the human population continues to grow. The United Nations estimates the world population will be 11.2 billion by 2100. There is no way to know whether human population growth will moderate to the point where the crisis described by Dr. Ehrlich will be averted. Another consequence of population growth is the change and degradation of the natural environment. Many countries have attempted to reduce the human impact on climate change by limiting their emission of greenhouse gases. However, a global climate change treaty remains elusive, and many underdeveloped countries trying to improve their economic condition may be less likely to agree with such provisions without compensation if it means slowing their economic development. Furthermore, the role of human activity in causing climate change has become a hotly debated socio-political issue in some developed countries, including the United States, despite the overwhelming scientific evidence. Thus, we enter the future with considerable uncertainty about our ability to curb human population growth and protect our environment to maintain the carrying capacity of the human species.

Visit this website and select "Launch the movie" for an animation discussing the global impacts of human population growth.

Populations typically do not live in isolation from other species. Populations that interact within a given habitat form a **community**. The number of species occupying the same habitat and their relative abundance is known as the **diversity** of the community. Areas with low species diversity, such as the glaciers of Antarctica, still contain a wide variety of living organisms, whereas the diversity of tropical rainforests is so great that it c annot be accurately assessed. Scientists study ecology at the community level to understand how species interact with each other and compete for the same resources.

Predation and Herbivory

Perhaps the classical example of species interaction is the predator-prey relationship. The narrowest definition of **predation** describes individuals of one population that kill and then consume the individuals of another population. Population sizes of predators and prey in a community are not constant over time, and they may vary in cycles that appear to be related. The most often cited example of predator-prey population dynamics is seen in the cycling of the lynx (predator) and the snowshoe hare (prey), using 100 years of trapping data from North America (Figure 1). This cycling of predator and prey population sizes lasts approximately ten years, with the predator population lagging one to two years behind the prey population. An apparent explanation for this pattern is that as the hare numbers increase, more food is available for the lynx, allowing the lynx population to increase as well. However, when the lynx population grows to a threshold level, they kill so many hares that hare numbers begin to decline, followed by a decline in the lynx population because of food scarcity. When the lynx population is low, the hare population size begins to increase due, in part, to low predation pressure, starting the cycle anew.

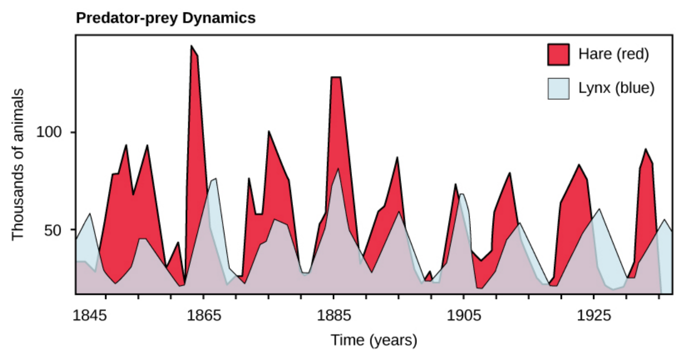


Figure 1. The cycling of snowshoe hare and lynx populations in Northern Ontario is an example of predator-prey dynamics.

Defense Mechanisms against Predation and Herbivory

Predation and predator avoidance are strongly influenced by natural selection. Any heritable character that allows an individual of a prey population to evade its predators better will be represented in greater numbers in later generations. Likewise, traits that allow a predator to more efficiently locate and capture its prey will lead to a greater number of offspring and an increase in the commonness of the trait within the population. Such ecological relationships between specific populations lead to adaptations driven by reciprocal evolutionary responses in those populations. Species have evolved numerous mechanisms to escape predation (including **herbivory**, the consumption of plants for food). Defenses may be mechanical, chemical, physical, or behavioral.

Mechanical defenses, such as the presence of armor in animals or thorns in plants, discourage predation and herbivory by discouraging physical contact (Figure 2a). Many animals produce or obtain chemical defenses from plants and store them to prevent predation. Many plant species produce secondary plant compounds that serve no function for the plant except that they are toxic to animals and discourage consumption. For example, the foxglove produces several compounds, including digitalis, that are extremely toxic when eaten (Figure 2b). Biomedical scientists have repurposed the chemical produced by foxglove as a heart medication, which has saved lives for many decades.

(a) (b)

Figure 2. The (a) honey locust tree uses thorns, a mechanical defense against herbivores, while the (b) foxglove uses a chemical defense: toxins produced by the plant can cause nausea, vomiting, hallucinations, convulsions, or death when consumed. (credit a: modification of work by Huw Williams; credit b: modification of work by Philip Jägenstedt)

Many species use their body shape and coloration to avoid being detected by predators. The tropical walking stick is an insect with a twig's coloration and body shape, making it very hard to see when stationary against a background of real twigs (Figure 3a). In another example, the chameleon can change its color to match its surroundings (Figure 3b).

(a) (b)

Figure 3. (a) The tropical walking stick and (b) the chameleon use their body shape and/or coloration to prevent detection by predators. (credit a: modification of work by Linda Tanner; credit b: modification of work by Frank Vassen)

Some species use coloration to warn predators that they are distasteful or poisonous. For example, the monarch butterfly caterpillar sequesters poisons from its food (plants and milkweeds) to make itself poisonous or distasteful to potential predators. The caterpillar is bright yellow and black to advertise its toxicity. The caterpillar can also pass the sequestered toxins on to the adult monarch, dramatically colored black and red, to warn potential predators. Fire-bellied toads produce toxins that make them distasteful to their potential predators (Figure 4). They have bright red or orange coloration on their bellies, which they display to a potential predator to advertise their poisonous nature and discourage an attack. Warning coloration only works if a predator uses eyesight to locate prey and can learn—a naïve predator must experience the negative consequences of eating one before it will avoid other similarly colored individuals.

Figure 4. The fire-bellied toad has bright coloration on its belly that serves to warn potential predators that it is toxic. (credit: modification of work by Roberto Verzo)

While some predators learn to avoid eating certain potential prey because of their coloration, other species have evolved mechanisms to mimic this coloration to avoid being eaten, even though they themselves may not be unpleasant to eat or contain toxic chemicals. In some cases of **mimicry**, a harmless species imitates the warning coloration of a harmful species. Assuming they share the same predators, this coloration then protects the harmless ones. Many insect species mimic the coloration of wasps, which are stinging, venomous insects, thereby discouraging predation (Figure 5).

Figure 5. One form of mimicry is when a harmless species mimics the coloration of a harmful species, as is seen with the (a) wasp (Polistes sp.) and the (b) hoverfly (Syrphus sp.). (credit: modification of work by Tom Ings)

Figure 6. Several unpleasant-tasting Heliconius butterfly species share a similar color pattern with better-tasting varieties, an example of mimicry. (credit: Joron M, Papa R, Beltrán M, Chamberlain N, Mavárez J, et al.)

In other cases of mimicry, multiple species share the same warning coloration, but all of them actually have defenses. The commonness of the signal improves the compliance of all potential predators. Figure 6 shows a variety of foul-tasting butterflies with similar coloration.

Go to this website (http://openstaxcollege.org/l/find_the_mimic2) to view stunning examples of mimicry.

Competitive Exclusion Principle

Resources are often limited within a habitat, and multiple species may compete to obtain them. Ecologists have understood that all species have an **ecological niche**: the unique set of resources a species uses, including its interactions with other species. The **competitive exclusion principle** states that two species cannot occupy the exact same niche in a habitat. In other words, different species cannot coexist in a community without competing for all the same resources. It is important to note that competition is bad for both competitors because it wastes energy. The competitive exclusion principle works because if there is competition between two species for the same resources, natural selection favors traits that lessen reliance on the shared resource, thus reducing competition. If either species cannot evolve to reduce competition, the species most efficiently exploiting the resource will drive the other species to extinction. An experimental example of this principle is shown in Figure 7 with two protozoan species: *Paramecium aurelia* and *Paramecium caudatum*. When grown individually in the laboratory, they both thrive. But when placed in the same test tube (habitat), *P. aurelia* outcompetes *P. caudatum* for food, leading to the latter's eventual extinction.

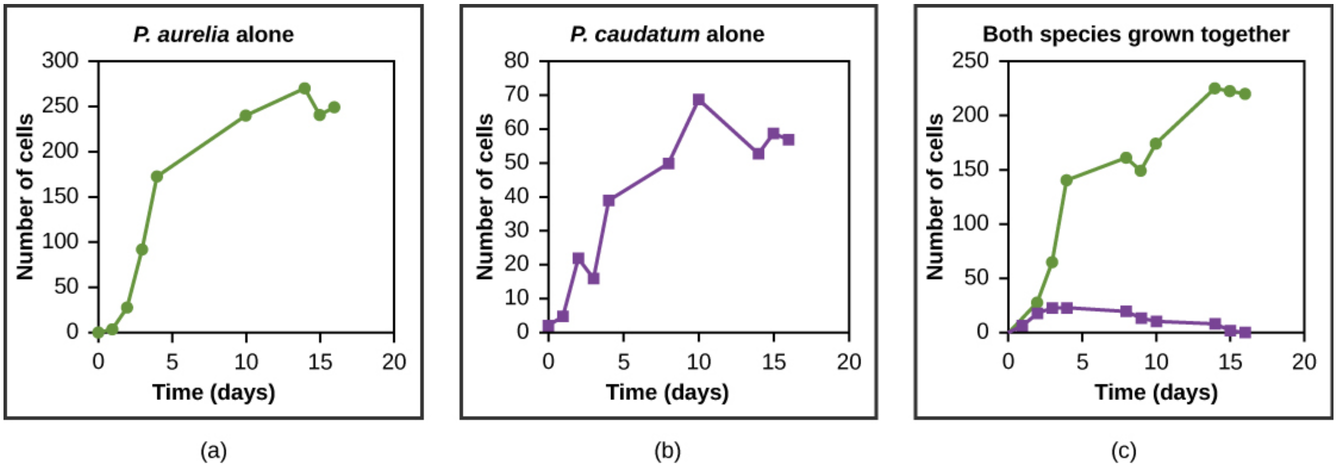


Figure 7. Paramecium aurelia and Paramecium caudatum grow well individually, but when they compete for the same resources, the P. aurelia outcompetes the P. caudatum.

Symbiosis

Symbiotic relationships are close, long-term interactions between individuals of different species. Symbioses may be commensal, in which one species benefits while the other is neither harmed nor benefited; mutualistic, in which both species benefit; or parasitic, in which the interaction harms one species and benefits the other.

Figure 8. The southern masked weaver is starting to make a nest in a tree in Zambezi Valley, Zambia. This is an example of a commensal relationship in which one species (the bird) benefits, while the other (the tree) neither benefits nor is harmed. (credit: "Hanay"/Wikimedia Commons)

Commensalism occurs when one species benefits from a close, prolonged interaction while the other neither benefits nor is harmed. Birds nesting in trees exemplify a commensal relationship (Figure 8).

The tree is not harmed by the presence of the nest among its branches. The nests are light and produce little strain on the structural integrity of the branch, and most of the leaves, which the tree uses to get energy by photosynthesis, are above the nest, so they are unaffected. The bird, on the other hand, benefits greatly. If the bird had to nest in the open, its eggs and young would be vulnerable to predators. Many potential commensal relationships are difficult to identify because it is difficult to prove that one partner does not derive some benefit from the presence of the other.

A second symbiotic relationship type is **mutualism**, in which two species benefit from their interaction. For example, termites have a mutualistic relationship with protists that live in the insect's gut (Figure 9a). The termite benefits from the ability of the protists to digest cellulose. However, the protists can digest cellulose only because of the presence of symbiotic bacteria within their cells that produce the cellulase enzyme. The termite itself cannot do this; without the protozoa, it would not be able to obtain energy from its food (cellulose from the wood it chews and eats). The protozoa benefit by having a protective environment and a constant supply of food from the wood-chewing actions of the termite. In turn, the protists benefit from the enzymes provided by their bacterial endosymbionts, while the bacteria benefit from a doubly protective environment and a constant source of nutrients from two hosts. Lichen is a mutualistic relationship between a fungus and photosynthetic algae or cyanobacteria (Figure 9b). The glucose produced by the algae provides nourishment for both organisms. In contrast, the physical structure of the lichen protects the algae from the elements and makes certain nutrients in the atmosphere more available to the algae. The algae of lichens can live independently, given the right environment, but many fungal partners cannot.

Figure 9. (a) Termites form a mutualistic relationship with symbiotic protozoa in their guts, which allow both organisms to obtain energy from the cellulose the termite consumes. (b) Lichen is a fungus that has symbiotic photosynthetic algae living in close association. (credit a: modification of work by Scott Bauer, USDA; credit b: modification of work by Cory Zanker)

A parasite is an organism that feeds off another without immediately killing the organism it is feeding on. In **parasitism**, the parasite benefits, but the organism being fed upon, the host, is harmed. The parasite usually weakens the host as it siphons resources the host normally uses to maintain itself. Parasites may kill their hosts, but there is usually selection to slow down this process to allow the parasite time to complete its reproductive cycle before it or its offspring can spread to another host. Parasitism is a form of predation.

The reproductive cycles of parasites are often very complex, sometimes requiring more than one host species. A tapeworm causes human disease when contaminated and undercooked meat such as pork, fish, or beef is consumed (Figure 10). The tapeworm can live inside the host's intestine for several years, benefiting from the host's food, and it may grow to be over 50 feet long by adding segments. The parasite moves from one host species to a second host species to complete its life cycle.

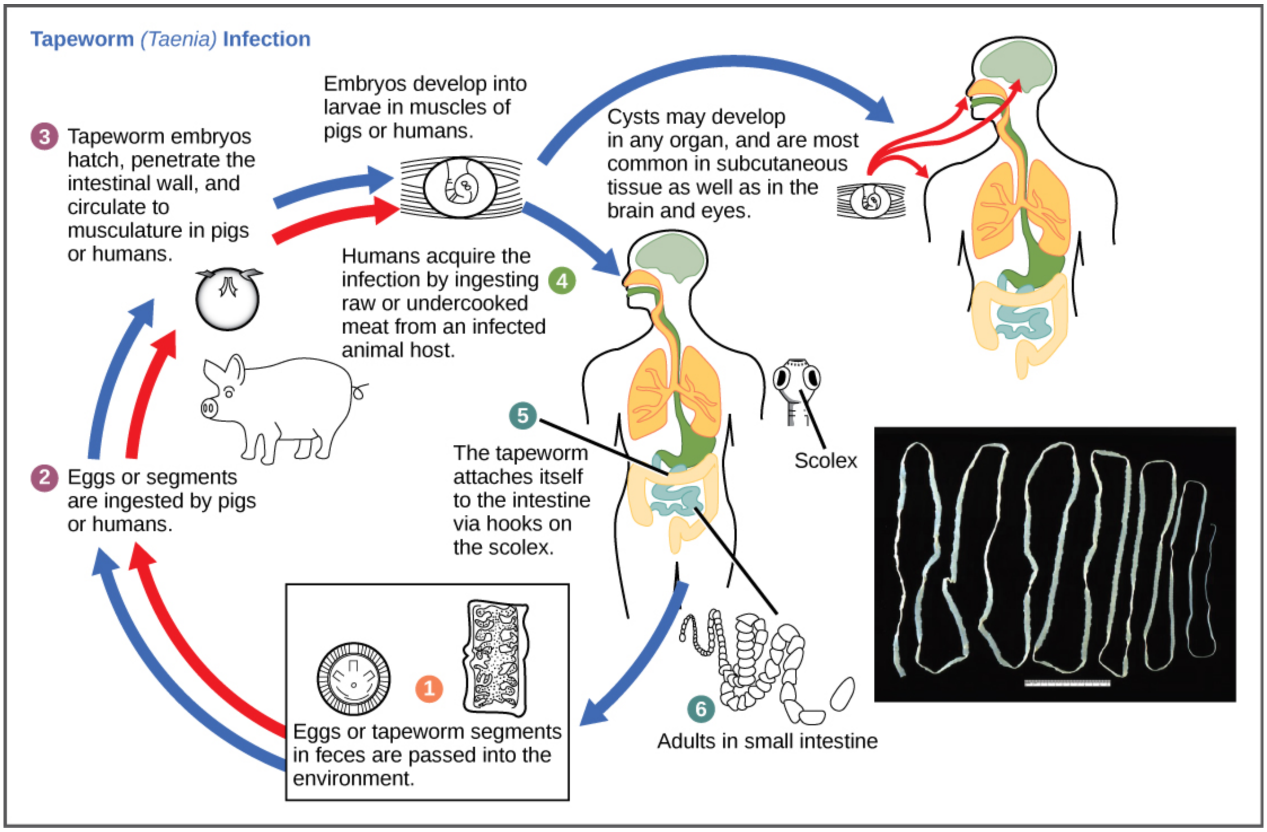


Figure 10. This diagram shows the tapeworm's life cycle, a human worm parasite. (credit: modification of work by CDC)

To learn more about "Symbiosis in the Sea," watch this webisode (https://www.blueworldtv.com/webisodes/watch/symbiosis-in-the-sea) of Jonathan Bird's Blue World.

Characteristics of Communities

Communities are complex systems characterized by their structure (the number and size of populations and their interactions) and dynamics (how the members and their interactions change over time). Understanding community structure and dynamics allows us to minimize impacts on ecosystems and manage the ecological communities we benefit from.

Ecologists have extensively studied one of the fundamental characteristics of communities: **biodiversity**. One measure of biodiversity ecologists use is the number of species in a particular area and their relative abundance. The area in question could be a habitat, a biome, or the entire biosphere. **Species richness** is the term used to describe the number of species living in a habitat or other unit. Species richness varies across the globe (Figure 11). Species richness is related to latitude: the greatest species richness occurs near the equator, and the lowest richness occurs near the poles. The exact reasons for this are not clearly understood. Other factors besides latitude influence species richness as well. For example, ecologists studying islands found that biodiversity varies with island size and distance from the mainland.

Relative abundance is the number of individuals in a species relative to the total number of individuals in all species within a system. Foundation species, described below, often have the highest relative abundance of species.

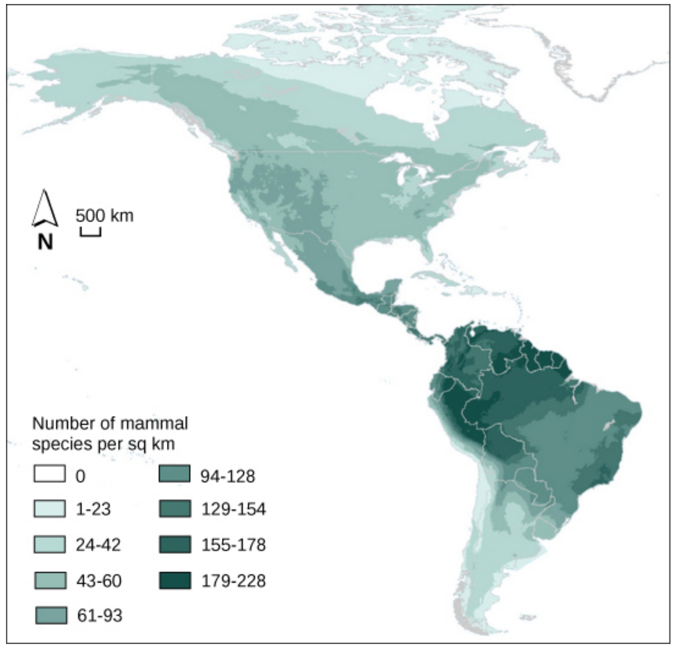


Figure 11. The greatest species richness for mammals in North America is associated with the equatorial latitudes. (credit: modification of work by NASA, CIESIN, Columbia University)

Foundation species are considered the “base” or “bedrock” of a community, having the greatest influence on its overall structure. They are often primary producers, and they are typically abundant organisms. For example, kelp, a species of brown algae, is a foundation species that form the basis of the kelp forests off the coast of California.

Foundation species may physically modify the environment to produce and maintain habitats that benefit the other organisms that use them. Examples include the kelp described above or tree species found in a forest. The photosynthetic corals of the coral reef also provide structure by physically modifying the environment (Figure 12). The exoskeletons of living and dead coral make up most of the reef structure, which protects many other species from waves and ocean currents.

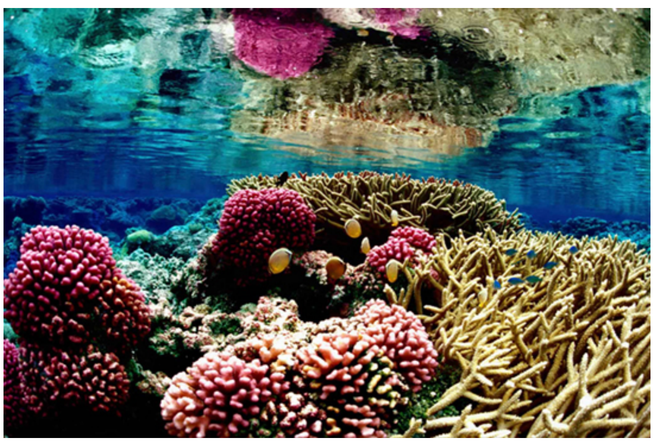


Figure 12. Coral is the foundation species of coral reef ecosystems. (credit: Jim E. Maragos, USFWS)

A **keystone species** is one whose presence has an inordinate influence in maintaining the prevalence of various species in an ecosystem, the ecological community’s structure, and sometimes its biodiversity. *Pisaster ochraceus*, the intertidal sea star, is a keystone species in the northwestern portion of the United States (Figure 13). Studies have shown that when this organism is removed from communities, mussel populations (their natural prey) increase, completely altering the species composition and reducing biodiversity. Another keystone species is the banded tetra, a fish in tropical streams that supply nearly all of the phosphorus, a necessary inorganic nutrient, to the rest of the community. The banded tetra feeds largely on insects from the terrestrial ecosystem and then excretes phosphorus into the aquatic ecosystem. The relationships between populations in the community, and possibly the biodiversity, would change dramatically if these fish were to become extinct.

Figure 13. The Pisaster ochraceus sea star is a keystone species. (credit: Jerry Kirkhart)

Invasive species are non-native organisms that, when introduced to an area out of their native range, alter the community they invade. In the United States, invasive species like the purple loosestrife (*Lythrum salicaria*) and the zebra mussel (*Dreissena polymorpha*) have drastically altered the ecosystems they invaded. Some well-known invasive animals include the emerald ash borer (*Agrilus planipennis*) and the European starling (*Sturnus vulgaris*). Whether enjoying a forest hike, taking a summer boat trip, or simply walking down an urban street, you have likely encountered an invasive species. One of the many recent proliferation of an invasive species concerns the Asian carp in the United States. Asian carp were introduced to the United States in the 1970s by fisheries (commercial catfish ponds) and sewage treatment facilities that used the fish's excellent filter-feeding abilities to clean their ponds of excess plankton. Some of the fish escaped, and by the 1980s, they had colonized many waterways of the Mississippi River basin, including the Illinois and Missouri Rivers. Voracious feeders and rapid reproducers, Asian carp may outcompete native species for food which could lead to their extinction. One species, the grass carp, feeds on phytoplankton and aquatic plants. It competes with native species for these resources and alters nursery habitats for other fish by removing aquatic plants. In some parts of the Illinois River, Asian carp constitute 95 percent of the community's biomass. Although edible, the fish is bony and not desired in the United States. The Great Lakes and their prized salmon and lake trout fisheries are being threatened by Asian carp. The carp are not yet present in the Great Lakes, and attempts are being made to prevent its access to the lakes through the Chicago Ship and Sanitary Canal, the only connection between the Mississippi River and Great Lakes basins. To prevent the Asian carp from leaving the canal, a series of electric barriers have been used to discourage their migration; however, the threat is significant enough that several states and Canada have sued to permanently remove the Chicago channel from Lake Michigan. Local and national politicians have weighed in on how to solve the problem. In general, governments have been ineffective in preventing or slowing the introduction of invasive species.

Community Dynamics

Community dynamics are the changes in community structure and composition over time, often following environmental disturbances such as volcanoes, earthquakes, storms, fires, and climate change. Communities with a relatively constant number of species are at equilibrium. The equilibrium is dynamic, with species identities and relationships changing over time but maintaining relatively constant numbers. Following a disturbance, the community may or may not return to the equilibrium state.

Succession describes the sequential appearance and disappearance of species in a community over time after a severe disturbance. In primary succession, newly exposed or newly formed rock is colonized by living organisms. In **secondary succession**, a part of an ecosystem is disturbed, and remnants of the previous community remain. In both cases, there is a sequential change in species until a more or less permanent community develops.

Primary Succession and Pioneer Species

Figure 14. During primary succession in lava on Maui, Hawaii, succulent plants are the pioneer species. (credit: Forest and Kim Starr)

Primary succession occurs when new land is formed or the soil and all life are removed from pre-existing land. An example of the former is the eruption of volcanoes on the Big Island of Hawaii, which results in lava that flows into the ocean and continually forms new land. This process adds approximately 32 acres of land to the Big Island annually. An example of pre-existing soil being removed is through the activity of glaciers. The massive weight of the glacier scours the landscape down to the bedrock as the glacier moves. This removes any original soil and leaves exposed rock once the glacier melts and retreats.

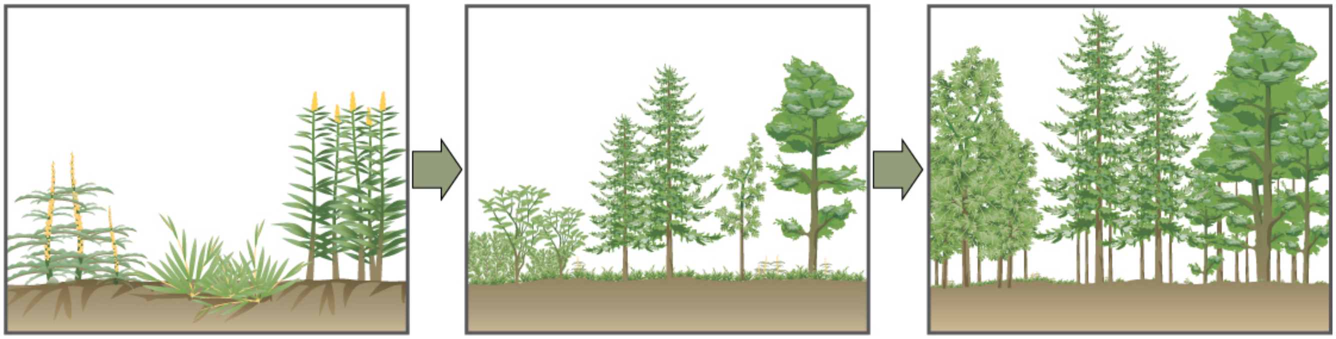
In both cases, the ecosystem starts with bare rock devoid of life. New soil is slowly formed as weathering and other natural forces break down the rock and lead to the establishment of hearty organisms, such as lichens and some plants, collectively known as **pioneer species** (Figure 14) because they are the first to appear. These species help to further break down the mineral-rich rock into the soil where other, less hardy but more competitive species, such as grasses, shrubs, and trees, will grow and eventually replace the pioneer species. Over time the area will reach an equilibrium state, with a set of organisms quite different from the pioneer species.

Secondary succession

A classic example of secondary succession occurs in forests cleared by wildfire or clearcut logging (Figure 15). Wildfires will burn most vegetation; unless the animals can flee the area, they are killed. Their nutrients, however, are returned to the ground in the form of ash. Thus, although the community has been dramatically altered, a soil ecosystem provides a foundation for rapid recolonization.

Before the fire, the vegetation was dominated by tall trees with access to the major plant energy resource: sunlight. Their height gave them access to sunlight while shading the ground and other low-lying species. After the fire, though, these trees are no longer dominant. Thus, the first plants to grow back are usually annual, followed within a few years by quickly growing and spreading grasses and other pioneer species. Due, at least in part, to changes in the environment brought on by the growth of grasses and forbs, shrubs emerged along with small trees over many years. These organisms are called intermediate species. Eventually, over 150 years or more, the forest will reach equilibrium and resemble the community before the fire. This equilibrium state is called the **climax community**, which will remain until the next disturbance. The climax community is typically characteristic of a given climate and geology. Although the community in equilibrium looks the same once attained, the equilibrium is dynamic, with constant changes in abundance and sometimes species identities.

Secondary Succession of an Oak and Hickory Forest



Pioneer species
Annual plants grow and are succeeded by grasses and perennials.

Intermediate species
Shrubs, then pines, and young oak and hickory begin to grow.

Climax community
The mature oak and hickory forest remains stable until the next disturbance.

Summary

Populations are individuals of a species that live in a particular habitat. Ecologists measure the characteristics of populations: size, density, and distribution pattern. Life tables are useful for calculating the life expectancies of individual population members. Survivorship curves show the number of individuals surviving at each age interval plotted versus time. Populations with unlimited resources grow exponentially—with an accelerating growth rate. When resources become limited, populations follow a logistic growth curve in which population size will decrease at the carrying capacity. Humans have increased their carrying capacity through technology, urbanization, and harnessing the energy of fossil fuels. Unchecked human population growth could have dire long-term effects on human welfare and Earth's ecosystems. Communities include all the different species living in a given area. The variety of these species is referred to as biodiversity. Species may form symbiotic relationships such as commensalism, mutualism, or parasitism. Its foundation and keystone species describe community structure. Communities respond to environmental disturbances by succession: the predictable appearance of different types of plant species until a stable community structure is established.

Chapter Attributions:

Chapter 5: Conservation and Biodiversity

Habitat destruction through deforestation, especially of tropical rainforests, as seen in this satellite view of Amazon rainforests in Brazil, is a major cause of the current decline in biodiversity. (credit: modification of work by Jesse Allen and Robert Simmon, NASA Earth Observatory)

Learning Outcomes

After studying this chapter, you should be able to**:**

- Describe biodiversity
- Explain how species evolve through natural selection
- Identify benefits of biodiversity to humans
- Explain the effects of habitat loss, exotic species, and hunting on biodiversity
- Identify the early and predicted effects of climate change on biodiversity
- Explain the legislative framework for conservation
- Identify examples of the effects of habitat restoration

Chapter Outline

Earth is home to an impressive array of life forms. From single-celled organisms to creatures made of many trillions of cells, life has taken on many wonderful shapes and evolved countless strategies for survival. Recall that cell theory dictates that all living things are made of one or more cells. Some organisms are made of just a single cell, thus called **unicellular**. Organisms containing more than one cell are said to be **multicellular.** Despite the wide range of organisms, only two fundamental cell plans exist: prokaryotic and eukaryotic. The main difference between these two cell plans is that eukaryotic cells have internal, membrane-bound structures called organelles (see chp 2.3). Thus, if you were to analyze the cells of any organism on Earth microscopically, you would find either prokaryotic or eukaryotic cells, depending on the type of organism.

Biologists name, group, and classify organisms based on similarities in genetics and morphology. This branch of biological science is known as **taxonomy**. Taxonomists group organisms into categories that range from very broad to very specific (Figure 1). The broadest category is called **domain**, and the most specific are **species** and subspecies (notice the similarities between the words *specific* and *species*). Currently, taxonomists recognize three domains: Bacteria, Archaea, and Eukarya. All life forms are classified within these three domains.

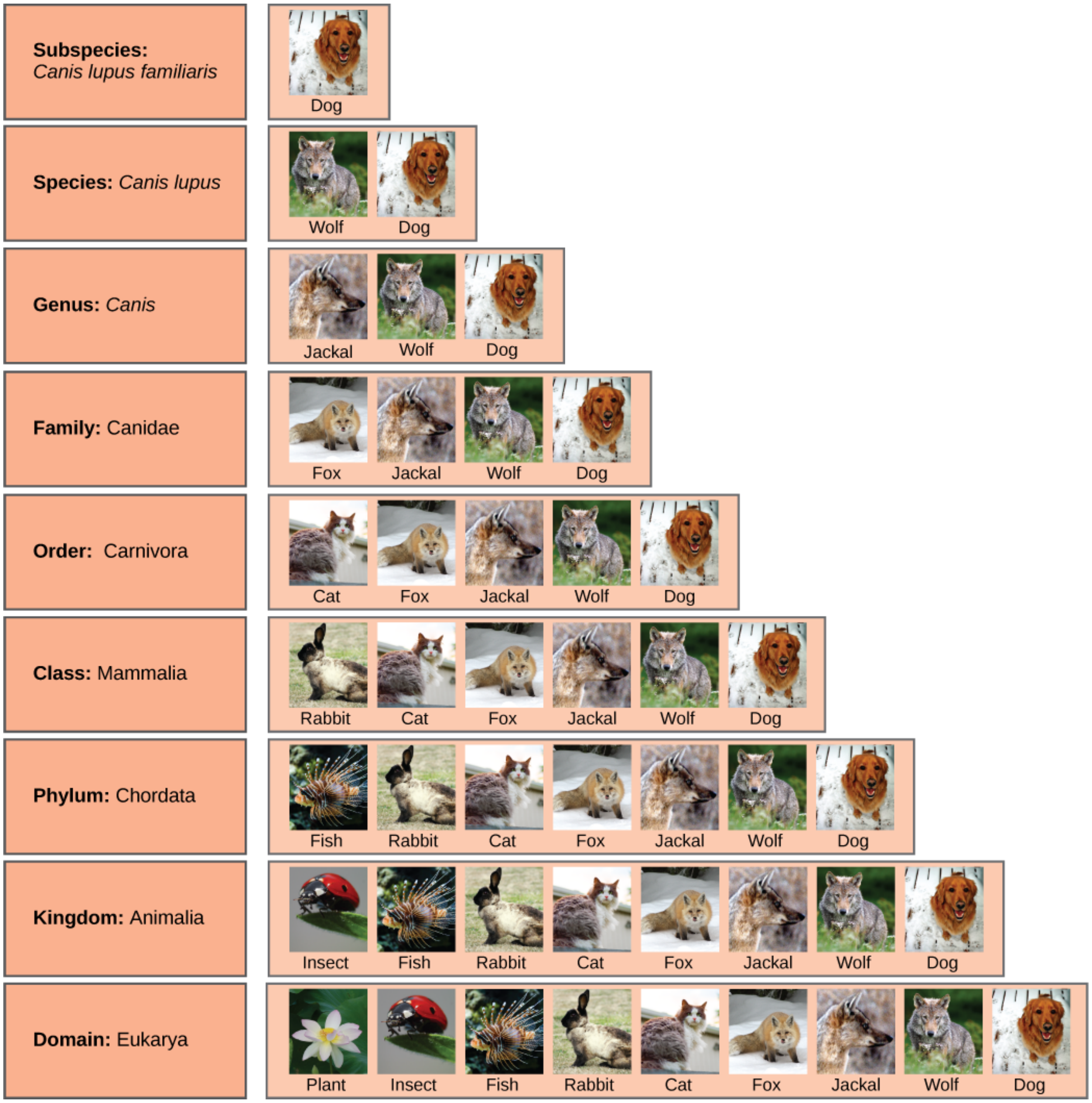


Figure 1. This illustration shows the taxonomic groups, in sequence, with examples. This illustration by OpenStax is licensed under CC BY 4.0

Domain Bacteria

Domain Bacteria includes prokaryotic, unicellular organisms (Figure 2). They are incredibly abundant and found in nearly every type of habitat, including your body. While many people view bacteria only as disease-causing organisms, most species are benign or beneficial to humans. While it is true that some bacteria may cause disease in people, this is more the exception than the rule.

Bacteria are well-known for their metabolic diversity. **Metabolism** is a general term describing the complex biochemistry that occurs inside cells. Many species of bacteria are **autotrophs**, meaning they can create their own food source without eating other organisms. Most autotrophic bacteria do this by using photosynthesis, a process that converts light energy into chemical energy that cells can utilize. A well-known and ecologically-important group of photosynthetic bacteria is **cyanobacteria**. These are sometimes referred to as blue-green algae, but this name is not appropriate because, as you will see shortly, algae belong to the domain Eukarya. Cyanobacteria play important roles in the food webs of aquatic systems such as lakes.

Other species of bacteria are **heterotrophs**, meaning they need to acquire food by eating other organisms. This classification includes the bacteria that cause human disease (*during an infection, the bacteria is eating you*). However, most heterotrophic bacteria are harmless to humans. You have hundreds of species of bacteria living on your skin and in your large intestine that do you no harm. Beyond your body, heterotrophic bacteria play vital roles in ecosystems, especially soil-dwelling bacteria that decompose living matter and make nutrients available to plants.

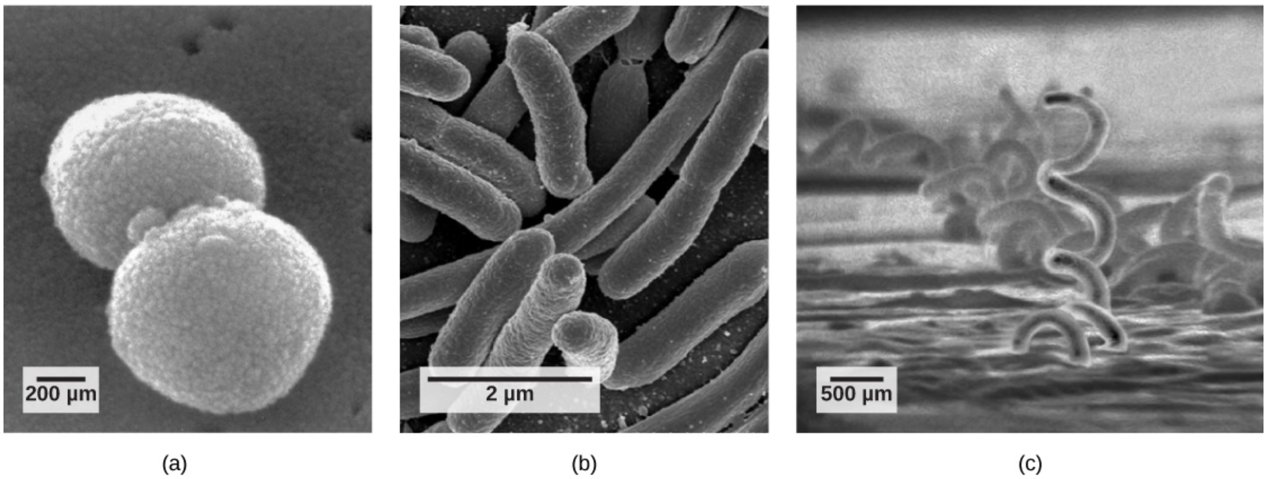


Figure 2. Many prokaryotes fall into three basic categories based on their shape: (a) cocci, or spherical; (b) bacilli, or rod-shaped; and (c) spirilla, or spiral-shaped. (credit a: modification of work by Janice Haney Carr, Dr. Richard Facklam, CDC; credit c: modification of work by Dr. David Cox, CDC; scale-bar data from Matt Russell). This figure by OpenStax is licensed under CC BY 4.0

Domain Archaea

Like bacteria, organisms in **domain Archaea** are prokaryotic and unicellular. Superficially, they look a lot like bacteria, and many biologists confused them as bacteria until a few decades ago. But hiding in their genes is a story that modern DNA analysis has recently revealed: archaeans are so different genetically that they belong in their own domain.

Many archaean species are found in some of the most inhospitable environments, areas of immense pressure (bottom of the ocean), salinity (such as the Great Salt Lake), or heat (geothermal springs). Organisms that can tolerate and even thrive in such conditions are known as **extremophiles**. (*It should be noted that many bacteria are also extremophiles*). Along with genetic evidence, the fact that a large percentage of archaeans are extremophiles suggests that they may be descendants of some of the most ancient lifeforms on Earth, life that originated on a young planet that was inhospitable by today's standards.

For whatever reason, archaeans are not as abundant in and on the human body as bacteria, and they cause substantially fewer diseases. Research on archaeans continues to shed light on this interesting and somewhat mysterious domain.

Domain Eukarya

This domain is most familiar to us because it includes humans and other animals, along with plants, fungi, and a lesser-known group, the protists. Unlike the other domains, **Domain Eukarya** contains multicellular organisms and unicellular species. The presence of eukaryotic cells characterizes the domain. For this domain, you will be introduced to several of its kingdoms. **Kingdom** is the taxonomic grouping immediately below the domain (see Figure 1).

Kingdom Animalia is comprised of multicellular, heterotrophic organisms. This kingdom includes humans and other primates, insects, fish, reptiles, and many other types of animals. **Kingdom Plantae** includes multicellular, autotrophic organisms. Besides a few species that are parasites, plants use photosynthesis to meet their energy demands.

Kingdom Fungi includes multicellular and unicellular, heterotrophic fungi. Fungi are commonly mistaken for plants because some species of fungi grow in the ground. Fungi are fundamentally different from plants in that they do not perform photosynthesis and instead feed on the living matter of others. Another misconception is that all fungi are mushrooms. A mushroom is a temporary reproductive structure used by some fungal species, but not all. Some fungi take the form of molds and mildew, which are commonly seen on rotting food. Lastly, **yeast** is unicellular fungi. Many yeast species are important to humans, especially bakers and brewers. Through their metabolism, these yeast produce CO2 gas and alcohol. The former makes bread rise, and the latter is the source of all alcoholic beverages.

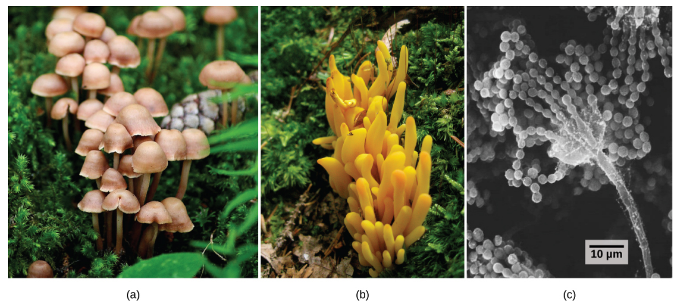


Figure 3. The (a) familiar mushroom is only one type of fungus. The brightly colored fruiting bodies of this (b) coral fungus are displayed. This (c) electron micrograph shows the spore-bearing structures of Aspergillus, a type of toxic fungi found mostly in soil and plants. (credit a: modification of work by Chris Wee; credit b: modification of work by Cory Zanker; credit c: modification of work by Janice Haney Carr, Robert Simmons, CDC; scale-bar data from Matt Russell). This work by OpenStax is licensed under CC BY 4.0.

Protists refer to a highly disparate group that was formerly its own kingdom until recent genetic analysis indicated that it should be split into many kingdoms (Figure 4). As a group, protists are very diverse and include unicellular, multicellular, heterotrophic, and autotrophic organisms. The term 'protist' was used as a catchall for any eukaryote that was neither animal, plant, or fungus. Examples of protists include macroalgae such as kelps and seaweeds, microalgae such as diatoms and dinoflagellates, and important disease-causing microbes such as *Plasmodium*, the parasite that causes malaria. Sadly, malaria kills hundreds of thousands of people every year.

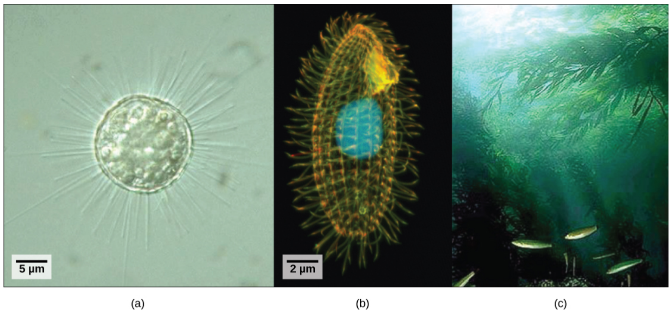


Figure 4. Protists range from the microscopic, single-celled (a) Acanthocystis turfacea and the (b) ciliate Tetrahymena thermophila to the enormous, multicellular (c) kelps (Chromalveolata) that extend for hundreds of feet in underwater "forests." (credit a: modification of work by Yuiuji Tsukii; credit b: modification of work by Richard Robinson, Public Library of Science; credit c: modification of work by Kip Evans, NOAA; scale-bar data from Matt Russell). This work by OpenStax is licensed under CC BY 4.0

With this cursory and fundamental understanding of biological diversity, you are now better equipped to study the role of biodiversity in the biosphere and in human economics, health, and culture. Each life form, even the smallest microbe, is a fascinating and complex living machine. This complexity means we will likely never fully understand each organism and how they interact with each other, with us, and with their environment. Thus, it is wise to value biodiversity and take measures to conserve it.

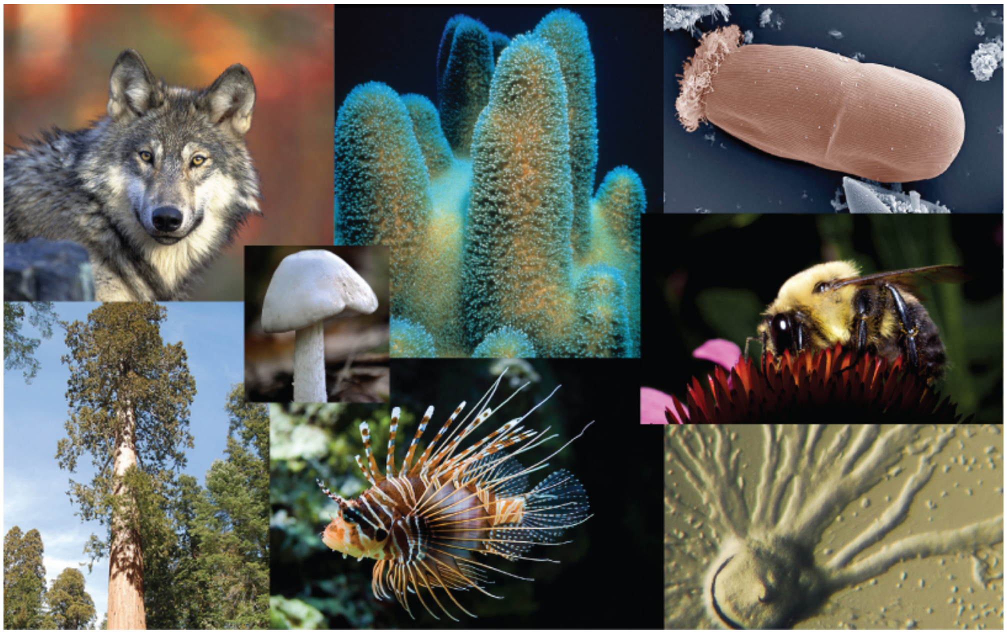


Figure 1. The diversity of life on Earth is the result of evolution, a continuous process that is still occurring. (credit "wolf": modification of work by Gary Kramer, USFWS; credit "coral": modification of work by William Harrigan, NOAA; credit "river": modification of work by Vojtěch Dostál; credit "protozoa": modification of work by Sharon Franklin, Stephen Ausmus, USDA ARS; credit "fish" modification of work by Christian Mehlführer; credit "mushroom," "bee": modification of work by Cory Zanker; credit "tree": modification of work by Joseph Kranak)

What biological process is responsible for biodiversity?

All species —from the bacteria on our skin to the birds outside—evolved from a different species at some point. Although it may seem that living things today stay much the same from generation to generation, that is not the case because evolution is ongoing. **Evolution** is the process through which the characteristics of a species change over time, which can ultimately cause new species to arise.

The theory of evolution is the unifying theory of biology, meaning it is the framework within which biologists ask questions about the living world. Its power is that it provides direction for predictions about living things that are borne out in experiment after experiment. The Ukrainian-born American geneticist Theodosius Dobzhansky famously wrote that "nothing makes sense in biology except in the light of evolution." He meant that the principle that all life has evolved and diversified from a common ancestor is the foundation from which we understand all other questions in biology.

Discovering How Populations Change

The theory of evolution by natural selection describes a mechanism for how species can change over time. That species change was suggested and debated well before Darwin. The view that species were unchanging was grounded in the writings of Plato, yet there were also ancient Greeks that expressed evolutionary ideas.

In the eighteenth century, ideas about the evolution of animals were reintroduced by various naturalists. At the same time, James Hutton, the Scottish naturalist, proposed that geological change occurred gradually by accumulating small changes from processes (over long periods of time) just like those happening today. This contrasted with the predominant view that the planet's geology resulted from catastrophic events occurring during a relatively brief past. The geologist Charles Lyell later popularized Hutton's view in the nineteenth century. Lyell became a friend to Darwin, and his ideas influenced Darwin's thinking. Lyell argued that the greater age of Earth gave more time for gradual change in species, and the process provided an analogy for gradual change in species.

Charles Darwin and Natural Selection

Natural selection as a mechanism for evolution was independently conceived and described by two naturalists, Charles Darwin and Alfred Russell Wallace, in the mid-nineteenth century. Importantly, each spent years exploring the natural world on tropic expeditions. From 1831 to 1836, Darwin traveled the world on *H.M.S. Beagle*, visiting South America, Australia, and the southern tip of Africa. Wallace traveled to Brazil to collect insects in the Amazon rainforest from 1848 to 1852 and the Malay Archipelago from 1854 to 1862. Darwin's journey, like Wallace's later journeys in the Malay Archipelago, included stops at several island chains, the last being the Galápagos Islands (west of Ecuador). On these islands, Darwin observed species of organisms on different islands that were clearly similar yet had distinct differences. For example, the ground finches inhabiting the Galápagos Islands comprised several species with unique beak shapes (Figure 2). He observed that these finches closely resembled another finch species on the mainland of South America and that the species in the Galápagos formed a graded series of beak sizes and shapes, with very small differences between the most similar. Darwin imagined that the island species might be all modified from one original mainland species. In 1860, he wrote, "Seeing this gradation and diversity of structure in one small, intimately related group of birds, one might really fancy that from an original paucity of birds in this archipelago, one species had been taken and modified for different ends."

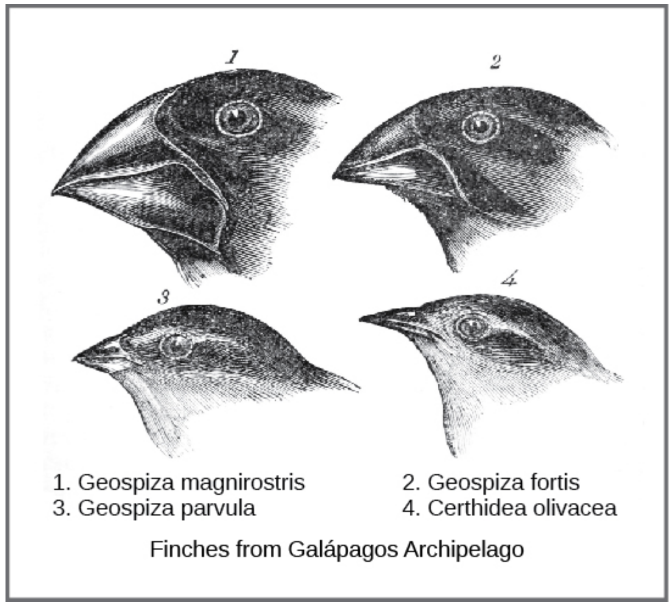


Figure 2. Darwin observed that beak shape varies among finch species. He postulated that the beak of an ancestral species had adapted over time to equip the finches to acquire different food sources. This illustration shows the beak shapes for four species of ground finch: 1. Geospiza magnirostris (the large ground finch), 2. G. fortis (the medium ground finch), 3. G. parvula (the small tree finch), and 4. Certhidea olivacea (the green-warbler finch).

Wallace and Darwin observed similar patterns in other organisms and independently conceived a mechanism to explain how and why such changes could occur. Darwin called this mechanism natural selection. Natural selection, Darwin argued, was an inevitable outcome of three principles that operated in nature. First, there exists variation in traits among individuals within a population, which are inherited, or passed from parent to offspring. Second, more offspring are produced than can survive; in other words, resources for survival and reproduction are limited. And lastly, there is competition for those resources in each generation. Out of these three principles, Darwin and Wallace reasoned that offspring with inherited characteristics that allow them to best compete for limited resources will survive and have more offspring than those individuals with variations that are less able to compete. Because characteristics are inherited, these traits will be better represented in the next generation. This will lead to a change in populations over generations, which Darwin called "**descent with modification**." In sum, we can define **natural selection** as a process that causes beneficial traits to become more common over time, causing the population to evolve.

Figure 3. (a) Charles Darwin and (b) Alfred Wallace wrote scientific papers on natural selection that were presented together before the Linnean Society in 1858.

Papers by Darwin and Wallace (Figure 3) presenting the idea of natural selection were read together in 1858 before the Linnaean Society in London. Darwin's book, On the Origin of Species, was published the following year, outlining his arguments for evolution by natural selection in considerable detail.

Natural selection can only occur if there is **variation** or differences among individuals. Importantly, these differences must have some genetic basis. Otherwise, natural selection would not change the next generation because there would be no way to transmit those traits from one generation to the next.

Genetic diversity in a population comes from two main sources: mutation and sexual reproduction. Mutation, a permanent change in DNA sequence, is the ultimate source of new genetic variation in any population. An individual with a mutated gene might have a different trait than others in the population. Without variation in traits, nature would not be able to select the traits best adapted for the organisms' environment at that particular time.

Evolutionary change in action

The development of antibiotic-resistant bacteria is an example of evolution through natural selection, and scientists have directly observed it. How does this happen? Imagine a person with a bacterial infection: their body is attacked by billions of bacteria. Because of genetic variation in populations, some individual bacteria may already possess traits that allow them to tolerate antibiotic drugs. When the infected person is prescribed antibiotics, the drug attacks and kills the entire population, except for those bacteria that can resist the drug. These bacteria survive because they have a beneficial trait, and thus nature is selected for it. The surviving population will all resist the drug and continue to reproduce, multiply, and pass down that beneficial trait to all offspring. The population had evolved because all individuals have the antibiotic-resistant trait, whereas before, it was rare. It is important to realize that evolution occurs at the population level and relies upon existing genetic variation. Without that variation, there is nothing for nature to select. The rise and spread of antibiotic-resistant bacteria is an emerging environmental issue and will be discussed in a later chapter.

The Biodiversity Crisis

Scientists estimate that species extinctions are currently 500–1000 times the normal, or background, rate seen previously in Earth's history. The current high rates will cause a precipitous decline in the planet's biodiversity in the next century or two. The loss of biodiversity will include many species we know today. Although it is sometimes difficult to predict which species will become extinct, many are listed as **endangered** (at great risk of extinction). However, many extinctions will affect species that have not yet been discovered. Most of these "invisible" species that will become extinct currently live in tropical rainforests like the Amazon basin. These rainforests are the most diverse ecosystems on the planet and are being destroyed rapidly by deforestation. Between 1970 and 2011, almost 20 percent of the Amazon rainforest was lost.

Biodiversity is a broad term for biological variety, and it can be measured at a number of organizational levels. Traditionally, ecologists have measured biodiversity by considering the number of species and the number of individuals of each species (known as **relative abundance**). However, scientists are using different measures of biodiversity, including genetic diversity, to help focus efforts to preserve the biologically and technologically important elements of biodiversity.

Figure 1. This tropical lowland rainforest in Madagascar is an example of a high biodiversity habitat. This location is protected within a national forest, yet only 10 percent of the original coastal lowland forest remains, and research suggests half the original biodiversity has been lost. (credit: Frank Vassen)

Biodiversity loss refers to the reduction of biodiversity due to displacement or extinction of species. The loss of a particular individual species may seem unimportant to some, especially if it is not a charismatic species like the Bengal tiger or the bottlenose dolphin. However, the current accelerated extinction rate means the loss of tens of thousands of species within our lifetimes. Much of this loss occurs in tropical rainforests like the one pictured in Figure 1, which are very high in biodiversity but are cleared for timber and agriculture. This is likely to affect human welfare through the collapse of ecosystems dramatically.

Environmental scientists recognize that human populations are embedded in ecosystems and depend on them, just as is every other species on the planet. Agriculture began after early hunter-gatherer societies settled in one place and heavily modified their immediate environment. This cultural transition has made it difficult for humans to recognize their dependence on living things other than crops and domesticated animals. Today our technology smooths out the harshness of existence and allows many of us to live longer, more comfortable lives. Still, ultimately the human species cannot exist without its surrounding ecosystems. Our ecosystems provide food, medicine, clean air and water, recreation, and spiritual and aesthetical inspiration.

Types of Biodiversity

A common meaning of biodiversity is simply the number of species in a location or on Earth; for example, the American Ornithologists' Union lists 2078 species of birds in North and Central America. This is one measure of the bird biodiversity on the continent. More sophisticated measures of diversity take into account the relative abundances of species. For example, a forest with ten equally common species of trees is more diverse than a forest with ten species, wherein just one of those species makes up 95 percent of the trees. Scientists have also identified alternate measures of biodiversity, some of which are important in planning how to preserve biodiversity.

Genetic diversity is one alternate concept of biodiversity. **Genetic diversity** is the raw material for evolutionary adaptation in a species and is represented by the variety of genes present within a population. A species' potential to adapt to changing environments or new diseases depends on this genetic diversity.

It is also useful to define **ecosystem diversity**: the number of different ecosystems on Earth or in a geographical area. The loss of an ecosystem means the loss of the interactions between species and the loss of biological productivity that an ecosystem can create. The prairie ecosystem is an example of a large extinct ecosystem in North America (Figure 2). Prairies once spanned central North America from the boreal forest in northern Canada down into Mexico. They are now all but gone, replaced by crop fields, pasture lands, and suburban sprawl. Many species survive, but the hugely productive ecosystem responsible for creating our most productive agricultural soils is now gone. As a consequence, their soils are now being depleted unless they are maintained artificially at great expense. The decline in soil productivity occurs because the interactions in the original ecosystem have been lost.

Figure 2. The variety of ecosystems on Earth—from coral reefs to prairie—enables a great diversity of species to exist. (credit "coral reef": modification of work by Jim Maragos, USFWS; credit: "prairie": modification of work by Jim Minnerath, USFWS)

Current Species Diversity

Despite considerable effort, knowledge of the planet's species is limited. A recent estimate suggests that only 13% of eukaryotic species have been named (Table 1). Estimates for the number of prokaryotic species are largely guesses, but that science has only begun cataloging their diversity. Given that Earth is losing species at an accelerating pace, science knows little about what is being lost.

Table 1. This table shows the estimated number of species by the taxonomic group—including both described (named and studied) and predicted (yet to be named) species.

Estimated Numbers of Described and Predicted species						
	Source: Mora et al., 2011		Source: Chapman, 2009		Source: Groombridge and Jenkins, 2002	
	Described	Predicted	Described	Predicted	Described	Predicted
Animals	1,124,516	9,920,000	1,424,153	6,836,330	1,225,500	10,820,000
Photosynthetic protists	17,892	34,900	25,044	200,500	—	—
Fungi	44,368	616,320	98,998	1,500,000	72,000	1,500,000
Plants	224,244	314,600	310,129	390,800	270,000	320,000
Non-photosynthetic protists	16,236	72,800	28,871	1,000,000	80,000	600,000
Prokaryotes	—	—	10,307	1,000,000	10,175	—
Total	1,438,769	10,960,000	1,897,502	10,897,630	1,657,675	13,240,000

There are various initiatives to catalog described species in accessible and more organized ways, and the internet is facilitating that effort. Nevertheless, at the current rate of species description, which according to the State of Observed Species[1] reports is 17,000–20,000 new species a year, it would take close to 500 years to describe all of the species currently in existence. The task, however, is becoming increasingly impossible over time as extinction removes species from Earth faster than they can be described.

Naming and counting species may seem an unimportant pursuit given the other needs of humanity, but it is not simply an accounting. Describing species is a complex process by which scientists determine an organism's unique characteristics and whether or not that organism belongs to any other described species. It allows scientists to find and recognize the species after the initial discovery to follow up on questions about its biology. That subsequent research will produce the discoveries that make the species valuable to humans and our ecosystems. Without a name and description, a species cannot be studied in depth and coordinated by multiple scientists.

The International Union for the Conservation of Nature (IUCN), which coordinates efforts to catalog and preserve biodiversity worldwide, defines biodiversity as "the variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems." Rather than just species, biodiversity, therefore, includes variation from the level of genes and genomes to that of ecosystems to biomes.

Even within a single ecosystem, the number of species can be impressive. For example, Brazil has a large dry forest and savanna region known as the Cerrado (see Figure Cerrado Forest (Figure 4.5)). This ecosystem alone hosts over 10,000 species of plants, almost 200 species of mammals, over 600 species of birds, and about 800 species of fish.

Figure 3. Cerrado Forest. Photograph of the Cerrado Forest. Source: C2rik via WikimediaCommons10.

Patterns of Biodiversity

Biodiversity is not evenly distributed on the planet. Lake Victoria contained almost 500 species of cichlids (just one family of fishes present in the lake) before introducing an exotic species in the 1980s and 1990s caused a mass extinction. All these species were found only in Lake Victoria, which is to say they were endemic. **Endemic species** are found in only one location. For example, the blue jay is endemic to North America, while the Barton Springs salamander is endemic to the mouth of one spring in Austin, Texas. Endemic species with highly restricted distributions, like the Barton Springs salamander, are particularly vulnerable to extinction.

Lake Huron contains about 79 species of fish, all of which are found in many other lakes in North America. What accounts for the difference in diversity between Lake Victoria and Lake Huron? Lake Victoria is a tropical lake, while Lake Huron is a temperate lake. Lake Huron, in its present form, is only about 7,000 years old, while Lake Victoria, in its present form, is about 15,000 years old. These two factors, latitude and age, are two of several hypotheses biogeographers have suggested explaining biodiversity patterns on Earth.

Biogeography is the study of the distribution of the world's species in the past and present. The work of biogeographers is critical to understanding our physical environment, how the environment affects species, and how changes in the environment impact the distribution of a species.

There are three main fields of study under the heading of biogeography: ecological biogeography, historical biogeography (called paleobiogeography), and conservation biogeography. Ecological biogeography studies the current factors affecting the distribution of plants and animals. Historical biogeography, as the name implies, studies the past distribution of species. On the other hand, conservation biogeography is focused on protecting and restoring species based on known historical and current ecological information.

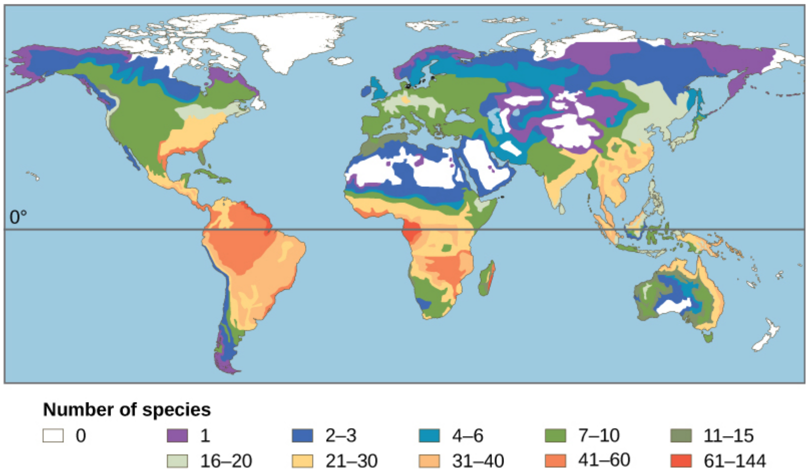


Figure 4. This map illustrates the number of amphibian species globally and shows the trend toward higher biodiversity at lower latitudes. A similar pattern is observed for most taxonomic groups.

One of the oldest observed patterns in ecology is that biodiversity typically increases as latitude declines. In other words, biodiversity increases closer to the equator (Figure 4). Generally, biodiversity is greatest in tropical areas, especially "rainforests," but terrestrial biodiversity "hotspots" exist on all the major continents.

Visit this website to view an interactive map of hotspots (https://www.conservation.org/priorities/biodiversity-hotspots).

It is not yet clear why biodiversity increases closer to the equator. Still, hypotheses include the greater age of the ecosystems in the tropics versus temperate regions, which were largely devoid of life or drastically impoverished during the last ice age. The greater age provides more time for **speciation,** the evolutionary process of creating new species. Another possible explanation is the greater energy the tropics receive from the sun. But scientists have not been able to explain how greater energy input could translate into more species. The complexity of tropical ecosystems may promote speciation by increasing the habitat complexity, thus providing more ecological niches. Lastly, the tropics have been perceived as being more stable than temperate regions, which have a pronounced climate and day-length seasonality. The stability of tropical ecosystems might promote speciation. Regardless of the mechanisms, it is certainly true that biodiversity is greatest in the tropics. There are also high numbers of endemic species.

Importance of Biodiversity

Loss of biodiversity may have reverberating consequences on ecosystems because of the complex interrelations among species. For example, the extinction of one species may cause the extinction of another. Biodiversity is important to the survival and welfare of human populations because it impacts our health and our ability to feed ourselves through agriculture and harvesting populations of wild animals.

Human Health

Many medications are derived from natural chemicals made by diverse organisms. For example, many plants produce compounds meant to protect the plant from insects and other animals that eat them. Some of these compounds also work as human medicines. Contemporary societies that live close to the land often have a broad knowledge of the medicinal uses of plants growing in their area. For centuries in Europe, older knowledge about the medical uses of plants was compiled in herbals—books that identified the plants and their uses. Humans are not the only animals to use plants for medicinal reasons. The other great apes, orangutans, chimpanzees, bonobos, and gorillas have all been observed self-medicating with plants.

Modern pharmaceutical science also recognizes the importance of these plant compounds. Significant medicines derived from plant compounds include aspirin, codeine, digoxin, atropine, and vincristine (Figure 5). Many medications were once derived from plant extracts but are now synthesized. It is estimated that, at one time, 25 percent of modern drugs contained at least one plant extract. That number has probably decreased to about 10 percent as synthetic versions of the plant compounds replace natural plant ingredients. Antibiotics, which are responsible for extraordinary improvements in health and lifespans in developed countries, are compounds largely derived from fungi and bacteria.

In recent years, animal venoms and poisons have excited intense research for their medicinal potential. By 2007, the FDA had approved five drugs based on animal toxins to treat diseases such as hypertension, chronic pain, and diabetes. Another five drugs are undergoing clinical trials, and at least six are being used in other countries. Other toxins under investigation come from mammals, snakes, lizards, various amphibians, fish, snails, octopuses, and scorpions.

Figure 5. Catharanthus roseus, the Madagascar periwinkle, has various medicinal properties. Among other uses, it is a source of vincristine, a drug used to treat lymphomas. (credit: Forest and Kim Starr)

Aside from representing billions of dollars in profits, these medications improve people's lives. Pharmaceutical companies are looking for new natural compounds that can function as medicines. It is estimated that one-third of pharmaceutical research and development is spent on natural compounds. About 35 percent of new drugs brought to market between 1981 and 2002 were from natural compounds.

Finally, it has been argued that humans benefit psychologically from living in a biodiverse world. The chief proponent of this idea is famed entomologist E. O. Wilson. He argues that human evolutionary history has adapted us to living in a natural environment and that built environments generate stresses that affect human health and well-being. There is considerable research into the psychologically regenerative benefits of natural landscapes, suggesting the hypothesis may hold some truth.

Agricultural

Since the beginning of human agriculture, more than 10,000 years ago, human groups have been breeding and selecting crop varieties. This crop diversity matched the cultural diversity of highly subdivided populations of humans. For example, potatoes were domesticated beginning around 7,000 years ago in the central Andes of Peru and Bolivia. The people in this region traditionally lived in relatively isolated settlements separated by mountains. The potatoes grown in that region belong to seven species, and the number of varieties likely is in the thousands. Each variety has been bred to thrive at particular elevations and soil and climate conditions. The diversity is driven by the diverse demands of the dramatic elevation changes, the limited movement of people, and the demands created by crop rotation for different varieties that will do well in different fields.

Potatoes are only one example of agricultural diversity. Every plant, animal, and fungus cultivated by humans has been bred from original wild ancestor species into diverse varieties arising from the demands for food value, adaptation to growing conditions, and resistance to pests. The potato demonstrates a well-known example of the risks of low crop diversity: during the tragic Irish potato famine (1845–1852 AD), the single potato variety grown in Ireland became susceptible to a potato blight—wiping out the crop. The crop loss led to famine, death, and mass emigration. Disease resistance is a chief benefit to maintaining crop biodiversity, and the lack of diversity in contemporary crop species carries similar risks. Seed companies, the source of most crop varieties in developed countries, must continually breed new varieties to keep up with evolving pest organisms. These same seed companies, however, have participated in the decline of the number of varieties available as they focus on selling fewer varieties in more areas of the world, replacing traditional local varieties.

The ability to create new crop varieties relies on the diversity of varieties available and the availability of wild forms related to the crop plant. These wild forms are often the source of new gene variants that can be bred with existing varieties to create varieties with new attributes. Loss of wild species related to a crop will mean the loss of potential for crop improvement. Maintaining the genetic diversity of wild species related to domesticated species ensures our continued food supply.

Since the 1920s, government agriculture departments have maintained seed banks of crop varieties as a way to maintain crop diversity. This system has flaws because, over time, seed varieties are lost through accidents, and there is no way to replace them. In 2008, the Svalbard Global Seed Vault on Spitsbergen Island, Norway (Figure 6) began storing seeds worldwide as a backup system to the regional seed banks. If a regional seed bank stores varieties in Svalbard, losses can be replaced from Svalbard should something happen to the regional seeds. The Svalbard seed vault is deep into the rock of the Arctic island. Conditions within the vault are maintained at ideal temperature and humidity for seed survival. Still, the deep underground location of the vault in the Arctic means that failure of the vault's systems will not compromise the climatic conditions inside the vault.

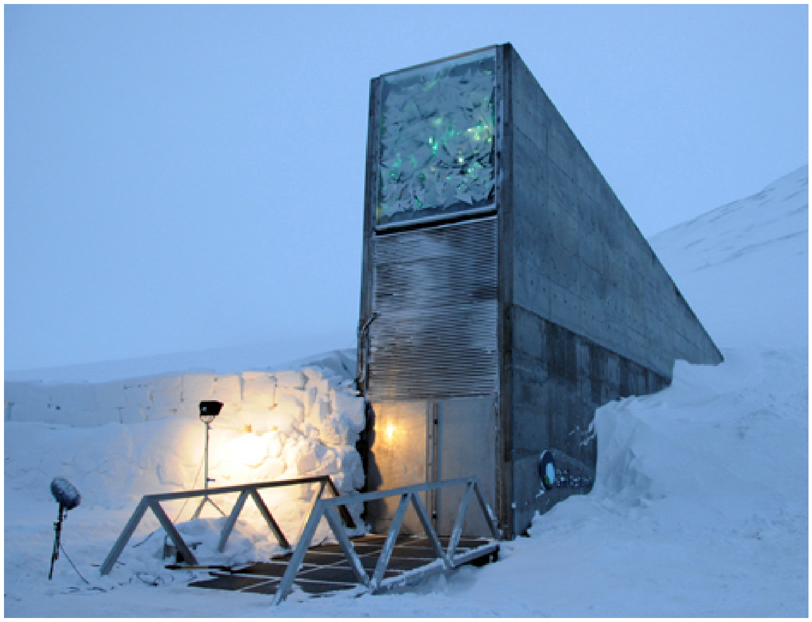


Figure 6. The Svalbard Global Seed Vault is a storage facility for seeds of Earth's diverse crops. (credit: Mari Tefre, Svalbard Global Seed Vault)

Although crops are largely under our control, our ability to grow them depends on the biodiversity of the ecosystems in which they are grown. Crops are grown in soil, and although some agricultural soils are rendered sterile using controversial pesticide treatments, most contain a huge diversity of organisms that maintain nutrient cycles—breaking down organic matter into nutrient compounds that crops need for growth. These organisms also maintain soil texture that affects water and oxygen dynamics, which are necessary for plant growth. Replacing the work of these organisms is not practically possible. These kinds of processes are called ecosystem services. They occur within ecosystems, such as soil ecosystems, due to the diverse metabolic activities of living organisms. Still, they benefit human food production, drinking water availability, and breathable air.

Other key ecosystem services related to food production are plant pollination and crop pest control. It is estimated that honeybee pollination within the United States brings in $1.6 billion annually; other pollinators contribute up to $6.7 billion. Over 150 crops in the United States require pollination to produce. Many honeybee populations are managed by beekeepers who rent out their hives' services to farmers. Honeybee populations in North America have suffered large losses caused by a syndrome known as colony collapse disorder, a new phenomenon with an unclear cause. Other pollinators include many other bee species and various insects and birds. Loss of these species would make growing crops requiring pollination impossible, increasing dependence on other crops.

Finally, humans compete for their food with crop pests, most of which are insects. Pesticides control these competitors, which are costly and lose their effectiveness over time as pest populations adapt. They also lead to collateral damage by killing non-pest species and beneficial insects like honeybees and risking the health of agricultural workers and consumers. Moreover, these pesticides may migrate from the fields where they are applied and damage other ecosystems like streams, lakes, and even the ocean. Ecologists believe that predators and parasites of those pests actually do the bulk of the work in removing pests, but the impact has not been well studied. A review article found that 74 percent of studies that looked for an effect of landscape complexity (forests and fallow fields near crop fields) on natural enemies of pests, the greater the complexity, the greater the effect of pest-suppressing organisms. Another experimental study found that introducing multiple enemies of pea aphids (an important alfalfa pest) significantly increased alfalfa yield. This study shows that a diversity of enemies is more effective at controlling than one single enemy. Loss of diversity in pest enemies will inevitably make growing food more difficult and costly. The world's growing human population faces significant challenges in the increasing costs and other difficulties associated with producing food.

Wild Food Sources

In addition to growing crops and raising food animals, humans obtain food resources from wild populations, primarily wild fish populations. For about one billion people, aquatic resources provide the main source of animal protein. But since 1990, production from global fisheries has declined. Despite considerable effort, few fisheries on Earth have managed sustainability.

Fishery extinctions rarely lead to the complete extinction of the harvested species but rather to a radical restructuring of the marine ecosystem in which a dominant species is so over-harvested that it becomes a minor player, ecologically. In addition to humans losing the food source, these alterations affect many other species in difficult or impossible ways to predict. The collapse of fisheries has dramatic and long-lasting effects on local human populations that work in the fishery. In addition, losing an inexpensive protein source to populations that cannot afford to replace it will increase the cost of living and limit societies in other ways. In general, the fish taken from fisheries have shifted to smaller species, and the larger species are overfished. The ultimate outcome could clearly be the loss of aquatic systems as food sources.

Visit this website (http://openstaxcollege.org/l/decliningfish2) to view a brief video discussing a study of declining fisheries.

The core threat to biodiversity on the planet, and therefore a threat to human welfare, is the combination of human population growth and the resources used by that population. The human population requires resources to survive and grow, and many of those resources are being removed unsustainably from the environment. The three greatest proximate threats to biodiversity are habitat loss, overharvesting, and the introduction of exotic species. The first two directly result from human population growth and resource use. The third results from increased mobility and trade. A fourth major cause of extinction, **anthropogenic** (human-caused) climate change, has not yet had a large impact, but it is predicted to become significant during this century. Global climate change is also a consequence of the human population's need for energy and the use of fossil fuels to meet those needs (Figure 1). Environmental issues, such as toxic pollution, have specific targeted effects on species but are not generally seen as threats at the magnitude of the others.

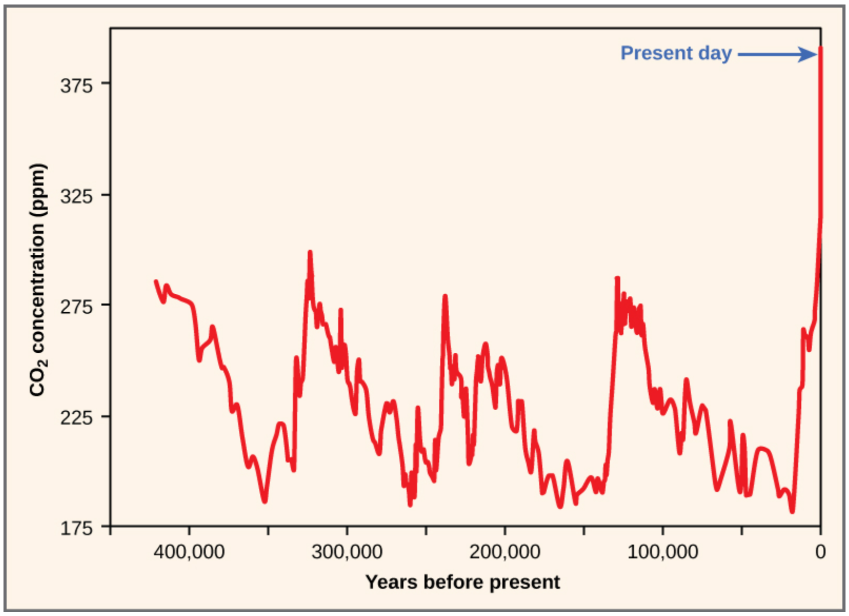


Figure 1. Atmospheric carbon dioxide levels fluctuate cyclically. However, the burning of fossil fuels in recent history has caused a dramatic increase in the levels of carbon dioxide in the Earth's atmosphere, which have now reached levels never before seen on Earth. Scientists predict that adding this "greenhouse gas" to the atmosphere is resulting in climate change that will significantly impact biodiversity in the coming century.

Habitat Loss

Humans rely on technology to modify their environment and make it habitable. Other species cannot do this. Eliminating their habitat—whether it is a forest, coral reef, grassland, or flowing river—will kill the individuals in the species. Remove the entire habitat, and the species will become extinct unless they are among the few species that do well in human-built environments. Human destruction of habitats (**habitat** generally refers to the part of the ecosystem required by a particular species) accelerated in the latter half of the twentieth century.

Consider the exceptional biodiversity of Sumatra: it is home to one species of orangutan, a species of critically endangered elephant, and the Sumatran tiger, but half of Sumatra's forest is now gone. The neighboring island of Borneo, home to other orangutan species, has lost a similar forest area. Forest loss continues in protected areas of Borneo. The orangutan in Borneo is listed as endangered by the International Union for Conservation of Nature (IUCN). Still, it is simply the most visible of thousands of species that will not survive the disappearance of the forests of Borneo. The forests are removed for timber and to plant palm oil plantations (Figure 2). Palm oil is used in many products, including food products, cosmetics, and biodiesel in Europe. A 5-year estimate of global forest cover loss from 2000 to 2005 was 3.1%. Much loss (2.4%) occurred in the tropics, where forest loss is primarily from timber extraction. These losses certainly also represent the extinction of species unique to those areas.

Figure 2. An oil palm plantation in Sabah Province Borneo, Malaysia, replaces the native forest habitat that a variety of species depended on to live. (credit: Lian Pin Koh)

Most consumers do not imagine their home improvement products might contribute to habitat loss and extinction of species. Yet the market for illegally harvested tropical timber is huge, and the wood products often find themselves in building supply stores in the United States. One estimate is that up to 10% of the imported timber in the United States, the world's largest consumer of wood products, is illegally logged. In 2006, this amounted to $3.6 billion in wood products. Most illegal products are imported from countries that act as intermediaries and are not the originators of the wood.

How is it possible to determine if a wood product, such as flooring, was harvested sustainably or legally? The Forest Stewardship Council (FSC) certifies sustainably harvested forest products. Looking for their certification on flooring and other hardwood products is one way to ensure that the wood has not been taken illegally from a tropical forest. There are certifications other than the FSC, but these are run by timber companies, thus creating a conflict of interest. Another approach is to buy domestic wood species. While it would be great if there was a list of legal versus illegal woods, it is not that simple. Logging and forest management laws vary from country to country; what is illegal in one country may be legal in another. Where and how a product is harvested and whether the forest from which it comes is being sustainably maintained all factor into whether a wood product will be certified by the FSC. It is always a good idea to ask where a wood product came from and how the supplier knows it was harvested legally.

Habitat destruction can affect ecosystems other than forests. Rivers and streams are important ecosystems and are frequently the target of habitat modification. Damming of rivers affects flow and access to habitat. Altering a flow regime can reduce or eliminate populations adapted to seasonal flow changes. For example, an estimated 91% of riverways in the United States have been modified with damming or stream bank modification. Many fish species in the United States, especially rare species or species with restricted distributions, have seen declines caused by river damming and habitat loss. Research has confirmed that species of amphibians that must carry out parts of their life cycles in aquatic and terrestrial habitats are at greater risk of population declines and extinction because of the increased likelihood that one of their habitats or access between them will be lost. This is of particular concern because amphibians have been declining in numbers and going extinct more rapidly than many other groups for various reasons.

Overharvesting

Overharvesting is a serious threat to many species, particularly to aquatic species. Many examples of regulated fisheries (including hunting marine mammals and harvesting crustaceans and other species) monitored by fisheries scientists have nevertheless collapsed. The western Atlantic cod fishery is the most spectacular recent collapse. While it was a hugely productive fishery for 400 years, the introduction of modern factory trawlers in the 1980s and the pressure on the fishery made it unsustainable. The causes of fishery collapse are both economic and political in nature.

Most fisheries are managed as a common resource, available to anyone willing to fish, even when the fishing territory lies within a country's territorial waters. Common resources are subject to an economic pressure known as the tragedy of the commons, in which fishers have little motivation to exercise restraint in harvesting a fishery when they do not own the fishery. The general outcome of harvests of resources held in common is their overexploitation. While large fisheries are regulated to attempt to avoid this pressure, it still exists in the background. This overexploitation is exacerbated when access to the fishery is open and unregulated, and technology allows fishers to overfish. In a few fisheries, continuing overfishing is more profitable than waiting for the fishery to recover. In these cases—whales are an example—economic forces will drive the fishing population to extinction.

Explore a U.S. Fish & Wildlife Service interactive map (http://openstaxcollege.org/l/habitat_map2) of critical habitats for endangered and threatened species in the United States. To begin, select "Visit the online mapper."

Coral reefs are extremely diverse marine ecosystems that face peril from several processes. Reefs are home to 1/3 of the world's marine fish species—about 4000 species—despite making up only one percent of marine habitat. Most home marine aquaria house coral reef species that are wild-caught organisms—not cultured organisms. Although no marine species are known to have been driven extinct by the pet trade, studies show that some species' populations have declined in response to harvesting, indicating that the harvest is not sustainable at those levels. There are also concerns about the effect of the pet trade on some terrestrial species, such as turtles, amphibians, birds, plants, and even the orangutans.

Bush meat is the generic term used for wild animals killed for food. Hunting is practiced worldwide, but hunting practices, particularly in equatorial Africa and parts of Asia, are believed to threaten several species with extinction. Traditionally, bush meat in Africa was hunted to feed families directly. However, recent commercialization of the practice now has bush meat available in grocery stores, which has increased harvest rates to the level of unsustainability. Additionally, human population growth has increased the need for protein foods that agriculture does not meet. Species threatened by the bush meat trade are mostly mammals, including many monkeys and the great apes in the Congo basin.

Figure 3. Harvesting of pangolins for their scales and meat, and as curiosities, has led to a drastic decline in population size for this fascinating creature. This work by David Brossard is licensed under CC BY 4.0

Invasive Species

Exotic species are species that humans have intentionally or unintentionally introduced into an ecosystem in which they did not evolve. Human transportation of people and goods, including the intentional transport of organisms for trade, has dramatically increased the introduction of species into new ecosystems. These new introductions are sometimes at distances well beyond the species' capacity to ever travel itself and outside the range of the species' natural predators.

Most exotic species introductions probably fail because of the low number of individuals introduced or poor adaptation to the ecosystem they enter. Some species, however, have characteristics that can make them especially successful in a new ecosystem. These exotic species often undergo dramatic population increases in their new habitat and reset the ecological conditions in the new environment, threatening their species. When this happens, the exotic species also become an **invasive species**. Invasive species can threaten other species through resource competition, predation, or disease.

Explore this interactive global database (http://openstaxcollege.org/l/exotic_invasiv2) of exotic or invasive species.

Lakes and islands are particularly vulnerable to extinction threats from introduced species. In Lake Victoria, the intentional introduction of the Nile perch was largely responsible for the extinction of about 200 species of cichlids. The accidental introduction of the brown tree snake via aircraft (Figure 4) from the Solomon Islands to Guam in 1950 has led to the extinction of three species of birds and three to five species of reptiles endemic to the island. Several other species are still threatened. The brown tree snake is adept at exploiting human transportation to migrate; one was found on an aircraft arriving in Corpus Christi, Texas. Constant vigilance on the part of the airport, military, and commercial aircraft personnel is required to prevent the snake from moving from Guam to other islands in the Pacific, especially Hawaii. Islands do not comprise a large area of land on the globe, but they contain a disproportionate number of endemic species because of their isolation from mainland ancestors.

Many introductions of marine and freshwater aquatic species have occurred when ships have dumped ballast water taken on at a port of origin into waters at a destination port. Water from the port of origin is pumped into tanks on a ship empty of cargo to increase stability. The water is drawn from the ocean or estuary of the port and typically contains living organisms such as plant parts, microorganisms, eggs, larvae, or aquatic animals. The water is pumped out before the ship takes on cargo at the destination port, which may be on a different continent. The zebra mussel was introduced to the Great Lakes from Europe before 1988 in ballast water. The zebra mussels in the Great Lakes have created millions of dollars in clean-up costs to maintain water intakes and other facilities. The mussels have also altered the ecology of the lakes dramatically. They threaten native mollusk populations but have benefited some species, such as smallmouth bass. The mussels are filter feeders and have dramatically improved water clarity, which has allowed aquatic plants to grow along shorelines, providing shelter for young fish where they did not exist before. The European green crab, *Carcinus maenas*, was introduced to San Francisco Bay in the late 1990s, likely in ship ballast water, and has spread north along the coast to Washington. The crabs have been found to dramatically reduce the abundance of native clams and crabs, increasing the prey species of those native crabs.

Figure 4. The brown tree snake, Boiga irregularis, is an exotic species that has caused numerous extinctions on the island of Guam since its accidental introduction in 1950. (credit: NPS)

Invading exotic species can also be disease organisms. It now appears that the global decline in amphibian species recognized in the 1990s is, in some parts, caused by the fungus *Batrachochytrium dendrobatidis*, which causes the disease chytridiomycosis (Figure 5). Evidence shows that the fungus is native to Africa and may have been spread worldwide by transporting a commonly used laboratory and pet species: the African clawed frog, *Xenopus laevis*. It may well be that scientists themselves are responsible for spreading this disease worldwide. The North American bullfrog, *Rana catesbeiana*, which has been widely introduced as a food animal but which easily escapes captivity, survives most infections of *B. dendrobatidis* and can act as a reservoir for the disease.

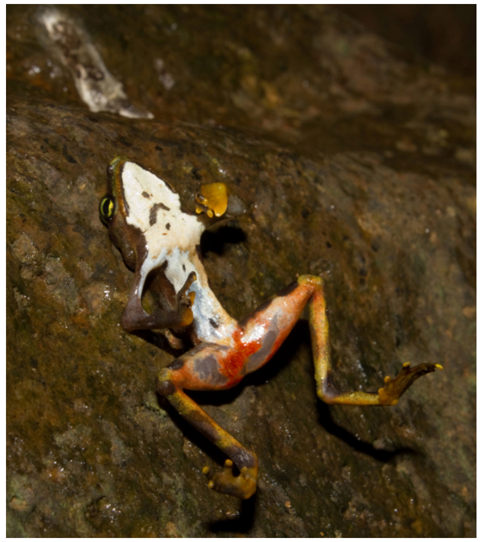


Figure 5. This Limosa harlequin frog (Atelopus limosus), an endangered species from Panama, died from a fungal disease called chytridiomycosis. The red lesions are symptomatic of the disease. (credit: Brian Gratwicke)

Early evidence suggests that another fungal pathogen, *Geomyces destructans*, introduced from Europe, is responsible for white-nose syndrome, which infects cave-hibernating bats in eastern North America and has spread from the point of origin in western New York State (Figure 6). The disease has decimated bat populations and threatens the extinction of species already listed as endangered: the Indiana bat, *Myotis sodalis*, and potentially the Virginia big-eared bat, *Corynorhinus townsendii virginianus*. How the fungus was introduced is unknown, but one logical presumption would be that recreational cavers unintentionally brought the fungus onto clothes or equipment from Europe.

Climate Change

Climate change, specifically the anthropogenic warming trend presently underway, is recognized as a major extinction threat, particularly when combined with other threats such as habitat loss. Anthropogenic warming of the planet has been observed. It is due to past and continuing emissions of greenhouse gases, primarily carbon dioxide, and methane, into the atmosphere caused by burning fossil fuels and deforestation. Scientists overwhelmingly agree humans cause the present warming trend, and some of the likely effects include dramatic and dangerous climate changes in the coming decades. Scientists predict that climate change will alter regional climates, including rainfall and snowfall patterns, making habitats less hospitable to the species living in them. The warming trend will shift colder climates toward the north and south poles, forcing species to move (if possible) with their adapted climate norms.

Figure 6. This little brown bat in Greeley Mine, Vermont, on March 26, 2009, was found to have white-nose syndrome. (credit: modification of work by Marvin Moriarty, USFWS).

The shifting ranges will impose new competitive regimes on species as they are in contact with other species not in their historic range. One such unexpected species contact is between polar bears and grizzly bears. Previously, these two species had separate ranges. Their ranges overlap, and there are documented cases of these two species mating and producing viable offspring. Changing climates also reduce species' delicate timing adaptations to seasonal food resources and breeding times. Scientists have already documented many contemporary mismatches to resource availability and timing shifts.

Other shifts in the range have been observed. For example, one study indicates that, on average, European bird species ranges have moved 91 km (56.5 mi) northward. The same study suggested that the optimal shift based on warming trends was double that distance, suggesting that the populations are not moving quickly enough. Range shifts have also been observed in plants, butterflies, other insects, freshwater fishes, reptiles, amphibians, and mammals.

Climate gradients will also move up mountains, eventually crowding species higher in altitude and eliminating the habitat for those species adapted to the highest elevations. Some climates will completely disappear. The rate of warming appears to be accelerated in the Arctic, which is recognized as a serious threat to polar bear populations that require sea ice to hunt seals during the winter months. Seals are a critical source of protein for polar bears. A decreasing sea ice coverage trend has occurred since observations began in the mid-twentieth century. The rate of decline observed in recent years is far greater than previously predicted by climate models.

Figure 7. The effect of global warming can be seen in the continuing retreat of Grinnell Glacier. The mean annual temperature in Glacier National Park has increased 1.33°C since 1900. The loss of glaciers results in the loss of summer meltwaters, sharply reducing seasonal water supplies and severely affecting local ecosystems. (credit: USGS, GNP Archives)

Finally, global warming will raise ocean levels due to meltwater from glaciers and the greater volume occupied by warmer water. Shorelines will be inundated, reducing island size, which will affect some species, and a number of islands will disappear entirely. Additionally, the gradual melting and subsequent refreezing of the poles, glaciers, and higher-elevation mountains—a cycle that has provided freshwater to environments for centuries—will be altered. This could result in an overabundance of salt water and a shortage of fresh water.

Suggested Supplementary Reading:

Hall. S. 2017. Could Genetic Engineering Save the Galápagos? *Scientific American*. December. p. 48-57.

This article explores the destructive nature of invasive species in the Galápagos Islands. Traditional efforts to eradicate invasive species, such as rats, can be expensive and cause ecological harm through the widespread distribution of poison. An alternate approach is genetic engineering in the form of a "gene drive," an emerging technology that could be better – or worse – for the environment.

Preserving biodiversity is an extraordinary challenge that must be met by a greater understanding of biodiversity, changes in human behavior and beliefs, and various preservation strategies.

Change in Biodiversity through Time

The number of species on the planet, or in any geographical area, results from an equilibrium of two ongoing evolutionary processes: speciation and extinction. When speciation rates begin to outstrip extinction rates, species will increase. Likewise, the reverse is true when extinction rates overtake speciation rates. Throughout the history of life on Earth, as reflected in the fossil record, these two processes have fluctuated to a greater or lesser extent, sometimes leading to dramatic changes in the number of species on the planet as reflected in the fossil record (Figure 1).

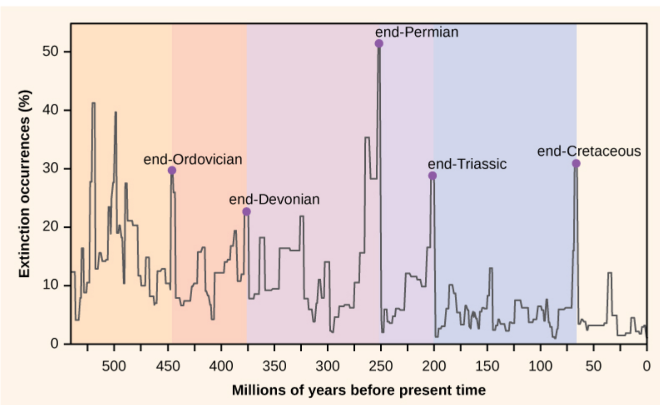


Figure 1. Extinction intensity, as reflected in the fossil record, has fluctuated throughout Earth's history. Sudden and dramatic losses of biodiversity, called mass extinctions, have occurred five times.

Paleontologists have identified five layers in the fossil record that appear to show sudden and dramatic losses in biodiversity. **Mass extinctions** are characterized by more than half of all species disappearing from the fossil record. There are much lesser, yet still dramatic, extinction events, but the five mass extinctions have attracted the most research into their causes. An argument can be made that the five mass extinctions are only the five most extreme events in a continuous series of large extinction events throughout the fossil record (since 542 million years ago). The most recent extinction in geological time, about 65 million years ago, saw the disappearance of most dinosaur species (except birds) and many other species. Most scientists now agree the main cause of this extinction was the impact of a large asteroid in the present-day Yucatán Peninsula and the subsequent energy release and global climate changes caused by dust ejected into the atmosphere.

Recent and Current Extinction Rates

Many scientists say that we are currently experiencing a sixth mass extinction, and it mostly has to do with the activities of humans. Numerous recent extinctions of individual species are recorded in human writings. Most of these coincided with the European colonies' expansion since the 1500s.

One of the earlier and popularly known examples is the dodo bird. The dodo bird lived in the forests of Mauritius, an island in the Indian Ocean. The dodo bird became extinct around 1662. It was hunted for its meat by sailors and was easy prey because the dodo, which did not evolve with humans, would approach people without fear. Introduced pigs, rats, and dogs brought to the island by European ships also killed dodo young and eggs (Figure 2).

Estimates of Present-day Extinction Rates

Estimates of extinction rates are hampered by the fact that most extinctions are probably happening without being observed. Humans often notice the extinction of a bird or mammal, especially if it has been hunted or used in some other way. But many organisms are less noticeable to humans (not necessarily of less value), and many are undescribed.

The **background extinction rate** is estimated to be about 1 per million species years (E/MSY). One “species year” is one species in existence for one year. One million species years could be one species persisting for one million years or a million species persisting for one year. If it is the latter, then one extinction per million species years would be one of those million species becoming extinct in that year. For example, if there are 10 million species in existence, we would expect ten species to become extinct in a year. This is the background rate.

One contemporary extinction-rate estimate uses the extinctions in the written record since 1500. This method yields an estimated 26 E/MSY for birds alone, almost three times the background rate. However, this value may be underestimated for three reasons. First, many existing species would not have been described until much later in the time period, and so their loss would have gone unnoticed. Second, we know the number is higher than the written record suggests because now extinct species are being described from skeletal remains that were never mentioned in written history. And third, some species are probably already extinct, even though conservationists are reluctant to name them as such. Considering these factors raises the estimated extinction rate to nearer 100 E/MSY. The predicted rate by the end of the century is 1500 E/MSY.

Figure 2. The dodo bird was hunted to extinction around 1662. (credit: Ed Uthman, taken in Natural History Museum, London, England)Steller’s sea cow became extinct in 1768; it was related to the manatee and probably once lived along the northwest coast of North America. Steller’s sea cow was discovered by Europeans in 1741, and it was hunted for meat and oil. A total of 27 years elapsed between the sea cow’s first contact with Europeans and the extinction of the species. The last Steller’s sea cow was killed in 1768. In another example, the last living passenger pigeon died in a zoo in Cincinnati, Ohio, in 1914. This species had once migrated in the millions but declined in numbers because of overhunting and loss of habitat through the clearing of forests for farmland. These are only a few recorded extinctions in the past 500 years. The International Union for Conservation of Nature (IUCN) keeps a list of extinct and endangered species called the Red List. The list is incomplete, but it describes 380 vertebrates that became extinct after 1500 AD, 86 of which were driven extinct by overhunting or overfishing.

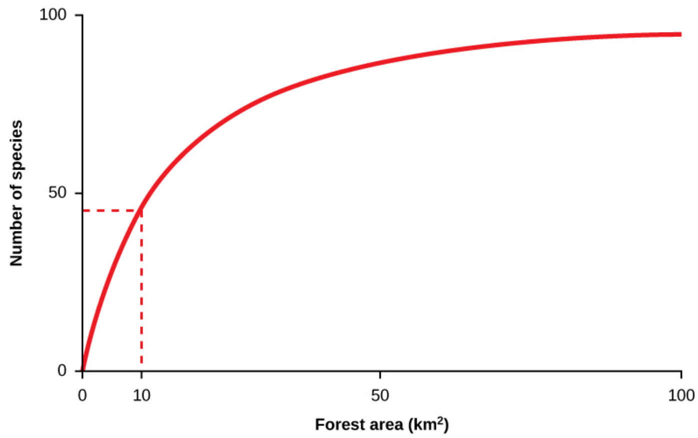


Figure 3. A typical species-area curve shows the cumulative number of species found as more and more area is sampled. The curve has also been interpreted to show the effect on species numbers of destroying habitat; a reduction in habitat of 90 percent from 100 km2 to 10 km2 reduces the number of species supported by about 50 percent.

A second approach to estimating present-time extinction rates is to correlate species loss with habitat loss, and it is based on measuring forest-area loss and understanding species–area relationships. The species-area relationship is the rate at which new species are seen when the area surveyed is increased (Figure 3). Likewise, if the habitat area is reduced, the species seen will also decline. This kind of relationship is also seen in the relationship between an island's area and the number of species present on the island: as one increases, so does the other, though not in a straight line. Estimates of extinction rates based on habitat loss and species–area relationships have suggested that with about 90 percent of habitat loss, an expected 50 percent of species would become extinct. Figure 3 shows that reducing forest area from 100 km^2 to 10 km^2, a decline of 90 percent, reduces the number of species by about 50 percent. Species–area estimates have led to present-day species extinction rates of about 1000 E/MSY and higher.

Go to this website (http://openstaxcollege.org/l/whats_missing2) for an interactive exploration of endangered and extinct species, their ecosystems, and the causes of their endangerment or extinction.

Conservation of Biodiversity

The threats to biodiversity have been recognized for some time. Today, the main efforts to preserve biodiversity involve legislative approaches to regulating human and corporate behavior, setting aside protected areas, and restoring habitats.

Changing Human Behavior

Legislation has been enacted to protect species throughout the world. The legislation includes international treaties as well as national and state laws. The **Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)** treaty came into force in 1975. The treaty, and the national legislation that supports it, provide a legal framework for preventing "listed" species from being transported across nations' borders, thus protecting them from being caught or killed when the purpose involves international trade. The listed species that are protected by the treaty number some 33,000. The treaty is limited in its reach because it only deals with the international movement of organisms or their parts. It is also limited by countries' ability or willingness to enforce the treaty and supporting legislation. The illegal trade in organisms and their parts is probably a hundreds of millions of dollars market.

Within many countries, some laws protect endangered species and regulate hunting and fishing. The **Endangered Species Act (ESA)** was enacted in the United States in 1973. When the Act lists an at-risk species, the U.S. Fish & Wildlife Service must develop a management plan to protect the species and bring it back to sustainable numbers. The ESA, and others like it in other countries, is a useful tool, but it suffers because it is often difficult to get a species listed or an effective management plan once a species is listed.

The **Migratory Bird Treaty Act** (MBTA) is an agreement between the United States and Canada signed into law in 1918 in response to declines in North American bird species caused by hunting. The Act now lists over 800 protected species. It makes it illegal to disturb or kill the protected species or distribute their parts (much of the hunting of birds in the past was for their feathers). Examples of protected species include northern cardinals, the red-tailed hawk, and the American black vulture. Global warming is expected to be a major driver of biodiversity loss. Many governments are concerned about the effects of anthropogenic global warming, primarily on their economies and food resources. Because greenhouse gas emissions do not respect national boundaries, the effort to curb them is international. The international response to global warming has been mixed. The **Kyoto Protocol**, an international agreement from the United Nations Framework Convention on Climate Change that committed countries to reduce greenhouse gas emissions by 2012, was ratified by some countries but spurned by others. Two countries that were especially important in terms of their potential impact that did not ratify the Kyoto Protocol were the United States and China. Some goals for reduction in greenhouse gasses were met and exceeded by individual countries, but worldwide, the effort to limit greenhouse gas production is not succeeding. A renegotiated 2016 treaty, called the **Paris Agreement**, once again brought nations together to take meaningful action on climate change. But like before, some nations are reluctant to participate.

Figure 4. National parks, such as Grand Teton National Park in Wyoming, help conserve biodiversity. (credit: Don DeBold)

Conservation in Preserves

Establishing wildlife and ecosystem preserves is one of the key tools in conservation efforts (Figure 4). A **preserve** is an area of land set aside with varying degrees of protection for the organisms that exist within the preserve's boundaries. In 2003, the IUCN World Parks Congress estimated that preserves of various kinds covered 11.5 percent of Earth's land surface. This area is large but only represents 9 out of 14 recognized major biomes, and research has shown that 12 percent of all species live outside preserves.

A **biodiversity hotspot** is a conservation concept developed by Norman Myers in 1988. Hotspots are geographical areas that contain high numbers of endemic species. The concept aimed to identify important locations on the planet for conservation efforts, a kind of conservation triage. By protecting hotspots, governments can protect a larger number of species. The original criteria for a hotspot included 1500 or more species of endemic plants and 70 percent of the area disturbed by human activity. There are now 34 biodiversity hotspots (Figure 5) that contain many endemic species, including half of Earth's endemic plants.

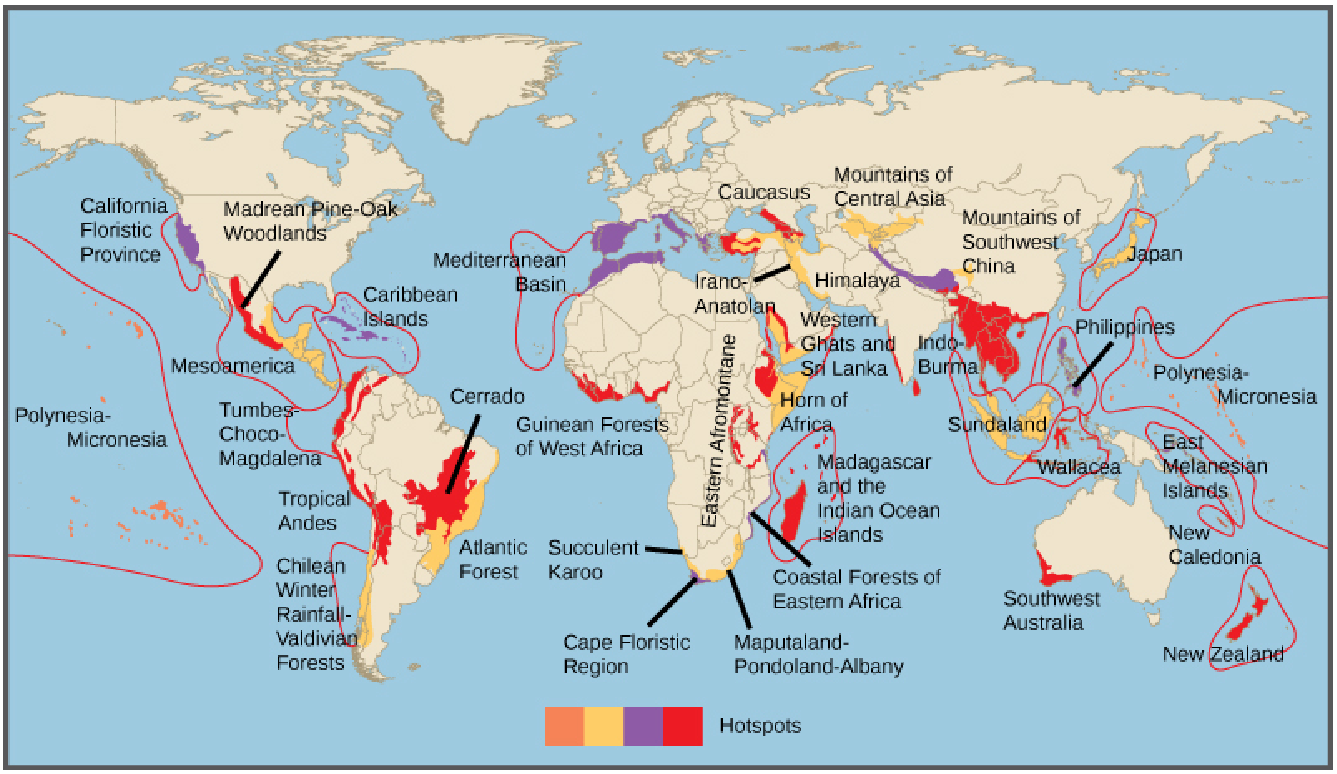


Figure 5. Conservation International has identified 34 biodiversity hotspots. Although these cover only 2.3 percent of the Earth's surface, 42 percent of the terrestrial vertebrate species and 50 percent of the world's plants are endemic to those hotspots.

There has been extensive research into optimal preservation designs for maintaining biodiversity. The fundamental principles behind much of the research have come from the seminal theoretical work of Robert H. MacArthur and Edward O. Wilson, published in 1967 on island biogeography.[1] This work sought to understand the factors affecting biodiversity on islands. Conservation preserves are "islands" of habitat within "an ocean" of non-habitat. In general, large preserves are better because they support more species, including species with large home ranges; they have more core areas of optimal habitat for individual species; they have more niches to support more species; and they attract more species because they can be found and reached more easily. One large preserve is better than the same area of several smaller preserves because there is more core habitat unaffected by less hospitable ecosystems outside the preserve boundary. For this reason, preserves in a square or circle shape will be better than those with many thin "arms." If preserves must be smaller, providing **wildlife corridors** (narrow strips of protected land) between two preserves is important so species and their genes can move between them. All of these factors are considered when planning the nature of a preserve before the land is set aside.

In addition to the physical specifications of a preserve, there are a variety of regulations related to the use of a preserve. These include timber extraction, mineral extraction, regulated hunting, human habitation, and non-destructive human recreation. Many decisions to include these other uses are based on political pressures rather than conservation considerations. On the other hand, in some cases, wildlife protection policies have been so strict that subsistence-living indigenous populations have been forced from ancestral lands that fell within a preserve. In other cases, even if a preserve is designed to protect wildlife, if the protections are not or cannot be enforced, the preserve status will have little meaning in the face of illegal poaching and timber extraction. This is a widespread problem with preserves in the tropics.

Climate change will create inevitable problems with the location of preserves as the species within them migrate to higher latitudes as the preserve's habitat becomes less favorable. Planning for the effects of global warming on future preserves or adding new preserves to accommodate the changes expected from global warming is in progress but will only be as effective as the accuracy of the predictions of the effects of global warming on future habitats.

Finally, an argument can be made that conservation preserves reinforce the cultural perception that humans are separate from nature, can exist outside of it, and can only operate in ways that damage biodiversity. Creating preserves reduces the pressure on human activities outside the preserves to be sustainable and non-damaging to biodiversity. Ultimately, the political, economic, and human demographic pressures will degrade and reduce the size of conservation preserves if the activities outside them are not altered to be less damaging to biodiversity.

Check out this interactive global data system (http://openstaxcollege.org/l/protected_area2) of protected areas. Review data about specific protected areas by location or study statistics on protected areas by country or region.

Habitat Restoration

Habitat restoration is the process of bringing an area back to its natural state before it was impacted through destructive human activities. It holds considerable promise as a mechanism for maintaining or restoring biodiversity. Reintroducing wolves, a top predator, to Yellowstone National Park in 1995 led to dramatic changes in the ecosystem that increased biodiversity. The wolves (Figure 6) function to suppress elk and coyote populations and provide more abundant resources to the detritivores. Reducing elk populations has allowed the revegetation of riparian (the areas along the banks of a stream or river) areas, which has increased the diversity of species in that habitat. The reduction of coyote populations by wolves has increased the prey species previously suppressed by coyotes. In this habitat, the wolf is a **keystone species** that maintain diversity within an ecosystem. Removing a keystone species from an ecological community causes a collapse in diversity. The results from the Yellowstone experiment suggest that restoring a keystone species effectively can restore biodiversity in the community. Ecologists have argued for identifying keystone species where possible and focusing protection efforts on these species. It makes sense to return the keystone species to the ecosystems where they have been removed.

Figure 6. This photograph shows the Gibbon wolf pack in Yellowstone National Park on March 1, 2007. Wolves have been identified as a keystone species. (credit: Doug Smith, NPS)

Other large-scale restoration experiments underway involve dam removal. In the United States, since the mid-1980s, many aging dams have been considered for removal rather than replacement because of shifting beliefs about the ecological value of free-flowing rivers. The measured benefits of dam removal include restoration of naturally fluctuating water levels (often, the purpose of dams is to reduce variation in river flows), which leads to increased fish diversity and improved water quality. In the Pacific Northwest of the United States, dam removal projects are expected to increase populations of salmon, which is considered a keystone species because it transports nutrients to inland ecosystems during its annual spawning migrations. In other regions, such as the Atlantic coast, dam removal has allowed the return of other spawning anadromous fish species (species born in fresh water, live most of their lives in salt water, and return to freshwater to spawn). Some of the largest dam removal projects have yet to occur or have happened too recently for the consequences to be measured, such as the Elwha Dam on the Olympic Peninsula of Washington State. The large-scale ecological experiments these removal projects constitute will provide valuable data for other dam projects slated for removal or construction.

The Role of Zoos and Captive Breeding

Figure 7. Zoos and captive breeding programs help preserve many endangered species, such as this golden lion tamarin. (credit: Garrett Ziegler)

Zoos have sought to participate in conservation through captive breeding programs and education (Figure 7). The transformation of the missions of zoos from collection and exhibition facilities to organizations dedicated to conservation is ongoing. In general, it has been recognized that, except in some specifically targeted cases, captive breeding programs for endangered species are inefficient and often prone to failure when the species are reintroduced to the wild. Zoo facilities are far too limited to contemplate captive breeding programs for the number of at-risk species. On the other hand, education is a potential positive impact of zoos on conservation efforts, particularly given the global trend to urbanization and the consequent reduction in contact between people and wildlife. A number of studies have been performed to look at the effectiveness of zoos on people’s attitudes and actions regarding conservation, and at present, the results tend to be mixed.

Summary

Biodiversity exists at multiple levels of organization and is measured in different ways depending on the goals of those taking the measurements. These include a number of species, genetic diversity, chemical diversity, and ecosystem diversity. Humans use many compounds that were first discovered or derived from living organisms as medicines: secondary plant compounds, animal toxins, and antibiotics produced by bacteria and fungi. Ecosystems provide ecosystem services that support human agriculture: pollination, nutrient cycling, pest control, and soil development and maintenance. Biodiversity loss threatens these ecosystem services and risks making food production more expensive or impossible. The core threats to biodiversity are human population growth and unsustainable resource use. Climate change is predicted to cause extinction in the coming century significantly. Exotic species have been the cause of a number of extinctions and are especially damaging to islands and lakes. International treaties such as CITES regulate the transportation of endangered species across international borders. The Endangered Species Act protects listed species in the United States but is hampered by procedural difficulties and a focus on individual species. The Migratory Bird Act is an agreement between Canada and the United States to protect migratory birds. Presently, 11 percent of Earth's land surface is protected somehow. Habitat restoration can restore ecosystems to previous biodiversity levels before species become extinct. Examples of restoration include the reintroduction of keystone species and the removal of dams on rivers.

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Chapter 6: Environmental Hazards and Human Health

Bayee Waqo (12) was named after her grandmother Bayee Chumee (82). When her son and his wife both died of AIDS, Chumee took on the care of their daughter, who was just two years old. Some years later, after repeated illness, the young girl was diagnosed HIV positive, and she has been on treatment since. At 82, Chumee is getting too weak for all the household chores, so her granddaughter helps by collecting firewood, fetching water, making coffee, and baking bread.

Learning Outcomes

After studying this chapter, you should be able to:

- Define environmental health
- Categorize environmental health risks
- Explain the concept of emerging diseases
- Summarize the principles of environmental toxicology
- Classify environmental contaminants

Chapter Outline

Our industrialized society dumps huge amounts of pollutants and toxic wastes into the earth's biosphere without fully considering the consequences. Such actions seriously degrade the earth's ecosystems' health, ultimately affecting human populations' health and well-being.

For most of human history, **biological agents** have been the most significant factor in health. These included pathogenic (disease-causing) organisms such as bacteria, viruses, protozoa, and internal parasites. In modern times, cardiovascular diseases, cancer, and accidents are the leading killers in most parts of the world. However, infectious diseases still cause about 22 million deaths yearly, mostly in undeveloped countries. These diseases include tuberculosis, malaria, pneumonia, influenza, whooping cough, dysentery, and Acquired Immune Deficiency Syndrome (AIDS). Most of those affected are children. Malnutrition, unclean water, poor sanitary conditions, and lack of proper medical care all play roles in these deaths. Compounding the problems of infectious diseases are drug-resistant pathogens, insecticide-resistant carriers, and overpopulation. Overuse of antibiotics has allowed pathogens to develop a resistance to drugs. For example, tuberculosis (TB) was nearly eliminated in most parts of the world, but drug-resistant strains have reversed that trend. Another example is malaria. The insecticide DDT (dichlorodiphenyltrichloroethane) was widely used to control malaria-carrying mosquito populations in tropical regions. However, after many years the mosquitoes developed a natural resistance to DDT and again spread the disease widely. Anti-malarial medicines were also over-prescribed, which allowed the malaria pathogen to become drug-resistant.

Chemical agents also have significant effects on human health. Toxic heavy metals, dioxins, pesticides, and endocrine disrupters are examples of these chemical agents. Heavy metals (e.g., mercury, lead, & cadmium) are typically produced as by-products of mining and manufacturing processes. They all biomagnify (become more concentrated in species with increasing food chain levels). For example, mercury from polluted water can accumulate in swordfish to levels toxic to humans. When toxic heavy metals enter the body, they accumulate in tissues and may eventually cause sickness or death. Studies show that people with above-average bone lead levels have an increased risk of developing attention deficit disorder and aggressive behavior. Lead can also damage brain cells and affect muscular coordination.

Environmental Persistence of DDT

The pesticide DDT has been widely used for decades. It was seen as an ideal pesticide because it is inexpensive and breaks down slowly in the environment. Unfortunately, the latter characteristic allows this chemical agent to biomagnify through the food chain. Populations of bird species at the top of the food chain, e.g., eagles and pelicans, are greatly affected by DDT in the environment. When these birds have sufficient levels of DDT, the shells of their eggs are so thin that they break, making reproduction impossible. After DDT was banned in the United States in 1972, affected bird populations, including the iconic bald eagle, made noticeable recoveries.

Figure 1. DDT was a commonly-used pesticide. "This work" by OpenStax is licensed under CC BY 4.0.

Environmental health is concerned with preventing disease, death, and disability by reducing exposure to adverse environmental conditions and promoting behavioral change. It focuses on the direct and indirect causes of diseases and injuries and taps resources inside and outside the healthcare system to help improve health outcomes.

Underlying Determinants	Possible Adverse Health and Safety Consequences
Inadequate water (quantity and quality), sanitation (wastewater and excreta removal) and solid waste disposal, improper hygiene (hand washing)	Diarrheas and vector-related diseases, eg, malaria, schistosomiasis, dengue
Improper water resource management (urban and rural), including poor drainage	Vector-related diseases, eg, malaria, schistosomiasis
Crowded housing and poor ventilation of smoke	Acute and chronic respiratory diseases, including lung cancer (from coal and tobacco smoke inhalation)
Exposures to vehicular and industrial air pollution	Respiratory diseases, some cancers, and loss of IQ in children
Population movement and encroachment and construction, which affect feeding and breeding grounds of vectors, such as mosquitoes	Vector-related diseases, eg, malaria, schistosomiasis, and dengue fever, may also help spread other infectious diseases eg HIV/AIDS, Ebola fever
Exposure to naturally occurring toxic substances	Poisoning from, eg, arsenic, manganese, and fluorides
Natural resource degradation, eg, mudslides, poor drainage, erosion	Injury and death from mudslides and flooding
Climate change, partly from combustion of greenhouse gases in transportation, industry and poor energy conservation in housing, fuel, commerce, industry	Injury/death from: extreme heat/cold, storms, floods, fires. Indirect effects: spread of vector-borne diseases, aggravation of respiratory diseases, population dislocation, water pollution from sea level rise, etc.
Ozone depletion from industrial and commercial activity	Skin cancer, cataracts. Indirect effects: compromised food production, etc.

Table 1. Typical Environmental Health Issues: Determinants and Health Consequences.

Poverty, Health, and Environment

Environmental health risks can be grouped into two broad categories. **Traditional hazards** are related to poverty and the lack of development and mostly affect developing countries and poor people. Their impact exceeds modern health hazards by ten times in Africa, five times in Asian countries (except for China), and 2.5 times in Latin America and the Middle East (Figure 1). Water-related diseases caused by inadequate water supply and sanitation impose an especially large health burden in Africa, Asia, and the Pacific region. In India alone, over 700,000 children under five die annually from diarrhea. In Africa, malaria causes about 500,000 deaths annually. More than half of the world's households use unprocessed *solid fuels*, particularly biomass (crop residues, wood, and dung) for cooking and heating in inefficient stoves without proper ventilation, exposing people—mainly poor women and children—to high levels of indoor air pollution (IAP). IAP causes about 2 million deaths each year.

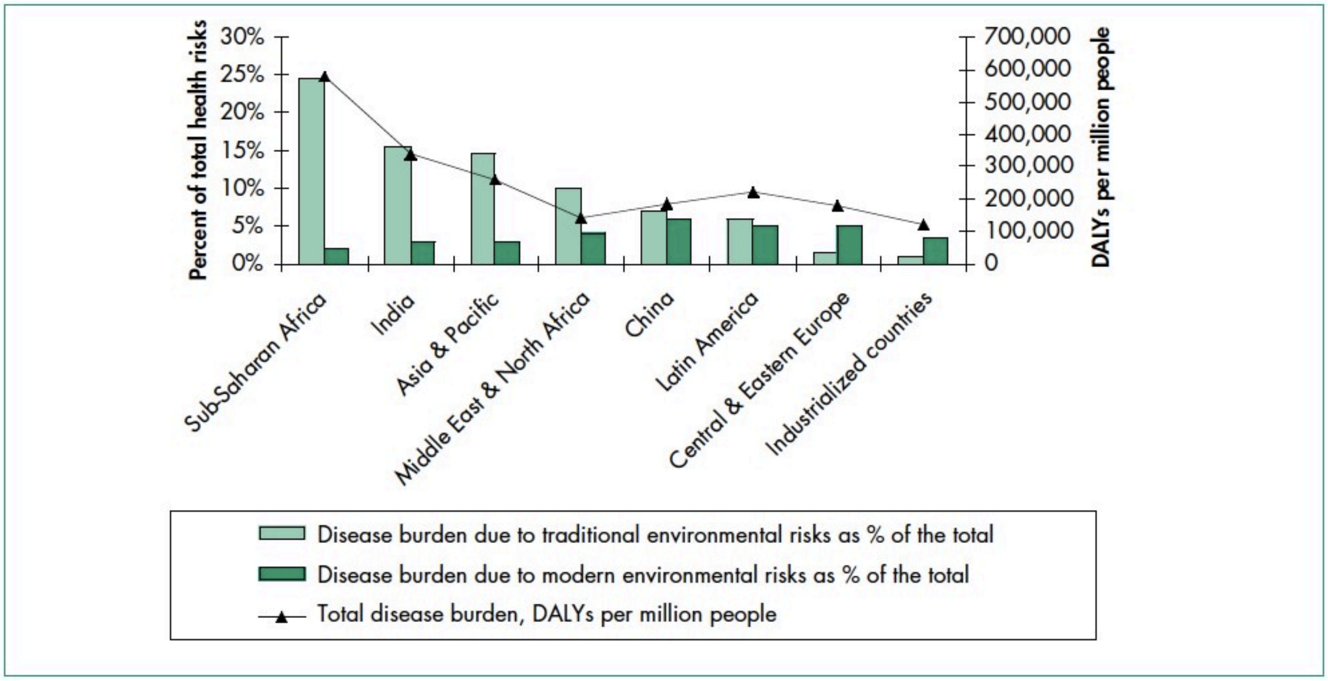

Figure 1. Traditional environmental health hazards prevail in developing countries, but modern risks are also significant.

Modern hazards caused by technological development prevail in industrialized countries with low exposure to traditional hazards. The contribution of modern environmental risks to the disease burden in most developing countries is similar to – and in quite a few countries, greater than – that in rich countries. Urban air pollution, for example, is highest in parts of China, India, and some cities in Asia and Latin America. Poor people increasingly experience a "**double burden**" of traditional and modern environmental health risks. Their total burden of illness and death from all causes per million people is about twice that in rich countries, and the disease burden from environmental risks is 10 times greater.

Environmental Health and Child Survival

Figure 2. Malnourished children in Niger during the 2005 famine.

Worldwide, the top killers of children under five are acute respiratory infections (indoor air pollution); diarrheal diseases (mostly from poor water, sanitation, and hygiene); and infectious diseases such as malaria. Children are especially susceptible to environmental factors that put them at risk of developing illness early in life. **Malnutrition** (the condition that occurs when the body does not get enough nutrients) is an important contributor to child mortality—malnutrition and environmental infections are inextricably linked. The World Health Organization (WHO) recently concluded that about 50% of the consequences of malnutrition are caused by inadequate water and sanitation provision and poor hygienic practices.

Poor Water and Sanitation Access

With 1.1 billion people lacking access to safe drinking water and 2.6 billion without adequate sanitation, the magnitude of the water and sanitation problem remains significant. Each year contaminated water and poor sanitation contribute to 5.4 billion cases of diarrhea worldwide and 1.6 million deaths, mostly among children under five years old. Intestinal worms, which thrive in poor sanitary conditions, infect close to 90 percent of children in the developing world and, depending on the severity of the infection, may lead to malnutrition, anemia, or stunted growth. About 6 million people are blind from trachoma, a disease caused by the lack of clean water and poor hygiene practices.

Indoor Air Pollution

Indoor air pollution—a much less publicized source of poor health—is responsible for more than 1.6 million deaths annually and 2.7% of the global disease burden. It is estimated that half of the world's population, mainly in developing countries, uses solid fuels (biomass and coal) for household cooking and space heating. Cooking and heating with such solid fuels on open fires or stoves without chimneys lead to indoor air pollution and respiratory infections. Exposure to these health-damaging pollutants is particularly high among women and children in developing countries, who spend the most time inside the household. As many as half of the deaths attributable to indoor use of solid fuel are of children under the age of five.

Malaria

Approximately 40% of the world's people—mostly those living in the world's poorest countries—are at risk from malaria. **Malaria** is an infectious disease spread by mosquitoes but caused by a single-celled parasite called *Plasmodium*. Every year, more than 200 million people become infected with malaria, and about 430,000 die, with most cases and deaths found in Sub-Saharan Africa. However, Asia, Latin America, the Middle East, and parts of Europe are also affected. Pregnant women are especially at high risk of malaria. Non-immune pregnant women risk both acute and severe clinical disease, resulting in fetal loss in up to 60% of such women and maternal deaths in more than 10%, including a 50% mortality rate for those with severe disease. Semi-immune pregnant women with malaria infection risk severe anemia and impaired fetal growth, even if they show no signs of acute clinical disease. An estimated 10,000 women and 200,000 infants die annually from malaria infection during pregnancy.

Emerging Diseases

Emerging and re-emerging diseases have been defined as infectious diseases of humans whose occurrence during the past two decades has substantially increased or threatens to increase in the near future relative to populations affected, geographic distribution, or magnitude of impacts. Examples include the Ebola virus, West Nile virus, Zika virus, sudden acute respiratory syndrome (SARS), H1N1 influenza; swine and avian influenza (swine, bird flu), HIV, and a variety of other viral, bacterial, and protozoal diseases.

Various environmental factors may contribute to the re-emergence of a particular disease, including temperature, moisture, human food or animal feed sources, etc. Disease re-emergence may be caused by the coincidence of several environmental and/or social factors to allow optimal conditions for disease transmission.

Ebola, previously known as Ebola hemorrhagic fever, is a rare and deadly disease caused by infection with one of the Ebola virus strains. Ebola can cause disease in humans and nonhuman primates. The 2014 Ebola epidemic is the largest in history (with over 28,000 cases and 11,302 deaths), affecting multiple countries in West Africa. A few cases were reported in Nigeria and Mali, and a single case was reported in Senegal; however, these cases were contained, with no further spread in these countries.

The **HIV/AIDS** epidemic has spread with ferocious speed. Virtually unknown 20 years ago, HIV has infected more than 60 million people worldwide. Approximately 14,000 new infections occur daily, more than half of them among young people below the age of 25. Over 95 percent of PLWHA (People Living With HIV/AIDS) are in low- and middle-income countries. Over 20 million have died from AIDS, over 3 million in 2002 alone. AIDS is now the leading cause of death in Sub-Saharan Africa and the fourth-biggest killer globally. The epidemic has cut life expectancy by more than ten years in several nations.

It seems likely that a wide variety of infectious diseases had affected human populations for thousands of years, emerging when the environmental, host, and agent conditions were favorable. Expanding human populations has increased the potential for infectious disease transmission due to close human proximity and increased the likelihood of humans being in “the wrong place at the right time” for disease (e.g., natural disasters or political conflicts). Global travel increases the potential for a disease carrier to transmit infection thousands of miles away in just a few hours, as evidenced by WHO precautions concerning international travel and health.

Antibiotic Resistance

Antibiotics and similar drugs, called antimicrobial agents, have been used for the last 70 years to treat patients with infectious diseases. Since the 1940s, these drugs have greatly reduced illness and death from infectious diseases. However, these drugs have been used so widely and for so long that the infectious organisms the antibiotics are designed to kill have adapted to them, making them less effective. **Antibiotic resistance** occurs when bacteria change, reducing the effectiveness of drugs, chemicals, or other agents designed to cure or prevent infections. This is caused by the process of evolution through natural selection (Figure 3). The antibiotic-resistant bacteria survive and continue to multiply, causing more harm.

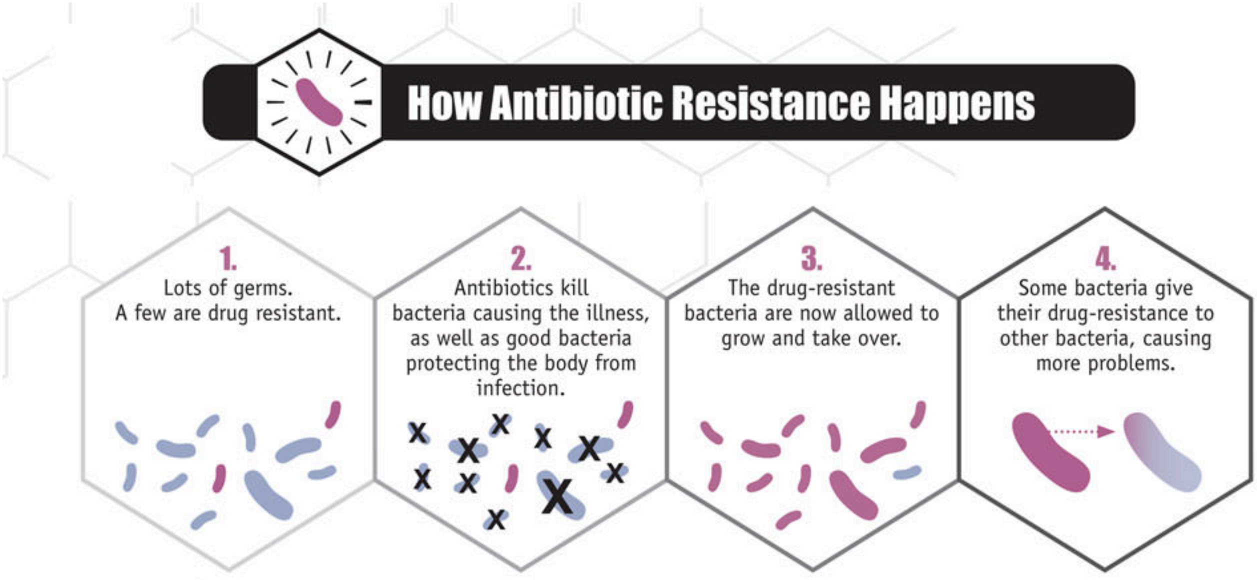

Figure 3. Antibiotic resistance is of increasing concern to medical professionals.

New forms of antibiotic resistance can easily cross international boundaries and spread between continents. Many forms of resistance spread with remarkable speed. Each year in the United States, at least 2 million people acquire serious infections with bacteria resistant to one or more antibiotics designed to treat those infections. At least 23,000 people die each year in the US due to these antibiotic-resistant infections. Many more die from other conditions that were complicated by an antibiotic-resistant infection. The use of antibiotics is the single most important factor leading to antibiotic resistance around the world.

Antibiotics are among the most commonly prescribed drugs used in human medicine. However, up to 50% of all the antibiotics prescribed for people are not needed or are not optimally effective as prescribed.

In recent years, there has been growing concern over methicillin-resistant Staphylococcus aureus (MRSA), a bacterium resistant to many antibiotics. In the community, most MRSA infections are skin infections. MRSA causes life-threatening bloodstream infections, pneumonia, and surgical site infections in medical facilities.

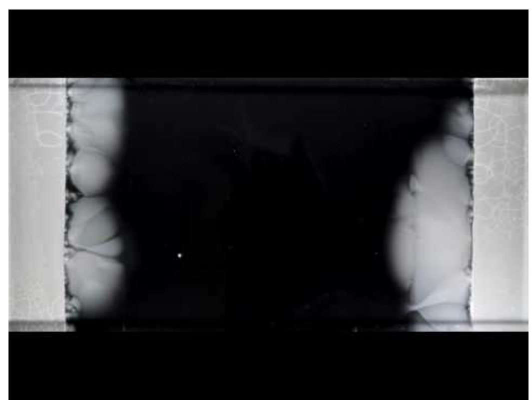

Figure 4. Click here for a video link (https://youtu.be/plVk4NVIUh8) to an experiment at Harvard Medical School, where bacteria adapt very quickly to apparently deadly conditions.

Suggested Supplementary Reading:

Koch, B.J. et al. 2017. Food-animal production and the spread of antibiotic resistance: the role of ecology. *Frontiers in Ecology and the Environment* (15)6: 309-318.

Notable Excerpts:

"Antibiotic use in food animals is correlated with antibiotic resistance among bacteria affecting human populations." p. 311

"Microbial genes encoding antibiotic resistance have moved between the food-animal and human health sectors, resulting in illnesses that could not be treated by antibiotics." p. 312

Environmental toxicology is the scientific study of the health effects of exposure to toxic chemicals (Table 1) occurring in the natural, work, and living environments. The term also describes the management of environmental toxins and toxicity and the development of protections for humans and the environment.

Routes of Exposure to Chemicals

In order to cause health problems, chemicals must enter your body. There are three main "routes of exposure," or ways a chemical can get into your body.

- Breathing (inhalation): Breathing in chemical gases, mists, or dust in the air.
- Skin or eye contact: Getting chemicals on the skin or the eyes. They can damage the skin or be absorbed through the skin into the bloodstream.
- Swallowing (ingestion): This can happen when chemicals have spilled or settled onto food, beverages, cigarettes, beards, or hands.

Once chemicals have entered your body, some can move into your bloodstream and reach internal "target" organs, such as the lungs, liver, kidneys, or nervous system.

Table 1. The ATSDR 2013 Substance Priority List. The table below lists the top 20 substances, in order of priority, which are determined to pose the most significant potential threat to human health. This priority list is not a list of "most toxic" substances but rather a prioritization of substances based on their frequency, toxicity, and potential for human exposure at various sites.

2013 RANK	**NAME**
1	ARSENIC
2	LEAD
3	MERCURY
4	VINYL CHLORIDE
5	POLYCHLORINATED BIPHENYLS
6	BENZENE
7	CADMIUM
8	BENZO(A)PYRENE
9	POLYCYCLIC AROMATIC HYDROCARBONS
10	BENZO(B)FLUORANTHENE
11	CHLOROFORM
12	AROCLOR 1260
13	DDT, P, P'-
14	AROCLOR 1254
15	DIBENZO(A,H)ANTHRACENE
16	TRICHLOROETHYLENE
17	CHROMIUM, HEXAVALENT
18	DIELDRIN
19	PHOSPHORUS, WHITE
20	HEXACHLOROBUTADIENE

What Forms Do Chemicals Take?

Chemical substances can take a variety of forms. They can be solids, liquids, dust, vapors, gases, fibers, mists, and fumes. The form a substance is in has a lot to do with how it gets into your body and what harm it can cause. A chemical can also change forms. For example, liquid solvents can evaporate and give off vapors you can inhale. Sometimes chemicals are in a form that can't be seen or smelled, so they can't be easily detected.

What Health Effects Can Chemicals Cause?

An **acute effect** of a contaminant (The term "**contaminant**" means hazardous substances, pollutants, pollution, and chemicals) is one that occurs rapidly after exposure to a large amount of that substance. A chronic effect of a contaminant results from exposure to small amounts of a substance over a long period of time. In such a case, the effect may not be immediately obvious. **Chronic effects** are difficult to measure, as the effects may not be seen for years. Long-term exposure to cigarette smoking, low-level radiation exposure, and moderate alcohol use are all thought to produce chronic effects.

Scientists have known that just about any substance is toxic in sufficient quantities for centuries. For example, small amounts of selenium are required by living organisms for proper functioning, but large amounts may cause cancer. The effect of a certain chemical on an individual depends on the dose (amount) of the chemical. This relationship is often illustrated by a dose-response curve which shows the relationship between the dose and the individual's response. **Lethal doses** in humans have been determined for many substances from information gathered from records of homicides, accidental poisonings, and testing on animals.

A dose that is lethal to 50% of a population of test animals is called the **lethal dose-50%** or **LD-50**. Determination of the LD-50 is required for new synthetic chemicals to measure their toxicity. A dose that causes 50% of a population to exhibit any significant response (e.g., hair loss, stunted development) is the **effective dose-50%** or **ED-50**. Some toxins have a threshold amount below which there is no apparent effect on the exposed population.

Environmental Contaminants

The contamination of the air, water, or soil with potentially harmful substances can affect any person or community. Contaminants (Table 2) are often chemicals found in the environment in amounts higher than what would be there naturally. We can be exposed to these contaminants from various residential, commercial, and industrial sources. Sometimes harmful environmental contaminants, such as mold or toxic algae bloom, occur biologically.

Table 2. Classification of Environmental Contaminants

Contaminant	Definition
Carcinogen	An agent which may produce cancer (uncontrolled cell growth), either by itself or in conjunction with another substance. Examples include formaldehyde, asbestos, radon, vinyl chloride, and tobacco.
Teratogen	A substance that can cause physical defects in a developing embryo. Examples include alcohol and cigarette smoke.
Mutagen	A material that induces genetic changes (mutations) in the DNA. Examples include radioactive substances, x-rays, and ultraviolet radiation.
Neurotoxicant	A substance that can cause an adverse effect on the chemistry, structure, or function of the nervous system. Examples include lead and mercury.
Endocrine disruptor	A chemical that may interfere with the body's endocrine (hormonal) system and produce adverse developmental, reproductive, neurological, and immune effects in both humans and wildlife. A wide range of substances, both natural and man-made, are thought to cause endocrine disruption, including pharmaceuticals, dioxin and dioxin-like compounds, arsenic, polychlorinated biphenyls (PCBs), DDT and other pesticides, and plasticizers such as bisphenol A (BPA).

An Overview of Some Common Contaminants

Arsenic is a naturally occurring element normally present throughout our environment in water, soil, dust, air, and food. Levels of arsenic can regionally vary due to farming and industrial activity as well as natural geological processes. The arsenic from farming and smelting tends to bind strongly to soil and is expected to remain near the land's surface for hundreds of years as a long-term source of exposure. Wood treated with chromate copper arsenate (CCA) is commonly found in decks and railings in existing homes and outdoor structures such as playground equipment. Some underground aquifers are in rock or soil with naturally high arsenic content.

Most arsenic gets into the body through ingestion of food or water. Arsenic in drinking water is a problem in many countries worldwide, including Bangladesh, Chile, China, Vietnam, Taiwan, India, and the United States. Arsenic may also be found in foods, including rice and some fish, where it is present due to uptake from soil and water. It can also enter the body by breathing dust containing arsenic. Researchers are finding that arsenic, even at low levels, can interfere with the body's endocrine system. Arsenic is also a known human carcinogen associated with skin, lung, bladder, kidney, and liver cancer.

Mercury is a naturally occurring metal, a useful chemical in some products, and a potential health risk. Mercury exists in several forms; the types people are usually exposed to are methylmercury and elemental mercury. Elemental mercury at room temperature is a shiny, silver-white liquid that can produce a harmful odorless vapor. Methylmercury, an organic compound, can build up in the bodies of long-living, predatory fish. To keep mercury out of the fish we eat and the air we breathe, it's important to take mercury-containing products to a hazardous waste facility for disposal. Common products sold today that contain small amounts of mercury include fluorescent lights and button-cell batteries.

Although fish and shellfish have many nutritional benefits, consuming large quantities of fish increases a person's exposure to mercury. Pregnant women who regularly eat fish high in mercury risk permanently damaging their developing fetuses. Children born to these mothers may exhibit motor difficulties, sensory problems, and cognitive deficits. Figure 1 identifies the typical (average) amounts of mercury in commonly consumed commercial and sport-caught fish.

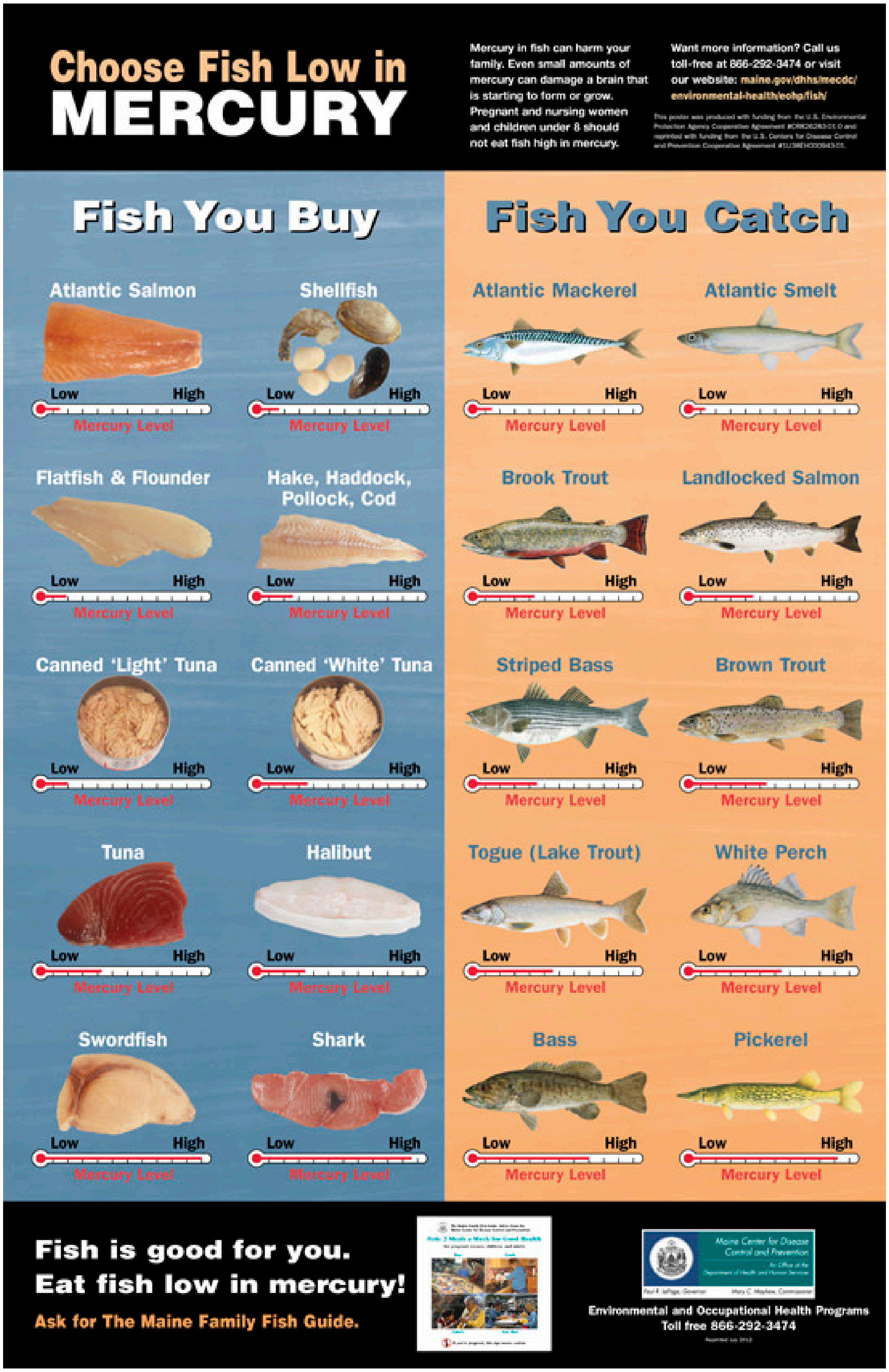

Figure 1. Mercury concentrations in fish can reach potentially dangerous levels (published by the Maine Center for Disease Control & Prevention).

Bisphenol A (BPA) is a chemical synthesized in large quantities for use primarily in producing polycarbonate plastics and epoxy resins. Polycarbonate plastics have many applications, including food and drink packaging, e.g., water and infant bottles, compact discs, impact-resistant safety equipment, and medical devices. Epoxy resins are used as lacquers to coat metal products such as food cans, bottle tops, and water supply pipes. Some dental sealants and composites may also contribute to BPA exposure. The primary source of exposure to BPA for most people is through the diet. Bisphenol A can leach into food from the protective internal epoxy resin coatings of canned foods and consumer products such as polycarbonate tableware, food storage containers, water bottles, and baby bottles. The degree to which BPA leaches from polycarbonate bottles into liquid may depend more on the temperature of the liquid or bottle than the age of the container. BPA can also be found in breast milk.

What can I do to prevent exposure to BPA?

Some animal studies suggest that infants and children may be the most vulnerable to the effects of BPA. Parents and caregivers can make the personal choice to reduce exposure of their infants and children to BPA:

- Don’t microwave polycarbonate plastic food containers. Polycarbonate is strong and durable but may break down from overuse at high temperatures over time.
- Plastic containers have recycle codes on the bottom. Some, but not all, plastics that are marked with recycling codes 3 or 7 may be made with BPA.
- Reduce your use of canned foods.
- Opt for glass, porcelain, or stainless steel containers, particularly for hot food or liquids, when possible.
- Use BPA-free baby bottles.

Phthalates are a group of synthetic chemicals used to soften and increase the flexibility of plastic and vinyl. Polyvinyl chloride is made softer and more flexible by the addition of phthalates. Phthalates are used in hundreds of consumer products. Phthalates are used in cosmetics and personal care products, including perfume, hair spray, soap, shampoo, nail polish, and skin moisturizers. They are used in consumer products such as flexible plastic and vinyl toys, shower curtains, wallpaper, vinyl miniblinds, food packaging, and plastic wrap. Exposure to low levels of phthalates may come from eating food packaged in plastic that contains phthalates or breathing dust in rooms with vinyl miniblinds, wallpaper, or recently installed flooring that contain phthalates. We can be exposed to phthalates by drinking water that contains phthalates. Phthalates are suspected to be endocrine disruptors.

Lead is a metal that occurs naturally in the rocks and soil of the earth’s crust. It is also produced by burning fossil fuels such as coal, oil, gasoline, natural gas, mining, and manufacturing. Lead has no distinctive taste or smell. The chemical symbol for elemental lead is Pb. Lead produces batteries, pipes, roofing, scientific electronic equipment, military tracking systems, medical devices, and products to shield X-rays and nuclear radiation. It is used in ceramic glazes and crystal glassware. Because of health concerns, lead and lead compounds were banned from house paint in 1978; solder used on water pipes in 1986; gasoline in 1995; solder used on food cans in 1996; and tin-coated foil on wine bottles in 1996. The U.S. Food and Drug Administration has limited the amount of lead that can be used in ceramics.

Lead and lead compounds are listed as “reasonably anticipated to be a human carcinogen.” It can affect almost every organ and system in your body. It can be equally harmful if breathed or swallowed. The part of the body most sensitive to lead exposure is the central nervous system, especially in children, who are more vulnerable to lead poisoning than adults. A child who swallows large amounts of lead can develop brain damage that can cause convulsions and death; the child can also develop blood anemia, kidney damage, colic, and muscle weakness. Repeated low levels of exposure to lead can alter a child's normal mental and physical growth and result in learning or behavioral problems. Exposure to high lead levels in pregnant women can cause miscarriage, premature births, and smaller babies. Repeated or chronic exposure can cause lead to accumulate in your body, leading to lead poisoning.

Formaldehyde is a colorless, flammable gas or liquid with a pungent, suffocating odor. It is a volatile organic compound, which is an organic compound that easily becomes a vapor or gas. It is also naturally produced in small, harmless amounts in the human body. The primary way we can be exposed to formaldehyde is by breathing air containing it. Releases of formaldehyde into the air occur from industries using or manufacturing formaldehyde, wood products (such as particle board, plywood, and furniture), automobile exhaust, cigarette smoke, paints and varnishes, and carpets and permanent press fabrics. Nail polish and commercially applied floor finish emit formaldehyde.

Figure 2. Nail products are known to contain toxic chemicals, such as dibutyl phthalate (DBP), toluene, and formaldehyde.

In general, indoor environments consistently have higher concentrations than outdoor environments because many building materials, consumer products, and fabrics emit formaldehyde. Levels of formaldehyde measured in indoor air range from 0.02–4 parts per million (ppm). In urban areas, formaldehyde levels in outdoor air range from 0.001 to 0.02 ppm.

Radiation

Radiation is energy given off by atoms and is all around us. We are exposed to radiation from natural sources like soil, rocks, and the sun daily. We are also exposed to radiation from man-made sources like medical X-rays and smoke detectors. We're even exposed to low radiation levels on cross-country flights, from watching television, and even from some construction materials. You cannot see, smell or taste radiation. Some types of radioactive materials are more dangerous than others. So it's important to carefully manage radiation and radioactive substances to protect health and the environment.

Radon is a radioactive gas that is naturally occurring, colorless, and odorless. It comes from the natural decay of uranium or thorium found in nearly all soils. It typically moves through the ground and into the home through cracks in floors, walls, and foundations. It can also be released from building materials or well water. Radon breaks down quickly, giving off radioactive particles. Long-term exposure to these particles can lead to lung cancer. Radon is the leading cause of lung cancer among nonsmokers, according to the U.S. Environmental Protection Agency, and the second leading cause behind smoking.

Bioremediation is a waste management technique that uses organisms such as plants, bacteria, and fungi to remove or neutralize pollutants from a contaminated site. According to the United States EPA, bioremediation is a “treatment that uses naturally occurring organisms to break down hazardous substances into less toxic or non-toxic substances.”

Bioremediation is widely used to treat human sewage and has also been used to remove agricultural chemicals (pesticides and fertilizers) that leach from soil into groundwater. Bioremediation can also remove toxic metals from water, such as selenium and arsenic compounds. Mercury is an example of a toxic metal that can be removed from an environment by bioremediation. Mercury is an active ingredient in some pesticides and is also a byproduct of certain industries, such as battery production. Mercury is usually present in very low concentrations in natural environments, but it is highly toxic because it accumulates in living tissues. Several species of bacteria can carry out the biotransformation of toxic mercury into nontoxic forms. These bacteria, such as *Pseudomonas aeruginosa*, can convert Hg^{2+} to Hg, which is less toxic to humans.

One of the most useful and interesting examples of the use of prokaryotes for bioremediation is the cleanup of oil spills. The importance of prokaryotes to petroleum bioremediation has been demonstrated in several oil spills in recent years, such as the Exxon Valdez spill in Alaska (1989) (Figure 1), the Prestige oil spill in Spain (2002), the spill into the Mediterranean from a Lebanon power plant (2006,) and more recently, the BP oil spill in the Gulf of Mexico (2010). To clean up these spills, bioremediation is promoted by adding inorganic nutrients that help bacteria already present in the environment to grow. Hydrocarbon-degrading bacteria feed on the hydrocarbons in the oil droplet, breaking them into inorganic compounds. Some species, such as *Alcanivorax borkumensis*, produce surfactants that solubilize the oil, while other bacteria degrade the oil into carbon dioxide. In the case of oil spills in the ocean, ongoing, natural bioremediation tends to occur since there are oil-consuming bacteria in the ocean before the spill. Under ideal conditions, it has been reported that up to 80 percent of the nonvolatile components in oil can be degraded within one year of the spill. Researchers have genetically engineered other bacteria to consume petroleum products; the first patent application for a bioremediation application in the U.S. was for a genetically modified oil-eating bacterium.

(a) (b)

Figure 1. (a) Cleaning up oil after the Valdez spill in Alaska, the workers hosed oil from beaches and then used a floating boom to corral the oil, which was finally skimmed from the water surface. Some species of bacteria are able to solubilize and degrade the oil. (b) One of the most catastrophic consequences of oil spills is the damage to fauna. (credit a: modification of work by NOAA; credit b: modification of work by GOLUBENKOV, NGO: Saving Taman)

There are a number of cost/efficiency advantages to bioremediation, which can be employed in areas that are inaccessible without excavation. For example, hydrocarbon spills (specifically, oil spills) or certain chlorinated solvents may contaminate groundwater, which can be easier to treat using bioremediation than more conventional approaches. This is typically much less expensive than excavation, followed by disposal elsewhere, incineration, or other off-site treatment strategies. It also reduces or eliminates the need for “pump and treat,” a practice common at sites where hydrocarbons have contaminated clean groundwater. Using prokaryotes for the bioremediation of hydrocarbons also has the advantage of breaking down contaminants at the molecular level instead of simply chemically dispersing the contaminant.

One of the most famous and important examples of groundwater pollution in the United States is the **Love Canal tragedy** in Niagara Falls, New York. It is important because the pollution disaster at Love Canal, along with similar pollution calamities at that time (Times Beach, Missouri and Valley of Drums, Kentucky), helped to create **Superfund**, a federal program instituted in 1980 and designed to identify and clean up the worst of the hazardous chemical waste sites in the United States.

Love Canal is a neighborhood in Niagara Falls named after a large ditch (approximately 15 m wide, 3–12 m deep, and 1600 m long) dug in the 1890s for hydroelectric power. The ditch was abandoned before it actually generated any power and went mostly unused for decades, except for swimming by local residents. In the 1920s, Niagara Falls began dumping urban waste into Love Canal, and in the 1940s, the U.S. Army dumped waste from World War II there, including waste from the frantic effort to build a nuclear bomb. Hooker Chemical purchased the land in 1942 and lined it with clay. Then, the company put into Love Canal an estimated 21,000 tons of hazardous chemical waste, including the carcinogens benzene, dioxin, and PCBs, in large metal barrels and covered them with more clay. In 1953, Hooker sold the land to the Niagara Falls school board for $1 and included a clause in the sales contract that described the land use (filled with chemical waste) and absolved them from any future damage claims from the buried waste. The school board promptly built a public school on the site and sold the surrounding land for a housing project that built 200 homes along the canal banks and another 1,000 in the neighborhood (Figure 1). The canal's clay cap and walls were breached during construction, damaging some metal barrels.

Figure 1. Love Canal. Source: US Environmental Protection Agency

Eventually, the chemical waste seeped into people's basements, and the metal barrels worked their way to the surface. Trees and gardens began to die; bicycle tires and the rubber soles of children's shoes disintegrated in noxious puddles. From the 1950s to the late 1970s, residents repeatedly complained of strange odors and substances that surfaced in their yards. City officials investigated the area but did not act to solve the problem. Local residents allegedly experienced major health problems, including high rates of miscarriages, birth defects, and chromosome damage, but New York State Health Department studies disputed that. Finally, in 1978 President Carter declared a state of emergency at Love Canal, making it the first human-caused environmental problem to be designated that way. The Love Canal incident became a symbol of improperly stored chemical waste. Clean up of Love Canal, funded by Superfund and finished in 2004, involved removing contaminated soil, installing drainage pipes to capture contaminated groundwater for treatment, and covering it with clay and plastic. In 1995, Occidental Chemical (the modern name for Hooker Chemical) paid $102 million to Superfund for cleanup and $27 million to the Federal Emergency Management Association for relocating more than 1,000 families. New York State paid $98 million to EPA, and the US government paid $8 million for pollution by the Army. The total clean-up cost was estimated to be $275 million.

The Love Canal tragedy helped to create Superfund, which has analyzed tens of thousands of hazardous waste sites in the U.S. and cleaned up hundreds of the worst ones. Nevertheless, over 1,000 major hazardous waste sites with a significant risk to human health or the environment are still being cleaned.

Summary

Environmental health is concerned with preventing disease, death, and disability by reducing exposure to adverse environmental conditions and promoting behavioral change. It focuses on the direct and indirect causes of diseases and injuries and taps resources inside and outside the healthcare system to help improve health outcomes. Environmental health risks can be grouped into two broad categories. Traditional hazards related to poverty and lack of development affect developing countries and poor people the most. Modern hazards caused by development that lacks environmental safeguards, such as urban (outdoor) air pollution and exposure to agro-industrial chemicals and waste, prevail in industrialized countries, where exposure to traditional hazards is low. Each year contaminated water and poor sanitation contribute to 5.4 billion cases of diarrhea worldwide and 1.6 million deaths, mostly among children under the age of five. Indoor air pollution—a much less publicized source of poor health—is responsible for more than 1.6 million deaths annually and 2.7 percent of the global disease burden.

Emerging and reemerging diseases have been defined as infectious diseases of humans whose occurrence during the past two decades has substantially increased or threatens to increase in the near future relative to populations affected, geographic distribution, or magnitude of impacts. Antibiotic resistance is a global problem. New forms of antibiotic resistance can cross international boundaries and spread between continents. Environmental toxicology is the scientific study of the health effects associated with exposure to toxic chemicals and systems occurring in the natural, work, and living environments; the management of environmental toxins and toxicity; and the development of protections for humans, animals, and plants. Environmental contaminants are chemicals found in the environment in amounts higher than what would be there naturally. We can be exposed to these contaminants from various residential, commercial, and industrial sources.

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Chapter 7: Water Availability and Use

Great Lakes from Space. The Great Lakes hold 21% of the world's surface fresh water. Lakes are an important surface water resource.

Learning Outcomes

After studying this chapter, you should be able to:

- Understand how the water cycle operates
- Know the causes and effects of depletion in different water reservoirs
- Understand how we can work toward solving the water supply crisis
- Understand the major kinds of water pollutants and how they degrade water quality
- Understand how we can work toward solving the crisis involving water pollution

Chapter Outline

- 7.1 Water Cycle and Fresh Water Supply
- 7.2 Water Supply Problems and Solutions
- 7.3. Water Pollution
- 7.4. Water Treatment
- 7.5. Case Study: The Aral Sea – Going, Going, Gone

- 7.6. Chapter Resources

Water, air, and food are people's most important natural resources. Humans can live only a few minutes without oxygen, less than a week without water, and about a month without food. Water also is essential for our oxygen and food supply. Plants break down water and use it to create oxygen during photosynthesis.

Water is the most essential compound for all living things. Human babies are approximately 75% water, and adults are 60% water. Our brain is about 85% water, blood, kidneys are 83% water, muscles are 76% water, and even bones are 22% water. We constantly lose water by perspiration; in temperate climates, we should drink about 2 quarts of water per day, and people in hot desert climates should drink up to 10 quarts of water per day. Loss of 15% of body water usually causes death.

Earth is truly the Water Planet. The abundance of liquid water on Earth's surface distinguishes us from other bodies in the solar system. About 70% of Earth's surface is covered by oceans, and approximately half of Earth's surface is obscured by clouds (also made of water) at any time. There is a very large volume of water on our planet, about 1.4 billion cubic kilometers (km3) (330 million cubic miles) or about 53 billion gallons per person on Earth. All of Earth's water could cover the United States to a depth of 145 km (90 mi). From a human perspective, the problem is that over 97% of it is seawater, which is too salty to drink or use for irrigation. The most commonly used water sources are rivers and lakes, which contain less than 0.01% of the world's water!

One of the most important environmental goals is to provide everyone with clean water. Fortunately, water is a renewable resource and is difficult to destroy. Evaporation and precipitation combine to replenish our fresh water supply constantly; however, water availability is complicated by its uneven distribution over the Earth. Arid climates and densely populated areas have combined in many parts of the world to create water shortages, which are projected to worsen in the coming years due to population growth and climate change. Human activities such as water overuse and pollution have significantly compounded the current water crisis. Hundreds of millions lack access to safe drinking water, and billions lack access to improved sanitation as simple as a pit latrine. As a result, nearly two million people die yearly from diarrheal diseases, and 90% of those deaths occur among children under the age of 5. Most of these are easily prevented deaths.

Water Reservoirs and Water Cycle

Water is the only common substance that occurs naturally on Earth in three forms: solid, liquid, and gas. It is distributed in various locations, called water reservoirs. The oceans are by far the largest reservoirs, with about 97% of all water, but that water is too saline for most human uses (Figure 1). Ice caps and glaciers are the largest reservoirs of fresh water, but this water is inconveniently located mostly in Antarctica and Greenland. Shallow groundwater is the largest reservoir of usable fresh water. Although rivers and lakes are the most heavily used water resources, they represent only a tiny amount of the world's water. If all of the world's water was shrunk to the size of 1 gallon, then the total amount of freshwater would be about 1/3 cup, and the amount of readily usable fresh water would be two tablespoons.

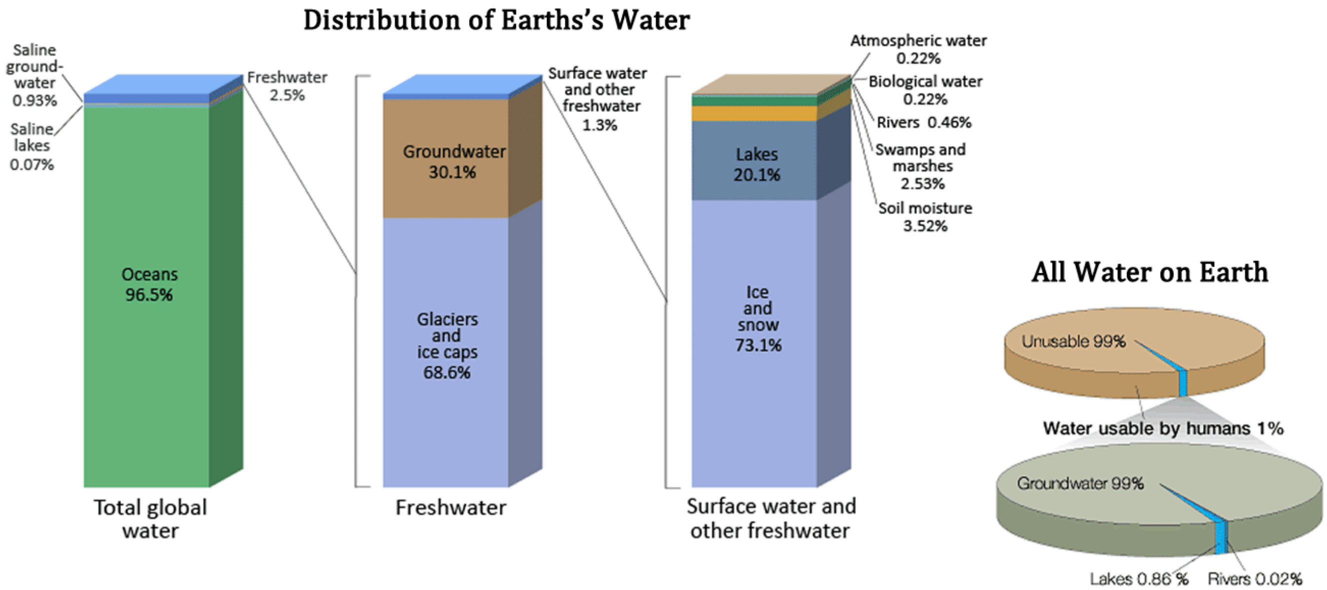


Figure 1. Earth's Water Reservoirs. Bar chart distribution of Earth's water including total global water, freshwater, surface water, and other fresh water and pie chart of water usable by humans and sources of usable water. Source: United States Geographical Survey Igor Skiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources

The **water** (or hydrologic) **cycle** (covered in Chapter 3.2) shows the movement of water through different reservoirs, including oceans, the atmosphere, glaciers, groundwater, lakes, rivers, and the biosphere. Solar energy and gravity drive the motion of water in the water cycle. Simply put, the water cycle involves water moving from oceans, rivers, and lakes to the atmosphere by evaporation, forming clouds. From clouds, it falls as precipitation (rain and snow) on both water and land. The water on land can either return to the ocean by surface runoff, rivers, glaciers, and subsurface groundwater flow or return to the atmosphere by evaporation or **transpiration** (water loss by plants to the atmosphere).

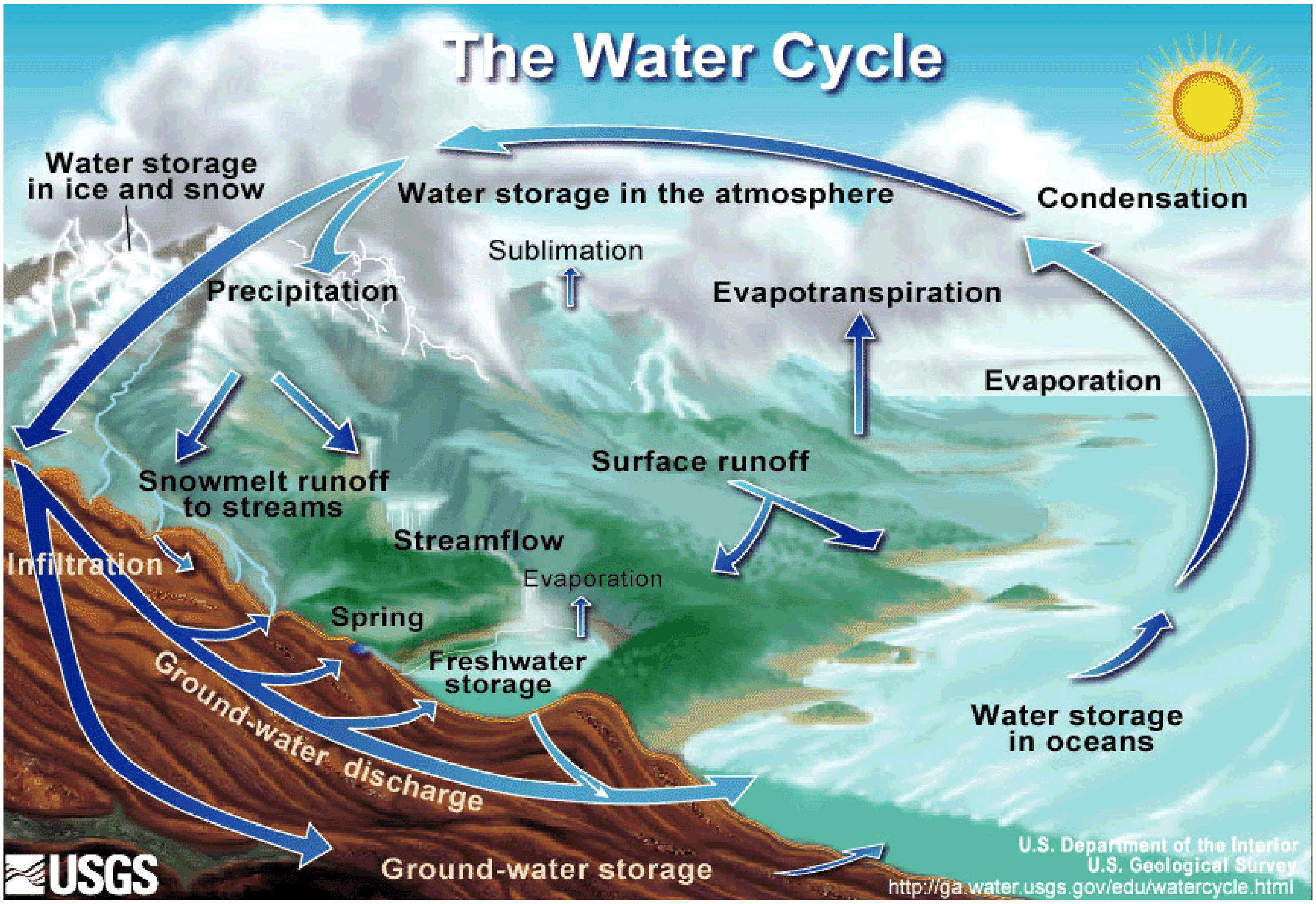


Figure 2.. Arrows depict the movement of water to different reservoirs located above, at, and below the Earth's surface. Source: United States Geological Survey

An important part of the water cycle is how water varies in salinity, which is the abundance of dissolved ions in water. The saltwater in the oceans is highly saline, with about 35,000 mg of dissolved ions per liter of seawater. **Evaporation** (where water changes from liquid to gas at ambient temperatures) is a distillation process that produces nearly pure water with almost no dissolved ions. Water vaporizes and leaves the dissolved ions in the original liquid phase. Eventually, **condensation** (where water changes from gas to liquid) forms clouds and sometimes precipitation (rain and snow). After rainwater falls onto land, it dissolves minerals in rock and soil, which increases its salinity. Most lakes, rivers, and near-surface groundwater are called freshwater and have a relatively low salinity. The next sections discuss important parts of the water cycle relative to freshwater resources.

Primary Fresh Water Resources: Precipitation

Precipitation levels are unevenly distributed around the globe, affecting freshwater availability (Figure 3). More precipitation falls near the equator, whereas less precipitation tends to fall near 30 degrees north and south latitude, where the world's largest deserts are located. These rainfall and climate patterns are related to global wind circulation cells. The intense sunlight at the equator heats the air, causing it to rise and cool, which decreases the ability of the air mass to hold water vapor and results in frequent rainstorms. Around 30 degrees north and south latitude, descending air conditions produce warmer air, which increases its ability to hold water vapor and results in dry conditions. The dry air conditions and the warm temperatures of these latitude belts favor evaporation. Global precipitation and climate patterns are also affected by the size of continents, major ocean currents, and mountains.

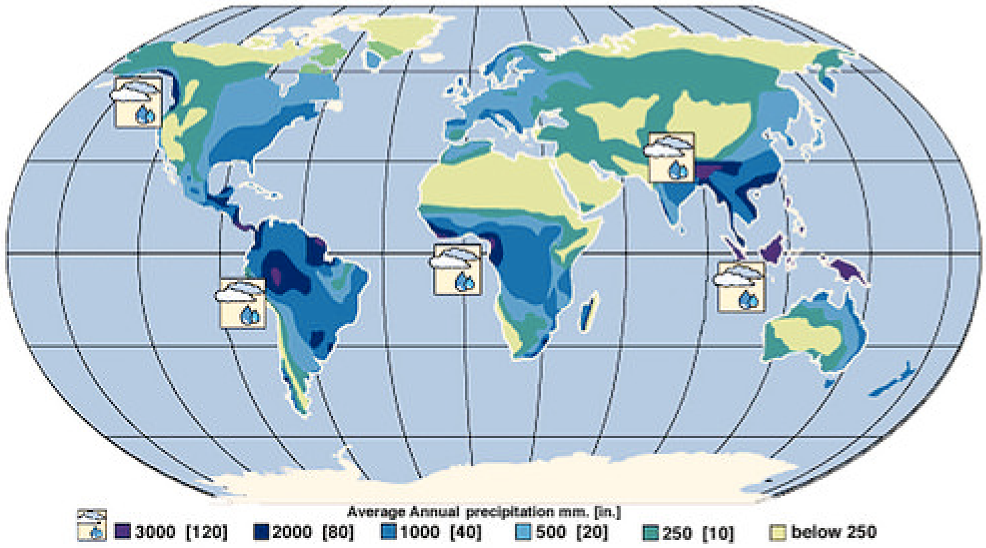


Figure 3. World Rainfall Map. The false-color map above shows the amount of rain that falls worldwide. High rainfall areas include Central and South America, western Africa, and Southeast Asia. Since these areas receive so much rainfall, they are where most of the world's rainforests grow. Areas with very little rainfall usually turn into deserts. The desert areas include North Africa, the Middle East, western North America, and Central Asia. Source: United States Geological Survey Earth Forum, Houston Museum Natural Science

Surface Water Resources: Rivers, Lakes, Glaciers

Figure 4. Surface runoff is part of overland flow in the water cycle Source: James M. Pease at Wikimedia Commons

Flowing water from rain and melted snow on land enters river channels by surface runoff (Figure 4) and groundwater seepage (Figure 5). **River discharge** describes the volume of water moving through a river channel over time (Figure 6). The relative contributions of surface runoff vs. groundwater seepage to river discharge depend on precipitation patterns, vegetation, topography, land use, and soil characteristics. Soon after a heavy rainstorm, river discharge increases due to surface runoff. The steady normal flow of river water is mainly from groundwater that discharges into the river. Gravity pulls river water downhill toward the ocean. Along the way, the moving water of a river can erode soil particles and dissolve minerals. Groundwater also contributes a large amount of the dissolved minerals in river water. The geographic area drained by a river and its tributaries is called a **drainage basin** or **watershed**. The Mississippi River drainage basin includes approximately 40% of the U.S., a measure that includes the smaller drainage basins, such as the Ohio River and Missouri River, that help to comprise it. Rivers are an important water resource for cropland irrigation and drinking water for many cities worldwide. Rivers that have had international disputes over water supply include Colorado (Mexico, southwest U.S.), Nile (Egypt, Ethiopia, Sudan), Euphrates (Iraq, Syria, Turkey), Ganges (Bangladesh, India), and Jordan (Israel, Jordan, Syria).

Figure 5. Groundwater Seepage. Groundwater seepage can be seen in Box Canyon in Idaho, where approximately ten cubic meters per second of seepage emanates from its vertical headwall. Source: NASA

In addition to rivers, lakes can also be an excellent source of fresh water for human use. They usually receive water from surface runoff and groundwater discharge. They tend to be short-lived on a geological time scale because they constantly fill in with sediment supplied by rivers. Lakes form in various ways, including glaciation, recent tectonic uplift (e.g., Lake Tanganyika, Africa), and volcanic eruptions (e.g., Crater Lake, Oregon). People also create artificial lakes (**reservoirs**) by damming rivers. Large changes in climate can result in major changes in a lake's size. As Earth was coming out of the last Ice Age about 15,000 years ago, the climate in the western U.S. changed from cool and moist to warm and arid, which caused more than 100 large lakes to disappear. The Great Salt Lake in Utah is a remnant of a much larger lake called Lake Bonneville.

Although **glaciers** represent the largest reservoir of fresh water, they generally are not used as a water source because they are located too far from most people (Figure 7). Melting glaciers do provide a natural source of river water and groundwater. During the last Ice Age, there was as much as 50% more water in glaciers than there is today, which caused sea level to be about 100 m lower. Over the past century, the sea level has risen partly due to melting glaciers. If Earth's climate continues to warm, the melting glaciers will cause an additional rise in sea level.

Figure 6. River Discharge Colorado River, U.S. Rivers are part of overland flow in the water cycle and an important surface water resource. Source: Gonzo fan2007 at Wikimedia Commons.

Figure 7. Mountain Glacier in Argentina Glaciers are the largest reservoir of fresh water but are not used much as a water resource directly by society because of their distance from most people. Source: Luca Galuzzi – www.galuzzi.it

Groundwater Resources

Although most people worldwide use surface water, groundwater is a much larger reservoir of usable fresh water, containing more than 30 times more water than rivers and lakes combined. Groundwater is a particularly important resource in arid climates, where surface water may be scarce. In addition, groundwater is the primary water source for rural homeowners, providing 98% of that water demand in the U.S. **Groundwater** is water located in small spaces, called **pore space**, between mineral grains and fractures in subsurface earth materials (rock or sediment). Most groundwater originates from rain or snowmelt, infiltrating the ground and moving down until it reaches the **saturated zone** (where groundwater completely fills pore spaces in earth materials).

Other groundwater sources include seepage from surface water (lakes, rivers, reservoirs, and swamps), surface water deliberately pumped into the ground, irrigation, and underground wastewater treatment systems (septic tanks). **Recharge areas** are locations where surface water infiltrates the ground rather than running into rivers or evaporating. Wetlands, for example, are excellent recharge areas. An **aquifer** is a large area of sub-surface, porous rock that holds water. Aquifers are commonly drilled, and wells are installed to provide water for agriculture and personal use. Examples of aquifers are earth materials with abundant, large, well-connected pore spaces such as sand, gravel, uncemented sandstone, and any highly fractured rock.

Water Use in the U.S. and World

People need water, oftentimes in large quantities, to produce the food, energy, and mineral resources they use. Consider, for example, these approximate water requirements for some things people in the developed world use every day: one tomato = 3 gallons; one kilowatt-hour of electricity from a thermoelectric power plant = 21 gallons; one loaf of bread = 150 gallons; one pound of beef = 1,600 gallons; and one ton of steel = 63,000 gallons. Human beings require only about 1 gallon per day to survive. Still, a typical person in a U.S. household uses approximately 100 gallons per day, which includes cooking, washing dishes and clothes, flushing the toilet, and bathing. The **water demand** of an area is a function of the population and other uses of water.

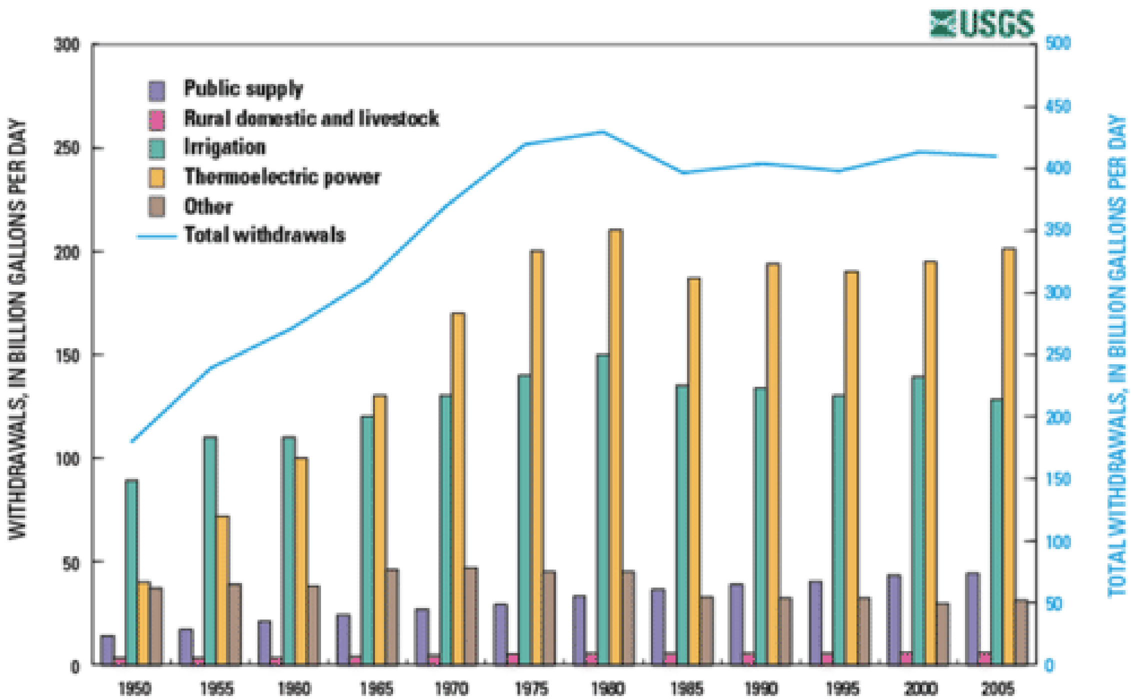


Figure 8. Trends in Total Water Withdrawals by Water-use Category, 1950-2005 Trends in total water withdrawals in the U.S. from 1950 to 2005 by water use category, including bars for thermoelectric power, irrigation, public water supply, and rural domestic and livestock. The thin blue line represents total water withdrawals using a vertical scale on the right. Source: United States Geological Survey

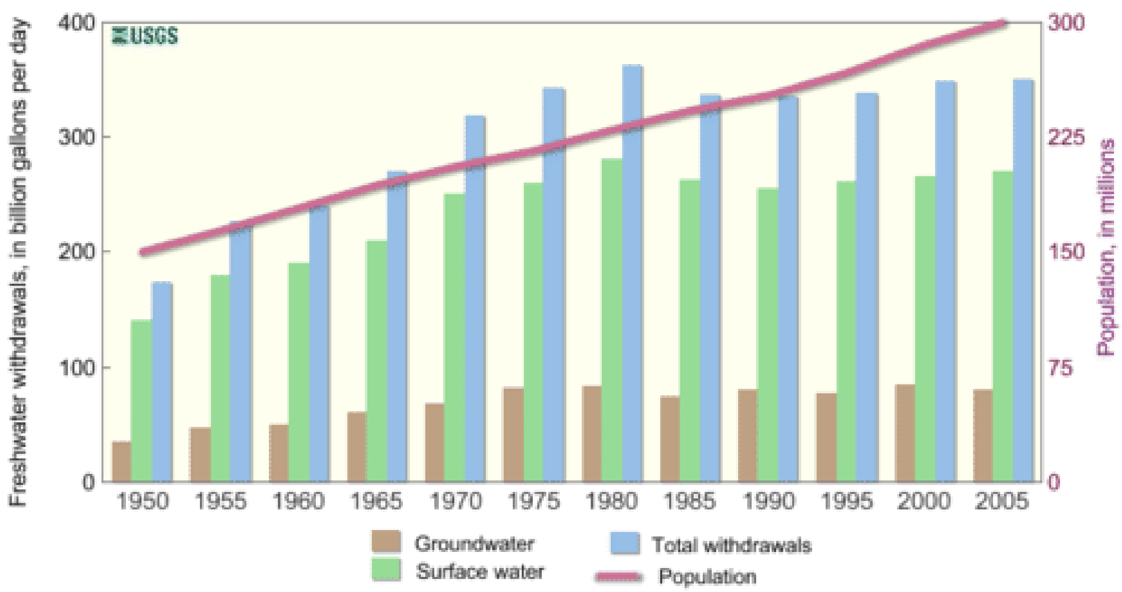


Figure 9. Trends in Source of Fresh Water Withdrawals in the U.S. from 1950 to 2005 Trends in the source of freshwater withdrawals in the U.S. from 1950 to 2005, including bars for surface water, groundwater, and total water. The red line gives the U.S. population using the vertical scale on the right. Source: United States Geological Survey

Global total water use is steadily increasing at a rate greater than world population growth (Figure 10). During the 20th century global population tripled, and water demand grew by a factor of six. The increase in global water demand beyond the population growth rate is due to an improved standard of living without an offset by water conservation. Increased production of goods and energy entails a large increase in water demand. The major global water uses are irrigation (68%), public supply (21%), and industry (11%).

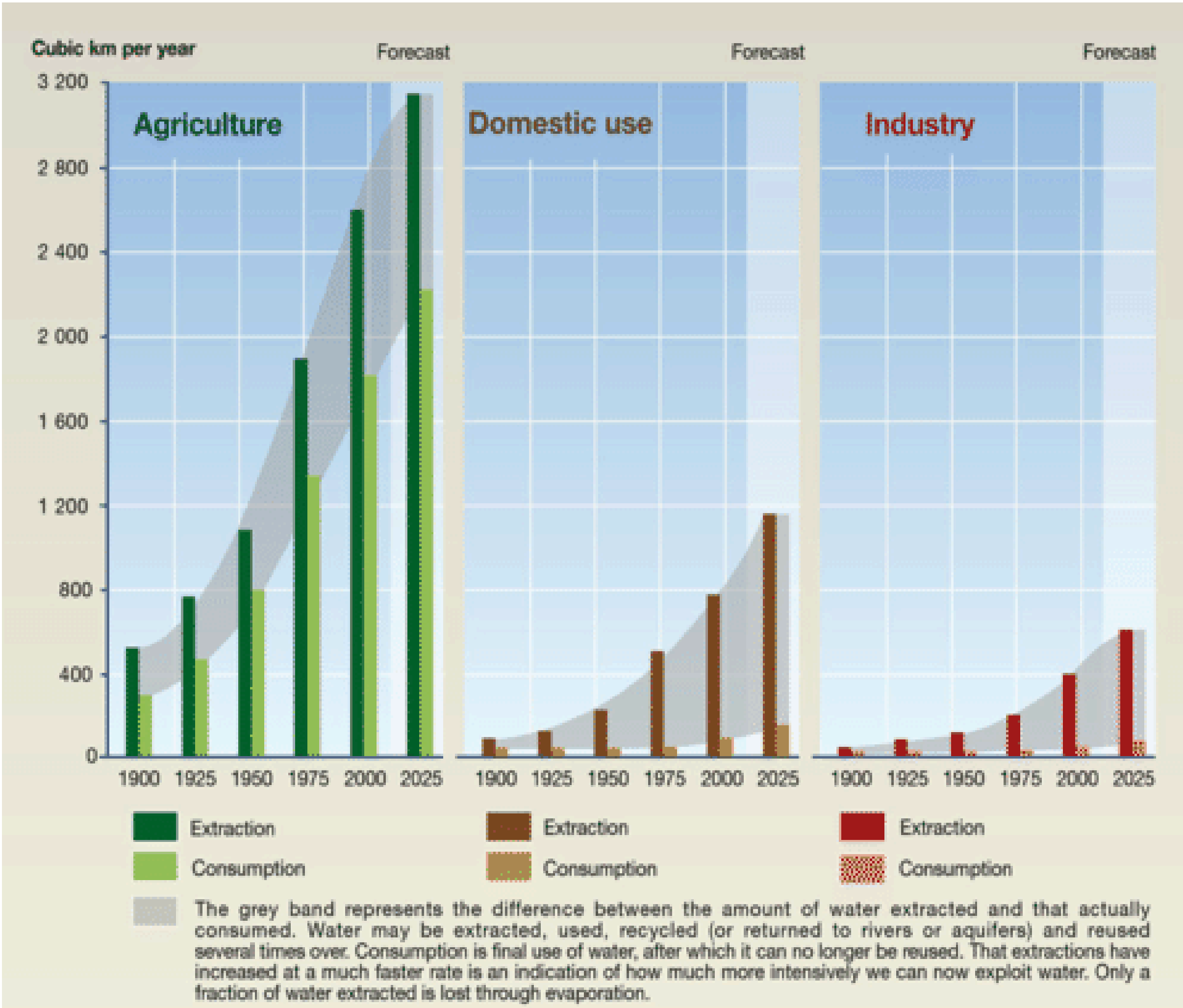


Figure 10. Trends in World Water Use from 1900 to 2000 and Projected to 2025 For each water major use category, including agriculture, domestic use, and industry trends. The darker-colored bar represents the total water extracted for that use category, and the lighter-colored bar represents water consumed (i.e., water not quickly returned to surface water or groundwater system) for that use category. Source: Igor A. Shiklomanow, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999

Water Supply Problems: Resource Depletion

As groundwater is pumped from water wells, there usually is a localized drop in the water table around the well called a cone of depression. When a large number of wells have been pumping water for a long time, the regional water table can drop significantly. This is called **groundwater mining**, which can force the drilling of deeper, more expensive wells that commonly encounter more saline groundwater. Rivers, lakes, and artificial lakes (reservoirs) can also be depleted due to overuse. Some large rivers, such as the Colorado in the U.S. and the Yellow in China, run dry in some years. The case history of the Aral Sea discussed later in this chapter involves the depletion of a lake. Finally, glaciers are being depleted due to accelerated melting associated with global warming over the past century.

Another water resource problem associated with groundwater mining is saltwater intrusion, where the overpumping of freshwater aquifers near ocean coastlines causes saltwater to enter freshwater zones. The drop of the water table around a **cone of depression** in an unconfined aquifer can change the direction of regional groundwater flow, sending nearby pollution toward the pumping well instead of away from it. Finally, problems of **subsidence** (gradual sinking of the land surface over a large area) and **sinkholes** (rapid sinking of the land surface over a small area) can develop due to a drop in the water table.

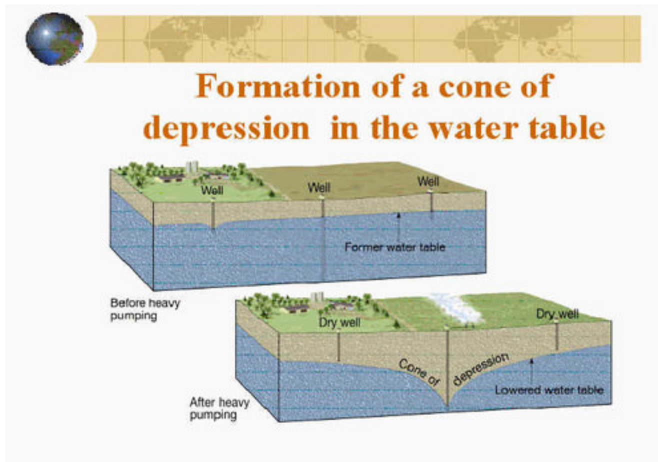


Figure 1. Formation of a Cone of Depression around a Pumping Water Well Source: Fayette County Groundwater Conservation District, TX

Water Supply Crisis

The **water crisis** is a global situation where people in many areas lack access to sufficient, clean, or both. This section describes the global situation involving water shortages, called **water stress**. Water stress is generally greatest in areas with very low precipitation (major deserts), large population density (e.g., India), or both. Global warming could worsen the water crisis by shifting precipitation patterns away from humid areas and melting mountain glaciers that recharge rivers downstream. Melting glaciers will also contribute to rising sea levels, worsening saltwater intrusion in aquifers near ocean coastlines.

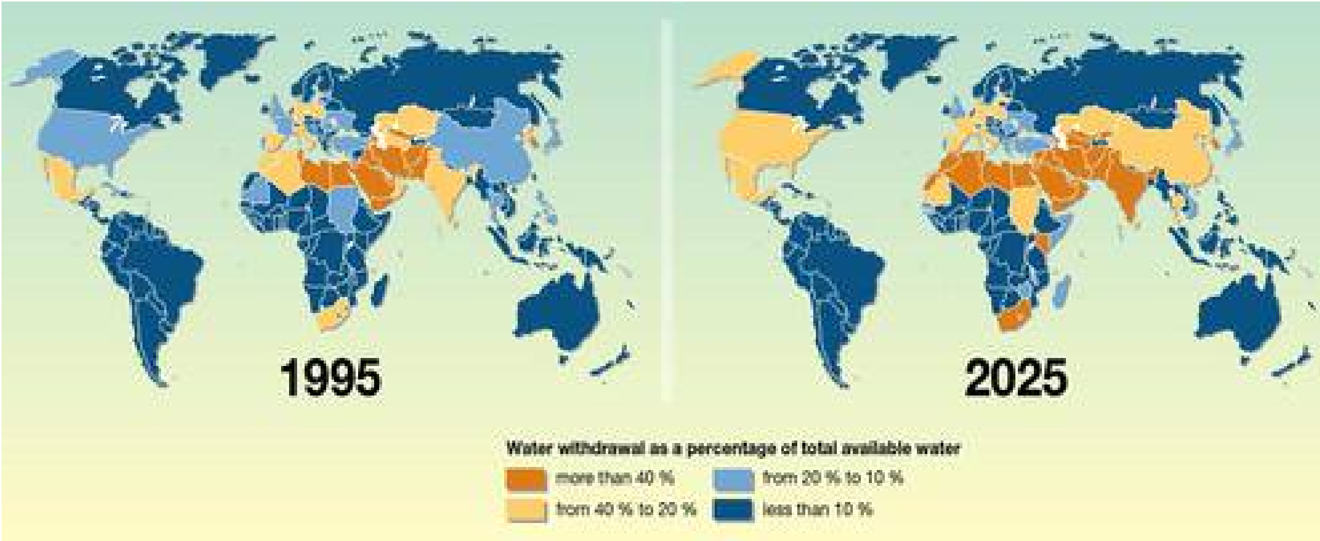


Figure 2. Countries Facing Water Stress in 1995 and Projected in 2025. Water stress is defined as having a high percentage of water withdrawal compared to the total available water in the area. Source: Philippe Rekacewicz (Le Monde diplomatique), February 2006

According to a 2006 United Nations Development Programme report, 700 million people (11% of the world's population) lived with water stress. Most of them live in the Middle East and North Africa. By 2025, the report projects that more than 3 billion people (about 40% of the world's population) will live in water-stressed areas, with the large increase coming mainly from China and India. The water crisis will also impact food production and our ability to feed the ever-growing population. We can expect future global tension and even conflict associated with water shortages and pollution. Historical and future areas of water conflict include the Middle East (Euphrates and Tigris River conflict among Turkey, Syria, and Iraq; Jordan River conflict among Israel, Lebanon, Jordan, and the Palestinian territories), Africa (Nile River conflict among Egypt, Ethiopia, and Sudan), Central Asia (Aral Sea conflict among Kazakhstan, Uzbekistan, Turkmenistan, Tajikistan, and Kyrgyzstan), and south Asia (Ganges River conflict between India and Pakistan).

Sustainable Solutions to the Water Supply Crisis?

The current and future water crisis described above requires multiple approaches to extending our fresh water supply and moving towards sustainability. Some of the longstanding traditional approaches include dams and aqueducts.

Reservoirs that form behind dams in rivers can collect water during wet times and store it for use during dry spells. They also can be used for urban water supplies. Other benefits of dams and reservoirs are hydroelectricity, flood control, and recreation. Some drawbacks are evaporative water loss in arid climates, downstream river channel erosion, and impact on the ecosystem, including a change from a river to a lake habitat and interference with migration and spawning of fish.

Figure 3. Hoover Dam, Nevada, U.S. Hoover Dam, Nevada, U.S. Behind the dam is Lake Mead, the largest reservoir in the U.S. White band reflects the lowered water levels in the reservoir due to drought conditions from 2000 – 2010. Source: Cygnusloop99 at Wikimedia Commons

Aqueducts can move water from where it is plentiful to where it is needed. Aqueducts can be controversial and politically difficult, especially if the water transfer distances are large. One drawback is that water diversion can cause drought in the area from where the water is drawn. For example, Owens Lake and Mono Lake in central California began disappearing after their river flow was diverted to the Los Angeles aqueduct. Owens Lake remains almost completely dry, but Mono Lake has recovered more significantly due to legal intervention.

One method that can actually increase the amount of fresh water on Earth is **desalination**, which involves removing dissolved salt from seawater or saline groundwater. Several ways to desalinate seawater include boiling, filtration, and electrodialysis. These procedures are moderate to very expensive and require considerable energy input, making the water produced much more expensive than fresh water from conventional sources. In addition, the process creates highly saline wastewater, which must be disposed of and creates a significant environmental impact. Desalination is most common in the Middle East, where energy from oil is abundant, but water is scarce.

Conservation means using less water and using it more efficiently. Around the home, conservation can involve both engineered features, such as high-efficiency clothes washers and low-flow showers and toilets, as well as behavioral decisions, such as growing native vegetation that requires little irrigation in desert climates, turning off the water while you brush your teeth, and fixing leaky faucets.

Figure 4. The California Aqueduct California Aqueduct in southern California, U.S. Source: David Jordan at en.Wikipedia

Rainwater harvesting involves catching and storing rainwater for reuse before it reaches the ground. Another important technique is **efficient irrigation,** which is extremely important because irrigation accounts for a much larger water demand than the public water supply. Water conservation strategies in agriculture include growing crops in areas where the natural rainfall can support them, more efficient irrigation systems such as drip systems that minimize losses due to evaporation, no-till farming that reduces evaporative losses by covering the soil and reusing treated wastewater from sewage treatment plants. Recycled wastewater has also been used to recharge aquifers.

The global water crisis also involves water pollution. For water to be useful for drinking and irrigation, it must not be polluted beyond certain thresholds. According to the World Health Organization, in 2008, approximately 880 million people (or 13% of the world population) did not have access to safe drinking water. At the same time, about 2.6 billion people (or 40% of the world's population) lived without improved sanitation, defined as having access to a public sewage system, septic tank, or even a simple pit latrine. Approximately 1.7 million people die yearly from diarrheal diseases associated with unsafe drinking water, inadequate sanitation, and poor hygiene. Almost all of these deaths are in developing countries, and around 90% occur among children under the age of 5 (Figure 1). Compounding the water crisis is the issue of social justice; poor people more commonly lack clean water and sanitation than wealthy people in similar areas. Globally, improving water safety, sanitation, and hygiene could prevent up to 9% of all diseases and 6% of all deaths.

In addition to the global waterborne disease crisis, chemical pollution from agriculture, industry, cities, and mining threatens global water quality. Some chemical pollutants have serious and well-known health effects, whereas others have poorly known long-term health effects. In the U.S., more than 40,000 water bodies currently fit the "impaired " definition set by the EPA, which means they could neither support a healthy ecosystem nor meet water quality standards. In Gallup public polls conducted over the past decade, Americans consistently put water pollution and water supply as the top environmental concerns over air pollution, deforestation, species extinction, and global warming.

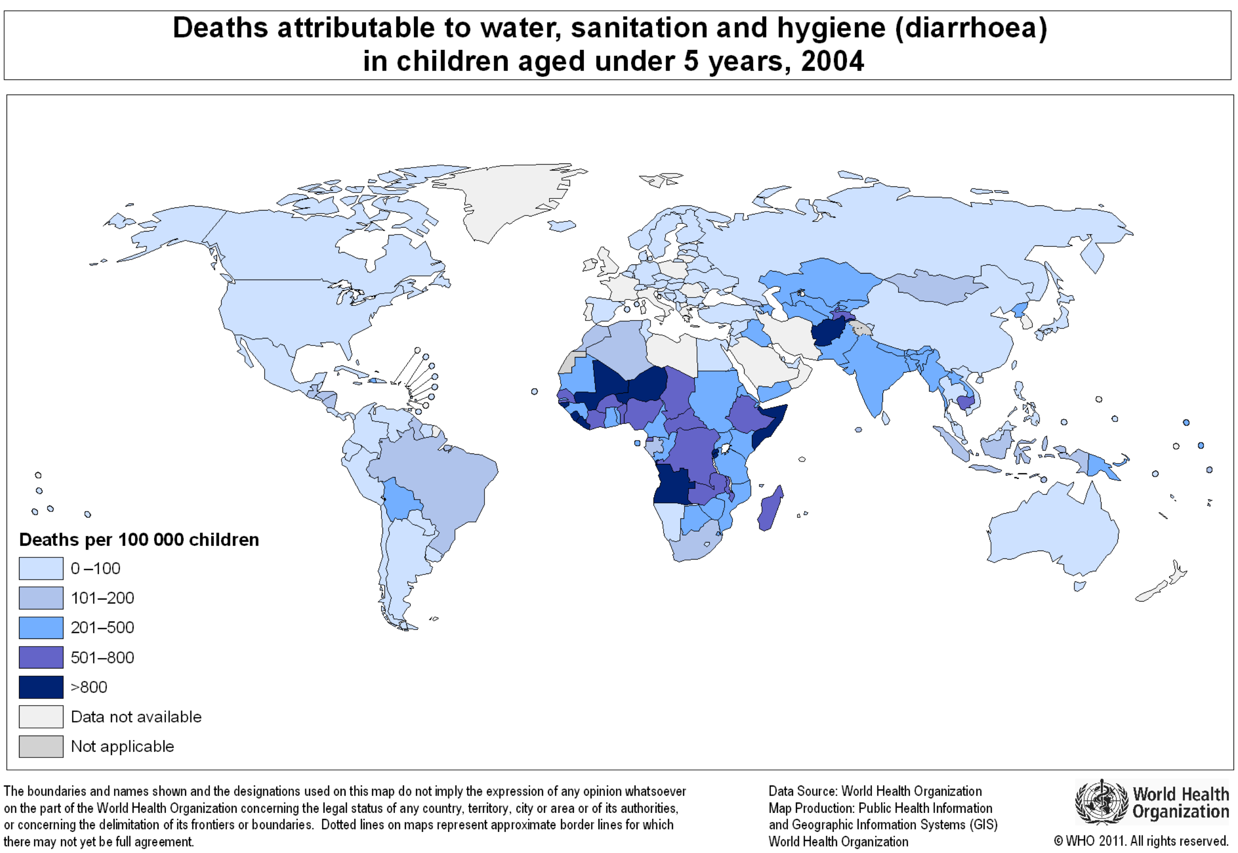


Figure 1. This work was created by the World Health Organization.

Any natural water contains dissolved chemicals, some of which are important human nutrients, while others can harm human health. The concentration of a water pollutant is commonly given in very small units such as parts per million (**ppm**) or even parts per billion (**ppb**). An arsenic concentration of 1 ppm means 1 part of arsenic per million parts of water. This is equivalent to one drop of arsenic in 50 liters of water. To give you a different perspective on appreciating small concentration units, converting one ppm to length units is 1 cm (0.4 in) in 10 km (6 miles), and converting one ppm to time units is 30 seconds in a year. **Total dissolved solids** (TDS) represent the total amount of dissolved material in water. Average TDS values for rainwater, river water, and seawater are about four ppm, 120 ppm, and 35,000 ppm, respectively.

Water Pollution Overview

Water pollution is water contamination by an excess amount of a substance that can cause harm to human beings and/or the ecosystem. The level of water pollution depends on the abundance of the pollutant, the ecological impact of the pollutant, and the use of the water. Pollutants are derived from biological, chemical, or physical processes. Although natural processes such as volcanic eruptions or evaporation sometimes can cause water pollution, most pollution is derived from human, land-based activities (Figure 2). Water pollutants can move through different water reservoirs as the water carries them through stages of the water cycle (Figure 3). **Water residence time** (the average time a water molecule spends in a water reservoir) is very important to pollution problems because it affects pollution potential. Water in rivers has a relatively short residence time, so pollution usually is there only briefly. Of course, river pollution may simply move to another reservoir, such as the ocean, where it can cause further problems. Groundwater is typically characterized by slow flow and longer residence time, which can make groundwater pollution particularly problematic. Finally, **pollution residence time** can be much greater than the water residence time because a pollutant may be taken up for a long time within the ecosystem or absorbed into the sediment.

Figure 2. Water Pollution. Obvious water pollution is in the form of floating debris; invisible water pollutants can sometimes be much more harmful than visible ones. Source: Stephen Codrington at Wikimedia Commons

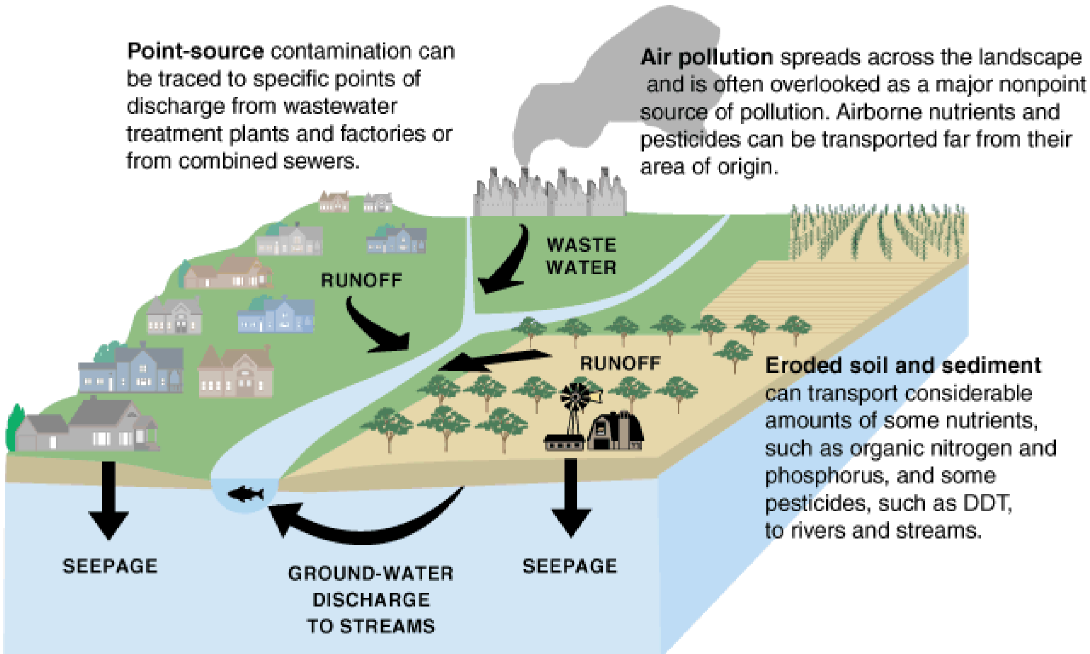


Figure 3. Sources of Water Contamination. Source: U.S. Geological Survey

Figure 4. Large animal farms are often called concentrated feeding operations (CFOs). These farms are considered potential point sources of pollution because untreated animal waste may enter nearby waterbodies as untreated sewage. Credit: ehp.gov

Pollutants enter water supplies from **point sources**, which are readily identifiable and relatively small locations, or **nonpoint sources**, which are large and more diffuse areas. Point sources of pollution include animal factory farms (Figure 4) that raise a large number and high density of livestock such as cows, pigs, and chickens. Also included are pipes from factories or sewage treatment plants. Combined sewer systems with single underground pipes to collect sewage and stormwater runoff from streets for wastewater treatment can be a major source of pollutants. During heavy rain, stormwater runoff may exceed sewer capacity, causing it to back up and spill untreated sewage directly into surface waters (Figure 5).

Nonpoint sources of pollution include agricultural fields, cities, and abandoned mines. Rainfall runs over the land and through the ground, picking up pollutants such as herbicides, pesticides, and fertilizer from agricultural fields and lawns; oil, antifreeze, animal waste, and road salt from urban areas; and acid and toxic elements from abandoned mines. Then, this pollution is carried into surface water bodies and groundwater. Nonpoint source pollution, which is the leading cause of water pollution in the U.S., is usually much more difficult and expensive to control than point source pollution because of its low concentration, multiple sources, and much greater volume of water.

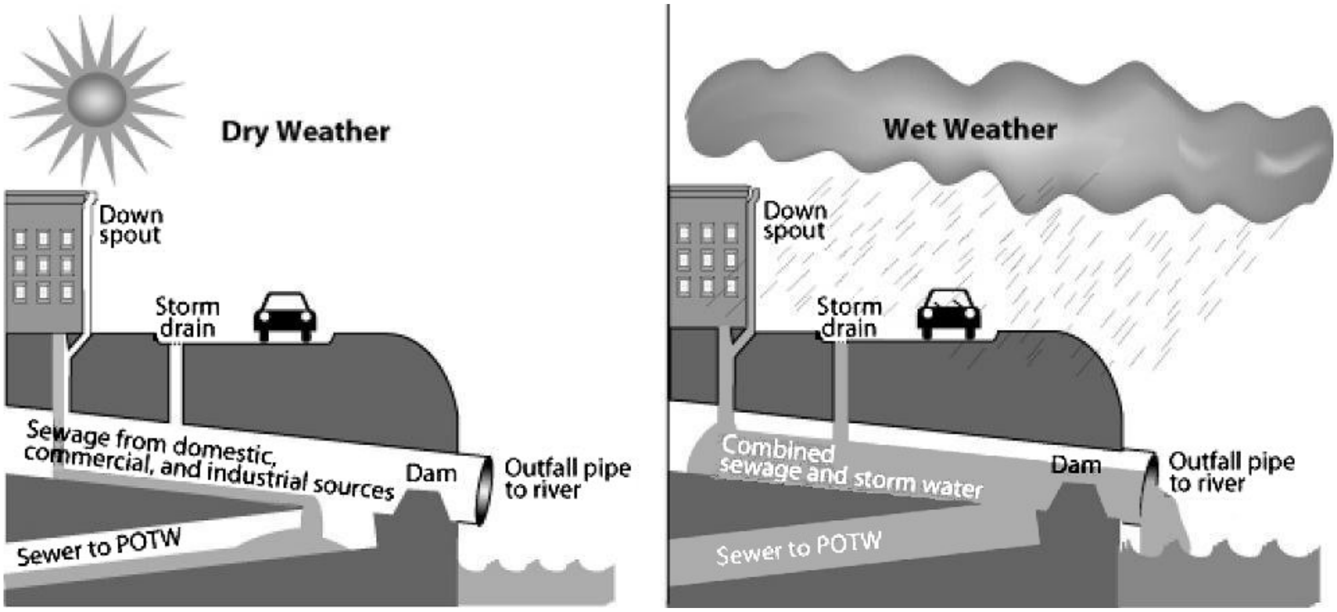


Figure 5. Combined Sewer System A combined sewer system is a possible major point source of water pollution during heavy rain due to overflow of untreated sewage. During dry weather (and small storms), all flows are handled by the publicly owned treatment works (POTW). During large storms, the relief structure allows some of the combined stormwater and sewage to be discharged untreated to an adjacent water body. Source: U.S. Environmental Protection Agency at Wikimedia Commons

Types of Water Pollutants

Oxygen-demanding waste is an extremely important pollutant to ecosystems. Most surface water in contact with the atmosphere has a small amount of dissolved oxygen, which aquatic organisms need for cellular respiration. Bacteria decompose dead organic matter and remove dissolved oxygen (O_2) according to the following reaction:

$$\text{organic matter} + O_2 \rightarrow CO_2 + H_2O$$

Too much decaying organic matter in water is a pollutant because it removes oxygen from water, which can kill fish, shellfish, and aquatic insects. The amount of oxygen used by **aerobic** (in the presence of oxygen) bacterial decomposition of organic matter is called **biochemical oxygen demand** (BOD). The major source of dead organic matter in many natural waters is sewage, whereas grass and leaves are minor sources. An unpolluted water body, concerning BOD, might be a turbulent river flowing through a natural forest. Turbulence continually brings water in contact with the atmosphere, where the O_2 content is restored. The dissolved oxygen content in such a river might range from 10 to 14 ppm O_2, and BOD is low, which supports clean-water fish such as trout. A polluted water body with high BOD might be a stagnant lake in an urban setting with pollution from sewage runoff. This results in a high input of organic carbon and has limited opportunities for water circulation and contact with the atmosphere. In such a lake, the dissolved O_2 content is typically ≤ 5 ppm O_2, BOD is high, and low O_2-tolerant fish, such as carp and catfish, dominate.

Figure 6. Algal Bloom in River in Sichuan, China Algal blooms can present problems for ecosystems and human society. Source: Felix Andrews44 via Wikimedia Commons

Excessive plant nutrients, particularly nitrogen (N) and phosphorous (P), are pollutants closely related to oxygen-demanding waste. Aquatic plants require about 15 nutrients for growth, most of which are plentiful in water. N and P are called **limiting nutrients**, however, because they usually are present in water at low concentrations, restricting the total amount of plant growth. This explains why N and P are major ingredients in most fertilizers. High concentrations of N and P from human sources (mostly agricultural and urban runoff, including fertilizer, sewage, and phosphorus-based detergent) can cause cultural **eutrophication**, which leads to the rapid growth of aquatic producers, particularly algae (Figure 6). Thick mats of floating algae or rooted plants lead to water pollution, damaging the ecosystem by clogging fish gills and blocking sunlight. A small percentage of algal species produce toxins that can kill animals, including humans. Exponential growths of these algae are called **harmful algal blooms**. When the prolific algal layer dies, it becomes oxygen-demanding waste, creating very low O_2 concentrations in the water (< 2 ppm O_2), a condition called **hypoxia.** This results in a **dead zone** because it causes death from asphyxiation to organisms that cannot leave that environment. An estimated 50% of North America, Europe, and Asia lakes are negatively impacted by cultural eutrophication. In addition, the size and number of marine hypoxic zones have grown dramatically over the past 50 years, including a very large dead zone located offshore Louisiana in the Gulf of Mexico. Cultural eutrophication and hypoxia are difficult to combat because they are caused primarily by nonpoint source pollution, which is difficult to regulate, and N and P, which are difficult to remove from wastewater.

Pathogens are disease-causing microorganisms, e.g., viruses, bacteria, parasitic worms, and protozoa, which cause various intestinal diseases such as dysentery, typhoid fever, and cholera. Pathogens are the major cause of the water pollution crisis discussed at the beginning of this section. Unfortunately, nearly a billion people worldwide are exposed to waterborne pathogen pollution daily, and around 1.5 million children, mainly in underdeveloped countries, die yearly of waterborne diseases from pathogens. Pathogens enter water primarily from human and animal fecal waste due to inadequate sewage treatment. In many underdeveloped countries, sewage is discharged into local waters either untreated or after only rudimentary treatment. In developed countries, untreated sewage discharge can occur from overflows of combined sewer systems, poorly managed livestock factory farms, and leaky or broken sewage collection systems. Water with pathogens can be remediated by adding chlorine or ozone, by boiling, or by treating sewage in the first place.

Oil spills are another kind of organic pollution. Oil spills can result from supertanker accidents such as the Exxon Valdez in 1989, which spilled 10 million gallons of oil into the rich ecosystem of coastal Alaska and killed massive numbers of animals. The largest marine oil spill was the Deepwater Horizon disaster, which began with a natural gas explosion (Figure 7) at an oil well 65 km offshore of Louisiana and flowed for 3 months in 2010, releasing an estimated 200 million gallons of oil. The worst oil spill ever occurred during the Persian Gulf War of 1991, when Iraq deliberately dumped approximately 200 million gallons of oil in offshore Kuwait and set more than 700 oil well fires that released enormous clouds of smoke and acid rain for over nine months.

Figure 7. Deepwater Horizon Explosion Boats fighting the fire from an explosion at the Deepwater Horizon drilling rig in the Gulf of Mexico offshore Louisiana on April 20, 2010. Source: United States Coast Guard via Wikimedia Commons

During an oil spill on water, oil floats to the surface because it is less dense than water, and the lightest hydrocarbons evaporate, decreasing the spill's size but polluting the air. Then, bacteria decompose the remaining oil in a process that can take many years. After several months only about 15% of the original volume may remain, but it is in thick asphalt lumps, a form that is particularly harmful to birds, fish, and shellfish. Cleanup operations can include skimmer ships that vacuum oil from the water surface (effective only for small spills), controlled burning (works only in early stages before the light, ignitable part evaporates but also pollutes the air), **dispersants** (detergents that break up oil to accelerate its decomposition, but some dispersants may be toxic to the ecosystem), and bioremediation (adding microorganisms that specialize in quickly decomposing oil, but this can disrupt the natural ecosystem).

Toxic chemicals involve many kinds and sources, primarily from industry and mining. General kinds of toxic chemicals include hazardous chemicals and persistent organic pollutants that include DDT (pesticide), dioxin (herbicide by-product), and PCBs (polychlorinated biphenyls, which were used as liquid insulators in electric transformers). **Persistent organic pollutants** (POPs) are long-lived in the environment, biomagnified through the food chain, and can be toxic. Another category of toxic chemicals includes radioactive materials such as cesium, iodine, uranium, and radon gas, which can result in long-term exposure to radioactivity if it gets into the body. A final group of toxic chemicals is heavy metals such as lead, mercury, arsenic, cadmium, and chromium, which can accumulate through the food chain. Heavy metals are commonly produced by industry and at metallic ore mines. Arsenic and mercury are discussed in more detail below.

Arsenic (As) has been famous as an agent of death for many centuries. Only recently have scientists recognized that health problems can be caused by drinking small arsenic concentrations in water over a long time. It enters the water supply naturally from weathering arsenic-rich minerals and human activities such as burning coal and smelting metallic ores. The worst case of arsenic poisoning occurred in Bangladesh's densely populated, impoverished country, which had experienced 100,000s deaths from diarrhea and cholera each year from drinking surface water contaminated with pathogens due to improper sewage treatment. In the 1970s, the United Nations provided aid for millions of shallow water wells, dramatically dropping pathogenic diseases. Unfortunately, many of the wells produced water naturally rich in arsenic. Tragically, an estimated 77 million people (about half of the population) inadvertently may have been exposed to toxic levels of arsenic in Bangladesh as a result. The World Health Organization has called it the largest mass poisoning of a population in history.

Mercury (Hg) is used in various electrical products, such as dry cell batteries, fluorescent light bulbs, and switches, as well as in manufacturing paint, paper, vinyl chloride, and fungicides. Mercury acts on the central nervous system and can cause loss of sight, feeling, hearing, nervousness, shakiness, and death. Like arsenic, mercury enters the water supply naturally from weathering of mercury-rich minerals and from human activities such as coal burning and metal processing. Mercury concentrates in the food chain, especially in fish, in a process caused **by biomagnification** (Figure 8). It acts on the central nervous system and can cause loss of sight, feeling, and hearing, as well as nervousness, shakiness, and death. Like arsenic, mercury naturally enters the water supply from weathering Hg-rich minerals and from human activities such as coal burning and metal processing. A famous mercury poisoning case in Minamata, Japan, involved methylmercury-rich industrial discharge that caused high Hg levels in fish. People in the local fishing villages ate fish up to three times per day for over 30 years, which resulted in over 2,000 deaths. During that time, the responsible company and national government did little to mitigate, help alleviate, or even acknowledge the problem.

Biomagnification represents the processes in an ecosystem that cause greater chemical concentrations, such as methylmercury, in organisms higher up the food chain. Mercury and methylmercury are present in only very small concentrations in seawater; however, algae absorb methylmercury at the base of the food chain. Then, small sh eat the algae, large sh and other organisms higher in the food chain eat the small sh, and so on. Fish and other aquatic organisms absorb methylmercury rapidly but eliminate it slowly from the body. Therefore, each step up the food chain increases the concentration from the step below. Largemouth bass can concentrate methylmercury up to 10 million times over the water concentration, and fish-eating birds can concentrate it even higher. Other chemicals that exhibit biomagnification are DDT, PCBs, and arsenic.

Hard water contains abundant calcium and magnesium, which reduces its ability to develop soapsuds and enhances scale (calcium and magnesium carbonate minerals) formation on hot water equipment. Water softeners remove calcium and magnesium, which allows the water to lather easily and resist scale formation. Hard water develops naturally from dissolved calcium and magnesium carbonate minerals in soil; it does not negatively affect people.

Groundwater pollution can occur from underground sources, and all pollution sources contaminate surface waters. Common sources of groundwater pollution are leaking underground storage tanks for fuel, septic tanks, agricultural activity, landfills, and fossil fuel extraction. Common groundwater pollutants include nitrate, pesticides, volatile organic compounds, and petroleum products. Another troublesome feature of groundwater pollution is that small amounts of certain pollutants, e.g., petroleum products and organic solvents, can contaminate large areas. In Denver, Colorado, 80 liters of several organic solvents contaminated 4.5 trillion liters of groundwater and produced a five km-long contaminant plume. A major threat to groundwater quality is from underground fuel storage tanks. Fuel tanks are commonly stored underground at gas stations to reduce explosion hazards. Before 1988 in the U.S., these storage tanks could be made of metal, which can corrode, leak, and quickly contaminate local groundwater. Now, leak detectors are required, and the metal storage tanks are supposed to be protected from corrosion or replaced with fiberglass tanks. There are around 600,000 underground fuel storage tanks in the U.S., and over 30% still do not comply with EPA regulations regarding release prevention or leak detection.

Resolution of the global water pollution crisis requires multiple approaches to improve the quality of our fresh water and move towards sustainability. The most deadly form of water pollution, pathogenic microorganisms that cause waterborne diseases, kills almost 2 million people annually in underdeveloped countries. The best strategy for addressing this problem is proper sewage (wastewater) treatment. Untreated sewage is a major cause of pathogenic diseases and a major source of other pollutants, including oxygen-demanding waste, nutrients (N and P, particularly), and toxic heavy metals. Wastewater treatment is done at a sewage treatment plant in urban areas and through a septic tank system in rural areas.

The main purpose of **sewage (wastewater) treatment** is to remove organic matter (oxygen-demanding waste) and kill bacteria. Special methods also can be used to remove nutrients and other pollutants. The numerous steps at a conventional sewage treatment plant include **pretreatment** (screening and removal of sand and gravel), **primary treatment** (settling or floatation to remove organic solids, fat, and grease), **secondary treatment** (aerobic bacterial decomposition of organic solids), **tertiary treatment** (bacterial decomposition of nutrients and filtration), **disinfection** (treatment with chlorine, ozone, ultraviolet light, or bleach to kill most microbes), and either **discharge** to surface waters (usually a local river) or reuse for some other purpose, such as irrigation, habitat preservation, and artificial groundwater recharge (Figure 1).

The concentrated organic solid produced during primary and secondary treatment is called **sludge**, which is treated in various ways, including landfill disposal, incineration, use as fertilizer, and anaerobic bacterial decomposition, done without oxygen. Anaerobic decomposition of sludge produces methane gas, which can be used as an energy source. To reduce water pollution problems, separate sewer systems (where street runoff goes to rivers and only wastewater goes to a wastewater treatment plant) are much better than combined sewer systems, which can overflow and release untreated sewage into surface waters during heavy rain. Some cities, such as Chicago, Illinois, have constructed large underground caverns and used abandoned rock quarries to hold storm sewer overflow. After the rain stops, the stored water goes to the sewage treatment plant for processing.

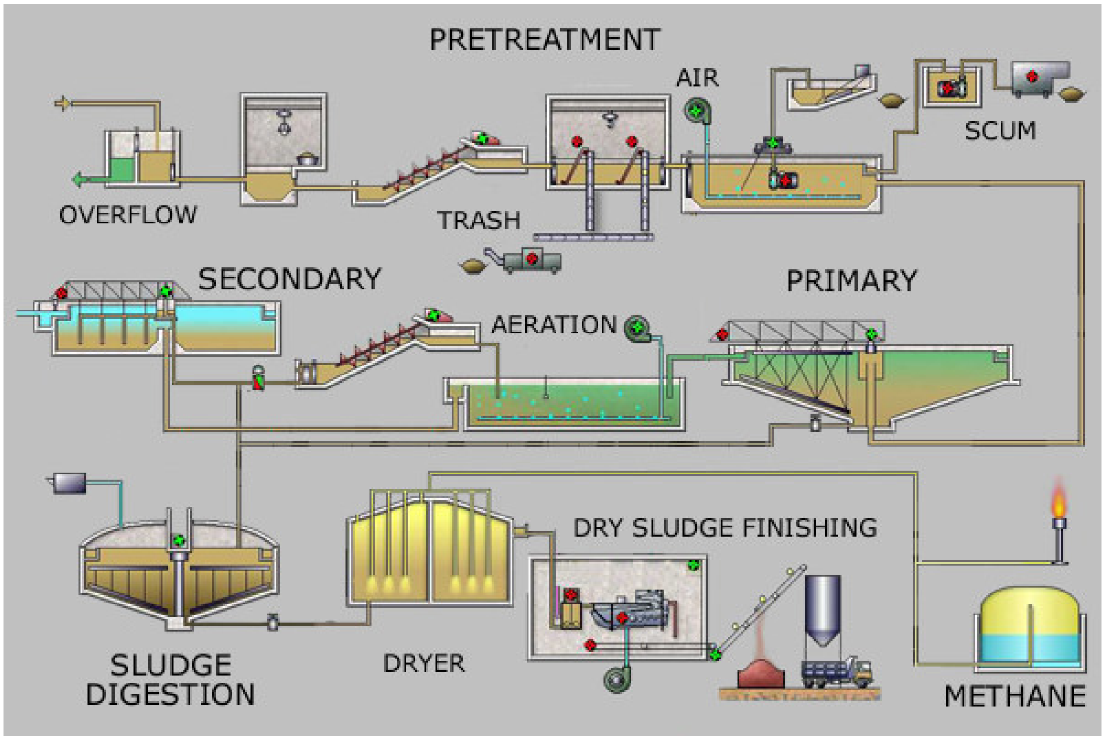


Figure 1. Steps at a Sewage Treatment Plant The numerous processing steps at a conventional sewage treatment plant include pretreatment (screening and removal of sand and gravel), primary treatment (settling or floatation to remove organic solids, fat, and grease), secondary treatment (aerobic bacterial decomposition of organic solids), tertiary treatment (bacterial decomposition of nutrients and filtration), disinfection (treatment with chlorine, ozone, ultraviolet light, or bleach), and either discharge to surface waters (usually a local river) or reuse for some other purpose, such as irrigation, habitat preservation, and artificial groundwater recharge. Source: Leonard G.via Wikipedia

A **septic tank system** is an individual sewage treatment system for homes in typically rural settings. The basic components of a septic tank system (Figure 2) include a sewer line from the house, a septic tank (a large container where sludge settles to the bottom and microorganisms decompose the organic solids anaerobically), and the drain field (network of perforated pipes where the clarified water seeps into the soil and is further purified by bacteria). Water pollution problems occur if the septic tank malfunctions, usually when a system is established in the wrong soil type or maintained poorly.

For many developing countries, financial aid is necessary to build adequate sewage treatment facilities. The World Health Organization estimates an estimated cost savings of between $3 and $34 for every $1 invested in clean water delivery and sanitation. The cost savings are from health care savings, work and school productivity gains, and prevented deaths. Simple and inexpensive techniques for treating water at home include chlorination, filters, and solar disinfection. Another alternative is to use constructed wetlands technology (marshes built to treat contaminated water), which is simpler and cheaper than a conventional sewage treatment plant.

Bottled water is not a sustainable solution to the water crisis. Bottled water is not necessarily any safer than the U.S. public water supply. It costs, on average, about 700 times more than U.S. tap water, and every year it uses approximately 200 billion plastic and glass bottles that have a relatively low rate of recycling. It uses much more energy than tap water, mainly in bottle manufacturing and long-distance transportation. If you don't like the taste of your tap water, then please use a water filter instead of bottled water!

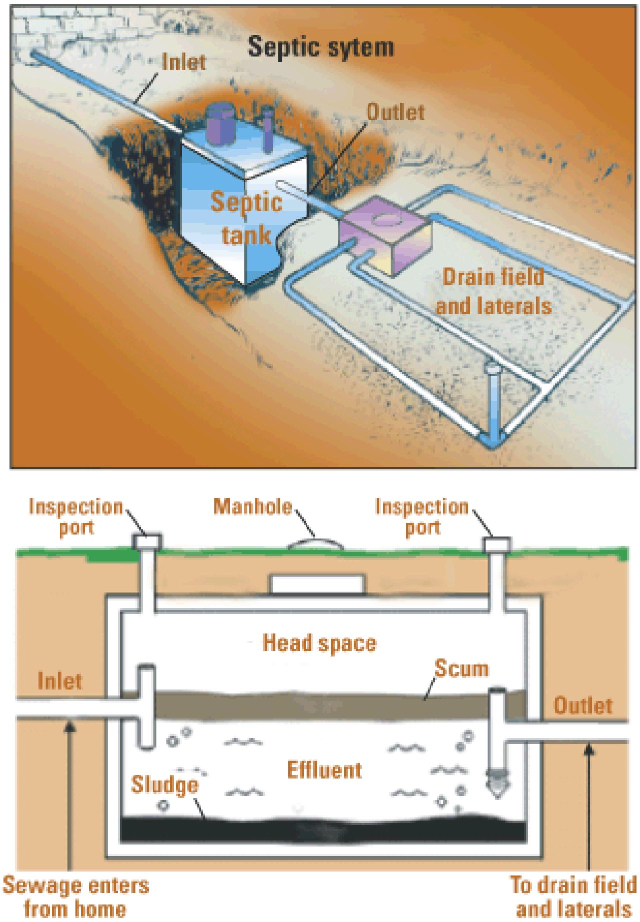
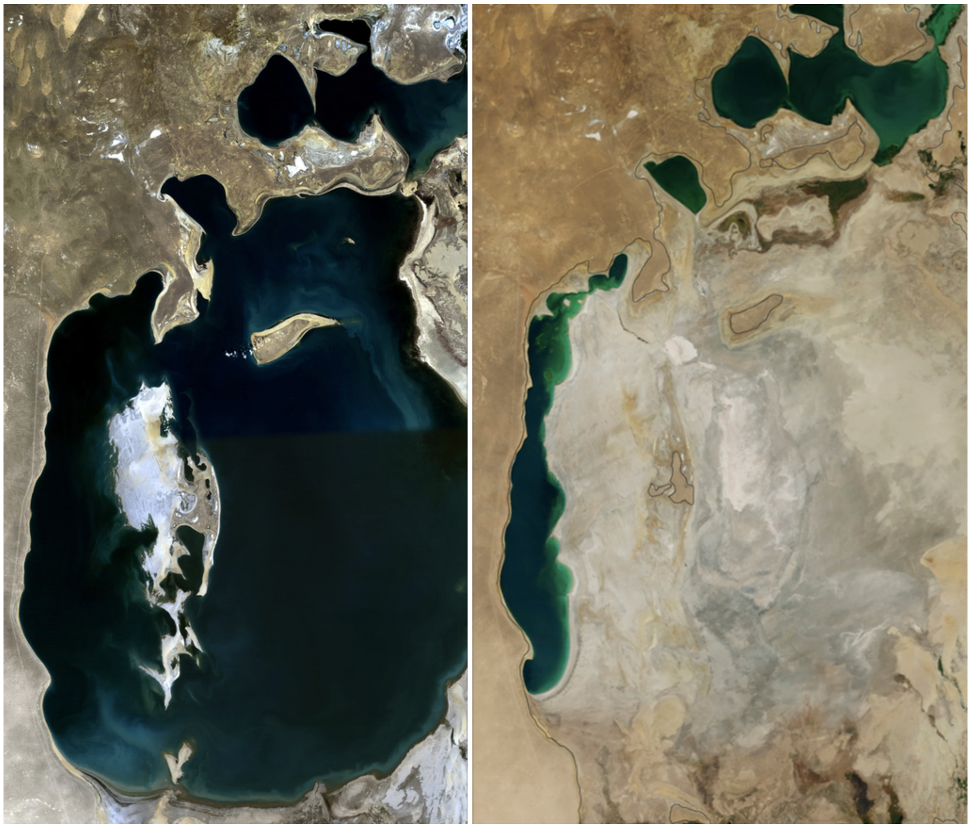


Figure 2. Septic System. Septic tank system for sewage treatment. Source: United States Geological Survey

Clean Water Act

Figure 3. Cuyahoga River is on fire. Source: National Oceanic and Atmospheric Administration

During the early 1900s, rapid industrialization in the U.S. resulted in widespread water pollution due to the free discharge of waste into surface waters. The Cuyahoga River in northeast Ohio caught fire numerous times, including a famous fire in 1969 that caught the nation's attention. In 1972 Congress passed one of the most important environmental laws in U.S. history, the Federal Water Pollution Control Act, more commonly called the **Clean Water Act**. The purpose of the Clean Water Act and later amendments is to maintain and restore water quality, or in simpler terms, to make our water swimmable and fishable. Dumping pollution into surface water became illegal unless there was formal permission, and U.S. water quality improved significantly as a result. More progress is needed because currently, the EPA considers over 40,000 U.S. water bodies as impaired, most commonly due to pathogens, metals, plant nutrients, and oxygen depletion. Another concern is protecting groundwater quality, which federal law has not addressed sufficiently.



A comparison of the Aral Sea in 1989 (left) and 2014 (right). Credit: This work is in the Public Domain, CC0

The Aral Sea is a lake located east of the Caspian Sea between Uzbekistan and Kazakhstan in central Asia. This area is part of the Turkestan desert, which is the fourth largest desert in the world; it is produced from a rain shadow effect by Afghanistan's high mountains to the south. Due to the arid and seasonally hot climate, there is extensive evaporation and limited surface waters. Summer temperatures can reach 60^{o}C (140^{o}F)! The Aral Sea's water supply is mainly from the Amu Darya and the Syr Darya, which carry snowmelt from mountainous areas. In the early 1960s, the then-Soviet Union diverted the Amu Darya and Syr Darya Rivers for irrigation of one of the driest parts of Asia to produce rice, melons, cereals, and especially cotton. The Soviets wanted cotton or white gold to become a major export. They were successful, and today Uzbekistan is one of the world's largest exporters of cotton. Unfortunately, this action eliminated any river inflow to the Aral Sea and caused it to disappear almost completely.

Figure 2. Map of Aral Sea Area Map shows the size of the lake in 1960 and the political boundaries of 2011. Countries in yellow are at least partially in the Aral Sea drainage basin. Source: Wikimedia Commons

In 1960, the Aral Sea was the fourth largest inland water body; only the Caspian Sea, Lake Superior, and Lake Victoria were larger. Since then, it has progressively shrunk due to rivers' evaporation and lack of recharge. Before 1965, the Aral Sea received 2060 km^3 of fresh water per year from rivers, and by the early 1980s, it received none. By 2007, the Aral Sea shrank to about 10% of its original size, and its salinity increased from about 1% dissolved salt to about 10% dissolved salt, which is three times more saline than seawater. These changes caused an enormous environmental impact. A once thriving fishing industry is dead, as are the 24 species of fish that used to live there; the fish could not adapt to the more saline waters. The current shoreline is tens of kilometers from former fishing towns and commercial ports. Large fishing boats lie in the dried-up lakebed of dust and salt. A frustrating part of the river diversion project is that many irrigation canals were poorly built, allowing abundant water to leak or evaporate. An increasing number of dust storms blow salt, pesticides, and herbicides into nearby towns, causing various respiratory illnesses, including tuberculosis.

Figure 3. This abandoned ship lies in a dried-up lake bed that was the Aral Sea near Aral, Kazakhstan Source: Staecker at Wikimedia Commons

The wetlands of the two river deltas and their associated ecosystems have disappeared. The regional climate is drier and has greater temperature extremes due to the absence of moisture and moderating influence from the lake. In 2003, some lake restoration work began on the northern part of the Aral Sea, and it provided some relief by raising water levels and reducing salinity somewhat. The southern part of the Aral Sea has seen no relief and remains nearly completely dry. The destruction of the Aral Sea is one of the planet's biggest environmental disasters caused entirely by humans. Lake Chad in Africa is another example of a massive lake nearly disappearing for the same reasons as the Aral Sea. The Aral Sea and Lake Chad are the most extreme examples of large lakes destroyed by unsustainable diversions of river water. Other lakes that have shrunk significantly due to human water diversions include the Dead Sea in the Middle East, Lake Manchar in Pakistan, and Owens Lake and Mono Lake in California.

Summary

Precipitation—a major control of freshwater availability—is unevenly distributed around the globe. More precipitation falls near the equator, and a tropical rainforest climate characterizes landmasses. Less precipitation tends to fall near 2030 north and south latitudes of the world's largest deserts. The water crisis refers to a global situation where people in many areas lack access to sufficient or clean water or both. The current and future water crisis requires multiple approaches to extending our fresh water supply and moving towards sustainability. Some of the longstanding traditional approaches include dams and aqueducts. Water pollution is water contamination by an excess amount of a substance that can cause harm to human beings and the ecosystem. The level of water pollution depends on the abundance of the pollutant, the ecological impact of the pollutant, and the use of the water. The most deadly form of water pollution, pathogenic microorganisms that cause waterborne diseases, kills almost 2 million people annually in underdeveloped countries. Solving the global water pollution crisis requires multiple approaches to improve freshwater quality. The best strategy for addressing this problem is proper sewage treatment. Untreated sewage is a major cause of pathogenic diseases and a major source of other pollutants, including oxygen-demanding waste, plant nutrients, and toxic heavy metals.

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Chapter Attributions:

Chapter 8: Food and Hunger

By learning skills like composting, crop diversification, organic pesticide production, seed multiplication, and agro-forestry, farmers in Malawi are increasing their ability to feed their families over the long term.

Learning Outcomes

After studying this chapter, you should be able to:

- Understand the major drivers of food insecurity
- Recognize the role of women in food and nutritional security
- Classify key food and nutritional sources
- Identify benefits and risks of genetic engineering

Chapter Outline

- 8.1 Food Security
- 8.2 Biotechnology and Genetic Engineering
- 8.3 Chapter Resources

Progress continues in the fight against hunger, yet many people lack the food they need for an active and healthy life. The latest available estimates indicate that about 795 million people worldwide – just over one in nine –still go to bed hungry every night, and an even greater number live in poverty (defined as living on less than $1.25 per day). Poverty—not food availability—is the major driver of food insecurity. Improvements in agricultural productivity are necessary to increase rural household incomes and access to available food but are insufficient to ensure food security. Evidence indicates that poverty reduction and food security do not necessarily move in tandem. The main problem is the lack of economic (social and physical) access to food at national and household levels and inadequate nutrition (or hidden hunger). Food security not only requires an adequate supply of food but also entails availability, access, and utilization by all—people of all ages, gender, ethnicity, religion, and socioeconomic levels.

From Agriculture to Food Security

Agriculture and food security are inextricably linked. The agricultural sector in each country is dependent on the available natural resources, as well as the politics that govern those resources. **Staple food crops** are the main source of dietary energy in the human diet, including rice, wheat, sweet potatoes, maize, and cassava.

Food security

Food security is essentially built on four pillars: **availability**, **access**, **utilization**, and **stability**. An individual must always have access to sufficient food of the right dietary mix (quality) to be food secure. Those who never have sufficient quality food are **chronically food insecure**.

When food security is analyzed at the national level, an understanding of national production is important, as the country's access to food from the global market, foreign exchange earnings, and citizens' consumer choices. Food security analyzed at the household level is conditioned by a household's own food production and household members' ability to purchase food of the right quality and diversity in the marketplace. However, it is only at the individual level that the analysis can be truly accurate because only through understanding who consumes what can we appreciate the impact of sociocultural and gender inequalities on people's ability to meet their nutritional needs.

The definition of food security is often applied at varying levels of aggregation, despite its articulation at the individual level. The importance of a pillar depends on the level of aggregation being addressed. At a global level, the important pillar is food **availability**. Does global agricultural activity produce sufficient food to feed all the world's inhabitants? The answer today is yes, but it may not be true in the future given the impact of a growing world population, emerging plant and animal pests and diseases, declining soil productivity and environmental quality, increasing use of land for fuel rather than food, and lack of attention to agricultural research and development, among other factors.

The third pillar, food **utilization**, essentially translates the food available to a household into nutritional security for its members. One aspect of utilization is analyzed in terms of distribution according to need. Nutritional standards exist for the actual nutritional needs of men, women, boys, and girls of different ages and life phases (that is, pregnant women). However, these "needs" are often socially constructed based on culture. For example, in South Asia, evidence shows that women eat after everyone else has eaten and are less likely than men in the same household to consume preferred foods such as meats and fish. Hidden hunger commonly results from poor food utilization: a person's diet lacks the appropriate balance of macro- (calories) and micronutrients (vitamins and minerals). Individuals may look well nourished and consume sufficient calories but be deficient in key micronutrients such as vitamin A, iron, and iodine.

Food **stability** is when a population, household, or individual has access to food at all times and does not risk losing access due to cyclical events, such as the dry season**.** When some lack food stability, they have **malnutrition,** a lack of essential nutrients. This is economically costly because it can cost individuals 10 percent of their lifetime earnings and nations 2 to 3 percent of gross domestic product (GDP) in the worst-affected countries (Alderman 2005). Achieving food security is even more challenging in the context of HIV and AIDS. HIV affects people's physical ability to produce and use food, reallocating household labor, increasing the work burden on women, and preventing widows and children from inheriting land and productive resources.

Obesity

Obesity means having too much body fat. It is not the same as being overweight, which means weighing too much. Obesity has become a significant global health challenge but is preventable and reversible. Over the past 20 years, a global overweight/obesity epidemic has emerged, initially in industrial countries and now increasingly in low- and middle-income countries, particularly in urban settings, resulting in a triple burden of undernutrition, micronutrient deficiency, and overweight/obesity. There is significant variation by region; some have very high rates of undernourishment and low rates of obesity, while in other regions, the opposite is true (Figure 1).

However, obesity has increased to the extent that the number of overweight people now exceeds the number of underweight people worldwide. The economic cost of obesity has been estimated at $2 trillion, accounting for about 5% of deaths worldwide. Almost 30% of the world's population, or 2.1 billion people, are overweight or obese, with 62% living in developing countries.

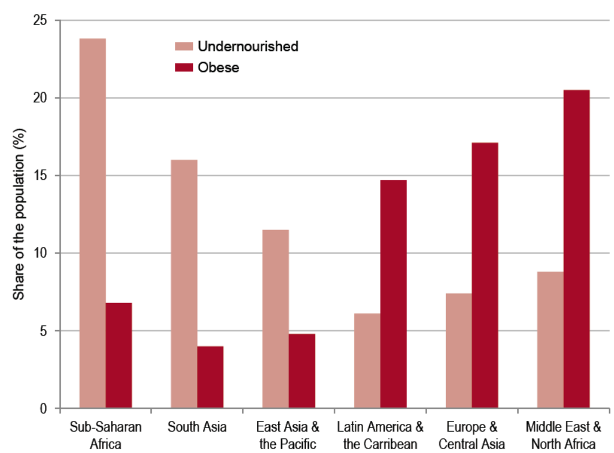

Figure 1. Obesity and undernourishment by region.

Obesity accounts for a growing level and share of worldwide noncommunicable diseases, including diabetes, heart disease, and certain cancers, that can reduce the quality of life and increase public health costs of already under-resourced developing countries. The number of overweight children is projected to double by 2030. Driven primarily by the increasing availability of processed, affordable, and effectively marketed food, the global food system is falling short with rising obesity and related poor health outcomes. Due to established health implications and rapid increase in prevalence, obesity is now a recognized major global health challenge.

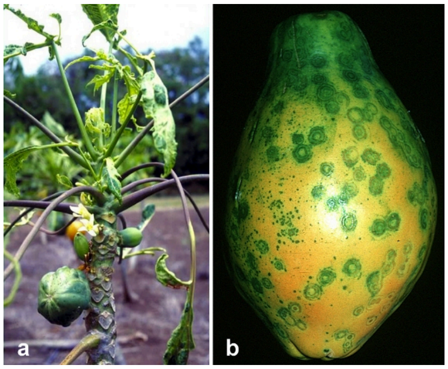

Figure 1. The symptoms of papaya ringspot virus are shown on the tree (a) and fruit (b). "This work" is in the Public Domain, CC0.

In the early 1990s, an emerging disease destroyed Hawaii's papaya production and threatened to decimate the $11 million industry (Figure 1). Fortunately, Dennis Gonsalves, raised on a sugar plantation and then became a plant physiologist at Cornell University, would develop papaya plants genetically engineered to resist the deadly virus. By the end of the decade, the Hawaiian papaya industry and the livelihoods of many farmers were saved thanks to the free distribution of Dr. Gonsalves's seeds.

Developing a new crop strain is an example of **agricultural biotechnology:** a range of tools that include both traditional breeding techniques and more modern lab-based methods. Traditional methods date back thousands of years, whereas biotechnology uses the tools of genetic engineering developed over the last few decades. **Genetic engineering** is the method scientists use to introduce new traits to an organism. This process results in **genetically modified organisms** or **GMOs**. For example, plants may be genetically engineered to produce characteristics to enhance food crops' growth or nutritional profile. GMOs that are crop species are commonly called **genetically engineered crops**, or **GE crops** for short.

The History of Genetic Modification of Crops

Nearly all the fruits and vegetables in your local market would not naturally occur. In fact, they exist only because of human intervention that began thousands of years ago. Humans created the vast majority of crop species using traditional breeding practices on naturally occurring wild plants. These practices rely upon **selective breeding** (human assisted-breeding of individuals with desirable traits). Traditional breeding practices, although low-tech and straightforward to perform, have the practical outcome of modifying an organism's genetic information, thus producing new traits.

An interesting example is maize (corn). Biologists have discovered that maize was developed from a wild plant called teosinte. Through traditional breeding practices, humans living thousands of years ago in what is now Southern Mexico began selecting for desirable traits until they could transform the plant into what is now known as maize. In doing so, they permanently (and unknowingly) altered its genetic instructions, allowing new traits to emerge. Considering this history, we might ask whether such a thing as "non-GMO" maize exists.

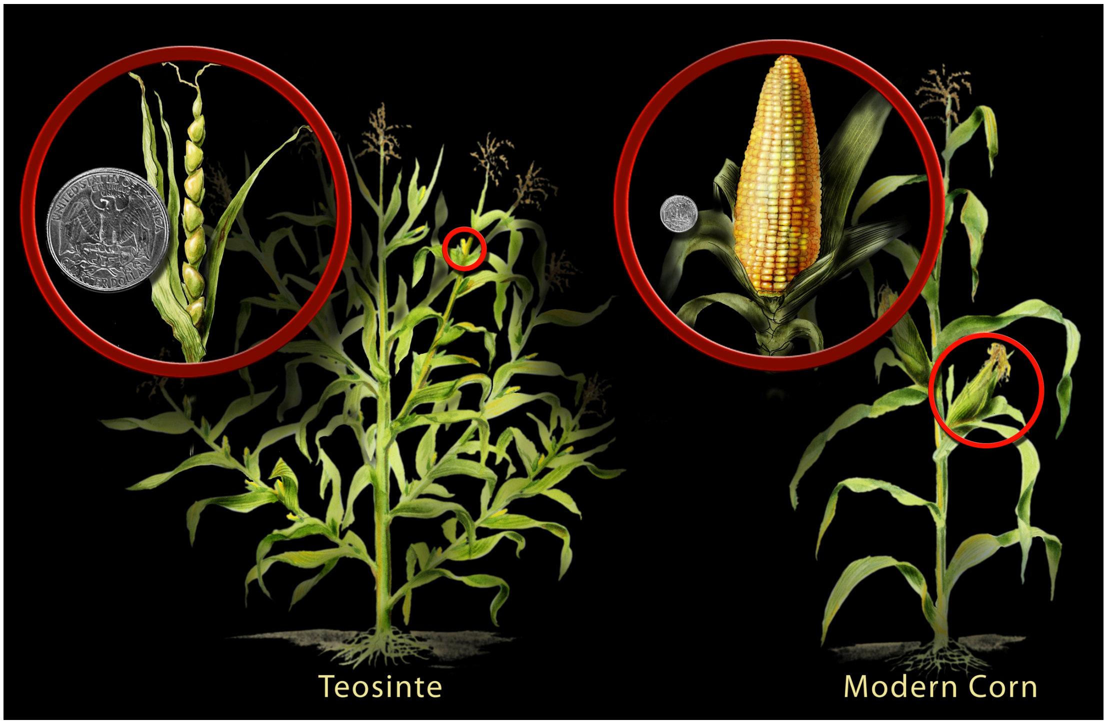

Figure 2. A wild grass called teosinte was genetically modified through selective breeding to produce what is now known as maize (corn). This transformation process started thousands of years ago by the indigenous people of what is now Mexico. "This work" by Nicolle Rager Fuller, National Science Foundation, is in the Public Domain, CC0.

This history of genetic modification is common to nearly all crop species. For example, cabbage, broccoli, brussel sprouts, cauliflower, and kale were all developed from a single species of wild mustard plant (Figure 2). Wild nightshade was the source of tomatoes, eggplant, tobacco, and potatoes, developed by humans 7,000 – 10,000 years ago in South America.

Figure 3. Brassica oleracea is a plant in the mustard family and is known as wild cabbage. From it were developed many familiar crops, such as cauliflower, broccoli, Brussel sprouts, and of course, cabbage."Brassica oleracea wild" by Kulac is licensed under CC BY-SA 4.0

Traditional Breeding v. Modern Genetic Engineering

To produce new traits in livestock, pets, crops, or other organisms, there almost always has to be an underlying change in that organism's genetic instructions. What many people might not understand is that traditional breeding practices do, in fact, result in permanent genetic changes and is, therefore, a type of genetic modification. This misunderstanding may arise because traditional breeding practices do not require sophisticated laboratory equipment or any knowledge of genetics, which some may see as a prerequisite for genetic modification.

How do traditional breeding practices compare to modern genetic engineering? Both result in changes to an organism's genetic information, but the magnitude of those changes varies among the two techniques (Figure 3). Traditional breeding shuffles all the genes between the two organisms being bred, which can number into the tens of thousands (maize, for example, has 32,000 genes). The results can be unpredictable when mixing such a large number of genes. Modern genetic engineering is more precise because scientists can modify a single gene. Also, genetic engineering can introduce a gene between two distantly-related species, such as inserting a bacterial gene into a plant. Such transfer might seem unusual, but it is not without its equivalent in nature. In **horizontal gene transfer**, DNA from one species can be inserted into a different species. One recent study, for example, has found that humans contain about 150 genes from other species, including bacteria.

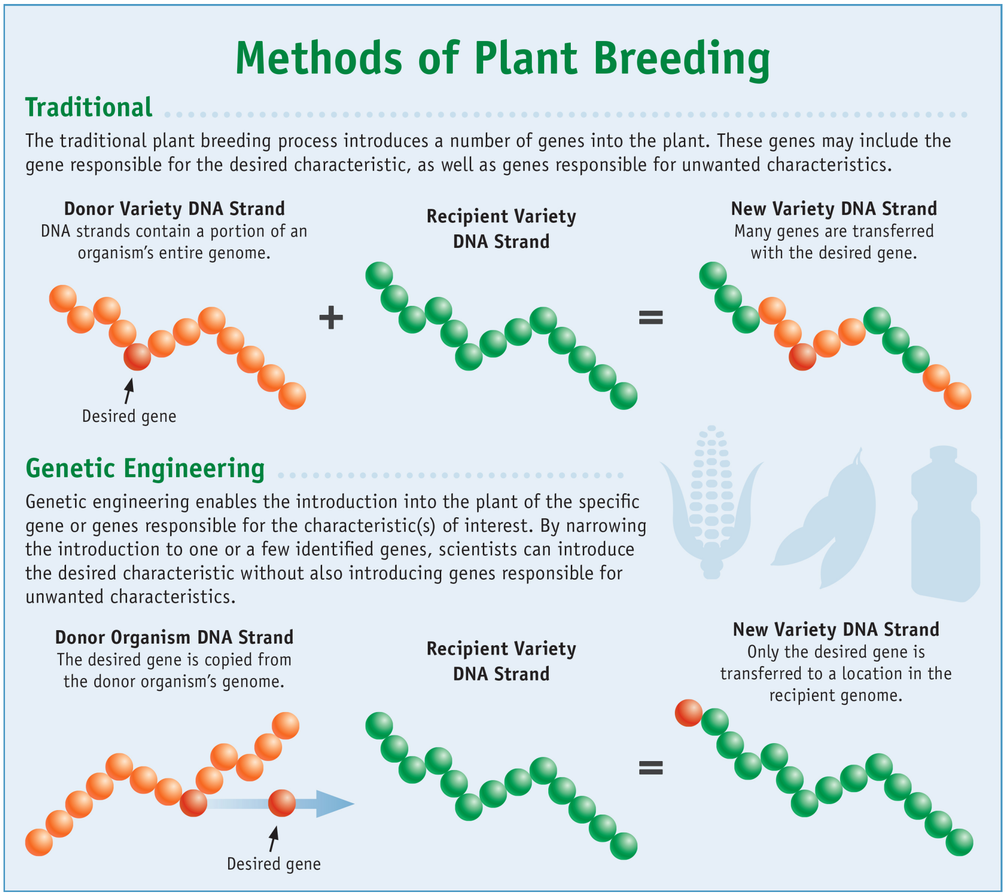

Figure 4. Both traditional breeding and modern genetic engineering produce genetic modifications. Genetic engineering allows for fewer and more precise genetic modifications. FDA graphic by Michael J. Ermarth (Methods of Plant Breeding) [CC0 Public Domain], via Wikimedia Commons.

Potential Benefits of Genetic Engineering

Enhanced nutrition

Advances in biotechnology may provide consumers with nutritionally enriched foods (Figure 4), longer-lasting, or lower levels of certain naturally occurring toxins present in some food plants. For example, developers use biotechnology to reduce saturated fats in cooking oils, reduce food allergens, and increase disease-fighting nutrients. Biotechnology may also be used to conserve natural resources, enable animals to use nutrients in feed more effectively, decrease nutrient runoff into rivers and bays, and help meet the increasing world food and land demands.

Figure 5. White rice and Golden rice. Genetically engineered "Golden Rice" contains up to 35 μg β-carotene per gram of rice, which could prevent millions of cases of blindness worldwide.

Cheaper and More Manageable Production

Biotechnology may provide farmers with tools to make production cheaper and more manageable. For example, some biotechnology crops can be engineered to tolerate specific herbicides, which makes weed control simpler and more efficient. Other crops have been engineered to be resistant to specific plant diseases and insect pests, which can make pest control more reliable and effective and/or can decrease the use of synthetic pesticides. These crop production options can help countries keep pace with demands for food while reducing production costs.

Improved pest control

Biotechnology has helped make pest control and weed management safer and easier while safeguarding crops against disease. For example, genetically engineered insect-resistant cotton has significantly reduced the use of persistent, synthetic pesticides that may contaminate groundwater and the environment. In terms of improved weed control, herbicide-tolerant soybeans, cotton, and corn enable the use of reduced-risk herbicides that break down more quickly in soil and are non-toxic to wildlife and humans.

Potential Concerns about Genetically Engineered Crops

The complexity of ecological systems presents considerable challenges for experiments assessing GE crops' risks and benefits. Assessing such risks is difficult because both natural and human-modified systems are highly complex and fraught with uncertainties that may not be clarified until long after an experimental introduction has been concluded. Critics of GE crops warn that their cultivation should be carefully considered within broader ecosystems because of their potential environmental benefits and hazards.

In addition to environmental risks, some people are concerned about the potential health risks of GE crops because they feel that genetic modification alters an organism's intrinsic properties or essence.

As discussed above, however, it is known that both traditional breeding practices and modern genetic engineering produce permanent genetic modifications. Further, traditional breeding practices actually have a larger and more unpredictable impact on a species' genetics because of its comparably crude nature. Considering this, it is wise that both new GE crops and traditionally produced crops should be studied for potential human health risks.

To address these various concerns, the US National Academies of Sciences, Engineering, and Medicine (NASEM) published a comprehensive, 500-page report in 2016 summarizing current scientific knowledge regarding GE crops. The report, titled *Genetically Engineered Crops: Experiences and Prospects*, reviewed more than 900 research articles, in addition to public comments and expert testimony. Results from this seminal report, hereafter referred to as the "**GE Crop Report**" for brevity, are shared in the subsections below.

Interbreeding with Native Species

Through interbreeding or hybridization, GE crops might share their genetically-modified DNA with wild relatives. This could affect the genetics of those wild relatives and have unforeseen consequences on their populations, and it could even have implications for the larger ecosystem. For example, if a gene engineered to confer herbicide resistance were to pass from a GE crop to a wild relative, it might transform the wild species into a '**super weed'** – a species that the herbicide could not control. Its rampant growth could displace other wild species and the wildlife that depends on it, thus inflecting ecological harm.

NASEM's GE Crop Report did find some evidence of genetic transfer between GE crops and wild relatives. However, there was no evidence of ecological harm from that transfer. Clearly, continued monitoring, especially for newly-developed crops, is warranted.

Consumer's Right to Choose

The International Federation of Organic Agriculture Movement has made stringent efforts to keep GE crops out of organic production. Yet, some US organic farmers have found their corn (maize) crops, including seeds, contain detectable levels of genetically engineered DNA. The organic movement is firmly opposed to any use of GE crops in agriculture, and organic standards explicitly prohibit their use (however, keep in mind that even "organic" maize has incurred significant genetic modification compared to its wild relative, teosinte). The farmers whose seed is contaminated have been under rigid organic certification, ensuring they did not use any genetically modified materials on their farms.

Any trace of GE crops must have come from outside their production areas. While the exact origin is unclear, the contamination has likely been caused by pollen drift from GE crop fields in surrounding areas. However, the contamination may have also come from the seed supply. Seed producers, who intended to supply GE crop-free seed, have also been confronted with genetic contamination and cannot guarantee that their seed is 100% GE crop-free.

Long-Term Ecological Effects

An early study indicated the pollen from a particular type of genetically modified corn might be harmful to the caterpillars of monarch butterflies, This type of corn, known as ***Bt* corn,** is genetically modified to produce a bacterial protein that acts as an insecticide. This trait is favorable because it reduces the amount of insecticides farmers use. Pollen from *Bt* corn can harm caterpillars, but only at very high concentrations. These concentrations are seldom reached in nature, and follow-up studies have found the effect of *Bt* corn to be negligible.

NASEM's GE Crop Report documents that other scientists questioned the validity of that initial monarch study, ultimately leading to a large, multi-national study funded by the US and Canada. They found that the vast majority of *Bt* corn grown did not represent a risk to monarchs. However, one strain of *Bt* corn did and was consequently removed from the market.

The GE Crop Report also mentioned a separate threat to monarchs: loss of milkweed, which is critical to the butterfly's lifecycle. Some GE crops are engineered to resist the herbicide glyphosate. Farmers using these crops can spray their entire field with the herbicide, which kills milkweed but not their GE crop. This can lower the amount of milkweed growing within the habitat range of monarchs. The report concluded that more studies are needed to quantify the actual impact this may be having on monarch populations.

Human Health Risk

At least some of the genes used in GE crops may not have been used in the food supply before, so GM foods may pose a potential risk to human health, such as producing new allergens. But this is also true of crops generated by traditional breeding practices (because both produce genetic modifications and thus new traits).

Like other 'controversial' scientific issues, the scientific consensus on GE crops is quite clear: they are safe. The UN's Food and Agriculture Organization has concluded that GMOs' risks to human and animal health are negligible. NASEM's GE Crop Report found "no substantiated evidence of a difference in risks to human health between current commercially available genetically engineered (GE) crops and conventionally bred crops, nor did it find conclusive cause-and-effect evidence of environmental problems from the GE crops." The American Medical Association's Council on Science and Public Health 2012 stated that "Bioengineered foods have been consumed for close to 20 years, and during that time, no overt consequences on human health have been reported and/or substantiated in the peer-reviewed literature." Similar statements have been made by the US National Resource Council and the American Association for the Advancement of Science, which publishes the preeminent scholarly journal *Science*.

The potential of GE crops to be allergenic is one of the potential adverse health effects, and it should continue to be studied, especially because some scientific evidence indicates that animals fed GE crops have been harmed. NASEM's GE Crop Report concluded that when developing new crops, it is the product that should be studied for potential health and environmental risks, not the process that achieved that product. What this means is because both traditional breeding practices and modern genetic engineering produce new traits through genetic modification, they both present potential risks. Thus, both should be adequately studied for the environment's safety and human health.

Intellectual Property Rights

Intellectual property rights are one of the important factors in the current debate on GE crops. GE crops can be patented by Agri-businesses, leading to them controlling and potentially exploiting agricultural markets. Some accuse companies, such as Monsanto, of allegedly controlling seed production and pricing, much to the detriment of farmers. NASEM's GE Crop Report recommends more research into how a few companies' concentration of seed markets and the subsequent reduction of free market competition may affect seed prices and farmers.

It should be noted that crops developed by traditional breeding can also be legally protected and controlled in ways similar to GE crops. From Oregon State University, Jim Myers notes, "In all but a few cases, all contemporary varieties developed by private breeders are [legally] protected, and most public varieties are protected as well."

Are GE Crops the Solution We Need?

Significant financial and intellectual resources have been allocated to answering the question: are GE crops safe? After many hundreds of scientific studies, the answer is yes. But a significant question still remains: are they necessary? Certainly, such as in instances like Hawaii's papaya, which was threatened with eradication due to aggressive disease, genetic engineering was a quick and effective solution that would have been extremely difficult, if not impossible, to solve using traditional breeding practices.

However, in many cases, the early promises of GE crops – that they would improve the nutritional quality of foods, confer disease resistance, and provide unparalleled advances in crop yields – have largely failed to come to fruition. NASEM's GE Crop Report states that while GE crops have resulted in the reduction of agricultural loss from pests, reduced pesticide use, and reduced rates of injury from insecticides for farm workers, they have not increased the rate at which crop yields are advancing when compared to non-GE crops. Additionally, while there are some notable exceptions, like golden rice or virus-resistant papayas, very few GE crops have been produced to increase nutritional capacity or to prevent plant disease that can devastate a farmer's income and reduce food security. Most GE crops are developed for only two purposes: to introduce herbicide resistance or pest resistance.

Genetic engineering of crops represents an important tool in a world of rapidly changing climate and a burgeoning human population. Still, as you will see in the next chapter, it is only one of many tools that agriculturists can use to produce enough food for all humans while simultaneously working to conserve the environment.

Suggested Supplementary Reading:

NASEM. 2016.*Genetically Engineered Crops: Experiences and Prospects*. http://nas-sites.org/ge-crops/category/report/

Summary

Progress continues in the fight against hunger, yet many people still lack the food they need for an active and healthy life. About 795 million people worldwide still go to bed hungry every night, and even more live in poverty. Poverty is the major driver of food insecurity. Improvements in agricultural productivity are necessary to increase rural household incomes and access to available food but are insufficient to ensure food security. Food security is essentially built on four pillars: availability, access, utilization, and stability. Women are crucial in translating the products of a vibrant agriculture sector into food and nutritional security for their households. They are often the farmers who cultivate food crops and produce commercial crops alongside the men in their households as a source of income. Over the past 20 years, a global obesity epidemic has emerged. Due to established health implications and rapid increase in prevalence, obesity is now a recognized major global health challenge, and no national success stories in curbing its growth have so far been reported. Genetic engineering is the method scientists use to introduce new traits or characteristics to an organism. Advocates say that applying genetic engineering in agriculture has benefited farmers, producers, and consumers. Critics advise that the risks of introducing a GMO into each new ecosystem must be examined on a case-by-case basis, alongside appropriate risk management measures.

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Chapter Attributions:

Chapter 9: Conventional and Sustainable Agriculture

Women farmers planted a rice field in West Sumatra.

Learning Outcomes

After studying this chapter, you should be able to:

- Describe the components of soils
- Discuss how land use affects global ecosystem conditions
- Identify environmental effects of pesticides
- Recognize the relationship between exposure to POPs and human health
- Explain alternative practices in farming and soil management

Chapter Outline

- 9.1 Soil Profiles and Processes
- 9.2 Soil-Plant Relations
- 9.3 Conventional Agriculture
- 9.4 Pests and Pesticides
- 9.5 Sustainable Agriculture
- 9.6 Chapter Resources

What is Soil?

The word "**soil**" has been defined differently by different scientific disciplines. In agriculture and horticulture, the soil generally refers to the medium for plant growth, typically material within the upper meter or two (Figure 1). We will use this definition in this chapter. Soil consists predominantly of mineral matter but contains organic matter (**humus**) and living organisms. The pore spaces between mineral grains are filled with varying proportions of water and air.

In common usage, the term soil is sometimes restricted to only the dark topsoil we plant our seeds or vegetables. In a more broad definition, civil engineers use the term soil for any unconsolidated (soft when wet) material that is not considered bedrock. Under this definition, soil can be several hundred feet thick! Ancient soils, sometimes buried and preserved in the subsurface, are called **paleosols** (Figure 2) and reflect past climatic and environmental conditions.

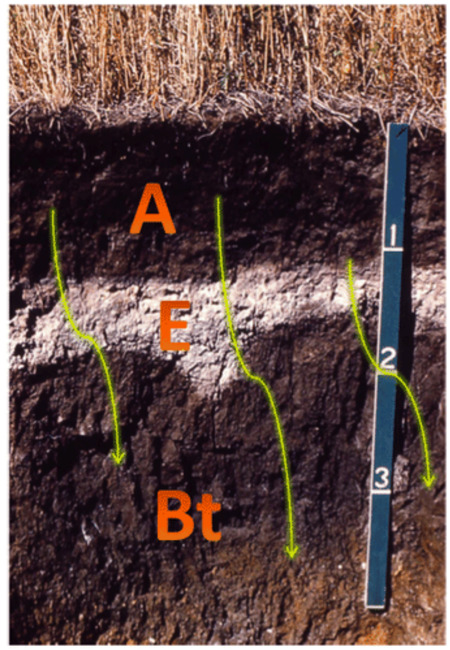

Figure 1. Soil Profile. Photograph shows a soil profile from South Dakota with A, E, and Bt horizons. The yellow arrows symbolize the translocation of fine clays to the Bt horizon. The scale is in feet. Source: University of Idaho and modified by D. Grimley.

Importance of Soil

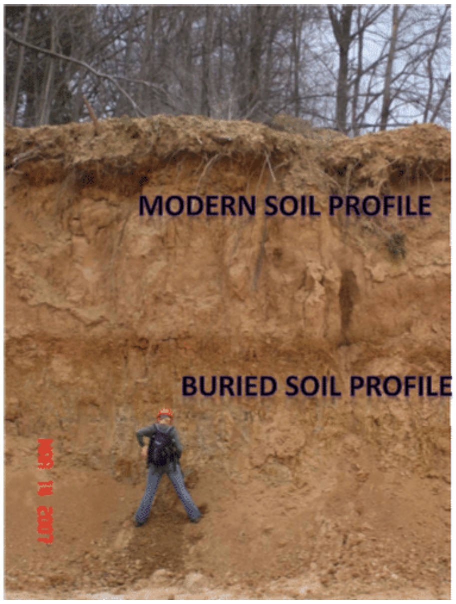

Figure 2. Modern versus Buried Soil Profiles. A buried soil profile, or paleosol (above geologist's head), represents soil development during the last interglacial period. A modern soil profile (Alfisol) occurs near the land surface. Source: D. Grimley.

Soil is important to our society primarily because it provides the foundation of agriculture and forestry. Of course, soil is also critical for terrestrial ecosystems and thus important to animals, plants, fungi, and microorganisms.

Soil plays a role in nearly all biogeochemical cycles on the Earth's surface. Global cycling of key elements such as carbon (C), nitrogen (N), sulfur (S), and phosphorous (P) all pass through the soil. In the hydrologic cycle, soil helps mediate precipitation flow from the surface into the groundwater. Microorganisms living in soil can also be important components of biogeochemical cycles through decomposition and other processes such as nitrogen fixation.

Soil Forming Factors

The fundamental factors that affect soil genesis can be categorized into five elements: climate, organisms, relief, parent material, and time. One could say that the relief, climate, and organisms dictate the local soil environment and act together to cause weathering and mixing of the soil parent material over time. As soil is formed, it often has distinct layers, formally described as "horizons." Upper horizons (labeled as the A and O horizons) are richer in organic material and so are important in plant growth, while deeper layers (such as the B and C horizons) retain more of the original features of the bedrock below (Figure 3).

Climate

The role of climate in soil development includes aspects of temperature and precipitation. Soils in very cold areas with permafrost conditions tend to be shallow and weakly developed due to the short growing season. Organic rich surface horizons are common in low-lying areas due to limited decomposition. In warm, tropical soils, soils tend to be thicker, with extensive leaching and mineral alteration. In such climates, organic matter decomposition and chemical weathering are accelerated.

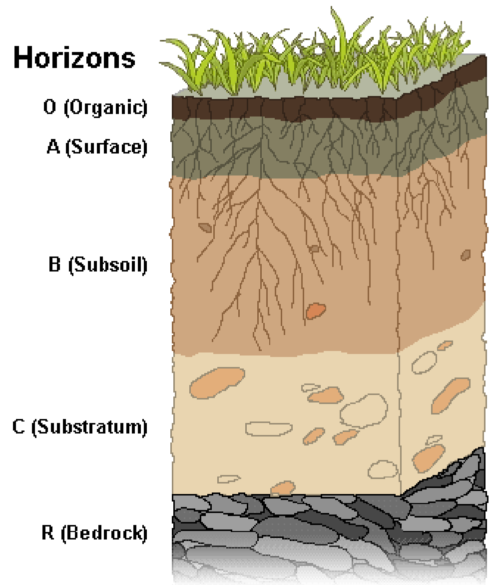

Figure 3. This image shows the different horizons, or layers, in soil. This work by Wilsonbiggs is licensed under CC BY-SA 4.0

Organisms

Animals, plants, and microorganisms are all important in soil development processes, supplying organic matter and/or nutrient cycling. Worms, nematodes, termites, ants, gophers, moles, etc., all cause considerable mixing of soil and help to blend soil, aerate and lighten the soil by creating pores (which help store water and air).

Plant life provides organic matter to the soil and helps to recycle nutrients with uptake by roots in the subsurface. The type of plant life in a given area, such as types of trees or grasses, depends on the climate, parent material, and soil type. With the annual dropping of leaves and needles, trees add organic matter to soil surfaces, helping to create a thin, organic-rich A or O horizon over time. Grasses have considerable root and surface masses that add to the soil each fall for annuals and short-lived perennials. For this reason, grassland soils have much thicker A horizons with higher organic matter contents and are more agriculturally productive than forest soils.

Relief (Topography and Drainage)

The local landscape can surprisingly strongly affect the soil on site. The local topography (**relief**) can have important microclimatic effects and affect soil erosion rates. Compared to flat regions, areas with steep slopes overall have more soil erosion, more runoff of rainwater, and less water infiltration, all of which lead to more limited soil development in very hilly or mountainous areas. In the northern hemisphere, south-facing slopes are exposed to more direct sunlight angles, thus warmer and drier than north-facing slopes. The cooler, moister north-facing slopes have a more dynamic plant community due to less evapotranspiration and, consequently, experience less erosion because of plant rooting of soil and have thicker soil development.

Soil drainage affects organic matter accumulation and preservation and local vegetation types. Well-drained soils, generally on hills or side slopes, are more brownish or reddish due to the conversion of ferrous iron (Fe^{2+}) to minerals with ferric (Fe^{3+}) iron. More poorly drained soils, in lowland, alluvial plains or upland depressions, tend more be more greyish, greenish-grey (gleyed), or dark colored due to iron reduction (to Fe^{2+}) and accumulation and preservation of organic matter in areas tending towards anoxic. Areas with poor drainage also tend to be lowlands into which soil material may wash and accumulate from surrounding uplands, often resulting in over-thickened A or O horizons. In contrast, steeply sloping areas in highlands may experience erosion and have thinner surface horizons.

Parent Material

The **parent material** of soil is the material from which the soil has developed, whether it be river sands, shoreline deposits, glacial deposits, or various types of bedrock. In youthful soils, the parent material has a clear connection to the soil type and has a significant influence. Over time, as weathering processes deepen, mix, and alter the soil, the parent material becomes less recognizable as chemical, physical, and biological processes take their effect. The type of parent material may also affect the rapidity of soil development. Highly weatherable parent materials (such as volcanic ash) will transform more quickly into highly developed soils, whereas quartz-rich parent materials, for example, will take longer to develop. Parent materials also provide nutrients to plants and can affect soil internal drainage (e.g., clay is more impermeable than sand and impedes drainage).

Time

Generally, soil profiles tend to become thicker (deeper), more developed, and more altered over time. However, the rate of change is greater for soils in the youthful stages of development. The degree of soil alteration and deepening slows with time and, after tens or hundreds of thousands of years, may approach an equilibrium condition where erosion and deepening (removals and additions) become balanced. **Young soils** (< 10,000 years old) are strongly influenced by parent material and typically develop horizons and character rapidly. **Moderate-age soils** (roughly 10,000 to 500,000 years old) are slowing in profile development and deepening and may begin to approach equilibrium conditions. **Old soils** (>500,000 years old) have generally reached their limit beyond soil horizons and physical structure but may continue to alter chemically or mineralogically.

Soil development is not always continual. Geologic events can rapidly bury soils (landslides, glacier advance, lake transgression), can cause removal or truncation of soils (rivers, shorelines), or can cause soil renewal with additions of slowly deposited sediment that add to the soil (wind or floodplain deposits). Biological mixing can sometimes cause soil regression, a reversal or bump in the road for the normal path of increasing development over time.

Soil plays a key role in plant growth. Beneficial aspects of plants include providing physical support, water, heat, nutrients, and oxygen (Figure 1). Mineral nutrients from the soil can dissolve in water and then become available to plants. Although many aspects of soil benefit plants, excessively high levels of trace metals (naturally occurring or anthropogenically added) or applied herbicides can be toxic to some plants.

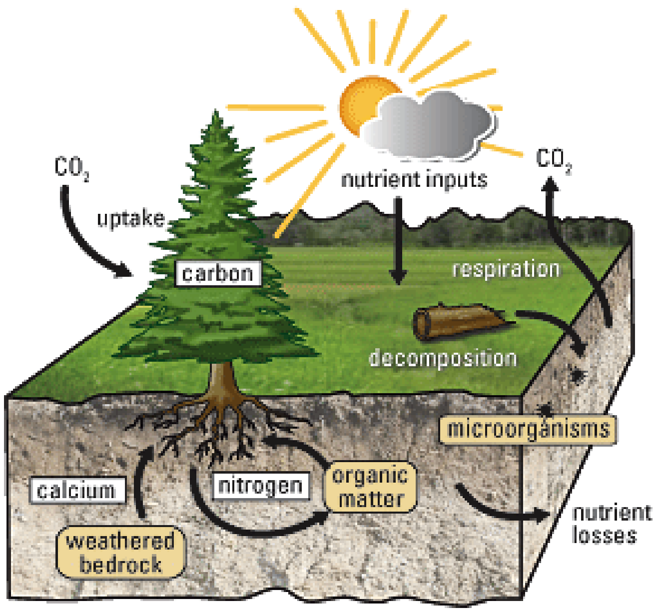

Figure 1. Soil-Plant Nutrient Cycle. This figure illustrates the uptake of nutrients by plants in the forest-soil ecosystem. Source: U.S. Geological Survey.

The soil's solids/water/air ratio is also critically important to plants for proper oxygenation levels and water availability. Too much porosity with air space, such as in sandy or gravelly soils, can lead to less available water to plants, especially during dry seasons when the water table is low. Too much water in poorly drained regions can lead to anoxic conditions in the soil, which may be toxic to some plants.

Nutrient Uptake by Plants

Several elements obtained from the soil are considered essential for plant growth. **Macronutrients**, including C, H, O, N, P, K, Ca, Mg, and S, are needed by plants in significant quantities. C, H, and O are mainly obtained from the atmosphere or rainwater. These three elements are the main components of most organic compounds, such as proteins, lipids, carbohydrates, and nucleic acids. The other six elements (N, P, K, Ca, Mg, and S) are obtained from plant roots from the soil. They are used for protein synthesis, chlorophyll synthesis, energy transfer, cell division, enzyme reactions, and **homeostasis** (the process regulating the conditions within an organism).

Micronutrients are essential elements needed only in small quantities but can still limit plant growth since these nutrients are not so abundant in nature. Micronutrients include iron (Fe), manganese (Mn), boron (B), molybdenum (Mo), chlorine (Cl), zinc (Zn), and copper (Cu). Some other elements tend to aid plant growth but are not absolutely essential.

Micronutrients and macronutrients are desirable in particular concentrations and can harm plant growth when concentrations in the soil solution are either too low (limiting) or too high (toxicity). Mineral nutrients are useful to plants only if they are in an extractable form in soil solutions, such as a dissolved ion, rather than a solid mineral. Due to concentration gradients, many nutrients move through the soil and into the root system, moving from high to low concentrations by diffusion. However, some nutrients are selectively absorbed by the root membranes, making concentrations higher inside the plant than in the soil.

The prevailing agricultural system, variously called "**conventional farming**," "modern agriculture," or "industrial farming," has delivered tremendous gains in productivity and efficiency. Food production worldwide has risen in the past 50 years; the World Bank estimates that between 70 percent and 90 percent of the recent increases in food production result from conventional agriculture rather than greater acreage under cultivation. U.S. consumers have come to expect abundant and inexpensive food.

Figure 1. Conventional agriculture depends on large investments in mechanized equipment powered mostly by fossil fuels. This has made agriculture efficient but has had an impact on the environment. Cotton Harvest by Kimberly Vardeman is licensed under CC BY 4.0.

Conventional farming systems vary from farm to farm and from country to country. However, they share many characteristics such as rapid technological innovation, large capital investments in equipment and technology, large-scale farms, single crops (**monocultures**); uniform high-yield hybrid crops, dependency on agribusiness, mechanization of farm work, and extensive use of pesticides, fertilizers, and herbicides. In the case of livestock, most production comes from systems where animals are highly concentrated and confined.

Both positive and negative consequences have come with the bounty associated with industrial farming. Some concerns about conventional agriculture are presented below.

Ecological Concerns

Agriculture profoundly affects many ecological systems. The negative effects of current practices include the following:

The decline in soil productivity can be due to wind and water erosion of exposed topsoil, soil compaction, loss of soil organic matter, water holding capacity, biological activity, and **salinization** (increased salinity) of soils in highly-irrigated farming areas. Converting land to the desert (**desertification)** can be caused by the overgrazing of livestock and is a growing problem, especially in parts of Africa.

Agricultural practices have been found to contribute to non-point source water pollutants, including salts, fertilizers (nitrates and phosphorus, especially), pesticides, and herbicides. Pesticides from every chemical class have been detected in groundwater and are commonly found in groundwater beneath agricultural areas. They are also widespread in the nation's surface waters. Eutrophication and "dead zones" due to nutrient runoff affect many rivers, lakes, and oceans. Reduced water quality impacts agricultural production, drinking water supplies, and fishery production. Water scarcity (discussed in the previous chapter) in many places is due to the overuse of surface and groundwater for irrigation with little concern for the natural cycle that maintains stable water availability.

Other environmental ills include over 400 insects and mite pests and more than 70 fungal pathogens that have become resistant to one or more pesticides. Pesticides have also placed stress on pollinators and other beneficial insect species. This, along with habitat loss due to converting wildlands into agricultural fields, has affected entire ecosystems (such as the practice of converting tropical rainforests into grasslands for raising cattle).

Agriculture's link to global climate change is just beginning to be appreciated. Destruction of tropical forests and other native vegetation for agricultural production has a role in elevated carbon dioxide levels and other greenhouse gases. Recent studies have found that soils may be large reservoirs of carbon.

Economic and Social Concerns

Economically, the U.S. agricultural sector includes a history of increasingly large federal expenditures. Also observed is a widening disparity between the income of farmers and the escalating concentration of **agribusiness—**industries involved with manufacturing, processing, and distributing farm products—into fewer and fewer hands. Market competition is limited, and farmers have little control over the prices of their goods. They continue to receive a smaller and smaller portion of consumer dollars spent on agricultural products.

Economic pressures have led to a tremendous loss to the number of farms, particularly small farms and farmers, during the past few decades. More than 155,000 farms were lost from 1987 to 1997. Economically, it is very difficult for potential farmers to enter the business today because of the high cost of doing business. Productive farmland also has been swallowed up by urban and suburban sprawl—since 1970, over 30 million acres have been lost to development.

Impacts on Human Health

Many potential health hazards are tied to farming practices. The general public may be affected by the sub-therapeutic use of antibiotics in animal production and the contamination of food and water by pesticides and nitrates. These are areas of active research to determine the levels of risk. The health of farm workers is also of concern, as their risk of exposure is much higher.

Philosophical Considerations

Historically, farming played an important role in our development and identity as a nation. From strongly agrarian roots, we have evolved into a culture with few farmers. Less than two percent of Americans now produce food for all U.S. citizens. Can sustainable and equitable food production be established when most consumers have little connection to the natural processes that produce their food? What intrinsically American values have changed and will change with the decline of rural life and farmland ownership?

The world population continues to grow. According to recent United Nations population projections, the world population will grow to 9.7 billion in 2050 and 11.2 billion in 2100. The rate of population increase is especially high in many developing countries. In these countries, the population factor, combined with rapid industrialization, poverty, political instability, large food imports, and debt burden, make long-term food security especially urgent.

Pests and Pesticides

Pests are organisms that occur where they are not wanted or that cause damage to crops or humans, or other animals. Thus, the term “pest” is highly subjective. A **pesticide** is a term for any substance intended for preventing, destroying, repelling, or mitigating any pest. Though often misunderstood to refer only to insecticides, pesticides also apply to herbicides, fungicides, and other substances used to control pests. By their very nature, most pesticides create some risk of harm—pesticides can cause harm to humans, animals, and/or the environment because they are designed to kill or otherwise adversely affect living things. At the same time, pesticides are useful to society because they can kill potential disease-causing organisms and control insects, weeds, worms, and fungi.

Figure 1. The cotton boll weevil is considered a major pest because of its damage to cotton plants. This work by Jimmy Smith is licensed under CC BY-NC-ND 4.0.

Pest Control is a Common Tool

Managing pests is essential to agriculture, public health, and maintaining power lines and roads. Chemical pest management has helped to reduce losses in agriculture and to limit human exposure to disease vectors, such as mosquitoes, saving many lives. Chemical pesticides can be effective, fast acting, and adaptable to all crops and situations. When first applied, pesticides can result in impressive production gains for crops. However, despite these initial gains, excessive use of pesticides can be ecologically unsound, leading to the destruction of natural enemies, increased pesticide resistance, and outbreaks of secondary pests.

These consequences have often resulted in higher production costs and environmental and human health costs– side effects that have been unevenly distributed. Despite the lion’s share of chemical pesticides being applied in developed countries, 99 percent of all pesticide poisoning cases occur in developing countries where regulatory, health, and education systems are weakest. Many farmers in developing countries overuse pesticides and do not take proper safety precautions because they do not understand the risks and fear smaller harvests. Making matters worse, developing countries seldom have strong regulatory systems for dangerous chemicals; pesticides banned or restricted in industrialized countries are used widely in developing countries. Farmers’ perceptions of appropriate pesticide use vary by setting and culture. Prolonged pesticide exposure has been associated with several chronic and acute health effects, like non-Hodgkin’s lymphoma and leukemia, cardiopulmonary disorders, neurological and hematological symptoms, and skin diseases.

BOX 1. HUMAN HEALTH, ENVIRONMENTAL, AND ECONOMIC EFFECTS OF PESTICIDE USE IN POTATO PRODUCTION IN ECUADOR

The International Potato Center (CIP) conducted an interdisciplinary and inter-institutional research intervention project dealing with pesticide impacts on agricultural production, human health, and the environment in Carchi, Ecuador. Carchi is Ecuador's most important potato-growing area, where smallholder farmers dominate production. They use tremendous amounts of pesticides to control the Andean potato weevil and the late blight fungus. Virtually all farmers apply to class 1b highly toxic pesticides using hand pump backpack sprayers.

The study found that the health problems caused by pesticides are severe and are affecting a high percentage of the rural population. Despite the existence of technology and policy solutions, government policies continue to promote the use of pesticides. The study conclusions concurred with those of the pesticide industry, "that any company that could not ensure the safe use of highly toxic pesticides should remove them from the market and that it is almost impossible to achieve safe use of highly toxic pesticides among small farmers in developing countries."

Source: Yanggen et al. 2003.

POPs

Persistent organic pollutants (POPs) are a group of organic chemicals, such as DDT, widely used as pesticides or industrial chemicals and pose risks to human health and ecosystems. POPs have been produced and released into the environment by human activity. They have the following three characteristics:

Persistent: POPs are chemicals that last a long time in the environment. Some may resist breakdown for years and even decades, while others could potentially break down into other toxic substances.

Bioaccumulative: POPs can accumulate in animals and humans, usually in fatty tissues and largely from the food they consume. As these compounds move up the food chain, they concentrate to levels that could be thousands of times higher than acceptable limits.

Toxic: POPs can cause various health effects in humans, wildlife, and fish. They have been linked to effects on the nervous system, reproductive and developmental problems, immune system suppression, cancer, and endocrine disruption. The deliberate production and use of most POPs have been banned worldwide, with some exemptions made for human health considerations (e.g., DDT for malaria control) and/or in very specific cases where alternative chemicals have not been identified. However, the unintended production and/or the current use of some POPs continue to be an issue of global concern. Even though most POPs have not been manufactured or used for decades, they continue to be present in the environment and thus potentially harmful. The same properties that originally made them so effective, particularly their stability, make them difficult to eradicate from the environment.

POPs and Health

The relationship between exposure to environmental contaminants such as POPs and human health is complex. There is mounting evidence that these persistent, bioaccumulation, and toxic chemicals (PBTs) cause long-term harm to human health and the environment. Drawing a direct link, however, between exposure to these chemicals and health effects is complicated, particularly since humans are exposed daily to many different environmental contaminants through the air they breathe, the water they drink, and the food they eat. Numerous studies link POPs with a number of adverse effects in humans. These include effects on the nervous system, problems related to reproduction and development, cancer, and genetic impacts. Moreover, there is mounting public concern over the environmental contaminants that mimic hormones in the human body (**endocrine disruptors**).

As with humans, animals are exposed to POPs in the environment through air, water, and food. POPs can remain in sediments for years, where bottom-dwelling creatures consume them and are then eaten by larger fish. Because tissue concentrations can increase or biomagnify at each food chain level, top predators (like largemouth bass or walleye) may have a million times greater concentrations of POPs than the water itself. The animals most exposed to PBT contaminants are those higher up the food web, such as marine mammals, including whales, seals, polar bears, and birds of prey and fish species, such as tuna, swordfish, and bass (Figure 2). Once POPs are released into the environment, they may be transported within a specific region and across international boundaries transferring among air, water, and land.

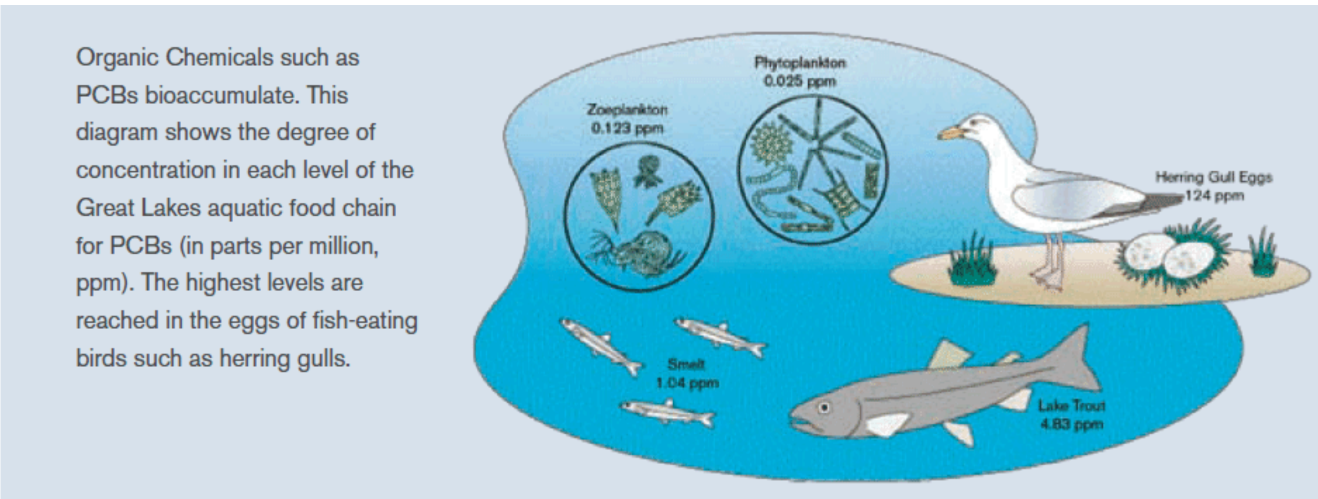

Figure 2. Bioaccumulation and biomagnification. U.S. EPA. Great Lakes: The Great Lakes Atlas: Chapter Four the Great Lakes Today – Concerns. January 2009

"Grasshopper Effect"

While generally banned or restricted, POPs make their way into and throughout the environment daily through a cycle of long-range air transport and deposition called the "**grasshopper effect.**"The "grasshopper" processes, illustrated in Figure 3, begin with releasing POPs into the environment. When POPs enter the atmosphere, they can be carried by wind currents, sometimes for long distances.

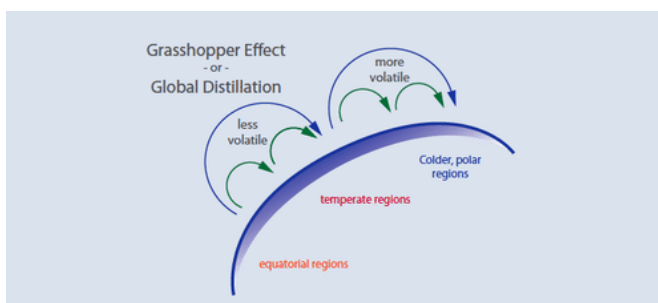

Figure 3. How POPs move throughout the environment. Source: Environment Canada. The Science and the Environment Bulletin. May/June 1998

They are deposited onto land or into water ecosystems through atmospheric processes, where they accumulate and potentially cause damage. From these ecosystems, they evaporate, again entering the atmosphere, typically traveling from warmer temperatures toward cooler regions. They condense out of the atmosphere whenever the temperature drops, eventually reaching the highest concentrations in circumpolar countries. Through these processes, POPs can move thousands of kilometers from their original release source in a cycle that may last decades.

"**Sustainable agriculture**" was addressed by Congress in the 1990 "Farm Bill." Under that law, "the term sustainable agriculture means an integrated system of plant and animal production practices having a site-specific application that will, over the long term:

- satisfy human food and fiber needs;
- enhance environmental quality and the natural resource base upon which the agricultural economy depends;
- make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls;
- sustain the economic viability of farm operations; and
- enhance the quality of life for farmers and society as a whole."

Organic Farming is Good for Farmers, Consumers, and the Environment

Organic agriculture is an ecological production management system that promotes and enhances biodiversity, biological cycles, and soil biological activity. Organic food is produced by farmers who emphasize using renewable resources and conserving soil and water to enhance environmental quality for future generations. Organic meat, poultry, eggs, and dairy products come from animals without antibiotics or growth hormones. Organic food is produced without using most conventional pesticides, fertilizers made with synthetic ingredients or sewage sludge, or GMOs.

Organic production, with the corresponding practices to maintain soil fertility and health, is a more benign alternative to conventional, high-value horticulture. The UN's Food and Agricultural Organization has endorsed the organic food movement, which maintains in a 2007 report that organic farming fights hunger, tackles climate change, and is good for farmers, consumers, and the environment. The strongest benefits of organic agriculture are its use of resources that are independent of fossil fuels, are locally available, incur minimal environmental stresses, and are cost-effective.

IPM is a Combination of Common-Sense Practices

Integrated Pest Management (IPM) refers to a mix of farmer-driven, ecologically-based pest control practices that seek to reduce reliance on synthetic chemical pesticides. It involves (a) managing pests (keeping them below economically damaging levels) rather than seeking to eradicate them; (b) relying, to the extent possible, on non-chemical measures to keep pest populations low; and (c) selecting and applying pesticides, when they have to be used, in a way that minimizes adverse effects on beneficial organisms, humans, and the environment. It is commonly understood that applying an IPM approach does not necessarily mean eliminating pesticide use. However, this is often the case because pesticides are often over-used for various reasons.

The IPM approach regards pesticides as mainly short-term corrective measures when more ecologically based control measures are not working adequately (sometimes referred to as using pesticides as the "last resort"). In those cases when pesticides are used, they should be selected and applied in such a manner as to minimize the amount of disruption that they cause to the environment, such as using products that are non-persistent and applying them in the most targeted way possible).

Biological Control

Biological control (biocontrol) is using one biological species to reduce populations of different species. There has been a substantial increase in the commercialization of biocontrol products, such as beneficial insects, cultivated predators, and natural or non-toxic pest control products. Biocontrol is being mainstreamed to major agricultural commodities, such as cotton, corn, and, most commonly, vegetable crops. Biocontrol is also slowly emerging in vector control in public health and in areas that, for a long time, mainly focused on chemical vector control in mosquito/malaria—and black fly/onchocerciasis—control programs. Successful and commercialized examples of biocontrol include ladybugs to depress aphid populations, parasitic wasps to reduce moth populations, the use of the bacterium *Bacillus thuringenensis* to kill mosquito and moth larvae, and the introduction of fungi, such as Trichoderma, to suppress fungal-caused plant diseases, leaf beetle (*Galerucella calmariensis*) to suppress purple loosestrife, a noxious weed (Figure 1). In these cases, the idea is not to completely destroy the pathogen or pest but rather to reduce the damage below economically significant values.

Figure 1. Young larvae of the leaf-beetle feed in and on the developing buds of plants, often destroying them. This may stunt plant growth and delay or prevent flowering. Adults (shown) and older larvae feed on leaves and cause severe defoliation. Leaf beetles can be used as biocontrol for invasive plants such as purple loosestrife.

Intercropping Promotes Plant Interactions

Figure 2. Intercropping alyssum (the flowering plants shown center left) with organic romaine lettuce for aphid control.

Intercropping means growing two or more crops in close proximity to each other during part or all of their life cycles to promote soil improvement, biodiversity, and pest management. Incorporating intercropping principles into an agricultural operation increases diversity and interaction between plants, arthropods, mammals, birds, and microorganisms resulting in a more stable crop ecosystem and more efficient use of space, water, sunlight, and nutrients (Figure 2). This collaborative type of crop management mimics nature and is subject to fewer pest outbreaks, improved nutrient cycling and crop nutrient uptake, and increased water infiltration and moisture retention. Soil quality, water quality, and wildlife habitat all benefit.

Organic Farming Practices Reduce Unnecessary Input Use

In modern agricultural practices, heavy machinery is used to prepare the seedbed for planting, to control weeds, and to harvest the crop. Heavy equipment has many advantages in saving time and labor but can cause soil compaction and disruption of the natural soil organisms. The problem with soil compaction is that increased soil density limits root penetration depth and may inhibit proper plant growth.

Alternative practices generally encourage **minimal tillage** or **no tillage methods**. Proper planning can simultaneously limit compaction, protect soil organisms, reduce costs (if performed correctly), promote water infiltration, and help prevent topsoil erosion (Figure 3).

Figure 3. Farmers should consider no-till farming as the most important tool to prevent soil moisture loss.

Tillage of fields does help to break up clods that were previously compacted, so best practices may vary at sites with different soil textures and compositions. Another aspect of soil tillage is that it may lead to more rapid decomposition of organic matter due to greater soil aeration. Over large farmland areas, this has the unintended consequence of releasing more carbon and nitrous oxides (greenhouse gases) into the atmosphere, thereby contributing to global warming effects. In no-till farming, carbon can actually become sequestered in the soil. Thus, no-till farming may be advantageous to sustainability issues on the local scale and global scale. No-till conservation farming systems have proved a major success in Latin America and are being used in South Asia and Africa.

Crop Rotation

Crop rotations are planned sequences of crops over time on the same field. Rotating crops provides productivity benefits by improving soil nutrient levels and breaking crop pest cycles. Farmers may also choose to rotate crops to reduce their production risk through diversification or to manage scarce resources, such as labor, during planting and harvesting timing. This strategy reduces pesticide costs by naturally breaking the cycle of weeds, insects, and diseases. Also, grass and legumes in a rotation protect water quality by preventing excess nutrients or chemicals from entering water supplies.

BOX 2. AN ALTERNATIVE TO SPRAYING: BOLLWORM CONTROL IN SHANDONG

Farmers in Shandong (China) have been using innovative methods to control bollworm infestation in cotton when this insect became resistant to most pesticides. Among the control measures implemented were:

1. The use of pest-resistant cultivars and interplanting of cotton with wheat or maize.
2. Use of lamps and poplar twigs to trap and kill adults to lessen the number of adults.
3. If pesticides were used, they were applied on parts of the cotton plant’s stem rather than by spraying the whole field (to protect natural enemies of the bollworm).

These and some additional biological control tools have effectively controlled insect populations and insect resistance, protected surroundings, and lowered costs.

The Future of the Sustainable Agriculture Concept

Many in the agricultural community have adopted the sense of urgency and direction pointed to by the sustainable agriculture concept. Sustainability has become an integral component of many government, commercial, and non-profit agriculture research efforts, and it is beginning to be woven into agricultural policy. Increasing numbers of farmers and ranchers have embarked on their own paths to sustainability, incorporating integrated and innovative approaches into their own enterprises.

Summary

In agriculture and horticulture, soil generally refers to the medium for plant growth, typically material within the upper meter or two. Soil plays a key role in plant growth. Beneficial aspects of plants include providing physical support, heat, water, nutrients, and oxygen. Heat, light, and oxygen are also obtained by the atmosphere, but the roots of many plants also require oxygen. The prevailing agricultural system has delivered tremendous gains in productivity and efficiency. Food production worldwide has risen in the past 50 years. On the other hand, agriculture profoundly affects many ecological systems. Negative effects of current practices include ecological concerns, economic and social concerns, and human health concerns. Pesticides from every chemical class have been detected in groundwater and are commonly found in groundwater beneath agricultural areas. Despite impressive production gains, excessive use of pesticides has proven to be ecologically unsound, leading to the destruction of natural enemies, the increase of pest resistance, pest resurgence, and outbreaks of secondary pests. These consequences have often resulted in higher production costs, lost markets due to undesirable pesticide residue levels, and environmental and human health costs. Alternative and sustainable practices in farming and land use include organic agriculture, integrated pest management, and biological control.

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Chapter Attributions:

Chapter 10: Air Pollution, Climate Change, and Ozone Depletion

Traffic congestion is a daily reality in India's urban centers. Slow speeds and idling vehicles produce, per trip, 4 to 8 times more pollutants and consume more carbon footprint fuels than free-flowing traffic. This 2008 image shows traffic congestion in Delhi.

Learning Outcomes

After studying this chapter, you should be able to:

- Identify sources of air pollution
- List common air pollutants
- Explain how the greenhouse effect causes the atmosphere to retain heat
- Explain how we know that humans are responsible for recent climate change
- List some effects of climate change
- Identify some climate change policies and adaptation measures

Chapter Outline

- 10.1 Atmospheric Pollution
- 10.2 Ozone Depletion
- 10.3 Acid Rain

- 10.4 Climate Change
- 10.5 Chapter Resources

Air pollution occurs in many forms but can generally be thought of as gaseous and particulate contaminants that are present in the earth's atmosphere. Chemicals discharged into the air that have a direct impact on the environment are called **primary pollutants**. These primary pollutants sometimes react with other chemicals in the air to produce **secondary pollutants**.

Air pollution is typically separated into two categories: outdoor and indoor air pollution. **Outdoor air pollution** involves exposures that take place outside of the built environment. Examples include fine particles produced by coal burning, noxious gases such as sulfur dioxide, nitrogen oxides, and carbon monoxide, ground-level ozone, and tobacco smoke. **Indoor air pollution** involves exposure to particulates, carbon oxides, and other indoor air or dust pollutants. Examples include household products and chemicals, out-gassing of building materials, allergens (cockroach and mouse dropping, mold, pollen), and tobacco smoke.

Sources of Air Pollution

A **stationary source** of air pollution refers to an emission source that does not move, also known as a point source. Stationary sources include factories, power plants, and dry cleaners. The term **area source** describes many small sources of air pollution located together whose individual emissions may be below thresholds of concern but whose collective emissions can be significant. Residential wood burners are a good example of a small source, but when combined with many other small sources, they can contribute to local and regional air pollution levels. Area sources can also be considered non-point sources, such as the construction of housing developments, dry lake beds, and landfills.

A **mobile source** of air pollution refers to a source capable of moving under its own power. Mobile sources generally imply "on-road" transportation, including cars, sport utility vehicles, and buses. In addition, there is also a "non-road" or "off-road" category that includes gas-powered lawn tools and mowers, farm and construction equipment, recreational vehicles, boats, planes, and trains.

Agricultural sources arise from operations that raise animals and grow crops, which can generate emissions of gases and particulate matter. For example, animals confined to a barn or restricted area produce large amounts of manure. Manure emits various gases, particularly ammonia, into the air. This ammonia can be emitted from animal houses, manure storage areas, or land after the manure is applied. In crop production, the misapplication of fertilizers, herbicides, and pesticides can potentially result in aerial drift of these materials, and harm may be caused.

Unlike the above-mentioned sources of air pollution, air pollution caused by **natural sources** is not caused by people or their activities. An erupting volcano emits particulate matter and gases, forest, and prairie fires can emit large quantities of "pollutants," dust storms can create large amounts of particulate matter, and plants and trees naturally emit volatile organic compounds which can form aerosols that can cause a natural blue haze. Wild animals in their natural habitat are also considered natural sources of "pollution."

Six Common Air Pollutants

The most common air pollutants are *particulate matter*, *ground-level ozone*, *carbon monoxide*, *sulfur oxides*, *nitrogen oxides*, and *lead*. These pollutants can harm health and the environment and cause property damage. Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats. The U.S. Environmental Protection Agency (EPA) regulates them by developing criteria based on human and environmental health considerations.

Ground-level ozone is not emitted directly into the air but is created by chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOC) in the presence of sunlight. Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of NOx and VOC. Breathing ozone can trigger various health problems, particularly for children, the elderly, and people of all ages with lung diseases such as asthma. Ground-level ozone can also have harmful effects on sensitive vegetation and ecosystems. (Ground-level ozone should not be confused with the ozone layer, which is high in the atmosphere and protects Earth from ultraviolet light; ground-level ozone provides no such protection).

Particulate matter, also known as particle pollution, is a complex mixture of extremely small particles and liquid droplets. Particle pollution comprises several components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. The size of particles is directly linked to their potential to cause health problems. EPA is concerned about particles that are 10 micrometers in diameter or smaller because those are the particles that generally pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects.

Carbon monoxide (CO) is a colorless, odorless gas emitted from combustion processes. Nationally and, particularly in urban areas, the majority of CO emissions to ambient air come from mobile sources. CO can cause harmful health effects by reducing oxygen delivery to the body's organs (like the heart and brain) and tissues. At extremely high levels, CO can cause death.

Nitrogen dioxide (NO_2) is one of a group of highly reactive gasses known as "oxides of nitrogen," or nitrogen oxides (NOx). Other nitrogen oxides include nitrous acid and nitric acid. EPA's National Ambient Air Quality Standard uses NO_2 as the indicator for the larger group of nitrogen oxides. NO2 forms quickly from emissions from cars, trucks, buses, power plants, and off-road equipment. In addition to contributing to the formation of ground-level ozone, and fine particle pollution, NO2 is linked with a number of adverse effects on the respiratory system.

Sulfur dioxide (SO_2) is one of a group of highly reactive gasses known as "oxides of sulfur." The largest sources of SO_2 emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO_2 emissions include industrial processes such as extracting metal from ore and burning high sulfur-containing fuels by locomotives, large ships, and non-road equipment. SO_2 is linked with a number of adverse effects on the respiratory system.

Lead is a metal found naturally in the environment and manufactured products. The major sources of lead emissions have historically been fuels in on-road motor vehicles (such as cars and trucks) and industrial sources. As a result of regulatory efforts in the U.S. to remove lead from on-road motor vehicle gasoline, emissions of lead from the transportation sector dramatically declined by 95 percent between 1980 and 1999, and levels of lead in the air decreased by 94 percent between 1980 and 1999. Today, the highest lead levels in the air are usually found near lead smelters. Today's major sources of lead emissions to the air are ore and metals processing and piston-engine aircraft operating on leaded aviation gasoline.

Indoor Air Pollution

Most people spend approximately 90 percent of their time indoors. However, the indoor air we breathe in homes and other buildings can be more polluted than outdoor air and can increase the risk of illness.

There are many sources of indoor air pollution in homes. They include biological contaminants such as bacteria, molds, and pollen, burning fuels and environmental tobacco smoke, building materials and furnishings, household products, central heating and cooling systems, and outdoor sources. Outdoor air pollution can enter buildings and become a source of indoor air pollution.

Sick building syndrome is a term used to describe situations where building occupants have health symptoms associated only with spending time in that building. Causes of sick building syndrome include inadequate ventilation, indoor air pollution, and biological contaminants. Usually, indoor air quality problems only cause discomfort. Most people feel better as soon as they remove the source of the pollution. Ensuring that your building is well-ventilated and getting rid of pollutants can improve indoor air quality.

Secondhand Smoke (Environmental Tobacco Smoke)

Secondhand smoke combines smoke from a cigarette and smoke breathed out by a smoker. When a non-smoker is around someone smoking, they breathe in secondhand smoke.

Secondhand smoke is dangerous to anyone who breathes it in. There is no safe amount of secondhand smoke. It contains over 7,000 harmful chemicals, at least 250 of which are known to damage human health. It can also stay in the air for several hours after somebody smokes. Even breathing secondhand smoke for a short time can hurt your body.

Over time, secondhand smoke can cause serious health issues in non-smokers. The only way to fully protect non-smokers from the dangers of secondhand smoke is not to allow smoking indoors. Separating smokers from nonsmokers (like “no smoking” sections in restaurants), cleaning the air, and airing outbuildings does not completely eliminate secondhand smoke.

Source: Smokefree.gov

The Ozone Layer

Ozone (O_3) is a gaseous molecule that occurs in different parts of the atmosphere (Figure 1). It is chemically reactive and is dangerous to plant and animal life when present in the lower portions of the atmosphere. This type of ozone, called **ground-level ozone**, is a significant hazard to human health and is associated with pollution from vehicle exhaust and other anthropogenic emissions (see section 10.1).

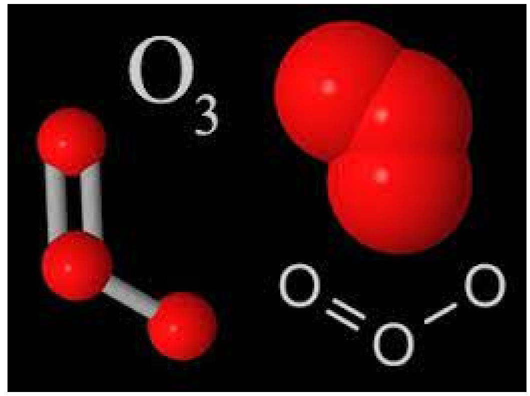


Figure 1. The ozone molecule is comprised of three oxygen atoms covalently bonded. "Ozone" by UCAR (Randy Russell) is licensed under CC BY-SA

Ozone in the upper atmosphere is naturally occurring and beneficial to life because it blocks harmful radiation from the sun. This type of ozone is called **stratospheric ozone**. Ozone in the stratosphere (Figure 2) forms when the energy of sunlight breaks apart the two oxygen atoms in an O2 molecule. Each lone oxygen atom can then combine with a different O_2 molecule to form O_3, ozone. The **ozone layer** is the portion of the stratosphere where ozone molecules are present, mixed in among the other gases that comprise the atmosphere (Figure 2).

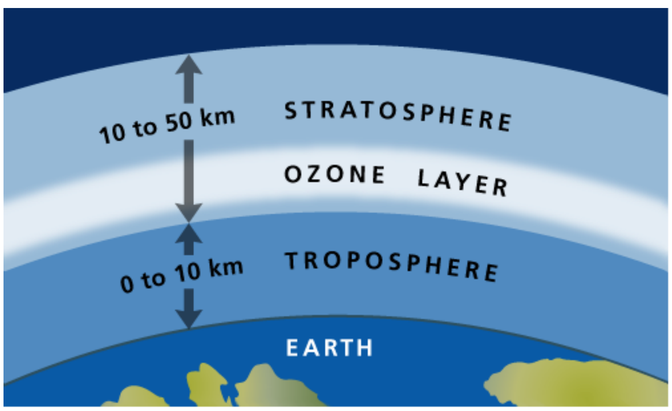


Figure 2. The ozone layer occurs in the region of the atmosphere called the stratosphere. This Photo by NC Climate Office is licensed under CC BY-SA.

Radiation from the sun is also called electromagnetic radiation or simply referred to as light. The sun emits different types of light, including but not limited to x-rays, visible light, microwaves, and ultraviolet light. The various types of light are distinguished by their different wavelengths. As the wavelength decreases, the amount of energy in that light increases. **Ultraviolet light**, for example, has shorter wavelengths than visible light and is thus more energetic. Ozone molecules absorb ultraviolet (UV) light, which is advantageous for life on Earth because UV light can break down important biomolecules such as DNA, leading to cell death and mutations.

Ozone Depletion

Unfortunately, the ozone layer that protects life on Earth from harmful UV light has been depleted due to human activities. The ozone depletion process begins when **CFCs** (chlorofluorocarbons) and other **ozone-depleting substances** (ODS) are emitted into the atmosphere. The industry used CFCs as refrigerants, degreasing solvents, and propellants. In the lower atmosphere, CFC molecules are extremely stable chemically and do not dissolve in the rain, and thus can linger for long periods. After several years, ODS molecules eventually reach the ozone layer in the stratosphere, starting about 10 kilometers above the Earth's surface.

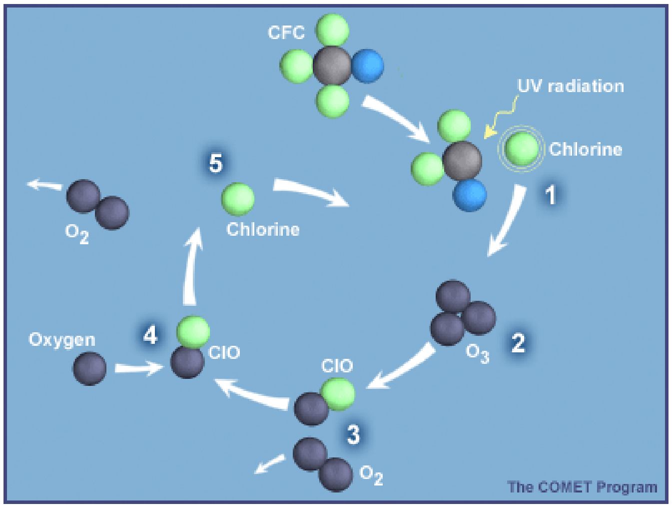


Figure 3. CFCs destroy ozone (O_3) when a chlorine atom breaks loose from the CFC and interacts with the oxygen atoms in the ozone molecule. This Photo by UCAR is licensed under CC BY-SA-NC.

Once in the stratosphere, CFCs and other ODS destroy ozone molecules. In the case of CFCs, UV light in the stratosphere knocks loose a chlorine atom from the molecule, which can then destroy numerous ozone molecules, as shown in Figure 3. In effect, ODS are removing ozone faster than it is created by natural processes (as described above), leading to a thinning of the ozone layer. This thinning represents a reduction in the concentration of ozone molecules in a particular portion of the stratosphere. Areas, where the ozone layer has thinned are commonly called holes. However, this is not entirely accurate because ozone is still present; it just exists at concentrations much lower than normal.

Policies to Reduce Ozone Destruction

Tackling the issue of ozone layer destruction is an example of global cooperation that produced meaningful action on a large-scale environmental problem. In 1973, scientists first calculated that CFCs could reach the stratosphere and destroy ozone. Based only on their calculations, the United States and most Scandinavian countries banned CFCs in spray cans in 1978.

But more confirmation that CFCs break down ozone was needed before additional action was taken. In 1985, members of the British Antarctic Survey reported that a 50% reduction in the ozone layer had been found over Antarctica in the previous three springs, a very important finding.

Two years after that seminal British Antarctic Survey report, an agreement titled the "Montreal Protocol on Substances that Deplete the Ozone Layer" was ratified by nations worldwide. The **Montreal Protocol,** as it is commonly called, controls the production and emission of 96 chemicals that damage the ozone layer. As a result, CFCs have been mostly phased out since 1995, although they were used in developing nations until 2010. Some of the less hazardous substances will not be phased out until 2030. The Montreal Protocol also requires that wealthier nations donate money to develop technologies that will replace these chemicals.

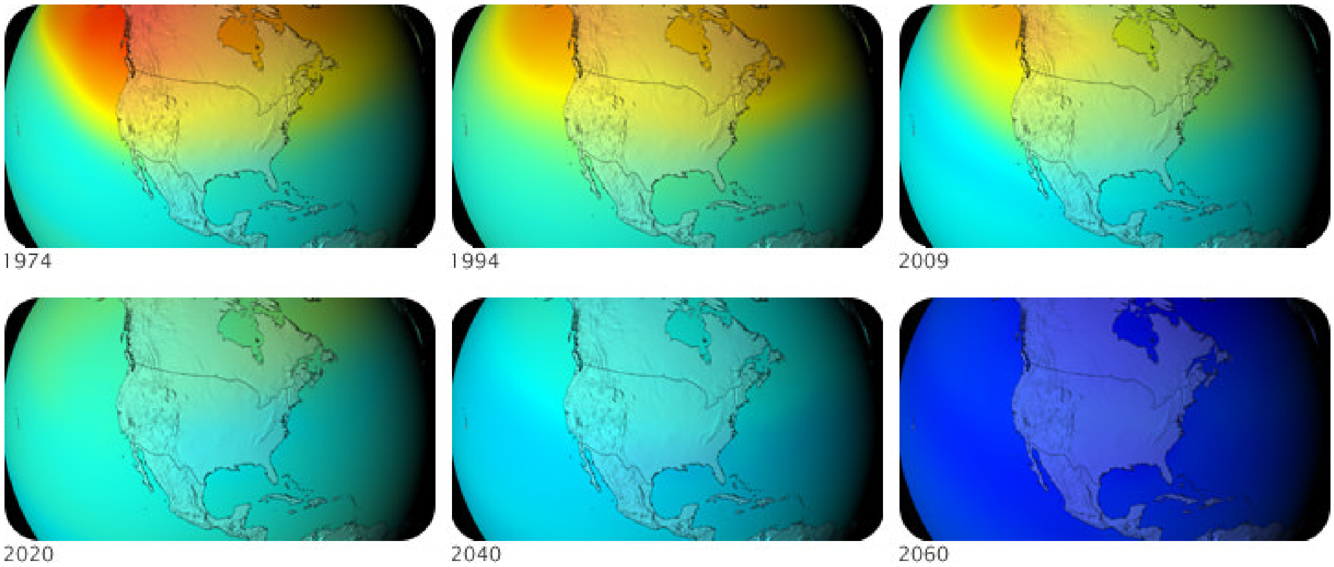


Figure 4. Ozone levels over North America decreased between 1974 and 2009. Models of the future predict what ozone levels would have been if CFCs were not being phased out. Warmer colors indicate more ozone.

The Montreal Protocol was a success, and scientists have found that the ozone layer is recovering and the size of the ozone "holes" are shrinking, thanks to a drastic reduction in the emission of ODS like CFCs. However, the recovery process is slow because CFCs take many years to reach the stratosphere and can survive there a long time before they break down and are rendered harmless. Thus, the ozone layer will take many more decades to recover fully.

However, constant vigilance and monitoring are needed as illegal production and emission of CFCs and other ODS threaten recovery efforts. In 2018, scientists from the US National Oceanic and Atmospheric Administration reported that emissions of a particular type of CFC had increased 25% since 2012. Follow-up studies have since approximated the emissions originating in particular regions of eastern Asia.

Health and Environmental Effects of Ozone Layer Depletion

There are three types of UV light, each distinguished by their wavelengths: UV-A, UV-B, and UV-C. Stratospheric ozone molecules absorb the sun's UV-C light and most of its UV-B light (Figure 5).

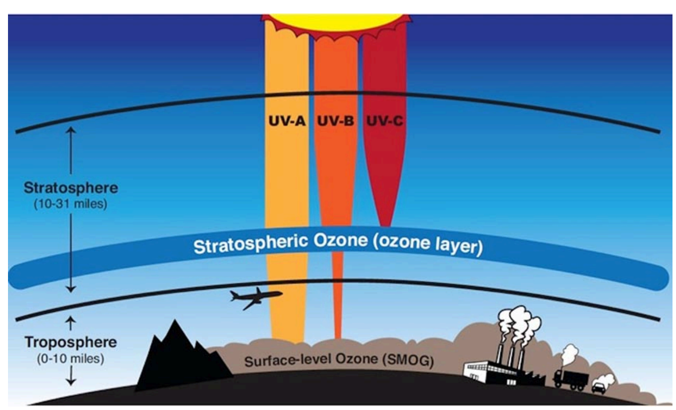


Figure 5. The ozone layer absorbs UV-B and UV-C light, protecting life on Earth from its harmful effects. This Photo by NASA is licensed under CCO Public Domain.

Reductions in stratospheric ozone levels led to higher levels of UV-B reaching the Earth's surface, which is a serious hazard to human health. Studies have shown that in the Antarctic, the amount of UV-B measured at the surface can double due to thinning of the ozone layer. UV-B harms cells because it can interact with biomolecules like DNA and damage them. This can lead to mutations and cell death. UV-B cannot penetrate multicellular organisms very far and thus tends only to affect cells near the surface, such as in the skin of animals. Microbes like bacteria, however, are composed of only one cell and can therefore be killed by UV-B.

Laboratory and epidemiological studies demonstrate that UV-B causes certain types of skin cancers in humans and plays a major role in developing malignant melanoma (a particularly dangerous form of skin cancer). In addition, UV-B causes cataracts, a clouding of the lens in the eye that can lead to poor vision or even blindness.

It is important to note that all sunlight contains some UV-B light, even with normal stratospheric ozone levels. Therefore, protecting your skin and eyes from the sun is important. Ozone layer depletion increases the amount of UV-B and the risk of health effects.

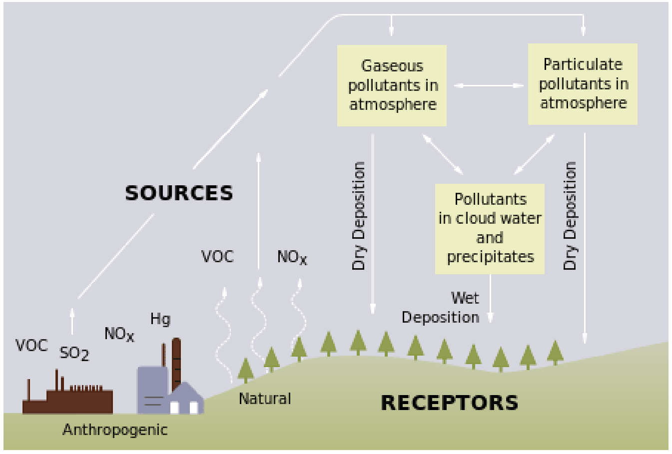


Figure 1. Processes involved in acid deposition.

Acid rain refers to a mixture of wet and dry deposition (deposited material) from the atmosphere containing higher than normal amounts of nitric and sulfuric acids. The precursors, or chemical forerunners, of acid rain formation result from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) resulting from fossil fuel combustion. Acid rain occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds. The result is a mild solution of sulfuric acid and nitric acid. When sulfur dioxide and nitrogen oxides are released from power plants and other sources, prevailing winds blow these compounds across state and national borders, sometimes over hundreds of miles.

Acid rain is measured using a scale called "pH." The lower a substance's pH, the more acidic it is. Pure water has a pH of 7.0. However, normal rain is slightly acidic because carbon dioxide (CO_2) dissolves into it, forming weak carbonic acid, giving the resulting mixture a pH of approximately 5.6 at typical atmospheric concentrations of CO_2. As of 2000, the most acidic rain falling in the U.S. has a pH of about 4.3.

Effects of Acid Rain

Acid rain causes **acidification** of lakes and streams and contributes to the damage of trees at high elevations (for example, red spruce trees above 2,000 feet) and many sensitive forest soils. In addition, acid rain accelerates the decay of building materials and paints, including irreplaceable buildings, statues, and sculptures that are part of our nation's cultural heritage. Before falling to the earth, sulfur dioxide (SO_2) and nitrogen oxide (NO_x) gases and their particulate matter derivatives—sulfates and nitrates—contribute to visibility degradation and harm public health.

The ecological effects of acid rain are most clearly seen in aquatic or water environments, such as streams, lakes, and marshes. Most lakes and streams have a pH between 6 and 8, although some lakes are naturally acidic even without the effects of acid rain. Acid rain primarily affects sensitive bodies of water in watersheds whose soils have a limited ability to neutralize acidic compounds (called "buffering capacity"). Lakes and streams become acidic (i.e., the pH value goes down) when the water and surrounding soil cannot buffer the acid rain enough to neutralize it. In areas where buffering capacity is low, acid rain releases aluminum from soils into lakes and streams; aluminum is highly toxic to many species of aquatic organisms. Acid rain causes slower growth, injury, or death of **forests**. Of course, acid rain is not the only cause of such conditions. Other factors contribute to the overall stress of these areas, including air pollutants, insects, disease, drought, or very cold weather. In most cases, the impacts of acid rain on trees are due to the combined effects of acid rain and these other environmental stressors.

Acid rain and the dry deposition of acidic particles contribute to the corrosion of **metals** (such as bronze) and the deterioration of paint and stone (such as marble and limestone). These effects significantly reduce the societal value of buildings, bridges, cultural objects (such as statues, monuments, and tombstones), and cars (Figure 2).

Figure 2. A gargoyle that has been damaged by acid rain.

Sulfates and nitrates that form in the atmosphere from sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions contribute to **visibility impairment,** meaning we cannot see as far or as clearly through the air. The pollutants that cause acid rain—sulfur dioxide (SO_2) and nitrogen oxides (NO_x)—damage **human health**. These gases interact in the atmosphere to form fine sulfate and nitrate particles that can be transported long distances by winds and inhaled deep into people's lungs. Fine particles can also penetrate indoors. Many scientific studies have identified a relationship between elevated levels of fine particles and increased illness and premature death from heart and lung disorders, such as asthma and bronchitis.

Earth's Temperature is a Balancing Act

Earth's temperature depends on the balance between energy entering and leaving the planet. When incoming energy from the sun is absorbed, Earth warms. When the sun's energy is reflected back into space, Earth avoids warming. When energy is released from Earth into space, the planet cools. Many factors, both natural and human, can cause changes in Earth's energy balance, including:

- Changes in the greenhouse effect, which affects the amount of heat retained by Earth's atmosphere;
- Variations in the sun's energy reaching Earth;
- Changes in the reflectivity of Earth's atmosphere and surface.

Scientists have pieced together a picture of Earth's climate, dating back hundreds of thousands of years, by analyzing a number of indirect measures of climate, such as ice cores, tree rings, glacier size, pollen counts, and ocean sediments. Scientists have also studied changes in Earth's orbit around the sun and the activity of the sun itself.

The historical record shows that the climate varies naturally over various time scales. In general, climate changes before the Industrial Revolution in the 1700s can be explained by natural causes, such as changes in solar energy, volcanic eruptions, and natural changes in greenhouse gas (GHG) concentrations. However, recent climate changes cannot be explained by natural causes alone. Research indicates that natural causes are unlikely to explain most observed warming, especially since the mid-20th century. Rather, it is extremely likely that human activities, especially our combustion of fossil fuels, explain most of that warming. The scientific consensus is clear: through alterations in the carbon cycle, humans are changing the global climate by increasing the impacts of the greenhouse effect.

The Greenhouse Effect Causes the Atmosphere to Retain Heat

Gardeners living in moderate or cool environments use greenhouses because they trap heat and create warmer environments than outside temperatures. This is great for plants that like heat or are sensitive to cold temperatures, such as tomato and pepper plants. Greenhouses contain glass or plastic that allows visible light from the sun to pass. This light, which is a form of energy, is absorbed by plants, soil, and surfaces and heats them. Some of that heat energy is then radiated outwards in the form of infrared radiation, a different form of energy. Unlike visible light, the glass of the greenhouse blocks the infrared radiation, thereby trapping the heat energy, causing the temperature within the greenhouse to increase.

The same phenomenon happens inside a car on a sunny day. Have you ever noticed how hotter a car can get compared to the outside temperature? Light energy from the sun passes through the windows and is absorbed by the surfaces in the car, such as the seats and the dashboard. Those warm surfaces then radiate infrared radiation, which cannot pass through the glass. This trapped infrared energy causes the air temperatures in the car to increase. This process is commonly known as the **greenhouse effect**.

The greenhouse effect also happens with the entire Earth. Of course, our planet is not surrounded by glass windows. Instead, the Earth is wrapped in an atmosphere that contains **greenhouse gases** (GHGs).

Much like the glass in a greenhouse, GHGs allow incoming visible light energy from the sun to pass, but they block infrared radiation radiating from Earth toward space (Figure 1). In this way, they help trap heat energy that subsequently raises air temperature. Being a greenhouse gas is a physical property of certain types of gases; because of their molecular structure, they absorb wavelengths of infrared radiation but are transparent to visible light. Some notable greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), and methane (CH_4). GHGs act like a blanket, making Earth significantly warmer than it would otherwise be. Scientists estimate that the average temperature on Earth would be -18º C without naturally-occurring GHGs.

What is Global Warming?

Global warming refers to the recent and ongoing rise in global average temperature near Earth's surface. It is caused mostly by increasing concentrations of greenhouse gases in the atmosphere. Global warming is causing climate patterns to change. However, global warming itself represents only one aspect of climate change.

What is Climate Change?

Climate change refers to any significant change in the measures of climate lasting for an extended period of time. In other words, climate change includes major changes in temperature, precipitation, or wind patterns, among other effects, that occur over several decades or longer.

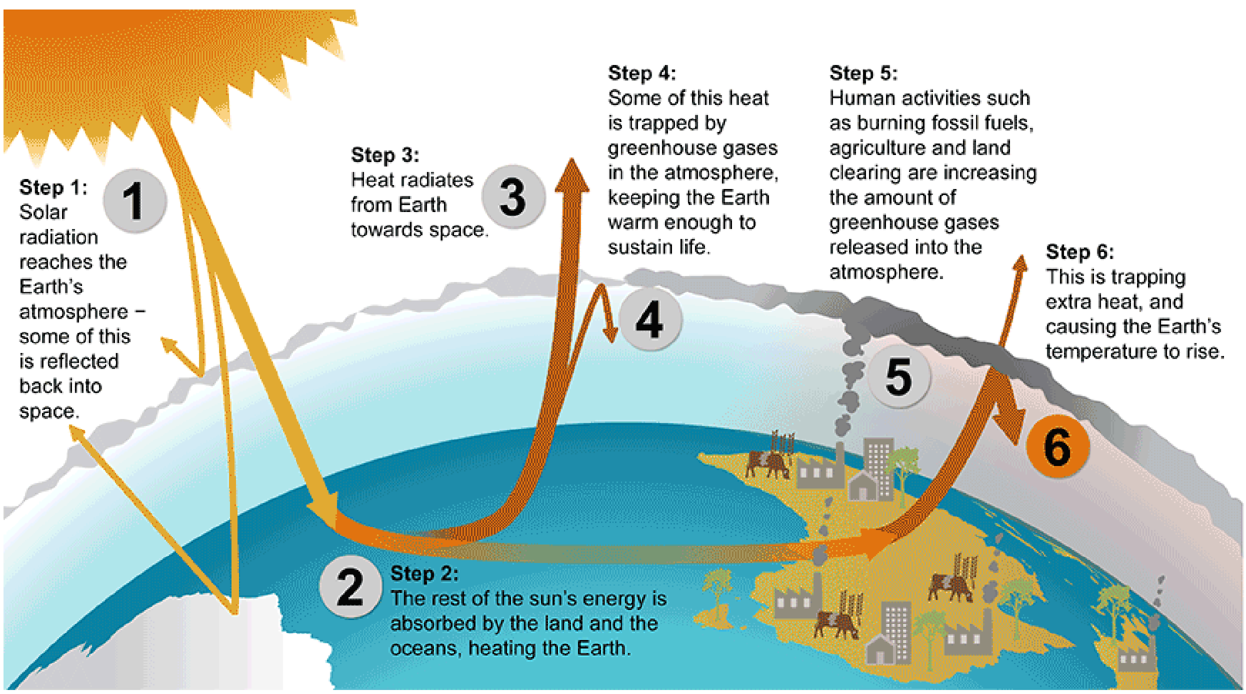


Figure 1. Enhanced Greenhouse Effect

The Main Greenhouse Gasses

The most important GHGs directly emitted by humans include CO_2 and methane. **Carbon dioxide** (CO_2) is the primary greenhouse gas that is contributing to recent global climate change. CO_2 is a natural component of the carbon cycle, involved in such activities as photosynthesis, respiration, volcanic eruptions, and ocean-atmosphere exchange. Human activities, primarily the burning of fossil fuels and changes in land use, release very large amounts of CO_2 into the atmosphere, causing its concentration in the atmosphere to rise.

Atmospheric CO_2 concentrations have increased by 45% since pre-industrial times, from approximately 280 parts per million (ppm) in the 18th century to 408 ppm in 2018. The current CO_2 level is higher than it has been in at least 800,000 years, based on evidence from ice cores that preserve ancient atmospheric gases. Human activities currently release over 30 billion tons of CO_2 into the atmosphere every year. While some volcanic eruptions released large quantities of CO_2 in the distant past, the U.S. Geological Survey (USGS) reports that human activities now emit more than 135 times as much CO_2 as volcanoes each year. This human-caused build-up of CO_2 in the atmosphere is like a tub filling with water, where more water flows from the faucet than the drain can take away.

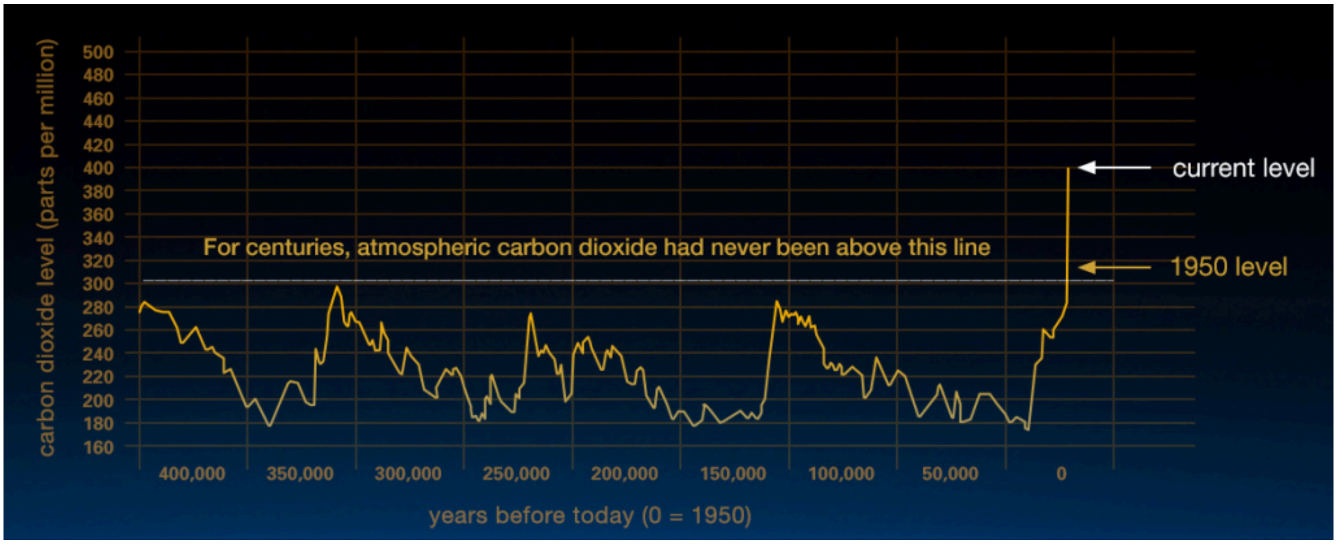


Figure 2. Based on comparing atmospheric samples contained in ice cores and more recent direct measurements, this graph provides evidence that atmospheric CO2 has increased since the Industrial Revolution. (Credit: Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO2 record.)

Methane (CH_4) is produced through both natural and human activities. For example, wetlands, agricultural activities, fossil fuel extraction, and transport emit CH_4. Methane is more abundant in Earth's atmosphere now than in at least the past 650,000 years. Due to human activities, CH_4 concentrations increased sharply during most of the 20th century and are now more than two-and-a-half times pre-industrial levels. In recent decades, the rate of increase has slowed considerably.

Other Greenhouse Gasses

Despite having a short atmospheric lifetime, water vapor is the most abundant greenhouse gas and also the most important in terms of its contribution to the natural greenhouse effect. Some human activities can influence local water vapor levels. However, on a global scale, the water vapor concentration is controlled by temperature, which influences overall rates of evaporation and precipitation. Therefore, direct human emissions do not substantially affect global water vapor concentration.

Ground-level ozone (O_3) has a short atmospheric lifetime and is a potent greenhouse gas. Chemical reactions create ozone from emissions of nitrogen oxides and volatile organic compounds from automobiles, power plants, and other industrial and commercial sources in the presence of sunlight (as discussed in section 10.1). In addition to trapping heat, ozone is a pollutant that can cause respiratory health problems and damage crops and ecosystems.

Changes in the Sun's Energy Affect how Much Energy Reaches Earth

Climate can be influenced by natural changes that affect how much solar energy reaches Earth. These changes include changes within the sun and changes in Earth's orbit. Changes occurring in the sun itself can affect the intensity of the sunlight that reaches the Earth's surface. The intensity of the sunlight can cause either warming (during periods of stronger solar intensity) or cooling (during periods of weaker solar intensity). The sun follows a natural 11-year cycle of small ups and downs in intensity, but the effect on Earth's climate is small. Changes in the shape of Earth's orbit and the tilt and position of Earth's axis can also affect the amount of sunlight reaching Earth's surface.

Changes in the sun's intensity have influenced Earth's climate in the past. For example, the so-called "**Little Ice Age**" between the 17th and 19th centuries may have been partially caused by a low solar activity phase from 1645 to 1715, which coincided with cooler temperatures. The Little Ice Age refers to a slight cooling of North America, Europe, and probably other areas around the globe. Changes in Earth's orbit have greatly impacted climate over tens of thousands of years. These changes appear to be the primary cause of past cycles of ice ages, in which Earth has experienced long periods of cold temperatures (ice ages) and shorter interglacial periods (periods between ice ages) of relatively warmer temperatures.

Changes in solar energy continue to affect climate. However, solar activity has been relatively constant, aside from the 11-year cycle, since the mid-20th century and therefore does not explain Earth's recent warming. Similarly, changes in the shape of Earth's orbit and the tilt and position of Earth's axis affect the temperature on relatively long timescales (tens of thousands of years) and, therefore, cannot explain the recent warming.

Changes in Reflectivity Affect How Much Energy Enters Earth's System

When sunlight energy reaches Earth, it can be reflected or absorbed. The amount that is reflected or absorbed depends on Earth's surface and atmosphere. Light-colored objects and surfaces, like snow and clouds, tend to reflect most sunlight, while darker objects and surfaces, like the ocean and forests, tend to absorb more sunlight. **Albedo** refers to the amount of solar radiation reflected from an object or surface, often expressed as a percentage. Earth as a whole has an albedo of about 30%, meaning that 70% of the sunlight that reaches the planet is absorbed. Sunlight that is absorbed warms Earth's land, water, and atmosphere.

Albedo is also affected by aerosols. **Aerosols** are small particles or liquid droplets in the atmosphere that can absorb or reflect sunlight. Unlike greenhouse gases (GHGs), the climate effects of aerosols vary depending on what they are made of and where they are emitted. Those aerosols that reflect sunlight, such as particles from volcanic eruptions or sulfur emissions from burning coal, have a cooling effect. Those that absorb sunlight, such as black carbon (a part of soot), have a warming effect.

Natural changes in albedo, like the melting of sea ice or increases in cloud cover, have contributed to climate change in the past, often acting as feedback to other processes. Volcanoes have played a noticeable role in climate. Volcanic particles that reach the upper atmosphere can reflect enough sunlight back to space to cool the planet's surface by a few tenths of a degree for several years. Volcanic particles from a single eruption do not produce long-term change because they remain in the atmosphere much shorter than GHGs.

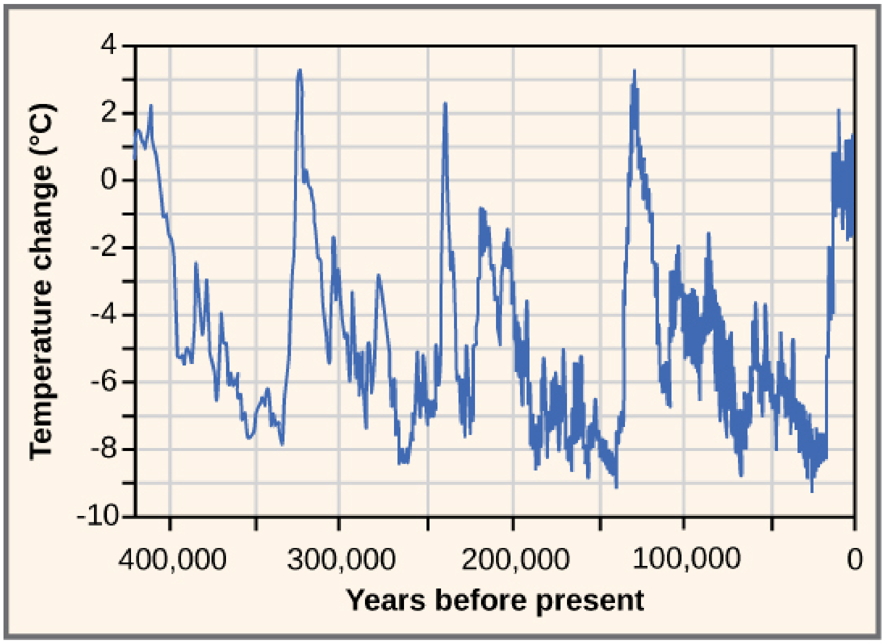
Human changes in land use and land cover have changed Earth's albedo. Processes such as deforestation, reforestation, desertification, and urbanization often contribute to changes in climate in the places they occur. These effects may be significant regionally but are smaller when averaged over the entire globe.

Scientific Consensus: Global Climate Change Is Real

The **Intergovernmental Panel on Climate Change** (IPCC) was created in 1988 by the United Nations Environment Programme and the World Meteorological Organization. It is tasked with evaluating and synthesizing the scientific evidence surrounding global climate change. The IPCC uses this information to evaluate current impacts and future risks and provide policymakers with assessments. These assessments are released about once every six years. The most recent report, the 5th Assessment, was released in 2013. Hundreds of leading scientists worldwide are chosen to author these reports. Over the history of the IPCC, these scientists have reviewed thousands of peer-reviewed, publicly available studies. The scientific consensus is clear: global climate change is real, and humans are very likely the cause of this change.

Additionally, the major scientific agencies of the United States, including the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), agree that climate change is occurring and humans are driving it. In 2010, the US National Research Council concluded, “Climate change is occurring, is very likely caused by human activities, and poses significant risks for a broad range of human and natural systems.” Many independent scientific organizations have released similar statements in the United States and abroad. This doesn’t necessarily mean that every scientist sees eye to eye on each component of the climate change problem, but broad agreement exists that climate change is happening and is primarily caused by excess greenhouse gases from human activities. Critics of climate change, driven by ideology instead of evidence, try to suggest to the public that there is no scientific consensus on global climate change. Such an assertion is patently false.

Current Status of Global Climate Change and Future Changes



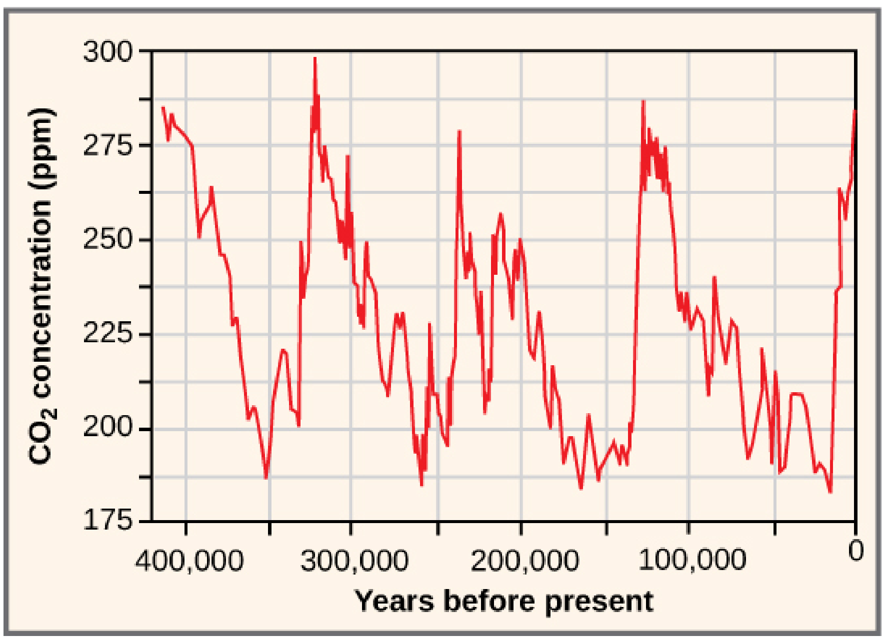


Figure 3. Ice at the Russian Vostok station in East Antarctica was laid down over the course of 420,000 years and reached a depth of over 3,000 m. By measuring the amount of CO_2 trapped in the ice, scientists have determined past atmospheric CO_2 concentrations. Temperatures relative to modern-day were determined from the amount of deuterium (an isotope of hydrogen) present.

Greenhouse gas concentrations in the atmosphere will continue to increase unless the billions of tons of anthropogenic emissions each year decrease substantially. Increased concentrations are expected to:

- Increase Earth's average temperature,
- Influence the patterns and amounts of precipitation,

- Reduce ice and snow cover, as well as permafrost,
- Raise sea level,
- Increase the acidity of the oceans.

These changes will impact our food supply, water resources, infrastructure, ecosystems, and even our own health. The magnitude and rate of future climate change will primarily depend on the following factors:

- The rate at which levels of greenhouse gas concentrations in our atmosphere continue to increase,
- How strongly features of the climate (e.g., temperature, precipitation, and sea level) respond to the expected increase in greenhouse gas concentrations,
- Natural influences on climate (e.g., from volcanic activity and changes in the sun's intensity) and natural processes within the climate system (e.g., changes in ocean circulation patterns).

Past and Present-day GHG Emissions Will Affect Climate Far into the Future

Many greenhouse gases stay in the atmosphere for long periods of time. As a result, even if emissions stopped increasing, atmospheric greenhouse gas concentrations would remain elevated for hundreds of years. Moreover, if we stabilized concentrations and the composition of today's atmosphere remained steady (which would require a dramatic reduction in current greenhouse gas emissions), surface air temperatures would continue to warm. This is because the oceans, which store heat, take many decades to respond to higher greenhouse gas concentrations fully. The ocean's response to higher greenhouse gas concentrations and higher temperatures will continue to impact climate over the next several decades to hundreds of years.

Future Temperature Changes

Climate models project the following key temperature-related changes:
Key Global Projections

- Average global temperatures are expected to increase by 2°F to 11.5°F by 2100, depending on future greenhouse gas emissions and the outcomes from various climate models.
- By 2100, the global average temperature is expected to warm at least twice as much as during the last 100 years.
- Ground-level air temperatures are expected to continue to warm more rapidly over land than oceans.
- Some parts of the world are projected to see larger temperature increases than the global average.

Future Precipitation and Storm Events

Patterns of precipitation and storm events, including rain and snowfall, will likely change. However, some of these changes are less certain than the changes associated with temperature. Projections show that future precipitation and storm changes vary by season and region. Some regions may have less precipitation, some may have more precipitation, and some may have little or no change. The amount of rain falling in heavy precipitation events will likely increase in most regions, while storm tracks are projected to shift towards the poles. Climate models project the following precipitation and storm changes:

- Global average annual precipitation through the end of the century is expected to increase, although changes in the amount and intensity of precipitation will vary by region.
- The intensity of precipitation events will likely increase on average. This will be particularly pronounced in tropical and high-latitude regions, which are also expected to experience overall increases in precipitation.
- The strength of the winds associated with tropical storms is likely to increase. The amount of precipitation falling in tropical storms is also likely to increase.
- Annual average precipitation is projected to increase in some areas and decrease in others.

Future Ice, Snowpack, and Permafrost

Arctic sea ice is already declining drastically. The area of snow cover in the Northern Hemisphere has decreased since 1970. Permafrost temperature has increased over the last century, making it more susceptible to thawing. Over the next century, it is expected that sea ice will continue to decline, glaciers will continue to shrink, snow cover will continue to decrease, and permafrost will continue to thaw.

For every 2°F of warming, models project about a 15% decrease in the extent of annually averaged sea ice and a 25% decrease in September Arctic sea ice. The coastal sections of the Greenland and Antarctic ice sheets are expected to continue to melt or slide into the ocean. If the rate of this ice melting increases in the 21st century, the ice sheets could significantly increase the global sea level. Glaciers are expected to continue to decrease in size. The melting rate is expected to continue increasing, contributing to rising sea levels.

Future Sea Level Change

Warming temperatures contribute to sea level rise by expanding ocean water, melting mountain glaciers and ice caps, and causing portions of the Greenland and Antarctic ice sheets to melt or flow into the ocean. Since 1870, global sea level has risen by about 8 inches. Estimates of future sea level rise vary for different regions, but global sea level for the next century is expected to rise at a greater rate than during the past 50 years. The contribution of thermal expansion, ice caps, and small glaciers to sea level rise is relatively well-studied, but the impacts of climate change on ice sheets are less understood and represent an active area of research. Thus, it is more difficult to predict how much changes in ice sheets will contribute to sea level rise. Greenland and Antarctic ice sheets could contribute an additional 1 foot of sea level rise, depending on how the ice sheets respond.

Regional and local factors will influence future relative sea level rise for specific coastlines worldwide. For example, relative sea level rise depends on land elevation changes that occur due to subsidence (sinking) or uplift (rising), in addition to local currents, winds, salinity, water temperatures, and proximity to thinning ice sheets. Assuming that these historical geological forces continue, a 2-foot rise in global sea level by 2100 would result in the following relative sea level rise:

- 2.3 feet at New York City
- 2.9 feet at Hampton Roads, Virginia
- 3.5 feet at Galveston, Texas
- 1 foot at Neah Bay in Washington state

Future Ocean Acidification

Ocean acidification is the process of ocean waters decreasing in pH. Oceans become more acidic as carbon dioxide (CO_2) emissions in the atmosphere dissolve in the ocean. This change is measured on the pH scale, with lower values being more acidic. The pH level of the oceans has decreased by approximately 0.1 pH units since pre-industrial times, equivalent to a 25% increase in acidity. The pH level of the oceans is projected to decrease even more by the end of the century as CO_2 concentrations are expected to increase for the foreseeable future. Ocean acidification adversely affects many marine species, including plankton, mollusks, shellfish, and corals. As ocean acidification increases, the availability of calcium carbonate will decline. Calcium carbonate is a key building block for the shells and skeletons of many marine organisms. If atmospheric CO_2 concentrations double, coral calcification rates are projected to decline by more than 30%. If CO_2 concentrations continue to rise at their current rate, corals could become rare on tropical and subtropical reefs by 2050.

Spread of Disease

This rise in global temperatures will increase the range of disease-carrying insects and the viruses and pathogenic parasites they harbor. Thus, diseases will spread to new regions of the globe. According to the World Health Organization, this spread has already been documented with dengue fever, a disease affecting hundreds of millions annually. Colder temperatures typically limit the distribution of certain species, such as the mosquitoes that transmit malaria, because freezing temperatures destroy their eggs.

The range of some disease-causing insects will expand, and the increasing temperatures will also accelerate their lifecycles, allowing them to breed and multiply quicker and perhaps evolve pesticide resistance faster. In addition to dengue fever, other diseases are expected to spread to new portions of the world as the global climate warms. These include malaria, yellow fever, West Nile virus, zika virus, and chikungunya.

Climate Change Affects Everyone

Our lives are connected to the climate**.** Human societies have adapted to the relatively stable climate we have enjoyed since the last ice age, which ended several thousand years ago. A warming climate will bring changes that can affect our water supplies, agriculture, power, transportation systems, the natural environment, and even our health and safety.

On average, carbon dioxide can stay in the atmosphere for nearly a century, so Earth will continue to warm in the coming decades. The warmer it gets, the greater the risk for more severe changes to the climate and Earth's system. Although it's difficult to predict the exact impacts of climate change, what's clear is that the climate we are accustomed to is no longer a reliable guide for what to expect in the future.

We can reduce the risks we will face from climate change**.** By making choices that reduce greenhouse gas pollution and preparing for the already underway changes, we can reduce risks from climate change. Our decisions today will shape the world our children and grandchildren will live in.

You Can Take Action

You can take steps at home, on the road, and in your office to reduce greenhouse gas emissions and the risks associated with climate change. Many of these steps can save you money. Some, such as walking or biking to work, can even improve your health! You can also get involved locally or in the state to support energy efficiency, clean energy programs, or other climate programs.

Suggested Supplementary Reading:

Intergovernmental Panel on Climate Change. 2013. 5th Assessment: Summary for Policymakers. <http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf>

NASA. 2018. Global Climate Change: Vital Signs of the Planet. Website. <https://climate.nasa.gov/>

This website by NASA provides a multi-media smorgasbord of engaging content. Learn about climate change using data collected by NASA satellites and more.

Summary

Air pollution can be thought of as gaseous and particulate contaminants that are present in the earth's atmosphere. Chemicals discharged into the air that directly impacts the environment are called primary pollutants. These primary pollutants sometimes react with other chemicals in the air to produce secondary pollutants. Common air pollutants, called criteria pollutants, are particle pollution, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead. These pollutants can harm health and the environment and cause property damage. The historical record shows that the climate system varies naturally over various time scales. In general, climate changes prior to the Industrial Revolution in the 1700s can be explained by natural causes, such as changes in solar energy, volcanic eruptions, and natural changes in greenhouse gas concentrations. Recent climate changes, however, cannot be explained by natural causes alone. Natural causes are unlikely to explain most observed warming, especially since the mid-20th century. Rather, human activities can explain most of that warming.

The primary human activity affecting the amount and rate of climate change is greenhouse gas emissions from burning fossil fuels. Greenhouse gas concentrations in the atmosphere will continue to increase unless the billions of tons of our annual emissions decrease substantially. Increased concentrations are expected to increase Earth's average temperature, influence the patterns and amounts of precipitation, reduce ice and snow cover, as well as permafrost, raise sea levels, and increase the acidity of the oceans. These changes will impact our food supply, water resources, infrastructure, ecosystems, and even our own health. Acid rain refers to a mixture of wet and dry deposition from the atmosphere containing higher-than-normal amounts of nitric and sulfuric acids. The precursors of acid rain formation result from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) resulting from fossil fuel combustion. Acid rain causes acidification of lakes and streams and damages trees and many sensitive forest soils. In addition, acid rain accelerates the decay of building materials and paints, contributes to the corrosion of metals, and damages human health. The ozone depletion process begins when CFCs and other ozone-depleting substances (ODS) are emitted into the atmosphere. Reductions in stratospheric ozone levels lead to higher levels of UVB reaching the Earth's surface. The sun's output of UVB does not change; rather, less ozone means less protection, and hence more UVB reaches the Earth. Ozone layer depletion increases the amount of UVB, leading to negative health and environmental effects.

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EPA. (n.d.). *Climate change.* Accessed August 31, 2015 at http://www.epa.gov/climatechange/. Modified from original.

University of California College Prep. (2012). *AP environmental science.* Retrieved from http://cnx.org/content/col10548/1.2/. Available under Creative Commons Attribution 4.0 International License. (CC BY 4.0). Modified from original.

Chapter Attribution:

Chapter 11: Conventional and Sustainable Energy

Wind farm near Copenhagen, Denmark. In 2014 wind power met 39% of electricity demand in Denmark.

Learning Outcomes

After studying this chapter, you should be able to:

- Outline the history of human energy use
- Understand the challenges to continued reliance on fossil energy
- Outline environmental impacts of energy use
- Understand the global capacity for each non-renewable energy source
- Evaluate the different energy sources based on their environmental impact
- Understand the key factors in the growth of renewable energy sources

Chapter Outline

Energy for lighting, heating, and cooling our buildings, manufacturing products, and powering our transportation systems comes from various natural sources. The earth's core provides geothermal energy. The gravitational pull of the moon and sun creates tides. The sun emits light (electromagnetic radiation), which creates the wind, powers the water (hydrologic) cycle, and enables photosynthesis. Plants, algae, and cyanobacteria utilize solar energy to grow and create biomass that can be burned and used for **biofuels**, such as wood, biodiesel, and bioethanol. Over the course of millions of years, biomass from photosynthetic organisms can create energy-rich **fossil fuels** through the geologic process of burial and transformation through heat and pressure.

Each of these types of energy can be defined as **renewable** or **non-renewable.** Renewable energy sources can be replenished within human lifespans. Examples include solar, wind, and biomass energy. Non-renewable energy is finite and cannot be replenished within a human timescale. Examples include nuclear energy and fossil fuels, which take millions of years to form. All energy sources have some environmental and health costs, and energy distribution is not equally distributed among all nations.

Environmental and Health Challenges of Energy Use

The environmental impacts of energy use on humans and the planet can happen anywhere during the life cycle of the energy source. The impacts begin with the extraction of the resource. They continue with the processing, purification, or manufacture of the source; its transportation to the place of energy generation, and ends with the disposal of waste generated during use.

The extraction of fossil fuels can be used as a case study because its use significantly impacts the environment. As we mine deeper into mountains, farther out at sea, or farther into pristine habitats, we risk damaging fragile environments, and the results of accidents or natural disasters during extraction processes can be devastating. Fossil fuels are often located far from where they are utilized, so they need to be transported by pipeline, tankers, rail, or trucks. These all present the potential for accidents, leakage, and spills. When transported by rail or truck, energy must be expended, and pollutants are generated. Processing petroleum, gas, and coal generates various emissions and wastes and utilizes water resources. Energy production at power plants results in air, water, and, often, waste emissions. Power plants are highly regulated in the United States by federal and state law under the Clean Air and Clean Water Acts, while the Nuclear Regulatory Commission regulates nuclear power plants.

Geopolitical Challenges of Fossil Fuels

Using fossil fuels has allowed much of the global population to reach a higher standard of living. However, this dependence on fossil fuels results in many significant impacts on society. Our modern technologies and services, such as transportation and plastics, depend in many ways on fossil fuels. If supplies become limited or extremely costly, our economies are vulnerable. If countries do not have their own fossil fuel reserves, they incur even more risk. The United States had become increasingly dependent on foreign oil since 1970 when our oil production peaked. The United States imported over half of the crude oil and refined petroleum products we consumed in 2009. Over half of these imports came from the Western Hemisphere (Figure 2).

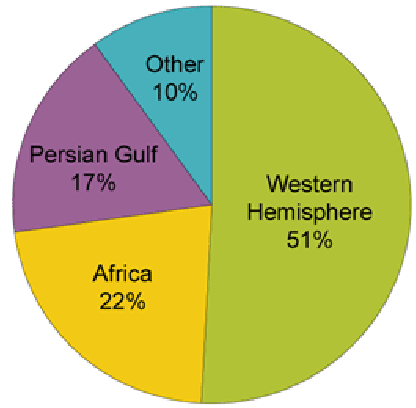

Figure 2. Sources of United States Net Petroleum Imports, 2009 Figure illustrates that the United States imported over half of the crude oil and refined petroleum products it consumed during 2009. Source: U.S. Energy Information Administration, Petroleum Supply Annual, 2009, preliminary data.

The **Organization of Petroleum Exporting Countries** (OPEC; Figure 3) is the major holder of oil reserves. As of 2018, there were 15 member countries in OPEC: Algeria, Angola, Congo, Ecuador, Equatorial Guinea, Gabon, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela. OPEC attempts to influence the amount of oil available to the world by assigning a production quota to each member except Iraq, for which no quota is presently set. Overall compliance with these quotas is mixed since the individual countries make the actual production decisions. These countries have a national oil company but also allow international oil companies to operate within their borders. They can restrict the amounts of production by those oil companies. Therefore, the OPEC countries greatly influence how much of world demand is met by OPEC and non-OPEC supply. A recent example is the price increases in 2011 after multiple popular uprisings in Arab countries, including Libya. This pressure has led the United States to develop policies that would reduce reliance on foreign oil, such as developing additional domestic sources and obtaining it from non-Middle Eastern countries such as Canada, Mexico, Venezuela, and Nigeria. However, since fossil fuel reserves create jobs and provide dividends to investors, a lot is at stake in a nation with oil reserves. Oil wealth may be shared with the country's inhabitants or retained by oil companies and dictatorships, such as in Nigeria before the 1990s.

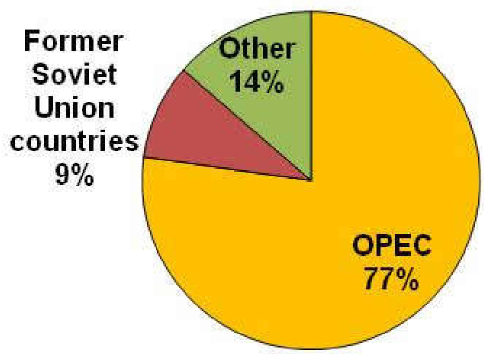

Figure 3. Proven Oil Reserves Holders Pie chart shows proven oil reserve holders. Source: C. Klein-Banai using data from BP Statistical Review of World Energy (2010)

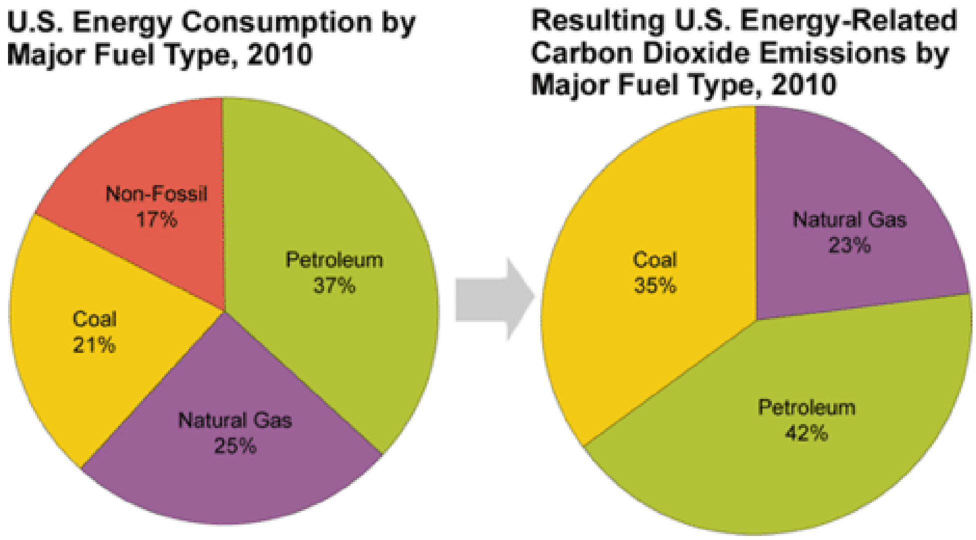

Figure 4. Fuel Type and Carbon Emissions The two charts show the relationship between fuel type and carbon emissions for U.S. energy consumption in 2010. Source: U.S. Energy Information Administration

Fossil Fuels

Fossil fuels come from the organic matter of plants, algae, and cyanobacteria that were buried, heated, and compressed under high pressure over millions of years. The process transformed the biomass of those organisms into three types of fossil fuels: oil, coal, and natural gas.

Petroleum (oil)

Thirty-seven percent of the world's energy and 43% of the United States's energy consumption comes from oil. Scientists and policy-makers often discuss when the world will reach **peak oil production**, the point at which oil production is at its greatest and then declines. It is generally thought that peak oil will be reached by the middle of the 21st Century, although making such estimates is difficult because many variables must be considered. Worldwide reserves are 1.3 trillion barrels or 45 years left at the current production level.

Environmental Impacts of Oil Extraction and Refining

Oil is usually found one to two miles (1.6 – 3.2 km) below the Earth's surface, whether on land or ocean. Once the oil is found and extracted, it must be refined, which separates and prepares the mix of crude oil into the different types for gas, diesel, tar, and asphalt. Oil refining is one of the top sources of air pollution in the United States for volatile organic hydrocarbons, toxic emissions, and the single largest source of carcinogenic benzene. When petroleum is burned as gasoline or diesel, or to make electricity or to power boilers for heat, it produces a number of emissions that have a detrimental effect on the environment and human health:

- Carbon dioxide (CO_2) is a greenhouse gas and a source of climate change.
- Sulfur dioxide (SO_2) causes acid rain, which damages plants and animals that live in water and increases or causes respiratory illnesses and heart diseases, particularly in vulnerable populations like children and the elderly.
- Nitrous oxides (NO_x) and Volatile Organic Carbons (VOCs) contribute to ground-level ozone, an irritant that causes lung damage.
- Particulate Matter (PM) produces hazy conditions in cities and scenic areas and combines with ozone to contribute to asthma and chronic bronchitis, especially in children and the elderly. Very small, or "fine PM," is also thought to penetrate the respiratory system more deeply and cause emphysema and lung cancer.
- Lead can have severe health impacts, especially for children.

Other domestic sources of oil are being considered conventional resources and are being depleted. These include **tar sands** – moist sand and clay deposits with 1-2 percent bitumen (thick and heavy petroleum-rich in carbon and poor in hydrogen). These are removed by strip mining (see section below on coal). Another source is **oil shale,** which is sedimentary rock filled with organic matter that can be processed to produce liquid petroleum. Extracted by strip mining or creating subsurface mines, oil shale can be burned directly like coal or baked in hydrogen to extract liquid petroleum. However, the net energy values are low and expensive to extract and process. These resources have severe environmental impacts due to strip mining, carbon dioxide, methane, and other air pollutants similar to fossil fuels.

As the United States tries to extract more oil from its own dwindling resources, they are drilling even deeper into the earth and increasing the environmental risks. The largest United States oil spill to date began in April 2010 when an explosion occurred on the Deepwater Horizon Oil Rig, killing 11 employees and spilling nearly 200 million gallons of oil before the resulting leak could be stopped. Wildlife, ecosystems, and people's livelihoods were adversely affected. A lot of money and huge amounts of energy were expended on immediate clean-up efforts. The long-term impacts are still not known. The National Commission on the Deepwater Horizon Oil Spill and Offshore Drilling was set up to study what went wrong.

The Global Dependence of Transportation on Oil

Two-thirds of oil consumption is devoted to transportation, fueling cars, trucks, trains, and airplanes. For the United States and most developed societies, transportation is woven into the fabric of our lives, a necessity as central to daily operations as food or shelter. The concentration of oil reserves in a few regions of the world makes much of the world dependent on imported energy for transportation. The rise in oil prices in the last decade makes dependence on imported energy for transportation an economic and an energy issue. The United States, for example, now spends upwards of $350 billion annually on imported oil, a drain of economic resources that could be used to stimulate growth, create jobs, build infrastructure, and promote social advances at home.

Coal

Unlike oil, **coal** is solid. Due to its relatively low cost and abundance, coal generates about half of the electricity consumed in the United States. Coal is the largest domestically produced source of energy. Coal production has doubled in the United States over the last sixty years (Figure 1). Current world reserves are estimated at 826,000 million tonnes, with nearly 30% of that in the United States. It is a major fuel resource that the United States controls domestically.

Figure 1. Historic U.S. Coal Production Graph shows U.S. Coal Production from 1950-2010. Source: U.S. Energy Information Administration

Coal is plentiful and inexpensive when looking only at the market cost relative to the cost of other sources of electricity, but its extraction, transportation, and use produces a multitude of environmental impacts that the market cost does not truly represent. Coal emits sulfur dioxide, nitrogen oxide, and mercury, which are linked to acid rain, smog, and health issues. Burning coal emits higher amounts of carbon dioxide per unit of energy than oil or natural gas. Coal accounted for 35% of the United States carbon dioxide emissions released into the Earth's atmosphere in 2010. Ash generated from combustion contributes to water contamination. Some coal mining has a negative impact on ecosystems and water quality and alters landscapes and scenic views (such as with mountaintop mining).

There are also significant health effects and risks to coal miners and those living near coal mines. Traditional underground mining is risky to mine workers due to the risk of entrapment or death. Over the last 15 years, the U.S. Mine Safety and Health Administration has published the number of mine worker fatalities, varying from 18-48 per year. Twenty-nine miners died on April 6, 2010, in an explosion at the Upper Big Branch coal mine in West Virginia, contributing to the uptick in deaths between 2009 and 2010. In other countries with fewer safety regulations, accidents occur more frequently. In May 2011, for example, three people died, and 11 were trapped in a coal mine in Mexico for several days. There is also risk of getting **black lung disease** (pneumoconiosis). This lung disease is caused by inhaling coal dust over a long time**.** It causes coughing and shortness of breath. If exposure is stopped, the outcome is good. However, the complicated form may cause shortness of breath that worsens.

Figure 2. Mountaintop Removal Coal Mining in Martin County, Kentucky Photograph shows mountaintop coal removal mining in Martin County, Kentucky. Source: Flashdark.

Mountaintop mining (MTM), while less hazardous to workers, negatively affects land resources. MTM is a surface mining practice involving the removal of mountaintops to expose coal seams and disposing of the associated mining waste in adjacent valleys. This form of mining is very damaging to the environment because it literally removes the tops of mountains, destroying the existing habitat. Additionally, the debris from MTM is dumped into valleys burying streams and other important habitats.

Natural Gas

Natural gas meets 20% of world energy needs and 25% of the United States' needs. **Natural gas** is mainly composed of methane (CH_4) and is a very potent greenhouse gas. There are two types of natural gas. **Biogenic gas** is found at shallow depths and arises from bacteria's anaerobic decay of organic matter, like landfill gas. **Thermogenic gas** comes from the compression of organic matter and deep heat underground. They are found with petroleum in reservoir rocks and with coal deposits, and these fossil fuels are extracted together.

Natural gas is released into the atmosphere from coal mines, oil and gas wells, natural gas storage tanks, pipelines, and processing plants. These leaks are the source of about 25% of total U.S. methane emissions, which translates to three percent of total U.S. greenhouse gas emissions. When natural gas is produced but cannot be captured and transported economically, it is "flared" or burned at well sites, which converts it to CO_2. This is considered safer and better than releasing methane into the atmosphere because CO_2 is a less potent greenhouse gas than methane.

In the last few years, a new reserve of natural gas has been identified: shale resources. The United States possesses 2,552 trillion cubic feet (Tcf) (72.27 trillion cubic meters) of potential natural gas resources, with shale resources accounting for 827 Tcf (23.42 tcm). As natural gas prices increased, extracting the gas from shale has become more economical. Figure 3 shows the past and forecasted U.S. natural gas production and the various sources. The current reserves are enough to last about 110 years at the 2009 rate of U.S. consumption (about 22.8 Tcf per year -645.7 bcm per year).

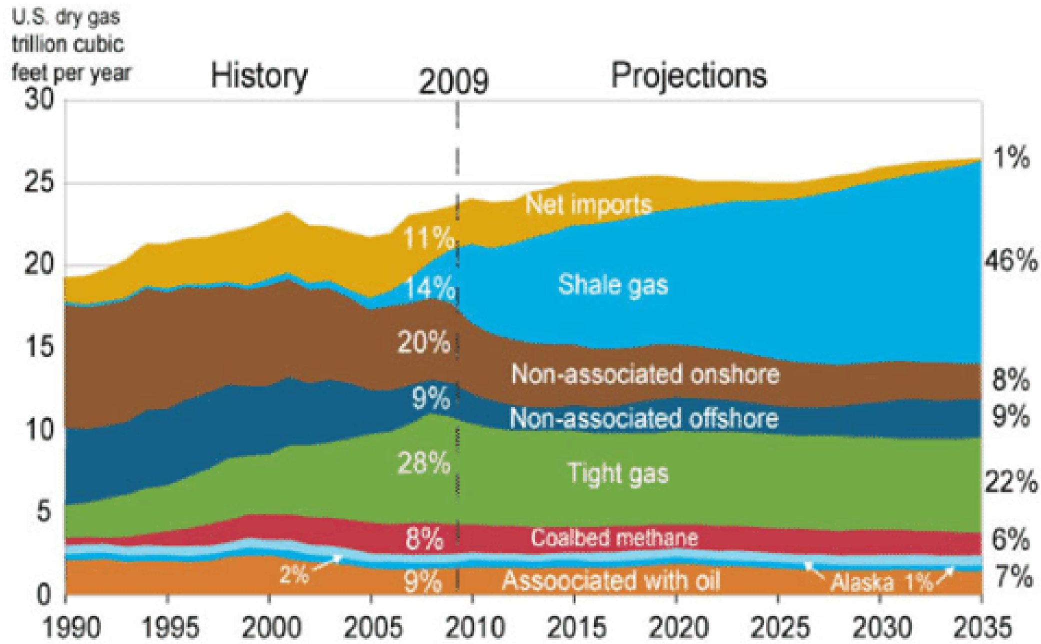

Figure 3. U.S. Natural Gas Supply, 1990-2035 Graph shows U.S. historical and projected natural gas production from various sources. Source: U.S. Energy Information Administration

Natural gas is a preferred fossil fuel when considering its environmental impacts. Specifically, when burned, much less carbon dioxide (CO_2), nitrogen oxides, and sulfur dioxide are omitted from the combustion of coal or oil. It also does not produce ash or toxic emissions.

Natural gas production can result in the production of large volumes of contaminated water. This water has to be properly handled, stored, and treated so that it does not pollute land and water supplies. Shale gas extraction is more problematic than traditional sources due to a process nicknamed **fracking** or fracturing of wells since it requires large amounts of water (Figure 4). The technique uses high-pressure fluids to fracture the normally hard shale deposits and release gas and oil trapped inside the rock. To promote gas flow out of the rock, small particles of solids are included in the fracturing liquids to lodge in the shale cracks and keep them open after the liquids are depressurized. The considerable use of water may affect water availability for other uses in some regions, which can affect aquatic habitats. If mismanaged, hydraulic fracturing fluid can be released by spills, leaks, or various other exposure pathways. The fluid contains potentially hazardous chemicals such as hydrochloric acid, glutaraldehyde, petroleum distillate, and ethylene glycol. The risks of fracking have been highlighted in popular culture in the documentary Gasland (2010).

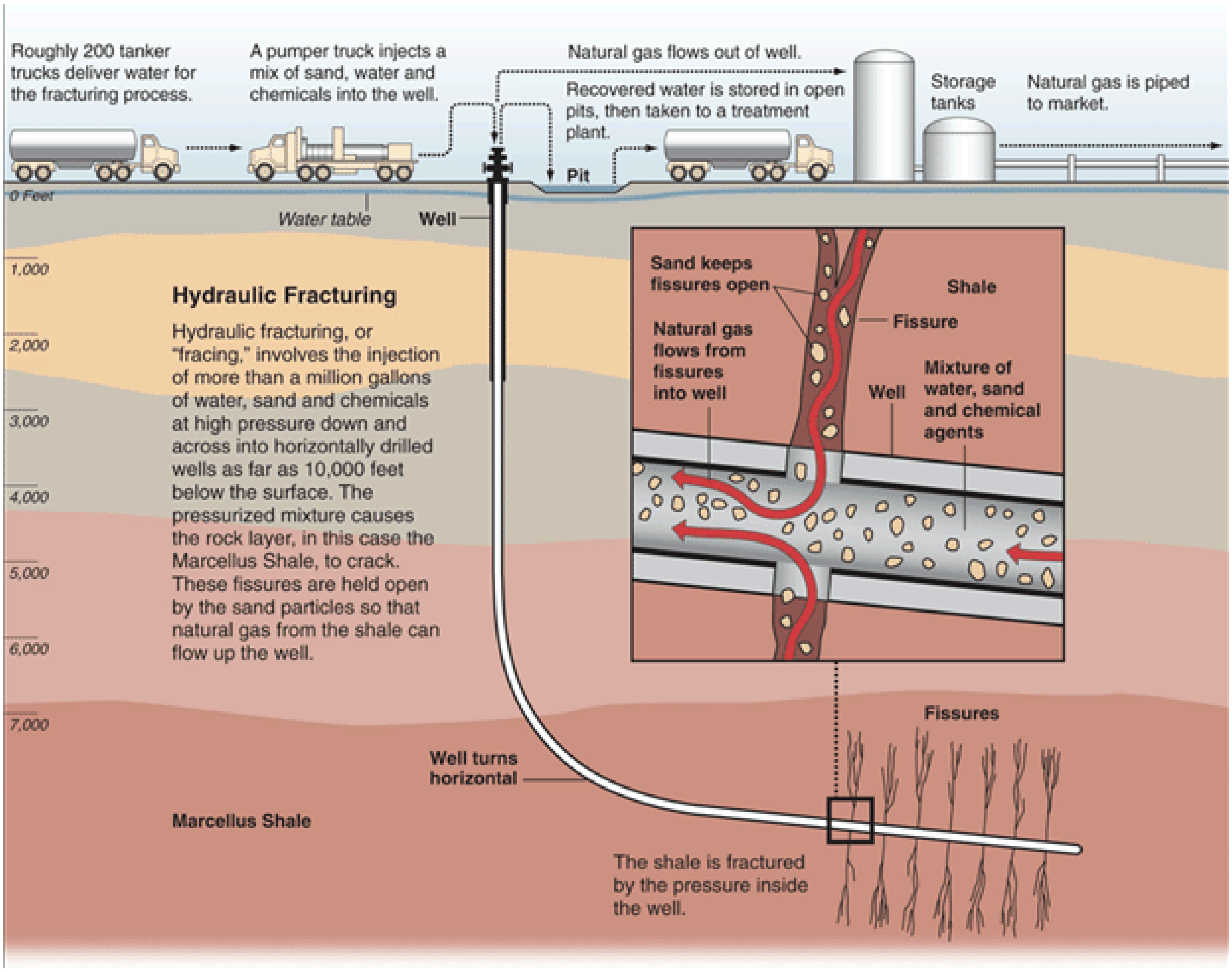

Figure 4. Graphic illustrates the process of hydraulic fracturing. Source: Al Granberg, ProPublica.

The raw gas from a well may contain many other compounds besides the methane being sought, including hydrogen sulfide, a very toxic gas. Natural gas with high concentrations of hydrogen sulfide is usually flared, which produces CO_2, carbon monoxide, sulfur dioxide, nitrogen oxides, and many other compounds. Natural gas wells and pipelines often have engines to run equipment and compressors, which produce additional air pollutants and noise.

Contributions of Coal and Natural Gas to Electricity Generation

Currently, the US's fossil fuels used for electricity generation are predominantly coal (44%) and natural gas (23%); petroleum accounts for approximately 1%. Coal electricity traces its origins to the early 20th Century, when it was the natural fuel for steam engines, given its abundance, high energy density, and low cost. Natural Gas is a later addition to the fossil electricity mix, arriving in significant quantities after World War II and with its greatest growth since 1990. Of the two fuels, coal emits almost twice the carbon dioxide as natural gas for the same heat output, making it a significantly greater contributor to global warming and climate change.

The Future of Natural Gas and Coal

The future development of coal and natural gas depends on the degree of public and regulatory concern for carbon emissions and the relative price and supply of the two fuels. Coal supplies are abundant in the United States, and the transportation chain from mines to power plants is well established. The primary unknown factor is the degree of public and regulatory pressure that will be placed on carbon emissions. Strong regulatory pressure on carbon emissions would favor the retirement of coal and the addition of natural gas power plants. This trend is reinforced by the recent dramatic expansion of shale gas reserves in the United States due to advances in drilling technology. Shale natural gas production increased 48% annually from 2006 – 2010, with more increases expected. Greater United States production of shale gas will gradually reduce imports and could eventually make the United States a net exporter of natural gas.

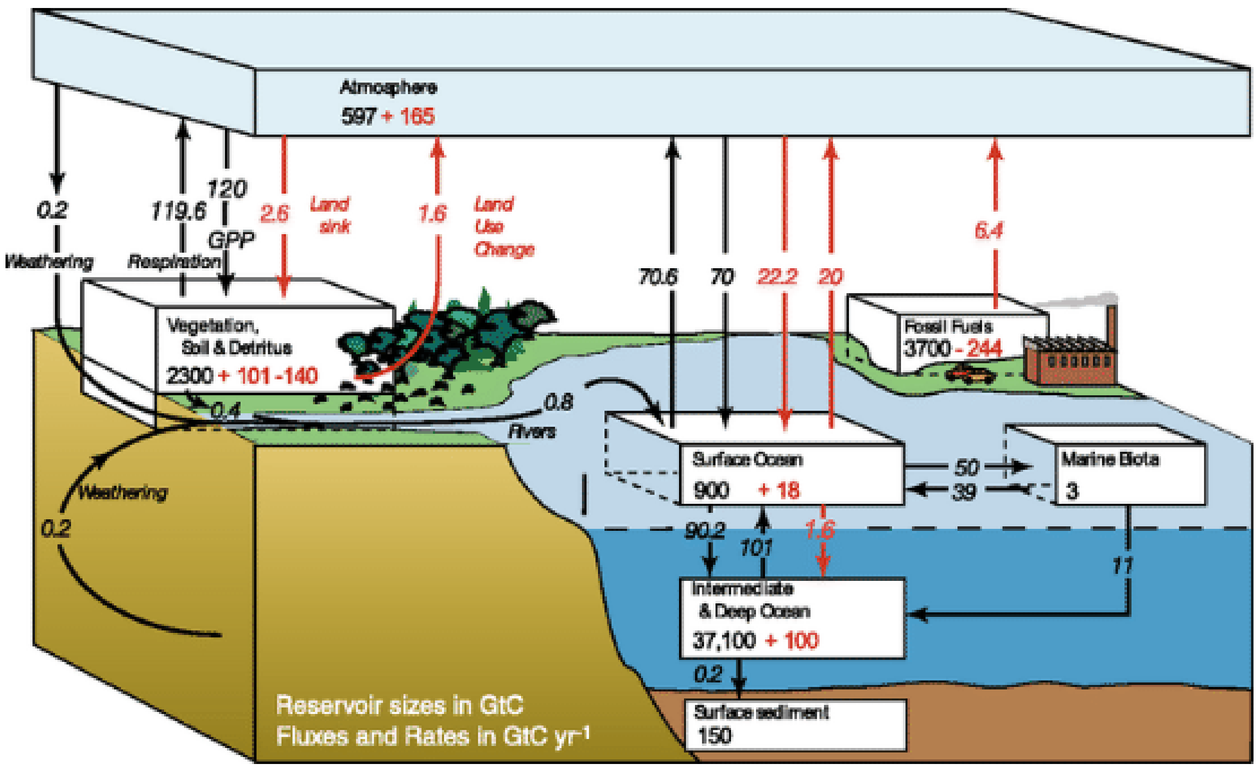

Figure 5. Global Carbon Cycle, the 1990s The global carbon cycle for the 1990s shows the main annual fluxes in GtC yr–1: pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red. Source: Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, figure 7.3

Nuclear Power

Nuclear power is energy released from the radioactive decay of elements, such as uranium, which releases large amounts of energy. Nuclear power plants produce no carbon dioxide and are often considered **alternative fuels** (fuels other than fossil fuels)**.** Currently, world electricity production from nuclear power is about 19.1 trillion KWh, with the United States producing and consuming about 22% of that. Nuclear power provides about 9% of the electricity in the United States (Figure 7).

There are environmental challenges with nuclear power. Mining and refining uranium ore and making reactor fuel demands a lot of energy. Also, nuclear power plants are very expensive and require large amounts of metal, concrete, and energy to build. The main environmental challenge for nuclear power is waste, including uranium mill tailings, spent (used) reactor fuel, and other radioactive wastes. These materials have long radioactive half-lives and thus threaten human health for thousands of years. The **half-life** of a radioactive element is the time it takes for 50% of the material to decay radioactively. The U.S. Nuclear Regulatory Commission regulates the operation of nuclear power plants and the handling, transportation, storage, and disposal of radioactive materials to protect human health and the environment.

By volume**,** the waste produced from mining uranium, called **uranium mill tailings,** is the largest waste and contains the radioactive element radium, which decays to produce radon, a radioactive gas. **High-level radioactive waste** consists of used nuclear reactor fuel. This fuel is in a solid form consisting of small fuel pellets in long metal tubes and must be stored and handled with multiple containment, first cooled by water and later in special outdoor concrete or steel containers that are cooled by air. There is no long-term storage facility for this fuel in the United States.

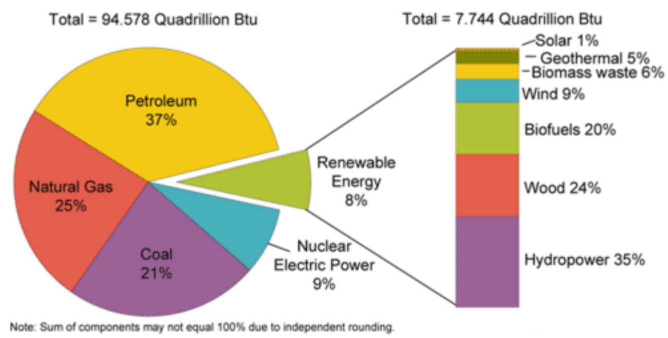

Figure 7. U.S. Energy Consumption by Energy Source, 2009 Renewable energy makes up 8% of U.S. energy consumption. Source: U.S. Energy Information Administration

Many other regulatory precautions govern permitting, construction, operation, and decommissioning of nuclear power plants due to risks from an uncontrolled nuclear reaction. The potential for air, water, and food contamination is high should an uncontrolled reaction occur. Even when planning for worst-case scenarios, unexpected events are always risks. For example, the March 2011 earthquake and subsequent tsunami that hit Japan resulted in reactor meltdowns at the Fukushima Daiichi Nuclear Power Station, causing massive damage to the surrounding area.

Debating Nuclear Energy

From a sustainability perspective, nuclear electricity presents an interesting dilemma. On the one hand, nuclear electricity produces no carbon emissions, a major sustainable advantage in a world facing anthropogenic climate change. On the other hand, nuclear electricity produces dangerous waste that i) must be stored out of the environment for thousands of years, ii) can produce bomb-grade plutonium and uranium that terrorists or others could divert to destroy cities and poison the environment, and iii) threatens the natural and built environment through accidental leaks of long-lived radiation. Thoughtful scientists, policymakers, and citizens must weigh the benefit of this source of carbon-free electricity against the environmental risk of storing spent fuel, the societal risk of nuclear proliferation, and the impact of accidental or deliberate release of radiation. There are very few examples of humans having the power to change the dynamics of the earth permanently. Global climate change from carbon emissions is one example, and radiation from the explosion of a sufficient number of nuclear weapons is another. Nuclear electricity touches both of these opportunities, on the positive side for reducing carbon emissions and the negative side for the risk of nuclear proliferation.

Nuclear electricity came into the energy scene remarkably quickly. Following the development of nuclear technology at the end of World War II for military ends, nuclear energy quickly acquired a new peacetime path for inexpensive electricity production. Eleven years after the end of World War II, a very short time in energy terms, the first commercial nuclear reactor produced electricity at Calder Hall in Sellafield, England. The number of nuclear reactors grew steadily to more than 400 by 1990, four years after the Chornobyl disaster in 1986 and eleven years following Three Mile Island in 1979. Since 1990, the number of operating reactors has remained approximately flat, with new construction balancing decommissioning due to public and government reluctance to proceed with nuclear electricity expansion plans.

The outcome of this debate will determine whether the world experiences a nuclear renaissance that has been in the making for several years. The global discussion has been strongly impacted by the unlikely nuclear accident in Fukushima, Japan, in March 2011. The Fukushima nuclear disaster was caused by an earthquake and tsunami that disabled the cooling system for a nuclear energy complex consisting of operating nuclear reactors and storage pools for underwater storage of spent nuclear fuel, ultimately causing a partial meltdown of some of the reactor cores and release of significant radiation. This event, 25 years after Chornobyl, reminds us that safety and public confidence are especially important in nuclear energy; without them, the expansion of nuclear energy will not happen.

Hydropower

Hydropower (hydroelectric) relies on water to spin turbines and create electricity. It is considered a clean and renewable energy source because it does not directly produce pollutants and because the power source is regenerated. Hydropower provides 35% of the United States renewable energy consumption.

Figure 1. Hoover Power Plant View of Hoover Power Plant on the Colorado River as seen from above. Source: U.S. Department of the Interior

Hydropower dams and the reservoirs they create can have environmental impacts. For example, the migration of fish to their upstream spawning areas can be obstructed by dams. In areas where salmon must travel upstream to spawn, such as along the Columbia River in Washington and Oregon, the dams block their way. This problem can be partially alleviated by using “fish ladders” that help salmon get around the dams. Fish traveling downstream, however, can get killed or injured as water moves through turbines in the dam. Reservoirs and the operation of dams can also affect aquatic habitats due to changes in water temperatures, water depth, chemistry, flow characteristics, and sediment loads, all of which can lead to significant changes in the ecology and physical characteristics of the river both upstream and downstream. As reservoirs fill with water, it may cause natural areas, farms, cities, and archeological sites to be inundated and force populations to relocate.

Small hydropower systems

Large-scale dam hydropower projects are often criticized for impacting wildlife habitat, fish migration, water flow, and quality. However, small **run-of-the-river projects** are free from many of the environmental problems associated with their large-scale relatives because they use the natural flow of the river and thus produce relatively little change in the stream channel and flow. The dams built for some run-of-the-river projects are very small and impound little water, and many projects do not require a dam at all. Thus, effects such as oxygen depletion, increased temperature, decreased flow, and impeded upstream migration are not problems for many run-of-the-river projects.

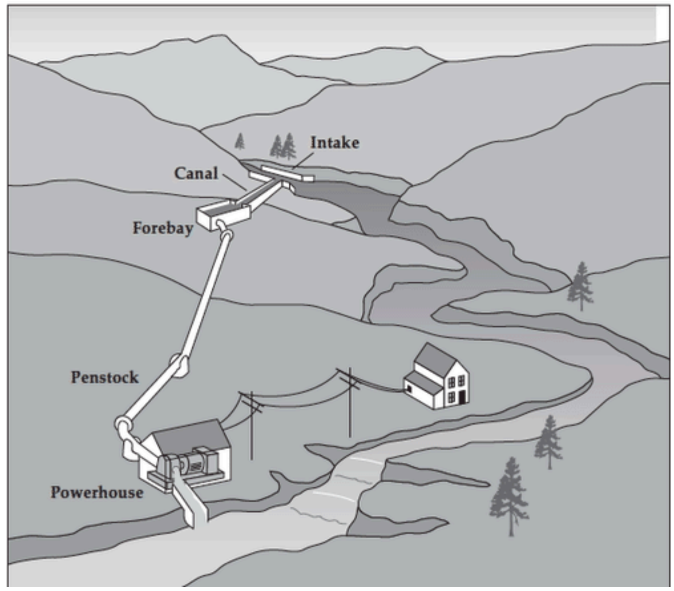

Figure 2. Micro hydropower system. Although there are several ways to harness moving water to produce energy, run-of-the-river systems, which do not require large storage reservoirs, are often used for micro-hydro and sometimes small-scale hydro projects. For run-of-the-river hydro projects, a portion of a river's water is diverted to a channel, pipeline, or pressurized pipeline (penstock) that delivers it to a waterwheel or turbine. The moving water rotates the wheel or turbine, which spins a shaft. The motion of the shaft can be used for mechanical processes, such as pumping water, or it can be used to power an alternator or generator to generate electricity.

Small hydropower projects offer emissions-free power solutions for many remote communities worldwide, such as those in Nepal, India, China, and Peru, as well as for highly industrialized countries like the United States. **Small hydropower systems** generate between .01 to 30 MW of electricity. Hydropower systems that generate up to 100 kilowatts (kW) of electricity are often called **micro hydropower** systems (Figure 2). Most of the systems used by home and small business owners would qualify as micro hydropower systems. A 10 kW system generally can provide enough power for a large home, a small resort, or a hobby farm.

Municipal Solid Waste

Municipal solid waste (MSW) is commonly known as garbage and can create electricity by burning it directly or by burning the methane produced as it decays. Waste-to-energy processes are gaining renewed interest as they can solve two problems at once: waste disposal and energy production from a renewable resource. Many environmental impacts are similar to those of a coal plant: air pollution, ash generation, etc. Because the fuel source is less standardized than coal and hazardous materials may be present in MSW, incinerators and waste-to-energy power plants need to clean the gases of harmful materials. The U.S. EPA regulates these plants very strictly and requires installing anti-pollution devices. Also, many toxic chemicals may break down into less harmful compounds while incinerating at high temperatures. The ash from these plants may contain high concentrations of various metals in the original waste. If ash is clean enough, it can be "recycled" as an MSW landfill cover or to build roads, cement blocks, and artificial reefs.

Biofuel

Figure 3. Woodchips Photograph shows a pile of woodchips, a type of biomass. Source: Ulrichulrich

Biomass refers to material made by organisms, such as cells and tissues. In terms of energy production, biomass is almost always derived from plants and algae to a lesser extent. For biomass to be a sustainable option, it usually needs to come from waste material, such as lumber mill sawdust, paper mill sludge, yard waste, or oat hulls from an oatmeal processing plant, material that would otherwise just rot. Livestock manure and human waste could also be considered biomass. Biomass can help mitigate climate change because, when burned, it adds no new carbon to the atmosphere. Returning to the carbon cycle (chapter 3), you will recall that photosynthesis removes CO_2 through carbon fixation. When biomass is burnt, CO_2 is created, which is equal to the amount of CO_2 captured during carbon fixation. Thus, biomass is a **carbon-neutral** energy source because it doesn't add new CO_2 to the carbon cycle. Each type of biomass must be evaluated for its environmental and social impact to determine if it is really advancing sustainability and reducing environmental impacts. For example, cutting down large swaths of forests just for energy production is not a sustainable option because our energy demands are so great that we would quickly deforest the world, destroying critical habitats.

Burning Wood

Wood and charcoal made from wood for heating and cooking can replace fossil fuels and reduce CO_2 emissions. If wood is harvested from forests or woodlots that have to be thinned or from urban trees that fall down or needed be cut down anyway, then using it for biomass does not impact those ecosystems. However, wood smoke contains harmful pollutants like carbon monoxide and particulate matter. Home heating is most efficient and least polluting when using a modern wood stove or fireplace insert that is designed to release small amounts of particulates. However, in places where wood and charcoal are major cooking and heating fuels, such as in undeveloped countries, the wood may be harvested faster than trees can grow, resulting in deforestation.

Biomass can be used in small power plants. For instance, Colgate College has had a wood-burning boiler since the mid-1980s, and in one year, it processed approximately 20,000 tons of locally and sustainably harvested wood chips, the equivalent of 1.17 million gallons (4.43 million liters) of fuel oil, avoiding 13,757 tons of emissions and saving the university over $1.8 million in heating costs. The University's steam-generating wood-burning facility now satisfies more than 75% of the campus's heat and domestic hot water needs.

Landfill Gas or Biogas

Landfill gas (**biogas**) is a man-made "biogenic" gas, as discussed above. Methane is formed due to biological processes in sewage treatment plants, waste landfills, anaerobic composting, and livestock manure management systems. This gas is captured and burned to produce heat or electricity. The electricity may replace electricity produced by burning fossil fuels and result in a net reduction in CO_2

emissions. The only environmental impacts are from the plant's construction, similar to that of a natural gas plant.

Bioethanol and Biodiesel

Bioethanol and **biodiesel** are liquid biofuels manufactured from plants, typically crops. Bioethanol can be easily fermented from sugar cane juice, as is done in Brazil. Bioethanol can also be fermented from broken-down corn starch, as is mainly done in the United States. The economic and social effects of growing plants for fuels need to be considered since the land, fertilizers, and energy used to grow biofuel crops could be used to grow food crops instead. The competition of land for fuel vs. food can increase the price of food, which has a negative effect on society. It could also decrease the food supply increasing malnutrition and starvation globally. Also, in some parts of the world, large areas of natural vegetation and forests have been cut down to grow sugar cane for bioethanol, soybeans, and palm oil trees to make biodiesel. This is not sustainable land use. Biofuels may be derived from parts of plants not used for food, such as stalks, thus reducing that impact. Biodiesel can be made from used vegetable oil and has been produced on a very local basis. Compared to petroleum diesel, biodiesel combustion produces fewer sulfur oxides, particulate matter, carbon monoxide, unburned, and other hydrocarbons but produces more nitrogen oxide.

Liquid biofuels typically replace petroleum and are used to power vehicles. Although ethanol-gasoline mixtures burn cleaner than pure gasoline, they also are more volatile and thus have higher "evaporative emissions" from fuel tanks and dispensing equipment. These emissions contribute to the formation of harmful ground-level ozone and smog. Gasoline requires extra processing to reduce evaporative emissions before it is blended with ethanol.

Geothermal Energy

Five percent of the United States renewable energy comes from **geothermal energy:** using the heat of Earth's subsurface to provide endless energy. Geothermal systems utilize a heat-exchange system that runs in the subsurface about 20 feet (5 meters) below the surface where the ground is at a constant temperature. The system uses the earth as a heat source (in the winter) or a heat sink (in the summer). This reduces the energy consumption required to generate heat from gas, steam, hot water, and conventional electric air-conditioning systems. The environmental impact of geothermal energy depends on how it is being used. Direct use and heating applications have almost no negative impact on the environment.

Geothermal power plants do not burn fuel to generate electricity, so their emission levels are very low. They release less than 1% of the carbon dioxide emissions of a fossil fuel plant. Geothermal plants use scrubber systems to clean the air of hydrogen sulfide that is naturally found in the steam and hot water. They emit 97% less acid rain-causing sulfur compounds than are emitted by fossil fuel plants. After the steam and water from a geothermal reservoir have been used, they are injected back into the earth.

Solar Energy

Solar power converts light energy into electrical energy and has a minimal environmental impact, depending on where it is placed. In 2009, 1% of the renewable energy generated in the United States was from solar power (1646 MW) out of 8% of the total electricity generated from renewable sources. **Photovoltaic (PV)** cell manufacturing generates some hazardous waste from the chemicals and solvents used in processing. Often solar arrays are placed on roofs of buildings or over parking lots or integrated into construction in other ways. However, large systems may be placed on land, particularly in deserts, where those fragile ecosystems could be damaged without care. Some solar thermal systems use potentially hazardous fluids (to transfer heat) that require proper handling and disposal. Concentrated solar systems may need to be cleaned regularly with water, which is also needed for cooling the turbine generator. Using water from underground wells may affect the ecosystem in some arid locations.

Figure 4. Rooftop Solar Installations Rooftop solar installation on Douglas Hall at the University of Illinois at Chicago does not affect land resources while producing electricity with zero emissions. Source: Office of Sustainability, UIC

Wind

Wind energy is a clean, renewable energy source with very few environmental challenges. Wind turbines are becoming a more prominent sight across the United States, even in regions with less wind potential. Wind turbines (often called windmills) do not release emissions that pollute the air or water (with rare exceptions) and do not require water for cooling. The U.S. wind industry had 40,181 MW of wind power capacity installed at the end of 2010, with 5,116 MW installed in 2010 alone, providing more than 20% of installed wind power around the globe. According to the American Wind Energy Association, over 35% of all new electrical generating capacity in the United States since 2006 was due to wind, surpassed only by natural gas.

Figure 5. Twin Groves Wind Farm, Illinois Wind power is becoming a more popular energy source in the United States. Source: Office of Sustainability, UIC

Because a wind turbine has a small physical footprint relative to the amount of electricity it produces, many wind farms are located on crop and pasture land. They contribute to economic sustainability by providing extra income to farmers and ranchers, allowing them to stay in business and keep their property from being developed for other uses. For example, energy can be produced by installing wind turbines in the Appalachian mountains of the United States instead of engaging in mountaintop removal for coal mining. Offshore wind turbines on lakes or the ocean may have smaller environmental impacts than turbines on land.

Wind turbines do have a few environmental challenges. Some people have aesthetic concerns when they see them on the landscape. A few wind turbines have caught on fire, and some have leaked lubricating fluids, though this is relatively rare. Some people do not like the sound that wind turbine blades make. Turbines have been found to cause bird and bat deaths, particularly if they are located along their migratory path. This is of particular concern if these are threatened or endangered species. There are ways to mitigate that impact, which is currently being researched. There are some small impacts from the construction of wind projects or farms, such as the construction of service roads, the production of the turbines themselves, and the concrete for the foundations. However, overall analysis has found that turbines make much more energy than the amount used to make and install them.

Interest in Renewable Energy

Strong interest in renewable energy in the modern era arose in response to the oil shocks of the 1970s when the Organization of Petroleum Exporting Countries (OPEC) imposed oil embargos and raised prices in pursuit of geopolitical objectives. The shortages of oil, especially gasoline for transportation, and the eventual rise in the price of oil by a factor of approximately ten from 1973 to 1981 disrupted the social and economic operation of many developed countries and emphasized their precarious dependence on foreign energy supplies. The reaction in the United States was a shift from oil and gas to plentiful domestic coal for electricity production and the imposition of fuel economy standards for vehicles to reduce oil consumption for transportation. Other developed countries without large fossil reserves, such as France and Japan, chose to emphasize nuclear (France to the 80% level and Japan to 30%) or to develop domestic renewable resources such as hydropower and wind (Scandinavia), geothermal (Iceland), solar, biomass and for electricity and heat. As oil prices collapsed in the late 1980s, interest in renewables, such as wind and solar, that faced significant technical and cost barriers, declined in many countries, while other renewables, such as hydropower and biomass, continued to experience growth.

The increasing price and volatility of oil prices since 1998 and the increasing dependence of many developed countries on foreign oil (60% of United States and 97% of Japanese oil was imported in 2008) spurred renewed interest in renewable alternatives to ensure energy security. A new concern not known in previous oil crises added further motivation: our knowledge of the emission of greenhouse gases and their growing contribution to climate change. An additional economic motivation, the high cost of foreign oil payments to supplier countries (approximately $350 billion/year for the United States at 2011 prices), grew increasingly important as developed countries struggled to recover from the economic recession of 2008. These energy securities, carbon emission, and climate change concerns drive significant increases in fuel economy standards, fuel switching of transportation from uncertain and volatile foreign oil to domestic electricity and biofuels, and electricity production from low carbon sources.

Physical Origin of Renewable Energy

Although renewable energy is often classified as hydro, solar, wind, biomass, geothermal, wave, and tide, all forms of renewable energy arise from only three sources: the light of the sun, the heat of the earth's crust, and the gravitational attraction of the moon and sun. Sunlight provides, by far, the largest contribution to renewable energy. The sun provides the heat that drives the weather, including forming high- and low-pressure areas in the atmosphere that make wind. The sun also generates the heat required for the vaporization of ocean water that ultimately falls over land creating rivers that drive hydropower, and the sun is the energy source for photosynthesis, which creates biomass. Solar energy can be directly captured for water and space heating, driving conventional turbines that generate electricity, and as excitation energy for electrons in semiconductors that drive photovoltaics. The sun is also responsible for the energy of fossil fuels, created from the organic remains of plants and sea organisms compressed and heated in the absence of oxygen in the earth's crust for tens to hundreds of millions of years. However, the time scale for fossil fuel regeneration is too long to consider them renewable in human terms.

Geothermal energy originates from heat rising to the surface from the earth's molten iron core created during the formation and compression of the early earth and from heat produced continuously by the radioactive decay of uranium, thorium, and potassium in the earth's crust. Tidal energy arises from the gravitational attraction of the moon and the more distant sun on the earth's oceans, combined with the earth's rotation. These three sources – sunlight, the heat trapped in the earth's core and continuously generated in its crust, and the moon's and sun's gravitational force on the oceans – account for all renewable energy.

Capacity and Geographical Distribution

Although renewable energies such as wind and solar have experienced strong growth in recent years, they still make up a small fraction of the world's total energy needs. The largest share comes from traditional biomass, mostly fuel wood gathered in traditional societies for household cooking and heating, often without regard for sustainable replacement. Hydropower is the next largest contributor, an established technology that experienced significant growth in the 20th Century. The other contributors are more recent and smaller in contribution: water and space heating by biomass combustion or harvesting solar and geothermal heat, biofuels derived from corn or sugar cane, and electricity generated from wind, solar, and geothermal energy. Despite their large capacity and significant recent growth, wind and solar electricity still contributed less than 1% of total energy in 2008.

The potential of renewable energy resources varies dramatically. Solar energy is by far the most plentiful, delivered to the earth's surface at a rate of 120,000 Terawatts (TW), compared to the global human use of 15 TW. To put this in perspective, covering 100×100 km2 of desert with 10% efficient solar cells would produce 0.29 TW of power, about 12% of the global human demand for electricity.

To supply all of the earth's electricity needs (2.4 TW in 2007) would require 7.5 such squares, an area about the size of Panama (0.05% of the earth's total land area). The world's conventional oil reserves are estimated at three trillion barrels, including all the oil that has already been recovered and remains for future recovery. The solar energy equivalent of these oil reserves is delivered to the earth by the sun in 1.5 days.

The geographical distribution of useable renewable energy is quite uneven. Sunlight, often considered relatively evenly distributed, is concentrated in deserts with rare cloud cover. Winds are up to 50% stronger and steadier offshore than on land. Hydroelectric potential is concentrated in mountainous regions with high rainfall and snowmelt. Biomass requires available land that does not compete with food production and adequate sun and rain to support growth.

Wind and Solar Resources in the United States

The United States has abundant renewable resources. The solar irradiation in the southwestern United States is exceptional, equivalent to that of Africa and Australia, which contain the best solar resources in the world. Much of the United States has solar irradiation as good or better than Spain, considered the best in Europe, and much higher than Germany. The variation in irradiation over the United States is about a factor of two, quite homogeneous compared to other renewable resources. The size of the United States adds to its resource, making it a prime opportunity for solar development.

While abundant, the wind resource of the United States is less homogeneous. Strong winds require steady gradients of temperature and pressure to drive and sustain them, and these are frequently associated with topological features such as mountain ranges or coastlines. The onshore wind map of the United States shows this pattern, with the best wind along a north-south corridor roughly at the mid-continent. Offshore winds over the Great Lakes and the east and west coasts are stronger and steadier though they cover smaller areas. The technical potential for onshore wind is over 8000 GW of capacity (Lu, 2009; Black & Veatch, 2007), and offshore is 800 – 3000 GW (Lu, 2009; Schwartz, Heimiller, Haymes, & Musial, 2010). For comparison, the United States used electricity in 2009 at the rate of 450 GW averaged over the day-night and summer-winter peaks and valleys.

Barriers to Deployment

Renewable energy faces several barriers to its widespread deployment. Cost is one of the most serious. Although renewables have declined significantly in recent years, most are still higher in cost than traditional fossil alternatives. Fossil energy technologies have a long experience in streamlining manufacturing, incorporating new materials, taking advantage of economies of scale, and understanding the energy conversion process's underlying physical and chemical phenomena. Natural gas and coal generate the lowest cost of electricity, with hydro and wind among the renewable challengers. Cost, however, is not an isolated metric; it must be compared with the alternatives. One of the uncertainties of the present business environment is the ultimate cost of carbon emissions. If governments put a price on carbon emissions to compensate for the social cost of global warming and the threat of climate change, the relative cost of renewables will become more appealing, even if their absolute cost does not change. This policy uncertainty in the eventual cost of carbon-based power generation is a major factor in the future economic appeal of renewable energy. A second barrier to the widespread deployment of renewable energy is public opinion. In the consumer market, sales directly sample public opinion, and the connection between deployment and public acceptance is immediate. Renewable energy is not a choice that individual consumers make. Instead, energy choices are made by city, state, and federal government policymakers, who balance concerns for the common good, for “fairness” to stakeholders, and for economic cost. Nevertheless, public acceptance is a major factor in balancing these concerns: a strongly favored or disfavored energy option will be reflected in government decisions through representatives elected by or responding to the public. The acceptance range goes from strongly positive for solar to strongly negative for nuclear. The disparity in the public acceptance and economic cost of these two energy alternatives is striking: solar is at once the most expensive alternative and the most acceptable to the public. The Fukushima nuclear disaster of 2011 illustrates public opinion’s importance. The earthquake and tsunami that ultimately caused a meltdown of fuel in several reactors of the Fukushima complex and the release of radiation in a populated area caused many of the public in many countries to question the safety of reactors and of the nuclear electricity enterprise generally. The response was rapid, with some countries registering public consensus for drastic action, such as shutting down nuclear electricity when the licenses for the presently operating reactors expire. Although its ultimate resolution is uncertain, the sudden and serious impact of the Fukushima event on public opinion shows the key role that social acceptance plays in determining our energy trajectory.

Combined Heat and Power as an Alternative Energy Source

Electricity in the United States is generated, for the most part, from central station power plants at a conversion efficiency of roughly 30 to 35 percent. Meaning for every 100 units of fuel energy in a simple cycle central station electric power plant, we get only 30 to 35 units of electricity. The remainder of the energy in the fuel is lost to the atmosphere in the form of heat.

The thermal requirements of our buildings and facilities are generally provided **on-site** through the use of a boiler or furnace. The efficiencies of this equipment have improved over the years. Having boilers and furnaces in commercial and industrial facilities with efficiencies of 80 percent and higher is common. Meaning for every 100 units of fuel energy in the boiler/furnace, we get about 80 units of useful thermal energy.

Commercial and industrial facilities that utilize the conventional energy system found in the United States (electricity supplied from the electric grid and thermal energy produced onsite through the use of a boiler/furnace) will oftentimes experience overall fuel efficiencies of between 40 to 55 percent (actual efficiency depends on the facilities heat to power ratio).

Combined Heat and Power (also known as CHP or "cogeneration") is an integrated system located at or near the building/facility that generates utility-grade electricity which satisfies at least a portion of the electrical load of the facility and captures and recycles the waste heat from the electric generating equipment to provide useful thermal energy to the facility.

CHP implies that heat and electricity are produced simultaneously in one process. The use of combined heat and power helps to improve the overall efficiency of electricity and heat production as these systems combine electricity production technologies with heat recovery equipment. Increasing the conversion efficiency of power generation through CHP helps reduce the environmental impact of power generation. These systems can reach fuel use efficiencies of as high as 75 to 85 percent (versus the conventional energy system at approximately 40 to 55 percent).

A well-designed, installed, and operated CHP system benefits the facility owner (end-user), the electric utility, and society. The high efficiency attained by the CHP system provides the end user with lower overall energy costs, improved electric reliability, improved electric power quality, and improved energy security. In areas where the electric utility distribution grid needs expansion and/or upgrades, CHP systems can provide the electric utility with a means of deferring costly modifications to the grid.

Although the electricity generated on-site by the end-user displaces the electricity purchased from the local electric utility and is seen as lost revenue by many utilities, energy efficiency and lower utility costs are in the best interest of the utility customer and should be considered a reasonable customer option by forward-looking customer oriented utilities. Finally, society, in general, benefits from the high efficiencies realized by CHP systems. The high efficiencies translate to fewer air pollutants (lower greenhouse gas and NOx emissions) than those produced from central station electric power plants.

Hydrogen and Electricity as Alternative Fuels

Since the early 20th Century, oil and the internal combustion engine have dominated transportation. The fortunes of oil and vehicles have been intertwined, with oil racing to meet the energy demands of the ever-growing power and number of personal vehicles, vehicles driving farther in response to growing interstate highway opportunities for long-distance personal travel and freight shipping, and greater personal mobility producing living patterns in far-flung suburbs that require oil and cars to function. In recent and future years, the greatest transportation growth will be in developing countries where the need and the transportation market are growing rapidly. China has an emerging middle class larger than the entire population of the United States, a sign that developing countries will soon direct or strongly influence the emergence of new technologies designed to serve their needs. Beyond deploying new technologies, developing countries have a potentially large second advantage: they need not follow the same development path through outdated intermediate technologies taken by the developed world. Leapfrogging directly to the most advanced technologies avoids legacy infrastructures and long turnover times, allowing innovation and deployment on an accelerated scale. The internal combustion engine and the vehicles it powers have made enormous engineering strides in the past half century, increasing efficiency, durability, and comfort and adding such now-standard features as air conditioning, cruise control, hands-free cell phone use, and global positioning systems. Simultaneously, the automobile industry has become global, dramatically increasing competition, consumer choice, and marketing reach. The most recent trend in transportation is dramatic swings in the price of oil, the lifeblood of traditional vehicles powered by internal combustion engines.

Hydrogen as an Alternative Fuel

The traditional synergy of oil with automobiles may now show signs of strain. The reliance of vehicles on one fuel whose price shows strong fluctuations and whose future course is ultimately unsustainable presents long-term business challenges. Motivated by these business and sustainability concerns, the automobile industry gradually diversified to other fuels. Hydrogen made its debut in the early 2000s and showed that it has the potential to power vehicles using fuel cells to produce on-board electricity for electric motors (Eberle and von Helmholt, 2010, Crabtree, Dresselhaus, & Buchanan, 2004). One advantage of hydrogen is efficiency, up to 50 percent or greater for fuel cells, and up to 90 percent or greater for electric motors powering the car, compared with 25 percent efficiency for an internal combustion engine. A second advantage is reduced dependence on foreign oil – hydrogen can be produced from natural gas or entirely renewable resources such as solar decomposition of water. A third potential advantage of hydrogen is environmental –the emissions from the hydrogen car are harmless: water and a small amount of heat, though the emissions from the hydrogen production chain may significantly offset this advantage. The vision of hydrogen cars powered by fuel cells remains strong. It must overcome significant challenges, however, before becoming practical, such as storing hydrogen on board vehicles at high densities, finding inexpensive and earth-abundant catalysts to promote the reduction of oxygen to water in fuel cells, and producing enough hydrogen from renewable sources such as solar-driven water splitting to fuel the automobile industry (Crabtree & Dresselhaus, 2008). The hydrogen and electric energy chains for automobiles are illustrated in Figure 1. Many scientists and automobile companies are exploring hydrogen as a long-term alternative to oil.

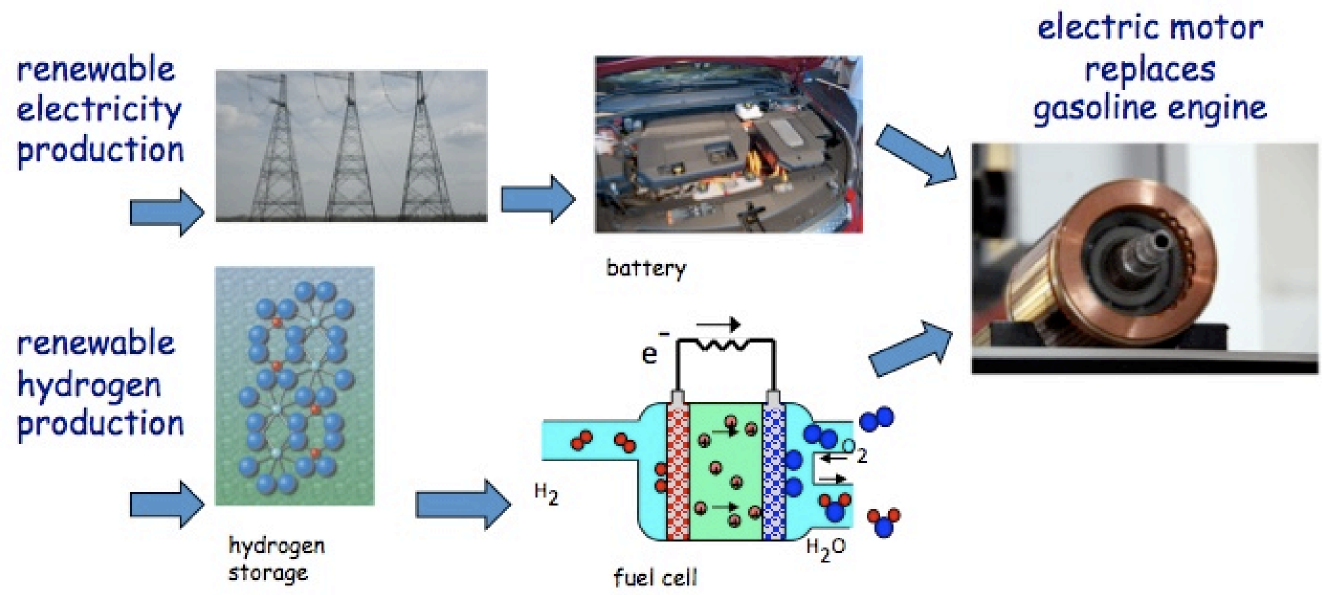

Figure 1. Electric Transportation: Transportation is electrified by replacing the gasoline engine with an electric motor, powered by electricity from a battery on board the car (upper panel) or electricity from a fuel cell and hydrogen storage system on board the car (lower panel). For maximum effectiveness, both routes require renewable production of electricity or hydrogen. Source: George Crabtree using images from Rondol, skinnylawyer, Tinu Bao, U.S. Department of Energy Office of Science

Electricity as an Alternative Fuel

Electric cars represent a second alternative to oil for transportation, with many similarities to hydrogen (see Figure Electric Transportation). Electric vehicles are run by an electric motor, as in a fuel cell car, up to four times as efficient as a gasoline engine. The electric motor is far simpler than a gasoline engine, having only one moving part, a shaft rotating inside a stationary housing and surrounded by a coil of copper wire. Electricity comes from a battery, whose storage capacity, like that of hydrogen materials, is too small to enable long-distance driving. Developing higher energy-density vehicle batteries is a major challenge for the electric car industry. The battery must be charged before driving, which can be done from the grid using excess capacity available at night, or during the day from special solar charging stations that do not add additional load to the grid. Because charging typically takes hours, a potentially attractive alternative is switching the battery out in minutes for a freshly charged one at special swapping stations. A large fleet of electric cars in the United States would require significant additional electricity, as much as 130 GW, if the entire passenger and light truck fleet were converted to electricity, or 30 percent of average United States electricity usage in 2008. The energy usage of electric cars is about a factor of four less than for gasoline cars, consistent with the higher efficiency of electric motors over internal combustion engines. Although gasoline cars vary significantly in energy efficiency, a “typical” middle-of-the-road value for a five-passenger car is 80kWh/100km. A typical electric car (such as the Think Ox from Norway, the Chevy Volt operating in its electric mode, or the Nissan Leaf) uses ~ 20kWh/100km. While the energy cost of electric cars at the point of use is significantly less, one must consider the cost at the point of production, the electricity generating plant. If the vehicle’s electricity comes from coal with a conversion efficiency of 33 percent, the primary energy cost is 60 kWh/100km, approaching but still smaller than the gasoline car. If combined cycle natural gas turbines generate electricity with 60 percent efficiency, the primary energy cost is 33 kWh/100km, less than half the primary energy cost for gasoline cars. These comparisons are presented in the Table below.

Comparison of energy use for gasoline-driven and battery-driven cars, for the cases of inefficient coal generation (33%) and efficient combined cycle natural gas generation (60%) of electricity. Source: George Crabtree.

	Gasoline Engine 5 passenger car	Battery Electric Nissan Leaf, Chevy Volt (battery mode), Think Ox
Energy use at point of use	80 kWh/100km	20 kWh/100km
Energy use at point of production: Coal at 33% efficiency		60 kWh/100km
Combined Cycle Natural Gas at 60% efficiency		33 kWh/100km

Comparison of carbon emissions from gasoline-driven and battery-driven cars, for the cases of high-emission coal generation (2.1 lb CO2/ kWh), lower-emission natural gas (1.3 lbCO2/kWh) and very low-emission nuclear, hydro, wind, or solar electricity.Source: George Crabtree.

	Gasoline Engine 5 passenger car	**Battery Electric Nissan Leaf, Chevy Volt (battery mode), Think Ox**
CO2 Emissions at point of use	41 lbs	~ 0
CO2 Emissions at point of production Coal@2.1 lb CO2/ kWh		42 lbs
Gas@1.3 lb CO2/ kWh		25 lbs
Nuclear, hydro, wind or solar		< 1 lb

The carbon footprint of electric cars requires a similar calculation. For coal-fired electricity producing 2.1 lb CO /kWh, driving 100km produces 42 lbs (19 kgs) of carbon dioxide; for gasfired electricity producing 1.3 lb CO /kWh, 100km of driving produces 26 lbs (11.7 kgs) of carbon dioxide. If electricity is produced by nuclear or renewable energy such as wind, solar or hydroelectric, no carbon dioxide is produced. For a "typical" gasoline car, 100km of driving produces 41 lbs (18.5 kgs) of carbon dioxide. Thus the carbon footprint of a "typical" electric car is, at worst equal, to that of a gasoline car and, at best, zero. Table Comparisons of Carbon Emissions summarizes the carbon footprint comparisons.

The Hybrid Solutions

Unlike electric cars, hybrid vehicles rely only on gasoline for their power. Hybrids do, however, have a supplemental electric motor and drive system that operates only when the gasoline engine performance is weak or needs a boost: on starting from a stop, passing, or climbing hills. Conventional gasoline cars have only a single engine that must propel the car under all conditions; it must, therefore, be sized to the largest task. Under normal driving conditions, the engine is larger and less efficient than it needs to be. The hybrid solves this dilemma by providing two drive trains, a gasoline engine for normal driving, and an electric motor for high power needs when starting, climbing hills, and passing. The engine and motor are tailored to their respective tasks, enabling each to be designed for maximum efficiency. As the electric motor is overall much more efficient, its use can raise fuel economy significantly.

The battery in hybrid cars has two functions: it drives the electric motor and also collects electrical energy from regenerative braking, converted from kinetic energy at the wheels by mall generators. Regenerative braking is effective in start-stop driving, increasing efficiency by up to 20 percent. Unlike

gasoline engines, electric motors use no energy while standing still; hybrids, therefore, shut off the gasoline engine when the car comes to a stop to save the idling energy. Gasoline engines are notoriously inefficient at low speeds (hence the need for low gear ratios), so the electric motor accelerates the hybrid to ~15 mph (24 kph) before the gasoline engine restarts. Shutting the gasoline engine off while stopped increases efficiency by as much as 17 percent. The energy-saving features of hybrids typically lower their energy requirements from 80 kWh/100km to 50-60 kWh/100km, a significant savings. However, it is important to note that despite a supplementary electric motor drive
system, all of a hybrid's energy comes from gasoline and none from the electricity grid.

The **plug-in hybrid** differs from conventional hybrids in tapping both gasoline and the electricity grid for its energy. Most plug-in hybrids are designed to run on electricity first and on gasoline second; the gasoline engine kicks in only when the battery runs out. The plugin hybrid is thus an electric car with a supplemental gasoline engine, the opposite of the conventional hybrid cars described above. The value of the plug-in hybrid is that it solves the "driving range anxiety" of the consumer: there are no worries about getting home safely from a trip that turns out to be longer than expected. The disadvantage of the plug-in hybrid is the additional supplemental gasoline engine technology, which adds cost and complexity to the automobile.

The Battery Challenge

To achieve reasonable driving range, electric cars and plug-in hybrids need large batteries, one of their greatest design challenges and a potentially significant consumer barrier to widespread sales. Even with the largest practical batteries, the driving range on electricity is limited, perhaps to ~100km. Designing higher energy density batteries is currently a major focus of energy research, with advances in Li-ion battery technology expected to bring significant improvements. The second potential barrier to public acceptance of electric vehicles is charging time, up to eight hours, from a standard household outlet. This may suit overnight charging at home but could be a problem for trips beyond the battery's range with a gasoline car; the driver fills up in a few minutes and is on his way. Novel infrastructure solutions, such as battery-swapping stations for long trips, are under consideration.

Comparing gasoline, electric, hybrid, and plug-in hybrid cars is interesting from a sustainability perspective. Hybrid cars take all their energy from gasoline, representing the least difference from gasoline cars. Their supplementary electric drive systems reduce gasoline usage by 30-40 percent, thus promoting the conservation of a finite resource and reducing reliance on foreign oil. Electric cars, however, get all of their energy from grid electricity, a domestic energy source, completely eliminating reliance on foreign oil and the use of finite oil resources. Their sustainability value is, therefore, higher than hybrids. Plug-in hybrids have the same potential as all-electric vehicles, provided their gasoline engines are used sparingly. Regarding carbon emissions, the sustainability value of electric vehicles depends entirely on the electricity source: neutral for coal, positive for gas, and highly positive for nuclear or renewable hydro, wind, or solar. From an energy perspective, electric cars use a factor of four less energy than gasoline cars at the point of use. Still, this advantage is partially compromised by inefficiencies at the point of electricity generation. Even inefficient coal-fired electricity leaves an advantage for electric cars, and efficient gas-fired combined cycle electricity leaves electric cars more than a factor of two more energy efficient than gasoline cars.

Electricity Grid and Sustainability Challenges

Over the past century and a half, **electricity** has emerged as a popular and versatile energy carrier.

Today, electricity is exploited not only for its diverse end uses, such as lighting, motion, refrigeration, communication, and computation but also as a primary energy carrier. Electricity is one of two backbones of the modern energy system (liquid transportation fuels are the other), carrying high-density energy over short and long
distances for diverse uses. In 2009, electricity consumed the largest share of the United States' primary energy, 38 percent, with transportation a close second at 37 percent. These two sectors also accounted for the largest shares of U.S. carbon emissions, 38 percent for electricity and 33 percent for transportation.

By far, most electricity is generated by the combustion of fossil fuels to turn steam or gas turbines. This is the least efficient step in the energy chain, converting only 36 percent of the chemical energy in the fuel to electric energy when averaged over the present gas and coal generation mix. It also produces all the carbon emissions of the electricity chain. Beyond production, electricity is a remarkably clean and efficient carrier. Conversion from the rotary motion of the turbine and generator to electricity, the delivery of electricity through the power grid, and the conversion to motion in motors for use in industry, transportation, and refrigeration can be more than 90 percent efficient. None of these steps produces greenhouse gas emissions. Electricity's post-production versatility, cleanliness, and efficiency make it a prime energy carrier for the future. Based on relatively plentiful domestic coal and gas, electricity generation is free of immediate fuel security concerns. The advent of electric cars promises to increase electricity demand and reduce dependency on foreign oil, while the growth of renewable wind and solar generation reduces carbon emissions. The primary sustainability challenges for electricity as an energy carrier are at the
production step: efficiency and emission of carbon dioxide and toxins.

The Electricity Grid: Capacity and Reliability

Beyond production, electricity faces challenges of capacity, reliability, and implementing storage and transmission required to accommodate the remoteness and variability of renewables. The largest capacity challenges are in urban areas, where 79 percent of the United States and 50 percent of the world population live. The high population density of urban areas requires a correspondingly high energy and electric power density. In the United States, 33 percent of electric power is used in the top 22 metro areas, and electricity demand is projected to grow 31 percent by 2035. This creates an "urban power bottleneck" where underground cables become saturated, hampering economic growth and the efficiencies of scale in transportation, energy use, and greenhouse gas emission that come with high population density. Saturation of existing cable infrastructure requires the installation of substantial new capacity, an expensive proposition for digging new underground cable tunnels.

The **reliability** of the electricity grid presents a second challenge. The United States' grid has grown continuously from its origins in the early 20th Century; much of its infrastructure is based on technology and design philosophy dating from the 1950s and 1960s when the major challenge was extending electrification to new rural and urban areas. Outside urban areas, the grid is mainly above ground, exposing it to weather and temperature extremes that cause most power outages. The response to outages is frustratingly slow and traditional– utilities are often first alerted to outages by telephoned customer complaints, and response requires sending crews to identify and repair the damage, much the same as we did 50 years ago. The United States' grid reliability is significantly lower than for newer grids in Europe and Japan, where the typical customer experiences ten to 20 times less outage time than in the United States. Reliability is especially important in the digital age when an interruption of even a fraction of a cycle can shut down a digitally controlled data center or fabrication line, requiring hours or days to restart.

Reliability issues can be addressed by implementing a **smart grid** with two-way communication between utility companies and customers that continuously monitors power delivery and the operational state of the delivery system and implements demand response measures adjusting the power delivered to individual customers in accordance with a previously established unique customer protocol. Such a system requires installing digital sensors that monitor power flows in the delivery system, digital decision and control technology, and digital communication capability like that already standard for communication via the Internet. For customers with on-site solar generation capability, the smart grid would monitor and control the selling of excess power from the customer to the utility.

Integrating Renewable Electricity on the Grid

Accommodating renewable electricity generation by wind and solar plants is among the grid's most urgent challenges. Leadership in promoting renewable electricity has moved from the federal to the state governments, many of which have legislated Renewable Portfolio Standards (RPS) that require 20 percent of state electricity generation to be renewable by 2020. Thirty states and the District of Columbia have such requirements, the most aggressive being California, with 33 percent renewable electricity required by 2020, and New York, with 30 percent by 2015. To put this legal requirement in perspective, wind and solar now account for about 1.6 percent of U.S. electricity production, approximately a factor of ten short of the RPS requirements. (Crabtree & Misewich, 2010).

Renewable Variability

The grid faces major challenges in accommodating the variability of wind and solar electricity. Without significant storage capacity, the grid must precisely balance generation to demand in real-time. The variability of demand controls the balancing process: demand varies by as much as a factor of two from night to day as people go through their daily routines. This predictable variability is accommodated by switching reserve generation sources in and out in response to demand variations. With **renewable generation**, variation can be up to 70 percent for solar electricity due to passing clouds and 100 percent for wind due to calm days, much larger than the variability of demand. At the present level of 1.6 percent wind and solar penetration, the relatively small variation in generation can be accommodated by switching in and out conventional resources to make up for wind and solar fluctuations. At the 20 percent penetration required by state Renewable Portfolio Standards, accommodating the variation in generation requires a significant increase in the conventional reserve capacity. At high penetration levels, each addition of wind or solar capacity requires a nearly equal addition of conventional capacity to provide generation when the renewables are quiescent. This double installation to ensure reliability increases the cost of renewable electricity and reduces its effectiveness in lowering greenhouse gas emissions.

A major complication of renewable variation is its unpredictability. Unlike demand variability, which is reliably high in the afternoon and low at night, renewable generation depends on weather and does not follow any pattern. Anticipating weather-driven wind and solar generation variability requires more sophisticated forecasts with higher accuracy and greater confidence levels than are now available. Because today's forecasts often miss the actual performance target, additional conventional reserves must be held ready to cover the risk of inaccuracies, adding another increase to the cost of renewable electricity. Storage of renewable electricity offers a viable route to meeting the variable generation challenge.

How to Transmit Electricity Over Long Distances

The final challenge for accommodating renewables is the long-distance transmission. Although long-distance delivery is possible where special high-voltage transmission lines have been located, the capacity and number of such lines are limited. The situation resembles automobile transportation before the interstate highway system was built in the 1950s. It was possible to drive coast to coast, but the driving time was long and uncertain, and the route was indirect. To use renewable electricity resources effectively, we must create a kind of interstate highway system for electricity.

Summary

We derive our energy from many resources with varying environmental challenges related to air and water pollution, land use, carbon dioxide emissions, resource extraction, supply, and related safety and health issues. Each resource needs to be evaluated within the sustainability paradigm. Coal (45 percent) and gas (23 percent) are the two primary fossil fuels for electricity production in the United States. Coal combustion produces nearly twice the carbon emissions of gas combustion. Increasing public opinion and regulatory pressure to lower carbon emissions are shifting electricity generation toward gas and away from coal. Oil for transportation and electricity generation are the two biggest primary energy users and producers of carbon emissions in the United States. Transportation almost completely depends on oil and internal combustion engines for its energy. Oil concentration in a few world regions creates a transportation energy security issue. Nuclear electricity offers the sustainable benefit of low-carbon electricity at the cost of storing spent fuel out of the environment for hundreds of thousands of years. Reprocessing spent fuel offered the advantages of higher energy efficiency and reduced spent fuel storage requirements with the disadvantage of a higher risk of weapons proliferation through the diversion of the reprocessed fuel stream.

Strong interest in renewable energy arose in the 1970s as a response to the shortage and high price of imported oil, which disrupted the orderly operation of the economies and societies of many developed countries. Today there are new motivations, including the realization that growing greenhouse gas emission accelerates global warming and threatens climate change, the growing dependence of many countries on foreign oil, and the economic drain of foreign oil payments that slow economic growth and job creation. There are three ultimate sources of all renewable and fossil energies: sunlight, the heat in the earth's core and crust, and the gravitational pull of the moon and sun on the oceans. Renewable energies are relatively recently developed and typically operate at lower efficiencies than mature fossil technologies. Like early fossil technologies, however, renewables can be expected to improve their efficiency and lower their cost over time, promoting their economic competitiveness and widespread deployment. The future deployment of renewable energies depends on many factors, including the availability of suitable land, the technological cost of conversion to electricity or other uses, the costs of competing energy technologies, and the future need for energy.

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Chapter Attribution:

Chapter 12: Solid and Hazardous Waste

A young boy recycling garbage in Saigon.

Learning Outcomes

After studying this chapter, you should be able to:

- Understand the environmental concerns with the growing quantities and improper management of wastes being generated
- Recognize various environmental regulations governing the management of solid and hazardous wastes
- Recognize integrated waste management strategies

Chapter Outline

- 12.1 Environmental Concerns with Wastes
- 12.2 Waste Management Strategies
- 12.3 Waste Policies
- 12.4 Case Study: Electronic Waste and Extended Producer Responsibility
- 12.5 Chapter 15 Resources

Managing Growing Waste Generation

An enormous quantity of waste is generated and disposed of annually. Alarmingly, this quantity continues to increase on an annual basis. Industries generate and dispose of over 7.6 billion tons of industrial solid wastes each year, and it is estimated that over 40 million tons of this waste is hazardous. Nuclear wastes, as well as medical wastes, are also increasing in quantity every year.

Generally speaking, developed nations generate more waste than developing nations due to higher consumption rates. Not surprisingly, the United States generates more waste per capita than any other country. High waste per capita rates are also very common throughout Europe and developed nations in Asia and Oceania. In the United States, about 243 million tons (243 trillion kg) of MSW is generated annually, equal to about 4.3 pounds (1.95 kg) of waste per person per day. Nearly 34 percent of MSW is recovered and recycled or composted, approximately 12 percent is burned in combustion facilities, and the remaining 54 percent is disposed of in landfills. Waste stream percentages also vary widely by region. For example, San Francisco, California, captures and recycles nearly 75 percent of its waste material, whereas Houston, Texas, recycles less than three percent.

Concerning waste mitigation options, landfilling is quickly evolving into a less desirable or feasible option. Landfill capacity in the United States has been declining primarily due to (a) older existing landfills that are increasingly reaching their authorized capacity, (b) the promulgation of stricter environmental regulations has made the permitting and siting of new landfills increasingly difficult, (c) public opposition (e.g., “Not In My Backyard” or **NIMBY**ism) delays or, in many cases, prevent the approval of new landfills or expansion of existing facilities.

Effects of Improper Waste Disposal and Unauthorized Releases

Before the passage of environmental regulations, wastes were disposed of improperly without considering the potential effects on public health and the environment. This practice has led to numerous contaminated sites where soils and groundwater have been contaminated and pose a risk to public safety. Of more than 36,000 environmentally impacted candidate sites, more than 1,400 sites are listed under the Superfund program National Priority List (NPL) that require immediate cleanup resulting from acute, imminent threats to environmental and human health. The USEPA identified about 2,500 additional contaminated sites that eventually require remediation. The United States Department of Defense maintains 19,000 sites, many of which have been extensively contaminated from various uses and disposal practices. Further, approximately 400,000 underground storage tanks have been confirmed or are suspected of leaking, contaminating underlying soils and groundwater. Over $10 billion (more than $25 billion in current dollars) were specifically allocated by CERCLA and subsequent amendments to mitigate impacted sites. However, the USEPA has estimated that the value of environmental remediation exceeds $100 billion. Alarmingly, if past expenditures on NPL sites are extrapolated across remaining and proposed NPL sites, this total may be significantly higher – well into the trillions of dollars.

It is estimated that more than 4,700 facilities in the United States currently treat, store, or dispose of hazardous wastes. About 3,700 facilities that house approximately 64,000 solid waste management units (SWMUs) may require corrective action. Accidental spillage of hazardous wastes and nuclear materials due to anthropogenic operations or natural disasters has also caused enormous environmental damage, as evidenced by the events such as the facility failure in Chornobyl, Ukraine (formerly USSR) in 1986, the effects of Hurricane Katrina that devastated New Orleans, Louisiana in 2005, and the 2011 Tōhoku earthquake and tsunami in Fukushima, Japan.

Adverse Impacts on Public Health

Various chemicals are present within waste materials, many of which pose a significant environmental concern. Though the **leachate** generated from the wastes may contain toxic chemicals, the concentrations and variety of toxic chemicals are quite small compared to hazardous waste sites. For example, explosives and radioactive wastes are primarily located at Department of Energy (DOE) sites because many facilities have historically been used for weapons research, fabrication, testing, and training. Organic contaminants are largely found at oil refineries or petroleum storage sites, and inorganic and pesticide contamination usually results from various industrial and agricultural activities. Yet, soil and groundwater contamination is not the only direct adverse effect of improper waste management activities – recent studies have also shown that greenhouse gas emissions from the wastes are significant, exacerbating global climate change.

A wide range of toxic chemicals, with an equally wide distribution of respective concentrations, is found in waste streams. These compounds may be present in concentrations that alone may threaten human health or have a synergistic/cumulative effect due to the presence of other compounds. Exposure to hazardous wastes has been linked to many types of cancer, chronic illnesses, and abnormal reproductive outcomes such as birth defects, low birth weights, and spontaneous abortions. Many studies have been performed on major toxic chemicals found at hazardous waste sites incorporating epidemiological or animal tests to determine their toxic effects.

As an example, the effects of radioactive materials are classified as **somatic** or **genetic**. The somatic effects may be immediate or occur over a long period of time. Immediate effects from large radiation doses often produce nausea and vomiting and may be followed by severe blood changes, hemorrhage, infection, and death. Delayed effects include leukemia and many types of cancer, including bone, lung, and breast. Genetic effects have been observed in which gene mutations or chromosome abnormalities result in measurable harmful effects, such as decreased life expectancy, increased susceptibility to sickness or disease, infertility, or even death during embryonic stages. Because of these studies, occupational dosage limits have been recommended by the National Council on Radiation Protection. Similar studies have been completed for a wide range of potentially hazardous materials. These studies have, in turn, been used to determine safe exposure levels for numerous exposure scenarios, including those that consider occupational safety and remediation standards for various land use scenarios, including residential, commercial, and industrial land uses.

Adverse Impacts on the Environment

The chemicals found in waste pose a threat to human health and have profound effects on entire ecosystems. Contaminants may change the chemistry of waters and destroy aquatic life and underwater ecosystems dependent upon more complex species. Contaminants may also enter the food chain through plants or microbiological organisms, and higher, more evolved organisms bioaccumulate the wastes through subsequent ingestion. The continued bioaccumulation results in increased contaminant mass and concentration as the contaminants move farther up the food chain. In many cases, toxic concentrations are reached, resulting in increased mortality of one or more species. As the populations of these species decrease, the natural inter-species balance is affected. With decreased numbers of predators or food sources, other species may be drastically affected, leading to a chain reaction that can affect a wide range of flora and fauna within a specific ecosystem. As the ecosystem continues to deviate from equilibrium, disastrous consequences may occur. Examples include the near extinction of the bald eagle due to persistent ingestion of DDT-impacted fish and the depletion of oysters, crabs, and fish in the Chesapeake Bay due to excessive quantities of fertilizers, toxic chemicals, farm manure wastes, and power plant emissions.

The long-recognized hierarchy of management of wastes, in order of preference, consists of prevention, minimization, recycling and **reuse, biological treatment**, incineration, and landfill disposal (see Figure 1 below).

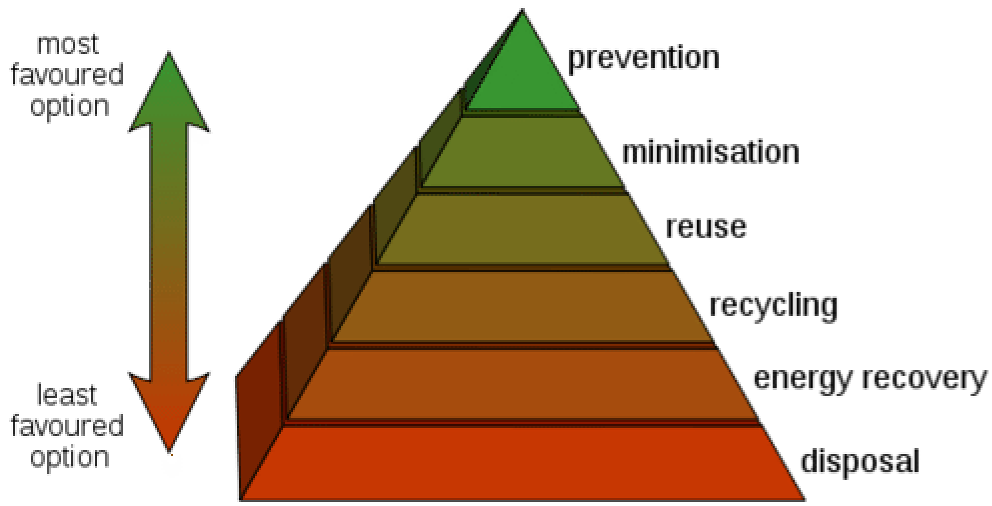


Figure 1. Hierarchy of Waste Management figure shows the hierarchy of management of wastes in order or preference, starting with prevention as the most favorable to disposal as the least favorable option. Source: Drstuey via Wikimedia Commons

Waste Prevention

The ideal waste management alternative is to prevent waste generation in the first place. Hence, **waste prevention** is a basic goal of all waste management strategies. Numerous technologies can be employed throughout the manufacturing, use, or post-use portions of product life cycles to eliminate waste and, in turn, reduce or **prevent pollution**. Some representative strategies include environmentally conscious manufacturing methods that incorporate less hazardous or harmful materials, the use of modern leakage detection systems for material storage, innovative chemical neutralization techniques to reduce reactivity or water-saving technologies that reduce the need for freshwater inputs.

Waste Minimization

In many cases, wastes cannot be outright eliminated from a variety of processes. However, numerous strategies can be implemented to reduce or minimize waste generation. **Waste minimization**, or source reduction, refers to the collective strategies of design and fabrication of products or services that minimize the amount of generated waste and/or reduce the toxicity of the resultant waste. Often these efforts come about from identified trends or specific products that may be causing problems in the waste stream and the subsequent steps taken to halt these problems. In industry, waste can be reduced by reusing materials, using less hazardous substitute materials, or modifying components of design and processing. Many benefits can be realized by waste minimization or source reduction, including reduced use of natural resources and the reduction of toxicity of wastes.

Waste minimization strategies are extremely common in manufacturing applications; the savings of material use preserves resources but also saves significant manufacturing-related costs. Advancements in streamlined packaging reduce material use, and increased distribution efficiency reduces fuel consumption and resulting air emissions. Further, engineered building materials can often be designed with specific favorable properties that, when accounted for in an overall structural design, can greatly reduce the overall mass and weight of material needed for a given structure. This reduces the need for excess material and reduces the waste associated with component fabrication.

The dry cleaning industry provides an excellent example of product substitution to reduce toxic waste generation. For decades, dry cleaners used tetrachloroethylene, or “perc” as a dry cleaning solvent. Although effective, tetrachloroethylene is a relatively toxic compound. Additionally, it is easily introduced into the environment, where it is highly recalcitrant due to its physical properties. Further, when its degradation occurs, the intermediate daughter products generated are more toxic to human health and the environment.

Because of its toxicity and impact on the environment, the dry cleaning industry has adopted new practices and increasingly utilizes less toxic replacement products, including petroleum-based compounds. Further, new emerging technologies are incorporating carbon dioxide and other relatively harmless compounds. While these substitute products have in many cases been mandated by government regulation, they have also been adopted in response to consumer demands and other market-based forces.

Recycling and Reuse

Recycling refers to the recovery of useful materials such as glass, paper, plastics, wood, and metals from the waste stream so they may be incorporated into the fabrication of new products. With the greater incorporation of recycled materials, the required use of raw materials for identical applications is reduced. Recycling reduces the need for natural resource exploitation for raw materials, but it also allows waste materials to be recovered and utilized as valuable resource materials. Recycling of wastes directly conserves natural resources, reduces energy consumption and emissions generated by the extraction of virgin materials and their subsequent manufacture into finished products, reduces overall energy consumption and greenhouse gas emissions that contribute to global climate change, and reduces the incineration or landfilling of the materials that have been recycled. Moreover, recycling creates several economic benefits, including the potential to create job markets and drive growth.

Commonly recycled materials include paper, plastics, glass, aluminum, steel, and wood. Additionally, many construction materials can be reused, including concrete, asphalt materials, masonry, and reinforcing steel. “Green” plant-based wastes are often recovered and immediately reused for mulch or fertilizer applications. Many industries also recover various by-products and/or refine and “re-generate” solvents for reuse. Examples include copper and nickel recovery from metal finishing processes; the recovery of oils, fats, and plasticizers by solvent extraction from filter media such as activated carbon and clays; and acid recovery by spray roasting, ion exchange, or crystallization. Further, a range of used food-based oils are being recovered and utilized in “biodiesel” applications.

Numerous examples of successful recycling and reuse efforts are encountered every day. In some cases, recycled materials are used as input materials and are heavily processed into end products. Common examples include the use of scrap paper for new paper manufacturing or the processing of old aluminum cans into new aluminum products. In other cases, reclaimed materials undergo little or no processing prior to their re-use.

Some common examples include the use of tree waste as wood chips or the use of brick and other fixtures in new structural construction. In any case, the success of recycling depends on the effective collection and processing of recyclables, markets for reuse (e.g. manufacturing and/or applications that utilize recycled materials), and public acceptance and promotion of recycled products and applications utilizing recycled materials.

Biological Treatment

Landfill disposal of wastes containing significant organic fractions is increasingly discouraged in many countries, including the United States. Such disposal practices are even prohibited in several European countries. Since landfilling does not provide an attractive management option, other techniques have been identified. One option is to treat waste so that biodegradable materials are degraded and the remaining inorganic waste fraction (known as residuals) can be subsequently disposed of or used for a beneficial purpose.

Biodegradation of wastes can be accomplished by using **aerobic** composting, a**naerobic digestion**, or **mechanical biological treatment** (MBT) methods. If the organic fraction can be separated from inorganic material, aerobic composting or anaerobic digestion can be used to degrade the waste and convert it into usable **compost**. For example, organic wastes such as food waste, yard waste, and animal manure that consist of naturally degrading bacteria can be converted under controlled conditions into compost, which can then be utilized as a natural fertilizer. Aerobic composting is accomplished by placing selected proportions of organic waste into piles, rows, or vessels, either in open conditions or within closed buildings fitted with gas collection and treatment systems. During the process, bulking agents such as wood chips are added to the waste material to enhance the aerobic degradation of organic materials. Finally, the material is allowed to stabilize and mature during a curing process where pathogens are concurrently destroyed. The end products of the composting process include carbon dioxide, water, and usable compost material.

Compost material may be used in a variety of applications. In addition to its use as a soil amendment for plant cultivation, compost can be used remediate soils, groundwater, and stormwater. Composting can be labor-intensive, and the quality of the compost is heavily dependent on proper control of the composting process. Inadequate control of the operating conditions can result in compost that is unsuitable for beneficial applications. Nevertheless, composting is becoming increasingly popular; composting diverted 82 million tons of waste material away from the landfill waste stream in 2009, increasing from 15 million tons in 1980. This diversion also prevented the release of approximately 178 million metric tons of carbon dioxide in 2009 – an amount equivalent to the yearly carbon dioxide emissions of 33 million automobiles.

In some cases, aerobic processes are not feasible. As an alternative, anaerobic processes may be utilized. Anaerobic digestion consists of degrading mixed or sorted organic wastes in vessels under anaerobic conditions. The anaerobic degradation process produces a combination of methane and carbon dioxide (biogas) and residuals (biosolids). Biogas can be used for heating and electricity production, while residuals can be used as fertilizers and soil amendments. Anaerobic digestion is a preferred degradation for wet wastes as compared to the preference of composting for dry wastes. The advantage of anaerobic digestion is biogas collection; this collection and subsequent beneficial utilization make it a preferred alternative to landfill disposal of wastes. Also, waste is degraded faster through anaerobic digestion as compared to landfill disposal.

Another waste treatment alternative, mechanical biological treatment (MBT), is not common in the United States. However, this alternative is widely used in Europe. During the implementation of this method, waste material is subjected to a combination of mechanical and biological operations that reduce volume through the degradation of organic fractions in the waste. Mechanical operations such as sorting, shredding, and crushing prepare the waste for subsequent biological treatment, consisting of either aerobic composting or anaerobic digestion. Following the biological processes, the reduced waste mass may be subjected to incineration.

Incineration

Waste degradation not only produces useful solid end-products (such as compost), but degradation by-products can also be used as a beneficial energy source. As discussed above, anaerobic digestion of waste can generate biogas, which can be captured and incorporated into electricity generation. Alternatively, waste can be directly incinerated to produce energy. Incineration consists of waste combustion at very high temperatures to produce electrical energy. The byproduct of incineration is ash, which requires proper characterization prior to disposal, or in some cases, beneficial re-use. It is widely used in developed countries due to landfill space limitations. It is estimated that about 130 million tons of waste are annually combusted in more than 600 plants in 35 countries. Further, incineration is often used to effectively mitigate hazardous wastes such as chlorinated hydrocarbons, oils, solvents, medical wastes, and pesticides.

Pros of Incinerators	**Cons of Incinerators**
The incinerated waste is turned into energy	The fly ash (airborne particles) has high levels of toxic chemicals, including dioxin, cadmium, and lead.
The volume of waste is reduced.	The initial construction costs are high.

Despite the advantages, incineration is often viewed negatively because of high initial construction costs, and emissions of ash, which is toxic (see Table above). Currently, many ‘next generation” systems are being researched and developed, and the USEPA is developing new regulations to carefully monitor incinerator air emissions under the Clean Air Act.

Landfill Disposal

Despite advances in reuse and recycling, landfill disposal remains the primary waste disposal method in the United States. As previously mentioned, the rate of MSW generation continues to increase, but overall landfill capacity is decreasing. New regulations concerning proper waste disposal and the use of innovative liner systems to minimize thepotential of groundwater contamination from leachate infiltration and migration have resulted in a substantial increase in the costs of landfill disposal. Also, public opposition to landfills continues to grow, partially inspired by memories of historic uncontrolled dumping practices and the resulting undesirable side effects of uncontrolled vectors, contaminated groundwater, unmitigated odors, and subsequent diminished property values.

Landfills can be designed and permitted to accept hazardous wastes in accordance with RCRA Subtitle C regulations, or they may be designed and permitted to accept municipal solid waste in accordance with RCRA Subtitle D regulations. Regardless of their waste designation, landfills are engineered structures consisting of bottom and side liner systems, leachate collection and removal systems, final cover systems, gas collection and removal systems, and groundwater monitoring systems. An extensive permitting process is required for siting, designing, and operating landfills. Post-closure monitoring of landfills is also typically required for at least 30 years. Because of their design, wastes within landfills are degraded anaerobically. During degradation, biogas is produced and collected. The collection systems prevent uncontrolled subsurface gas migration and reduce the potential for explosive conditions. The captured gas is often used in cogeneration facilities for heating or electricity generation. Further, upon closure, many landfills undergo “land recycling” and are redeveloped as golf courses, recreational parks, and other beneficial uses. Wastes commonly exist in dry conditions within landfills, and as a result, the rate of waste degradation is commonly very slow. These slow degradation rates are coupled with slow rates of degradation-induced settlement, which can in turn complicate or reduce the potential for beneficial land re-use at the surface. Recently, the concept of bioreactor landfills has emerged, which involves the recirculation of leachate and/or injection of selected liquids to increase the moisture in the waste, which in turn induces rapid degradation. The increased rates of degradation increase the rate of biogas production, which increases the potential of beneficial energy production from biogas capture and utilization.

Regulatory Framework in the United States

During the course of the 20th century, especially following World War II, the United States experienced unprecedented economic growth. Much of the growth was fueled by rapid and increasingly complex industrialization. With advances in manufacturing and chemical applications also came increases in the volume and, in many cases, the toxicity of generated wastes. Furthermore, few, if any, controls or regulations were in place concerning the handling of toxic materials or the disposal of waste products. The continued industrial activity led to several high-profile examples of detrimental environmental consequences resulting from these uncontrolled activities. Finally, several forms of intervention, both in the form of government regulation and citizen action, occurred in the early 1970s. Ultimately, several regulations were promulgated on the state and federal levels to ensure the safety of public health and the environment. For waste materials, the Resource Conservation and Recovery Act (RCRA), enacted by the United States Congress in 1976 and amended in 1984, provides a comprehensive framework for properly managing hazardous and non-hazardous solid wastes in the United States. RCRA stipulates broad and general legal objectives while mandating the United States Environmental Protection Agency (USEPA) to develop specific regulations to implement and enforce the law. States and local governments can either adopt the federal regulations or they may develop and enforce more stringent regulations than those specified in RCRA. Similar regulations have been developed or are being developed worldwide to manage waste similarly in other countries.

The broad goals of RCRA include (1) the protection of public health and the environment from the hazards of waste disposal; (2) the conservation of energy and natural resources; (3) the reduction or elimination of waste; and (4) the assurance that wastes are managed in an environmentally-sound manner (e.g., the remediation of waste which may have spilled, leaked, or been improperly disposed of). It should be noted here that the RCRA focuses only on active and future facilities and does not address abandoned or historical sites. These types of environmentally impacted sites are managed under a different regulatory framework, known as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, more commonly known as “Superfund.”

Solid Waste Regulations

RCRA defines solid waste as any garbage or refuse, sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semi-solid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities. In general, solid waste can be categorized as either **non-hazardous waste** or **hazardous waste**.

Non-hazardous solid waste can be trash or garbage generated from residential households, offices, and other sources. Generally, these materials are classified as **municipal solid waste** (MSW). Alternatively, industrial solid waste is collectively known as non-hazardous materials that result from producing goods and products by various industries (e.g., coal combustion residues, mining wastes, cement kiln dust). Because they are classified as non-hazardous materials, many municipal solid and industrial waste components have potential for recycling and reuse. Significant efforts are underway by both government agencies and industry to advance these objectives.

Hazardous waste generated by many industries and businesses (e.g., dry cleaners and auto repair shops) is constituted of materials that are dangerous or potentially harmful to human health and the environment. Waste is classified as hazardous if it exhibits at least one of these four characteristics:

- **Ignitability** refers to the creation of fires under certain conditions, including spontaneously combustible materials or those with a flash point less than 140 F.
- **Corrosivity** refers to the capability to corrode metal containers, including materials with a pH less than or equal to 2 or greater than or equal to 12.5.
- **Reactivity** refers to materials susceptible to unstable conditions such as explosions, toxic fumes, gases, or vapors when heated, compressed, or mixed with water under normal conditions.
- **Toxicity** is substances that can induce harmful or fatal effects when ingested, absorbed, or inhaled.

Radioactive Waste Regulations

Although non-hazardous waste and hazardous waste are regulated by RCRA, nuclear or radioactive waste is regulated under the Atomic Energy Act of 1954 by the Nuclear Regulatory Commission (NRC) in the United States.

Radioactive wastes are characterized according to four categories: (1) **High-level waste** (HLW), (2) **Transuranic waste** (TRU), (3) **Low-level waste** (LLW), and (4) **Mill tailings**. Various radioactive wastes decay at different rates, but health and environmental dangers due to radiation may persist for hundreds or thousands of years.

High-level waste is typically liquid or solid waste resulting from government defense-related activities, nuclear power plants, and spent fuel assemblies. These wastes are extremely dangerous due to their heavy concentrations of radionuclides, and humans must not come into contact with them.

Transuranic waste mainly results from reprocessing spent nuclear fuels and the fabrication of nuclear weapons for defense projects. They are characterized by moderately penetrating radiation and a decay time of approximately twenty years until safe radionuclide levels are achieved. Following the passage of a reprocessing ban in 1977, most of this waste generation ended. Even though the ban was lifted in 1981, Transuranic waste remains rare because reprocessing nuclear fuel is expensive. Further, political and social pressures minimize these activities because the extracted plutonium may be used to manufacture nuclear weapons.

Low-level wastes include much of the remainder of radioactive waste materials. They constitute over 80 percent of the volume of all nuclear wastes but only about two percent of total radioactivity. Low-level waste includes all of the previously cited sources of High-level waste and Transuranic waste, plus wastes generated by hospitals, industrial plants, universities, and commercial laboratories. Low-level waste is much less dangerous than High-level waste, and NRC regulations allow some very low-level wastes to be released into the environment. Low-level wastes may also be stored or buried until the isotopes decay to low enough so they may be disposed of as non-hazardous waste. Low-level waste disposal is managed at the state level, but the USEPA and NRC establish requirements for operation and disposal. The Occupational Health and Safety Administration (OSHA) is responsible for setting the standards for workers exposed to radioactive materials.

International Regulatory Framework

The 1992 Basel Convention

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal first came into force in 1992. The Convention puts an onus on exporting countries to ensure that hazardous wastes are managed in an environmentally sound manner in the country of import. The Basel Convention places obligations on countries that are party to the Convention. 151 Countries have ratified the Basel Convention as of December 2002. These have obligations to:

- Minimize generations of hazardous waste;
- Ensure adequate disposal facilities are available;
- Control and reduce international movements of hazardous waste;
- Ensure environmentally sound management of waste; and
- Prevent and punish illegal traffic.

The 1995 Waigani Convention

The Basel Convention establishes a global control system for shipping hazardous waste from one country to another. States that are Parties to the Convention must not trade hazardous wastes with non-Parties. Still, an exception to this is provided for in Article 11 of the Convention, whereby Parties may enter into agreements or arrangements with other Parties or non-Parties.

These agreements or arrangements can also set out controls different from those prescribed by the Convention itself, provided such controls do not reduce the level of environmental protection intended by the Convention.

The **Waigani Conventio**n is to ban the importation of hazardous and radioactive wastes into Forum Island Countries and to control the transboundary movement and management of hazardous wastes within the South Pacific Region. This agreement was enforced in October 2001. The Convention also enables Australia to receive hazardous wastes exported from South Pacific Forum Island countries that are not Parties to the Basel Convention. There are 24 countries within the coverage area of the Waigani Convention. As of December 2002, ten parties had ratified the Waigani Convention. These were Australia, the Cook Islands, the Federated States of Micronesia, Kiribati, New Zealand, Papua New Guinea, Samoa, Solomon Islands, Tuvalu, and Vanuatu.

Electronic waste, commonly known as e-waste, refers to discarded electronic products such as televisions, computers and computer peripherals (e.g., monitors, keyboards, disk drives, and printers), telephones and cellular phones, audio and video equipment, video cameras, fax and copy machines, video game consoles, and others (see Figure 1 below).

Figure 1. Electronic Waste Photograph shows many computers piled up in a parking lot as waste. Source: Bluedisk via Wikimedia Commons

In the United States, it is estimated that about 3 million tons of e-waste are generated each year. This waste quantity includes approximately 27 million units of televisions, 205 million units of computer products, and 140 million units of cell phones. Less than 15 to 20 percent of the e-waste is recycled or refurbished; the remaining percentage is commonly disposed of in landfills and/or incinerated. It should be noted that e-waste constitutes less than 4 percent of total solid waste generated in the United States. However, with tremendous growth in technological advancements in the electronics industry, many electronic products are becoming obsolete quickly, thus increasing the production of e-waste very rapidly. The quantities of e-waste generated are also increasing rapidly in other countries, such as India and China, due to the high demand for computers and cell phones.

In addition to the growing quantity of e-waste, the hazardous content of e-waste is a major environmental concern. It poses risks to the environment if these wastes are improperly managed once they have reached the end of their useful life. Many e-waste components contain toxic substances, including heavy metals such as lead, copper, zinc, cadmium, and mercury, and organic contaminants, such as flame retardants (polybrominated biphenyls and polybrominated diphenyl ethers). Releasing these substances into the environment and subsequent human exposure can lead to serious health and pollution issues. Concerns have also been raised regarding releasing toxic constituents of e-waste into the environment if landfilling and/or incineration options are used to manage the e-waste.

Various regulatory and voluntary programs have been instituted to promote the reuse, recycling, and safe disposal of bulk e-waste. Reuse and refurbishing has been promoted to reduce raw material use, energy consumption, and water consumption associated with manufacturing new products. Recycling and recovering elements such as lead, copper, gold, silver, and platinum can yield valuable resources that may cause pollution if improperly released into the environment. The recycling and recovery operations have to be conducted with extreme care, as the exposure of e-waste components can result in adverse health impacts on the workers performing these operations. For economic reasons, recycled e-waste is often exported to other countries for recovery operations. However, lax regulatory environments in many of these countries can lead to unsafe practices or improper disposal of bulk residual e-waste, adversely affecting vulnerable populations.

There are no specific federal laws dealing with e-waste in the United States, but many states have recently developed e-waste regulations that promote environmentally sound management. For example, California passed the Electronic Waste Recycling Act in 2003 to foster recycling, reuse, and environmentally sound disposal of residual bulk e-waste. Yet, despite recent regulations and advances in reuse, recycling, and proper disposal practices, additional sustainable strategies to manage e-waste are urgently needed.

One sustainable strategy used to manage e-waste is extended producer responsibility (EPR), also known as product stewardship. This concept holds manufacturers liable for the entire life-cycle costs associated with the electronic products, including disposal costs, and encourages the use of environmental-friendly manufacturing processes and products. Manufacturers can pursue EPR in multiple ways, including reuse/refurbishing, buy-back recycling, and energy production or beneficial reuse applications. Life-cycle assessment and cost methodologies may be used to compare the environmental impacts of these different waste management options. Incentives or financial support are also provided by some government and/or regulatory agencies to promote EPR. Using non-toxic and easily recyclable materials in product fabrication is a major component of any EPR strategy. A growing number of companies (e.g., Dell, Sony, HP) are embracing EPR with various initiatives toward achieving sustainable e-waste management.

EPR is a preferred strategy because the manufacturer bears financial and legal responsibility for their products; hence, they are incentivized to incorporate green design and manufacturing practices that incorporate easily recyclable and less toxic material components while producing electronics with longer product lives. One obvious disadvantage of EPR is the higher manufacturing cost, which leads to increased costs of electronics to consumers.

There is no specific federal law requiring EPR for electronics. Still, the United States Environmental Protection Agency (USEPA) undertook several initiatives to promote EPR to achieve the following goals: (1) foster environmentally conscious design and manufacturing, (2) increase purchasing and use of more environmentally sustainable electronics, and (3) increase safe, environmentally sound reuse and recycling of used electronics. To achieve these goals, USEPA has been engaged in various activities, including the promotion of environmental considerations in product design, the development of evaluation tools for environmental attributes of electronic products, the encouragement of recycling (or ecycling), and the support of programs to reduce e-waste, among others. More than 20 states in the United States and various organizations worldwide have already developed laws and/or policies requiring EPR in some form when dealing with electronic products. For instance, the New York State

Wireless Recycling Act emphasizes that authorized retailers and service providers should be compelled to participate in take-back programs, thus allowing increased recycling and reuse of e-waste. Similarly, Maine is the first U.S. state to adopt a household e-waste law with EPR.

In Illinois, Electronic Products Recycling & Reuse Act requires electronic manufacturers to participate in managing discarded and unwanted electronic products from residences. The Illinois EPA has also compiled e-waste collection site locations where the residents can give away their discarded electronic products at no charge. Furthermore, USEPA compiled a list of local programs and manufacturers/retailers that can help consumers properly donate or recycle e-waste.

Overall, the growing quantities and environmental hazards associated with electronic waste are of major concern to waste management professionals worldwide. Current management strategies, including recycling and refurbishing, have not been successful. As a result, EPR regulations are rapidly evolving worldwide to promote sustainable e-waste management. However, neither a consistent framework nor assessment tools to evaluate EPR have been fully developed.

Summary

Many wastes, such as high-level radioactive wastes, will remain dangerous for thousands of years, and even MSW can produce dangerous leachate that could devastate an entire ecosystem if allowed to infiltrate into and migrate within groundwater. Environmental professionals must deal with problems associated with increased generation of waste materials to protect human health and the environment. The solution must focus on reducing the sources of waste and the safe disposal of waste. It is, therefore, extremely important to know the waste's sources, classifications, chemical compositions, and physical characteristics and understand the strategies for managing them. Waste management practices vary not only from country to country but also based on the type and composition of waste. Regardless of the geographical setting of the type of waste that needs to be managed, resource conservation is the governing principle in developing any waste management plan. Natural resource and energy conservation are achieved by managing materials more efficiently. Reduction, reuse, and recycling are primary strategies for effectively reducing waste quantities. Further, proper waste management decisions have increasing importance, as the consequences of these decisions have broader implications concerning greenhouse gas emissions and global climate change. As a result, several public and private partnership programs are under development with the goal of reducing waste by adopting new and innovative waste management technologies. Because waste is an inevitable by-product of civilization, successfully implementing these initiatives will directly affect societies' enhanced quality of life worldwide.

References:

https://upload.wikimedia.org/wikipedia/commons/thumb/b/be/Young_garbage_recycler_in_Saigon.jpg/512pxYoung_garbage_recycler_in_Saigon.jpg.

Chapter attributions:

Chapter 13: Environmental Economics and Policies

Cuyahoga River in Peninsula, OH. Thanks to the Clear Water Act, billions of pounds of pollution have been kept out of the river.

Learning Outcomes

After studying this chapter, you should be able to:

- Define cost-benefit analysis.
- Explain why discounting is controversial.
- Explain the concept of external cost.
- Know what incentive policies are, what they do, and their strengths and weaknesses.
- List major international and US environmental laws and regulations.

Chapter Outline

- 13.1 Environmental Economics
- 13.2 Environmental Laws and Regulations

- 13.3 Chapter 16 Resources

Environmental and natural resource economists study the tradeoffs associated with one of the most important scarce resources we have—nature. Economists mean something very specific when they use the word **efficient**. An allocation is generally efficient if it maximizes social well-being or **welfare**. Traditional economics defines welfare as total net benefits—the difference between the total benefits everyone in society gets from market goods and services and the total costs of producing those things. Environmental economists enhance the definition of welfare. The values of environmental goods like wildlife count on the "benefit" side of net benefits, and damages to environmental quality from production and consumptive processes count as costs.

Under ideal circumstances, market outcomes are efficient. In perfect markets for regular goods, goods are produced at the point where the cost to society of producing the last unit, **the marginal cost**, is equal to the amount a consumer is willing to pay for that last unit. This **marginal benefit** means that the net benefits in the market are maximized. Regular goods are supplied by industry such that supply is equivalent to the marginal production costs to the firms, and consumers demand them in such a way that we can read the marginal benefit to consumers of the demand curve; when the market equilibrates at a price that causes quantity demanded to equal the quantity supplied at that price, it is also true that marginal benefit equals marginal cost.

A well-functioning market would use non-renewable resources such as oil efficiently. It is socially efficient to use a non-renewable resource over time such that the price rises at the same rate as the interest rate. Increasing scarcity pushes the price up, stimulating efforts to use less of the resource and invest in research to make "backstop" alternatives more cost-effective. Eventually, the cost of the resource rises to the point where the backstop technology is competitive, and the market switches from the nonrenewable resource to the backstop. We see this with copper; high prices of non-renewable copper trigger substitution to other materials, like fiber optics for telephone cables and plastics for pipes. We would surely see the same thing happen with fossil fuels; if prices are allowed to rise with scarcity, firms have more incentives to engage in research that lowers the cost of backstop technologies like solar and wind power, and we will eventually just switch. Unfortunately, many conditions can lead to **market failure** such that the market outcome does not maximize social welfare. The extent to which net benefits fall short of their potential is called **deadweight loss**. Deadweight loss can exist when not enough of a good is produced, too much of a good is produced, or production is not done in the most cost-effective (least expensive) way possible, where costs include environmental damages. Some market failures (and thus deadweight loss) are extremely common in environmental settings.

Externalities

In a market economy, people and companies choose to balance the costs and benefits that accrue to them. These side effects can be seen as ways in which a producer's actions impact a bystander's well-being. The market fails to allocate adequate resources to address such side effects because it only concerns buyers and sellers, not the environment's well-being. When this is true, economists say there are externalities, and individual actions do not typically yield efficient outcomes. A **negative externality** is a cost associated with an action not borne by the person who chooses to take that action.

When external costs occur, a company's private production cost and social cost of production are at odds. The firm does not consider the cost of pollution cleanup to be relevant, while society does. The social costs of production include the negative effects of pollution and the cost of treatment. As a result, the social costs exceed the private production costs. When external pollution and treatment costs are included in the production cost of the product, the supply curve intersects the demand curve at a higher price point. As a result of the higher price, there will be less demand for the product and less pollution produced.

For example, exhaust pollutants from automobiles adversely affect the health and welfare of the human population. However, oil companies consider their cost of producing gasoline to include only their exploration and production costs. Therefore, any measures to reduce exhaust pollutants represent an external cost. The government tries to help reduce the problem of exhaust pollutants by setting emissions and fuel-efficiency standards for automobiles. It also collects a gasoline tax that increases the final price of gasoline, which may encourage people to drive less. Sometimes, pollution results from production because no property rights are involved. For example, suppose a paper manufacturer dumps waste in a privately owned pond. In that case, the landowner generally takes legal action against the paper firm, claiming compensation for a specific loss in property value caused by industrial pollution. In contrast, the air and most waterways are not owned by individuals or businesses but are considered public goods. Because no property rights are involved, the generation of pollution does not affect supply and demand.

Firms are incentivized to use public goods in the production process because doing so does not cost anything. If the paper manufacturer can minimize production costs by dumping wastes for free into the local river, it will do so. The consequences of this pollution include adverse impacts on the fish and animal populations that depend on the water, degradation of the surrounding environment, decreased quality of water used in recreation and business, human health problems, and the need for extensive treatment of drinking water by downstream communities. An important role of the government is to protect public goods, especially those with multiple uses, from pollution by companies seeking to minimize company costs and maximize profits. People desire clean water for recreation and drinking, and the government must act to protect the broad interests of society from the narrow profit-driven focus of companies.

Other examples of negative externalities in environmental settings include:

- Companies that spill oil into the ocean do not bear the full costs of the resulting harm to the marine environment, which include everything from degraded commercial fisheries to reduced endangered sea turtle populations).
- Commuters generate air pollution emissions, which lower the ambient quality of the air in areas they pass through and cause health problems for other people.
- Developers who build houses in bucolic exurban settings cause habitat fragmentation and biodiversity loss, inflicting a cost on the public.

A **positive externality** is a benefit associated with an action not borne by the person who chooses to take that action. Positive externalities exist in the world of actions and products that affect the environment, including:

- A homeowner who installs a rain barrel to collect unchlorinated rainwater for her garden and improves stream habitat in her watershed by reducing stormwater runoff.
- A delivery company that re-optimizes its routing system to cut fuel costs also improves local air quality by reducing vehicle air pollution emissions.
- A farmer who plants winter cover crops to increase soil productivity will also improve water

quality in local streams by reducing erosion.

Public Goods and Common-Pool Resources

In two broad cases, market outcomes are rarely efficient: public goods and common-pool resources. The market failures in these settings are related to the problems we saw with externalities. A pure public good is defined as being nonexclusive and nonrival in consumption. If something is nonexclusive, people cannot be prevented from enjoying its benefits. A private house is exclusive because doors, windows, and an alarm system can be used to keep nonowners out. On the other hand, a lighthouse is non-exclusive because ships at sea cannot be prevented from seeing its light. A nonrival good in consumption has a marginal benefit that does not decline with the number of people who consume it. A sandwich is completely rival in consumption: if I eat it, you cannot. On the other hand, the beauty of a fireworks display is completely unaffected by the number of people who look at it. Some elements of the environment are pure public goods: Clean air in a city provides health benefits to everyone, and people cannot be prevented from breathing.

The efficient amount of a public good is still where social marginal benefit equals the marginal cost of provision. However, the social marginal benefit of one unit of a public good is often very large because many people in the society can benefit from that unit simultaneously. One lighthouse prevents all the ships in an area from running aground in a storm. In contrast, the social marginal benefit of a sandwich is just the marginal benefit gained by the one person who gets to eat it. Society could figure out the efficient amount of public good to provide—say, how much to spend on cleaner cars that reduce air pollution in a city. Unfortunately, private individuals acting independently are unlikely to provide an efficient amount of the public good because of the free rider problem. If my neighbors reduce pollution by buying clean electric cars or commuting via train, I can benefit from that cleaner air; thus, I might try to avoid doing anything costly myself in hopes that everyone else will clean the air for me. Evidence suggests that people do not behave entirely like free riders – they contribute voluntarily to environmental groups and public radio stations. However, the levels of public-good provision generated by a free market are lower than would be efficient. The ozone layer is too thin; the air is too dirty. Public goods have big multilateral positive externality problems.

In contrast, a common-pool resource (also sometimes called an open-access resource) suffers from big multilateral negative externality problems. This situation is sometimes called the "**tragedy of the commons**." Like public goods, common-pool resources are non-excludable. However, they are highly rival in use. Many natural resources have common pool features: Water in a river can be removed by anyone near it for irrigation, drinking, or industrial use; the more water one set of users removes, the less water there is available for others. Swordfish in the ocean can be caught by anyone with the right boat and gear, and the more fish are caught by one fleet of boats, the fewer remain for other fishers to catch. Many people can cut down old-growth timber in a developing country, and slow regrowth means that the more timber one person cuts, the less it is available for others. One person's use of a common-pool resource negatively affects all the other users. Thus, these resources are prone to overexploitation. One person in Indonesia might want to harvest tropical hardwood timber slowly and sustainably, but the trees they forebear from cutting today might be cut down by someone else tomorrow. The difficulty of managing common-pool resources is evident worldwide in rapid rates of tropical deforestation, dangerous over-harvesting of fisheries, and battles fought over mighty rivers that have been reduced to dirty trickles. The tragedy of the commons occurs most often when the value of the resource is great, the number of users is large, and the users do not have social ties to one another, but common-pool resources are not always abused.

Incentive Policies

Incentive policies try to use market forces for what they do best—allocating resources cost-effectively within an economy—while correcting the market failures associated with externalities, public goods, and common pool resources.

Taxing Pollution

One way to "internalize" some of the external pollution costs is for the government to tax pollution. A pollution tax would require that polluting firms pay a tax based on the air, water, and land pollution they generate. This tax would raise the private production cost of a company to include the social cost of production. In addition, the government could use the generated tax revenues to help mitigate the effects of pollution. Thus, if we think the social cost of a ton of carbon dioxide (because of its contribution to climate change) is $20, then we could charge a tax of $20 per emitted ton of carbon dioxide. The easiest way to do this would be to tax fossil fuels according to the amount of carbon dioxide emitted when they are burned.

If a price is placed on carbon dioxide, all agents would be incentivized to reduce their carbon dioxide emissions to the point where the cost to them of reducing one more unit (their marginal abatement cost) is equal to the per unit tax. Therefore, several good things happen. All carbon dioxide sources are abating to the same marginal abatement cost, so the total abatement is accomplished most cost-effectively. Furthermore, total emissions in the economy will decrease to a socially efficient level. Firms and individuals have very broad incentives to change things to reduce carbon dioxide emissions—reduce output and consumption, increase energy efficiency, switch to low-carbon fuels— and strong incentives to figure out how to innovate so those changes are less costly. Finally, the government could use the revenue it collects from the tax to correct any inequities in the distribution of the program's cost among people in the economy or to reduce other taxes on things like income.

While taxes on externality-generating activities have many good features, they also have drawbacks and limitations. First, while an externality tax can yield an efficient outcome (where costs and benefits are balanced for the economy as a whole), that only happens if policymakers know enough about the value of the externality to set the tax at the right level. If the tax is too low, we will have too much harmful activity; if the tax is too high, the activity will be excessively suppressed. Second, even if we can design a perfect externality tax in theory, such a policy can be difficult to enforce. The enforcement agency needs to be able to measure the total quantity of the thing being taxed. In some cases, that is easy—in the case of carbon dioxide, for example, the particular fixed link between carbon dioxide emissions and quantities of fossil fuels burned means that by measuring fossil fuel consumption, we can measure the vast majority of carbon dioxide emissions. However, many externality-causing activities or materials are difficult to measure in total. Nitrogen pollution flows into streams due to fertilizer applications on suburban lawns. Still, it is impossible to measure the total flow of nitrogen from a single lawn over a year so that one could tax the homeowner for that flow. Third, externality taxes face strong political opposition from companies and individuals who don't want to pay the tax. Even if the government uses the tax revenues to do good things or reduce other tax rates, the group that disproportionately pays the tax is incentivized to lobby heavily against such a policy. This phenomenon is at least partly responsible because there are no examples of pollution taxes in the U.S. Instead, U.S. policymakers have implemented mirror-image subsidy policies, giving subsidies for activities that reduce negative externalities rather than taxing activities that cause those externalities.

Tradable Permits

Another major type of incentive policy is a tradable permit scheme. Tradable permits are very similar to externality taxes but can have important differences. These policies are colloquially known as "cap and trade." If we know the efficient amount of the activity to have (e.g., number of tons of pollution, amount of timber to be logged), the policymaker can set a cap on the total amount of the activity equal to the efficient amount. Permits are created such that each permit grants the holder permission for one unit of the activity. The government distributes these permits to the affected individuals or firms and permits them to sell (trade) them to one another. To comply with the policy (and avoid punishment, such as heavy fines), all agents must hold enough permits to cover their total activity for the time period. The government doesn't set a price for the activity in question. Still, the permit market yields a price for the permits that give all the market participants strong incentives to reduce their externality-generating activities, to make cost-effective trades with other participants, and to innovate to find cheaper ways to comply. Tradable permit policies have been used in several environmental and natural resource policies. The European Union used a tradable permit market as part of its policy to reduce carbon dioxide emissions under the Kyoto Protocol. Individual tradable quotas for fish in Alaska and New Zealand fisheries have been used to rationalize fishing activity and keep total catches down to efficient and sustainable levels. Economists think differently about costs than engineers or other physical scientists, and several key insights about the economics of cost evaluation are important for policy analysis. Viewed through an inverse lens, all these ideas are important for benefit estimation as well.

Discounting and Cost-Benefit Analysis

Economists have developed a tool for comparing net benefits at different points in time called **discounting**. Discounting converts a quantity of money received at some point in the future into a quantity directly compared to money received today, controlling for the time preference. A particular cost or benefit is worth less in present value terms the farther into the future it accrues and the higher the value of the discount rate. These fundamental features of discounting create controversy over the use of discounting because they make projects to deal with long-term environmental problems seem unappealing. The most pressing example of such controversy swirls around the analysis of climate-change policy. Climate-change mitigation policies typically incur immediate economic costs (e.g., switching from fossil fuels to more expensive forms of energy) to prevent environmental damages from climate change several decades in the future. Discounting lowers the present value of the future improved environment while leaving the present value of current costs largely unchanged. **Cost-benefit analysis** is just that: an analysis of the costs and benefits of a proposed policy or project. To carry out a cost-benefit analysis, one carefully specifies the change to be evaluated, measures the costs and benefits of that change for all years affected by the change, finds the totals of the presented discounted values of those costs and benefits, and compares them. Some studies look at the difference between the benefits and the costs (the net present value), while others look at the ratio of benefits to costs. A "good" project is one with a net present value greater than zero and a benefit/cost ratio greater than one. The result of a cost-benefit analysis depends on a large number of choices and assumptions. What discount rate is assumed? What is the status quo counterfactual against which the policy is evaluated? How are the physical effects of the policy being modeled? Which costs and benefits are included in the analysis—are non-use benefits left out? Good cost-benefit analyses should make all their assumptions clear and transparent.

The cost-benefit analysis gives us a rough sense of whether or not a project is a good idea. However, it has many limitations. Here we discuss several other measures of whether a project is desirable. Economists use all these criteria when evaluating whether a policy is a right approach for solving a problem with externalities, public goods, and common-pool resources.

Efficiency

A policy is efficient if it maximizes the net benefits society could get from an action of that kind. Such efficiency will occur when the marginal benefits of the policy are equal to its marginal costs. Sometimes a cost-benefit analysis will try to estimate the total costs and benefits for several policies with different degrees of stringency to see if one is better. However, only information about the marginal benefit and marginal cost curves will ensure that the analyst has found an efficient policy. Unfortunately, such information is often very hard to find or estimate.

Cost Effectiveness

Estimating the benefits of environmental policy can be particularly difficult, and benefit estimates are necessary for finding efficient policies. Sometimes policy goals are just set through political processes—reducing sulfur dioxide emissions by 10 million tons below 1980 levels in the Clean Air Act acid rain provisions, cutting carbon dioxide emissions by 5% from 1990 levels in the Kyoto Protocol—without being able to know whether those targets are efficient. However, we can still evaluate whether a policy will be cost-effective and achieve its goal in the least expensive way possible. For example, for total pollution reduction to be distributed cost-effectively between all the sources that contribute pollution to an area (e.g., a lake or an urban airshed), it must be true that each of the sources is cleaning up such that they all face the same marginal costs of further abatement. If one source had a high marginal cost and another's marginal cost was very low, switching some of the cleanups from the first source to the second could reduce the total cost.

Incentives to Innovate

At any one point, the cost of pollution control or resource recovery depends on the current state of technology and knowledge. For example, the cost of reducing carbon dioxide emissions from fossil fuels depends in part on how expensive solar and wind power are, and the cost of wetland restoration depends on how quickly ecologists can get new wetland plants to be established. Everyone in society benefits if those technologies improve and the marginal cost of any given level of environmental stewardship declines. Thus, economists think a lot about which kinds of policies give people incentives to develop cheaper ways to clean and steward the environment.

Fairness

A project can have very high aggregate net benefits but distribute the costs and benefits very unevenly within society. We may have ethical and practical reasons not to want a highly unfair policy. Some people have strong moral or philosophical preferences for policies that are equitable. In addition, if the costs of a policy are borne disproportionately by a single group of people or firms, that group is likely to fight against it in the political process. Simple cost-benefit analyses do not speak to issues of equity. However, it is common for policy analyses to break total costs and benefits down among subgroups to see if uneven patterns exist in their distribution. Studies can break down policy effects by income category to see if a policy helps or hurts people disproportionately, depending on whether they are wealthy or poor. Other analyses carry out regional analyses of policy effects. For example, climate-change mitigation policy increases costs disproportionately for poor households because of patterns in energy consumption across income groups. Furthermore, the benefits and costs of such a policy are not uniform across space in the U.S. The benefits of reducing the severity of climate change will accrue largely to those areas that would be hurt most by global warming (coastal states hit by sea level rise and more hurricanes, Western states hit by severe water shortages). At the same time, the costs will fall most heavily on regions of the country with economies dependent on sales of oil and coal.

Some of our evaluative criteria are closely related; a policy cannot be efficient if it is not cost-effective. However, other criteria have nothing to do with each other; a policy can be efficient but not equitable, and vice versa. Cost-benefit analyses provide crude litmus tests—we surely do not want to adopt policies with costs exceeding their benefits. However, good policy development and evaluation consider a broader array of criteria.

Gross National Product and Its Alternatives

Most countries strive to increase their capacities to produce goods and services and consider doing so a positive sign of development. Economic growth is stimulated by population growth, which increases the consumption of natural resources and the per capita consumption of goods and services. Various indicators are used to measure economic growth. One is the Gross National Product (GNP), which represents the total market value of final goods and services produced by a country during a given period (usually one year). Unfortunately, GNP does not consider the global nature of many companies. If a company produces goods in a foreign country, the "home" country does not benefit from that production. Thus, if Pepsi bottles and sells soda in Japan, those revenues should not be included in the GNP of the United States. The GDP (Gross Domestic Product) provides a better indicator of the health of a country's economy. This measure refers to the value of the goods and services produced within the boundaries of an economy during a given period of time.

The GNP and GDP are economic measures that indicate nothing about a country's social or environmental conditions. They are not measures of the quality of life. Severe environmental problems can raise the GNP and GDP because the funds used to clean up environmental contamination (such as hazardous waste sites) help to create new jobs and increase the consumption of natural resources. Alternative GDP systems have been suggested based on genuine well-being and progress. The UN Human Development Index is an estimate of the quality of life in a country based on three indicators: life expectancy, literacy rate, and per capita GNP. The Genuine Progress Index (GPI) is based on measurements that include health care, safety, a clean environment, pollution, and crime. The Environmental Performance Index (EPI) is based on indicators tracked in two categories: protection of human health from environmental harm and protection of ecosystems.

Although environmental laws are generally considered a 20th-century phenomenon, attempts have been made to legislate environmental controls throughout history. In 2,700 B.C., the Middle Eastern civilization in Ur passed laws protecting the few remaining forests in the region. In 80 A.D., the Roman Senate passed a law to protect water stored for dry periods to be used for street and sewer cleaning. During American colonial times, **Benjamin Franklin** argued for "public rights" laws to protect the citizens of Philadelphia against industrial pollution produced by animal hide tanners.

Significant environmental action began at the beginning of the 20th century. In 1906, Congress passed the "Antiquities Act," which authorized the president to protect areas of federal lands as national monuments. A few years later, **Alice Hamilton** pushed for government regulations concerning toxic industrial chemicals. She fought, unsuccessfully, to ban the use of lead in gasoline. She also supported the legal actions taken by women dying of cancer from their exposure to the radium then used in glow-in-the-dark watch dials. During the early 1960s, biologist **Rachel Carson** pointed out the need to regulate pesticides such as DDT to protect the health of wildlife and humans.

With the establishment of the **Environmental Protection Agency (EPA**) in 1970, environmental law became a field substantial enough to occupy lawyers full-time. Since then, federal and state governments have passed numerous laws and created a vast network of complicated rules and regulations regarding environmental issues. Moreover, international organizations and agencies, including the **United Nations,** the W**orld Bank**, and the **World Trade Organization,** have also contributed to environmental rules and regulations.

Because of the legal and technical complexities of the subjects covered by environmental laws, persons dealing with such laws must be knowledgeable in law, science, and public policy. Environmental laws today encompass various subjects such as air and water quality, hazardous wastes, and biodiversity. These environmental laws aim to prevent, minimize, remedy, and punish actions that threaten or damage the environment and those that live in it. However, some believe these laws unreasonably limit the freedom of people, organizations, corporations, and government agencies by controlling their actions.

Federal Laws

Early attempts by Congress to enact laws affecting the environment included the **Antiquities Act** in 1906, the **National Park Service Act** in 1916, the **Federal Insecticide, Fungicide, and Rodenticide Act** in 1947, and the W**ater Pollution Control Act** in 1956. The **Wilderness Act** of 1964 protected large areas of pristine federal lands from development and ushered in the new age of environmental activism that began in the 1960s. However, it was the **National Environmental Policy Act (NEPA)** enacted in 1969 and the formation of the Environmental Protection Agency (EPA) in 1970 that started environmental legislation in earnest. The main objective of these two federal enactments was to assure that the environment would be protected from public and private actions that failed to consider the costs of damage inflicted on the environment.

Many consider NEPA the most far-reaching environmental legislation ever passed by Congress. The basic purpose of NEPA is to force governmental agencies to consider the effects of their decisions on the environment comprehensively. This is effected by requiring agencies to prepare detailed **Environmental Impact Statements** (EIS) for proposed projects. The EPA is the government's environmental watchdog. It is charged with monitoring and analyzing the state of the environment, conducting research, and working closely with state and local governments to devise pollution control policies. The EPA is also empowered to enforce those environmental policies. Unfortunately, the agency is sometimes caught up in conflicts between the public wanting more regulation for environmental reasons and businesses wanting less regulation for economic reasons. Consequently, the development of a new regulation can take many years.

Since 1970, Congress has enacted several important environmental laws, including provisions to protect the environment and natural resources. Some of the more notable laws include:

- The **Federal Clean Air Act** (1970, 1977, and 1990) established national standards for regulating the emission of pollutants from stationary and mobile sources.
- The **Federal Water Pollution Control Act** (1972), amended by the **Clean Water Act** (1977, 1987), established water quality standards; provides for the regulation of the discharge of pollutants into navigable waters and the protection of wetlands.
- The **Federal Safe Drinking Water Act** (1974, 1977, and 1986) set drinking water standards for levels of pollutants, authorizing the regulation of the discharge of pollutants into underground drinking water sources.
- The **Toxic Substances Control Act** (1976) provided for regulating chemical substances by the EPA and the safety testing of new chemicals.
- The **Resource Conservation and Recovery Act** (1976) established cradle-to-grave regulations for handling hazardous wastes.
- The **Comprehensive Environmental Response, Compensation, and Liability Act** (1980), also known as the **Superfund** program, provided for the cleanup of the worst toxic waste sites.
- The **Food Security Act** (1985, 1990) was later amended by the **Federal Agriculture Improvement and Reform Act** (1996), discouraged cultivating environmentally sensitive lands, especially wetlands, and authorized incentives for farmers to withdraw highly erodible lands from production.

Applying or enforcing environmental law is not always straightforward, and problems can arise. The biggest problem is that Congress often fails to allocate the funds necessary for implementing or enforcing the laws. Administrative red tape may make it impossible to enforce a regulation on time. It also may be unclear which agency (or branch of an agency) is responsible for enforcing a particular regulation. Furthermore, agency personnel declines to enforce regulation for political reasons.

State Laws

Most states, like California, have enacted their own environmental laws and established agencies to enforce them. California faced some of its first environmental challenges in the mid-1800s concerning debris from the hydraulic mining of gold. Water quality concerns, dangers of flooding, negative impact on agriculture, and hazards to navigation prompted the state to act.

Some of California's environmental regulations preceded similar federal laws. For example, California established the nation's first air quality program in the 1950s. Much of the federal Clean Air Act amendments of 1990 were based upon the **California Clean Air Act of 1988**. California also pioneered advances in vehicle emission controls, control of toxic air pollutants, and control of stationary pollution sources before federal efforts in those areas. The **Porter-Cologne Act of 1970**, based on the state's water quality program, also served as the model for the federal Clean Water Act.

International Treaties and Conventions

Conventions, or treaties, generally set forth international environmental regulations. These conventions and treaties often result from efforts by international organizations such as the **United Nations (UN)** or the **World Bank**. However, it is often difficult, if not impossible, to enforce these regulations because of the sovereign rights of countries. In addition, rules and regulations outlined in such agreements may be no more than non-binding recommendations, and often countries are exempted from regulations due to economic or cultural reasons. Despite these shortcomings, the international community has achieved some success via its environmental agreements. These include an international convention that placed a moratorium on whaling (1986) and a treaty that banned the ocean dumping of waste (1991).

The UN often facilitates international environmental efforts. In 1991, the UN enacted an **Antarctica Treaty**, which prohibits the mining of the region, limits pollution of the environment, and protects its animal species. The United Nations Environment Program (UNEP) is a branch of the UN that specifically deals with worldwide environmental problems. It has helped with several key efforts at global environmental regulations:

- The **1987 Montreal Protocol on Substances that Deplete the Ozone Layer**. As a result of this global agreement, industrialized countries have ceased or reduced the production and consumption of ozone-depleting substances such as chlorofluorocarbons.
- The **Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade**. This agreement enhances the world's technical knowledge and expertise in hazardous chemicals management.
- The **Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)**. This agreement protects over 30,000 of the world's endangered species.
- In 1995 **UNEP and the International Olympic Committee (IOC)** signed a partnership agreement to develop environmental guidelines for sports federations and countries bidding to host the Olympic games.
- The **Rotterdam Convention** (1998) addressed the growing trade in hazardous pesticides and chemicals. Importing countries must give explicit informed consent before hazardous chemicals can cross their borders.
- The **International Declaration on Cleaner Production** (1998). The signatories commit their countries to implement cleaner industrial production and subsequent monitoring efforts.

In 1992, the UN member nations committed their resources to limit greenhouse gas (e.g., carbon dioxide) emissions at or below 1990 levels, as put forth by the **UN Framework Convention on Climate Change**. Unfortunately, the agreement was non-binding, and by the mid-1990s, it had not affected carbon emissions. The 1997 **Kyoto Protocol** was a binding resolution to reduce greenhouse gases. Although the United States initially supported the resolution, the Senate failed to ratify the treaty, and by 2001, President Bush opposed the resolution as threatening the United States economy.

California's state environmental regulations are sometimes more stringent than federal laws (e.g., the California Clean Air Act and vehicle emissions standards). In other program areas, no comparable federal legislation exists. For example, the **California Integrated Waste Management Act** established a comprehensive, statewide system of permitting, inspections, enforcement, and maintenance for solid waste facilities and set minimum standards for solid waste handling and disposal to protect air, water, and land from pollution. Also, **Proposition 65 (Safe Drinking Water and Toxic Enforcement Act)** requires the Governor to publish a list of chemicals known to the State of California to cause cancer, birth defects, or other reproductive harm.

Despite the state's leadership in environmental programs and laws, the creation of a cabinet-level environmental agency in California lagged more than two decades behind the establishment of the federal EPA. Originally, the organization of California's environmental quality programs was highly fragmented. Each program handled a specific environmental problem (e.g., the **Air Resources Board**), with enforcement responsibility falling to state and local governments. It was not until 1991 that a California EPA was finally established and united the separate programs under one agency.

Summary

Environmental and natural resource economists study the tradeoffs associated with one of the most important scarce resources we have—nature. Economic activity generally affects the environment, usually negatively. Natural resources are used, and large amounts of waste are produced. These side effects can be seen as ways in which a producer's actions impact a bystander's well-being. The market fails to allocate adequate resources to address such external costs because it only concerns buyers and sellers, not the environment's well-being. Only direct costs are considered relevant. External costs are harmful social or environmental effects caused by the production or consumption of economic goods. A cost-benefit analysis provides an estimate of the most economically efficient level of pollution reduction that is practical. Environmental laws today encompass various subjects, such as air and water quality, hazardous wastes, and biodiversity. These environmental laws aim to prevent, minimize, remedy, and punish actions that threaten or damage the environment and those that live in it. Conventions, or treaties, generally set forth international environmental regulations. These conventions and treaties often result from efforts by international organizations such as the United Nations (UN) or the World Bank. However, it is often difficult, if not impossible, to enforce these regulations because of the sovereign rights of countries. In addition, rules and regulations outlined in such agreements may be no more than non-binding recommendations, and often countries are exempted from regulations due to economic or cultural reasons. Despite these shortcomings, the international community has achieved some success via its environmental agreements. These include an international convention that placed a moratorium on whaling and a treaty that banned the ocean dumping of waste.

Chapter Attributions:

Chapter 14: Sustainability and Urban Infrastructure

Walkability is a key component of any sustainable neighborhood. Walkability not only reduces energy use, but also in- creases public health. Picture shows a pedestrian street in Ljubljana, Slovenia.

Learning Outcomes

After studying this chapter, you should be able to:

- Define urbanization
- Recognize some of the main urbanization challenges facing the developing world
- Describe impacts from urban sprawl
- Explain green urbanism

Chapter Outline

- 14.1 Urbanization and Cities
- 14.2 Urbanization Around the World
- 14.3 The Impacts of Urban Sprawl

- 14.4 The Sustainable City
- 14.5 Case Study: Responding to a New Paradigm—The Challenge for Local Authorities
- 14.6 Chapter Resources

Urbanization is the study of the social, political, and economic relationships in cities, and someone specializing in **urban sociology** would study those relationships. In some ways, cities can be microcosms of universal human behavior, while in others, they provide a unique environment that yields their own brand of human behavior. There is no strict dividing line between rural and urban; there is a continuum where one bleeds into the other. However, once a geographically concentrated population has reached approximately 100,000 people, it typically behaves like a city regardless of its designation. There are three prerequisites for the development of a city.

First, a **good environment** with fresh water and a favorable climate; second, **advanced technology**, producing a food surplus to support non-farmers; and third, **strong social organization** to ensure social stability and a stable economy. Most scholars agree that the first cities were developed somewhere in ancient Mesopotamia, though there are disagreements about exactly where. Most early cities were small by today's standards, and the largest city around 100 CE was most likely Rome, with about 650,000 inhabitants. The factors limiting the size of ancient cities included a lack of adequate sewage control, limited food supply, and immigration restrictions. For example, serfs were tied to the land, and transportation was limited and inefficient. Today, the primary influence on cities' growth is economic forces.

Growth of Urban Populations

Urbanization levels are affected by two things – migration and natural increase. **Migration** is the movement of the population from one area to another. Some migrations are forced, voluntary, permanent, temporary, international, and regional. Rural-to-urban migration is the movement of people from the countryside to city areas. This type of migration happened in developed countries from the 18th century onwards on a large scale and has gradually slowed down. However, many developing countries are experiencing massive rural-to-urban migration, mainly of young males, into the major cities. The major reasons for migration can be classified into push and pull factors.

A **push factor** can force or encourage people to move away from a country. Push factors include famine (as in Ethiopia in the 1980s), drought, flooding, a lack of employment opportunities, population growth, overpopulation, and civil war. A **pull factor** encourages people to move to a city. Pull factors include the chance of a better job, better access to education and services, and a higher standard of living. These factors have contributed to millions of people in developing countries moving to cities, creating mass urbanization. **Natural increase** (a population increase due to more births and fewer deaths) also significantly affects urbanization rates. Natural increase is stimulated by better access to medical care, improved water supplies, sanitary conditions, and wealth.

Suburbs and Exurbs

As cities grew and became more crowded (and often more impoverished and costly), more and more people began to migrate back out of them. But instead of returning to rural small towns (like they had resided in before moving to the city), these people needed close access to the cities for their jobs. In the 1850s, suburbs developed as the urban population greatly expanded and transportation options improved. **Suburbs** are the communities surrounding cities, typically close enough for a daily commute but far enough away to allow for more space than city living affords. The bucolic suburban landscape of the early 20th century has largely disappeared due to sprawl.

Urban sprawl contributes to traffic congestion, which contributes to commuting time. Commuting times and distances have continued to increase as new suburbs developed farther and farther from city centers. Simultaneously, this dynamic contributed to an exponential increase in natural resource use, like petroleum, which sequentially increased pollution in the form of carbon emissions (negative aspects of urban sprawl will be explored further in the following section).

As the suburbs became more crowded and lost their charm, those who could afford it turned to the **exurbs**. These communities exist outside the ring of suburbs and are typically populated by even wealthier families who want more space and have the resources to lengthen their commute. It is interesting to note that, unlike U.S. cities, Canadian cities have always retained a fairly large elite residential presence in enclaves around the city centers, a pattern that has been augmented in recent decades by patterns of inner-city resettlement by elites (Caulfield 1994; Keil and Kipfer 2003). As cities evolve from industrial to postindustrial, this practice of gentrification becomes more common. **Gentrification** refers to members of the middle and upper classes entering city areas that have been historically less affluent and renovating properties. At the same time, the poor urban underclass is forced by resulting price pressures to leave those neighborhoods. This practice is widespread, and the lower class is pushed into increasingly decaying portions of the city.

The city centers, suburbs, exurbs, and metropolitan areas combine to form a **metropolis**. New York was the first North American **megalopolis**, a huge urban corridor encompassing multiple cities and their surrounding suburbs. The Toronto-Hamilton-Oshawa and Calgary-Edmonton corridors are similar megalopolis formations. These metropolises use vast natural resources and are a growing part of the North American landscape.

In North America, other urban centers experienced a growth spurt during the Industrial Era. In 1800, the only city in the world with a population of over 1 million was Beijing, but by 1900, there were 16 cities with a population of over 1 million. The development of factories brought people from rural to urban areas, and new technology increased the efficiency of transportation, food production, and food preservation. For example, from the mid-1670s to the early 1900s, London increased its population from 550,000 to 7 million.

The growth in global urbanization in the 20th and 21st centuries follows the blueprint of North American cities. Still, it occurs much more quickly and at larger scales, especially in peripheral and semi-peripheral countries. Shanghai almost tripled its population from 7.8 million to 20.2 million between 1990 and 2011, adding the equivalent of the population of New York City in 20 years. It is projected to reach 28.4 million by 2025, third in size behind Tokyo (38.7 million) and New Delhi (32.9 million).

Urban Environmental Problems of the Developing World

Global urbanization reached the 50 percent mark in 2008, meaning that more than half of the global population lived in cities compared to only 30 percent 50 years ago. Access to basic services—clean water, sanitation, electricity, and roads—are some of the main urbanization challenges facing the developing world.

Municipal waste management is a crucial service cities provide, but it is often inefficient and underperforming in developing countries. Low-income countries face the most acute challenges with solid waste management. In low-income countries, cities collect less than half the waste stream. Of this, only about half is processed to minimum acceptable standards. Improper waste management, especially open dumping and open burning, significantly affects water bodies, air, and land resources. People who live near or work with solid waste have increased disease burdens. Unmanaged waste also frequently blocks drainage systems and worsens flooding. Even when collected and transported, waste in dumpsites and landfills contributes to greenhouse gas emissions.

Roughly 2.6 billion people in the developing world lack adequate **sanitation**, and facilities are often overloaded, disrepair, or unused. Even though the sanitation gap is twice as large as the water supply, investments in sanitation and hygiene have lagged far behind those in water and other “social” sectors, such as health and education. The main costs of urban sanitation services are sewers and sewage treatment. Whereas sewers contribute to public health by reducing everyday contact with sewage (especially by children), wastewater treatment is designed largely to meet ecological objectives and not public health ones. Urban utilities, by and large, are not well designed or staffed to address off-network solutions for water supply or sanitation, yet those solutions are likely to be the most important first steps of progress in environmental health for many of the urban poor.

Experience suggests that demand for car ownership increases dramatically at annual household incomes of $6,000–$8,000. If history repeats itself, an additional 2.3 billion cars will be added by 2050, mostly in developing countries, given expected economic growth and past patterns of motorization. For instance, in the six largest cities in India, the population doubled between 1981 and 2001, but the number of motor vehicles increased eight times over the same period. Between 2000 and 2013, car ownership in China increased more than six times. Similar trends are seen in other fast-growing economies. Increased income levels, cheaper personal vehicles, increased travel distances, and inadequate public transport systems have made the personal motorcar an increasingly attractive travel option. The associated health costs are high—in Beijing, the health costs from local **air pollution** are estimated at $3.5 billion annually. In Pakistan, more than 22,600 adult deaths were attributable to urban ambient air pollution in 2005. Air pollution causes more than 80,000 hospital admissions per year, nearly 8,000 cases of chronic bronchitis, and almost 5 million lower respiratory cases among children under five.

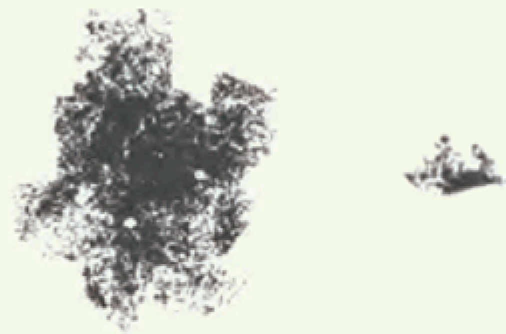
Slum cities refer to the development on the outskirts of cities of unplanned shantytowns or squats without access to clean water, sanitation, or other municipal services. These slums exist largely outside the rule of law and have become centers for child labor, prostitution, criminal activities, and struggles between gangs and paramilitary forces for control. Mike Davis (2006) estimates that there are 200,000 slum cities worldwide, including Karantina in Beirut, the Favéla in Rio de Janeiro, the “City of the Dead” in Cairo, and Santa Cruz Meyehualco in Mexico City. He notes that while slum residents constitute only 6 percent of the urban population in developed countries, they constitute 78.2 percent of city dwellers in semi-peripheral countries. In Davis’s analysis, neoliberal restructuring and the Structural Adjustment Programs of the World Bank and the International Monetary Fund (IMF) are largely responsible for creating the informal economy and withdrawing the state from urban planning and providing services. As a result, slum cities have become the blueprint for urban development in the developing world.

Urban sprawl is the extension of low-density residential, commercial, and industrial development into areas beyond a city's boundaries that occur unplanned or uncoordinatedly (Figure 1). It is generally characterized by the following:

- low-density development that is dispersed and situated on large lots (greater than one acre)
- geographic separation of essential places such as work, home, school, and shopping
- high dependence on automobiles for travel
- increased impervious surface area in watersheds
- habitat fragmentation and degradation

Figure 1. Sprawling area. An aerial photo of Bellefonte, Pennsylvania, USA.

Urban sprawl combines low density and fragmentation of the urban area (Figure 2), increases the average travel distances for daily trips, and hinders a shift toward less energy-intensive transportation modes. The sprawling nature of cities is critically important because of the major impacts of increased energy, land, and soil consumption. These impacts threaten the natural and rural environments, raising greenhouse gas emissions that cause climate change and elevated air and noise pollution levels, often exceeding the agreed human safety limits. Thus, urban sprawl produces many adverse impacts that directly affect the quality of life.



	Sprawling City	Compact City
Location	Atlanta	Barcelona
Urban Population (million inhabitants)	2.5	2.8
Urban Area (km^2)	4,280	162
Urban Density (pph)	6	173
Energy Consumption Per Capita for Private Transportation (MJoules)	80	9

Figure 2. Sprawl vs. Compact Cities. An often-cited example of urban sprawl is Atlanta, GA (US), which has a population similar to Barcelona but occupies an urban area that is 26 times as large.

Health

If communities are not walkable or bikeable, we must drive to schools, shops, parks, entertainment, play dates, etc. Thus we become more sedentary. Residents of sprawling counties were likely to walk less during leisure time and weigh more than residents of compact counties. A sedentary lifestyle increases the risk of overall mortality, cardiovascular disease, and some types of cancer. Low physical fitness's effect is comparable to hypertension, high cholesterol, and diabetes.

Consumption of Energy

The growing energy consumption is a consequence of the increasing consumption of land and reductions in population densities as cities sprawl. Generally, compact urban developments with higher population densities are more energy efficient. Evidence from 17 cities worldwide shows a consistent link between population density and energy consumption (Figure 3), particularly high energy consumption rates associated with lower population densities, characteristic of sprawling environments, dependent on lengthy distribution systems that undermine efficient energy use.

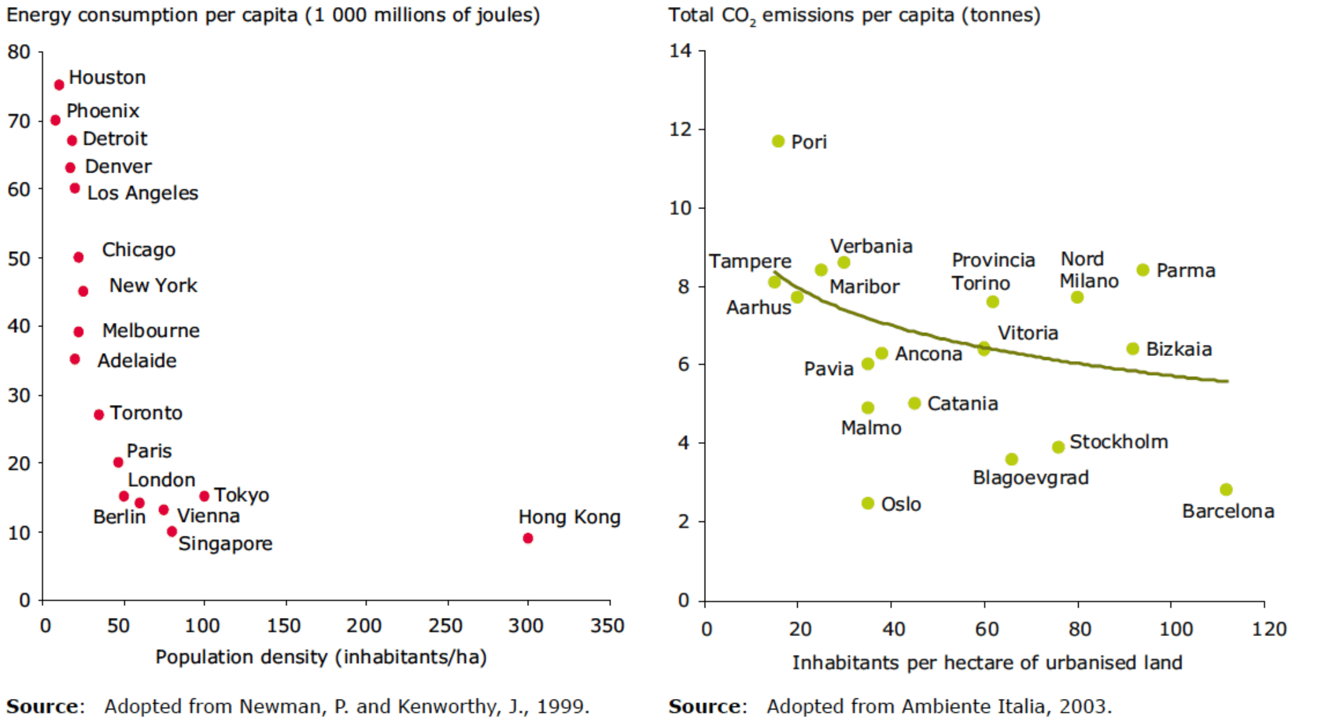


Figure 3. Left: Population density and energy consumption, selected World cities. Right: Population density and CO2 emissions, selected European cities.

Transport-related energy consumption in cities depends on various factors, including the nature of the rail and road networks, the extent of the development of mass transportation systems, and the modal split between public and private transport. Evidence shows a significant increase in travel-related energy consumption in cities as densities fall. Essentially, the sprawling city is dominated by relatively energy-inefficient car use, as the car is frequently the only practical alternative to more energy-efficient, but typically inadequate, relatively and increasingly expensive public transportation systems. Increased transport-related energy consumption is, in turn leading to an increase in the emission of CO into the atmosphere. Urban sprawl poses significant threats to the commitments to reduce GHG gas emissions.

Air pollution

Using fossil fuels also emits other gases and particulates that degrade air quality (note that commuters generate air pollution emissions, which lowers the ambient quality of the air in areas they pass through and causes health problems for other people). Longer transportation distances intensify traffic congestion, resulting in lost productivity, and increase the need for more extensive infrastructure (such as more highways) that negatively impact the environment by increasing impervious cover and requiring more natural resources. Finally, traffic congestion and air pollution from driving contribute to an estimated 900,000 fatalities annually.

Natural and Protected areas

The impacts of sprawl on natural areas are significant. The considerable impact of urban sprawl on natural and protected areas is exacerbated by the increased proximity and accessibility of urban activities to natural areas, imposing stress on ecosystems and species through noise and air pollution. Immediate impacts such as the loss of agricultural and natural land or the fragmentation of forests (Figure below), wetlands, and other habitats are well-known direct and irreversible impacts. Urban land fragmentation, with the disruption of migration corridors for wildlife species, isolates these populations and can reduce natural habitats so that the minimum area required for the viability of species populations is no longer maintained.

The environmental impacts of sprawl are evident in a number of ecologically sensitive areas located in coastal zones and mountain areas. The Mediterranean coast, one of the world's 34 biodiversity hotspots, is particularly affected, and the increased demand for water for urban use competes with irrigation water for agricultural land. This problem has been exacerbated by the increased development of golf courses in Spain, where the over-extraction of groundwater has led to saltwater intrusion into the groundwater. Increased transit and tourist traffic, particularly day tourism from the big cities, also adds to exploiting the mountain areas as a natural resource for 'urban consumption' by the lowland populations.

Figure 4. Forrest Fragmentation

Rural Environments

The growth of European cities in recent years has primarily occurred on former agricultural land. Typically, urban development and agriculture compete for the same land, as agricultural lands adjacent to existing urban areas are also ideal for urban expansion. The loss of agricultural land has a major impact on biodiversity, with the loss of valuable biotopes for many animals, particularly birds. Sprawling cities also threaten to consume the best agricultural lands, displacing agricultural activity to less productive areas (requiring higher inputs of water and fertilizers) and more remote upland locations (with increased risk of soil erosion).

Soil

Urban sprawl and urban land development dramatically transform soil properties, reducing its capacity to perform its essential functions. These impacts are evident in the extent of soil compaction, leading to impairment of soil functions; loss of water permeability (soil sealing) which dramatically decreases; loss of soil biodiversity; and reductions of the capacity for the soil to act as a carbon sink. In Germany, for example, it is estimated that 52 % of the soil in built-up areas is sealed (or the equivalent of 15 m2 per second over a decade). In addition, rainwater that falls on sealed areas is heavily polluted by tire abrasion, dust, and high concentrations of heavy metals, which degrade the hydrological system when washed into rivers.

Water Quality

Increasing numbers of roads and parking lots are needed to support an automobile transportation system, which leads to increased non-point source water pollution and contamination of water supplies (road runoff of oil/gas, metals, nutrients, and organic waste, to name a few) with possible impacts on human health. Increased erosion and stream siltation cause environmental damage and may affect water treatment plants and thus affect water quality.

Socio-economic Impacts

From a social perspective, urban sprawl generates greater segregation of residential development according to income. Consequently, it can exacerbate urban social and economic divisions. The socioeconomic character of suburban and peripheral areas is typified by middle and upper-income families with children with the necessary mobility and lifestyle to enable them to function effectively in these localities. However, the suburban experience for other groups, including the young and old, who lack mobility and resources, can be very different and reduce social interaction. Furthermore, large segments of urban society are excluded from living in such areas. From an economic perspective, urban sprawl is, at the very least, a more costly form of urban development due to the following:

- increased household spending on commuting from home to work over longer and longer distances;
- the cost to businesses of the congestion in sprawled urban areas with inefficient transportation systems;
- the additional costs of extending urban infrastructures across the urban region include utilities and related services.

Urban sprawl inhibits the development of public transport and solutions based on the development of mass transportation systems and the provision of alternative choices in transportation that are essential to ensure the efficient working of urban environments. These conclusions are reinforced by experience from both Munich and Stockholm, where the efficient control of urban sprawl and a resulting increase in population densities fosters the use of public transport and reduces the growth of car use.

Social Capital

On the social sustainability side, we can look at social capital, otherwise defined as the “connectedness” of a group built through behaviors such as *social networking and civic engagement*, along with attitudes such as trust and reciprocity. Greater social capital has been associated with healthier behaviors, better self-rated health, and fewer negative results, such as heart disease. However, social capital has been diminishing over time. Proposed causes include long commute times observed in sprawling metropolitan areas. As of 2011, according to an article in the Chicago Tribune, Chicago commuting times are some of the worst – with Chicagoans spending 70 hours per year more on the road than they would if there was no congestion – up from 18 hours in 1982. They have an average commute time of 34 minutes each way. These drivers also use 52 more gallons per year per commuter.

Sustainability, from science to philosophy to lifestyle, expresses how we shape our cities. Cities are not just a collection of structures but groups of people living different lifestyles together. When we ask if a lifestyle is sustainable, we ask if it can endure. Some archaeologists posit that environmental imbalance doomed many failed ancient civilizations. What could a sustainable city look like, how would it function, and how can we avoid an imbalance that will lead to the collapse of our material civilization?

Throughout history, settlement patterns have been set by technology and commerce. Civilizations have produced food, clothing, and shelter and accessed foreign markets to purchase and sell goods. Workers traditionally had to live near their occupation, although, in modern industrial times, advanced transportation systems have enabled us to live quite a distance from where we work.

In hindsight, we can see how reliance on water and horse-drawn transportation shaped historical civilizations and how this equation was radically altered with the rise of the automobile following World War II. While attempting to envision the "Sustainable City," we must discern what factors will influence its shape and form in the future.

Green Urbanism and Sustainable Cities

Green urbanism is a conceptual model that seeks to transform and re-engineer existing city districts and regenerate the post-industrial city center. It promotes the development of socially and environmentally sustainable city districts. The following principles of green urbanism (Figure 1) offer practical steps toward sustainable cities, harmonizing growth and usage of resources.

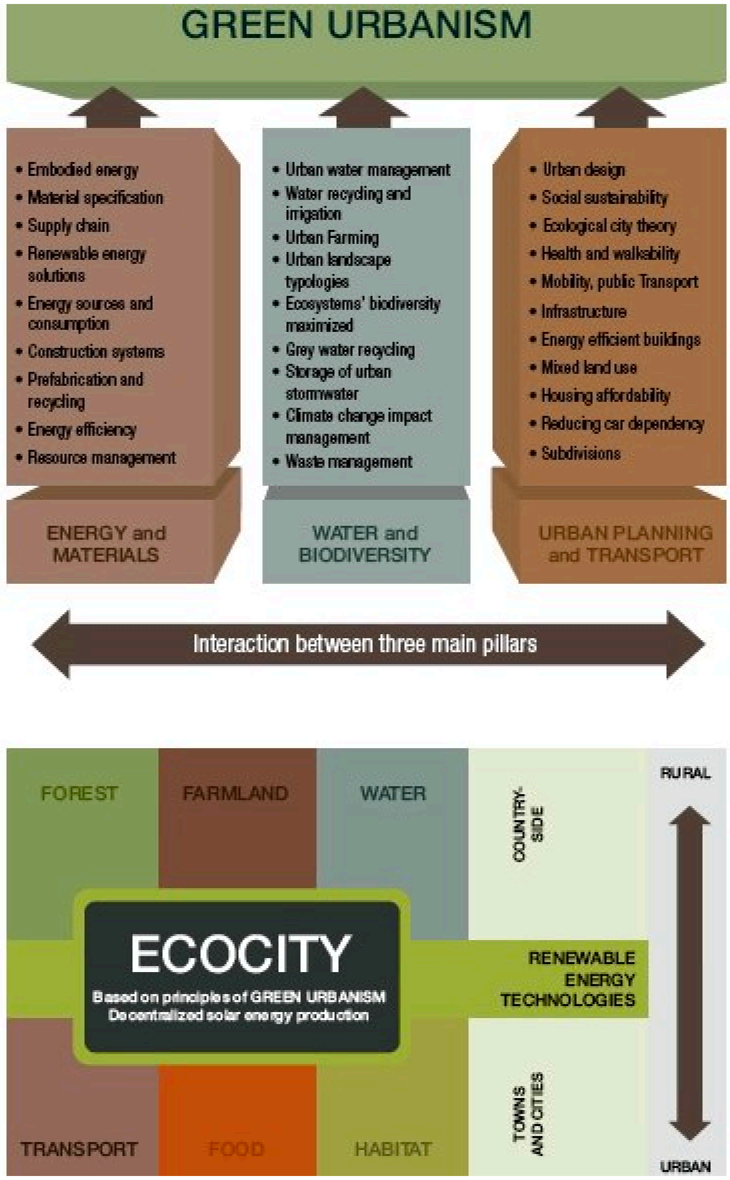


Figure 1. Green Urbanism

Climate and Context

Every site or place has unique conditions regarding orientation, solar radiation, rain, humidity, prevailing wind direction, topography, shading, lighting, noise, air pollution, and so on. The various aspects of this principle include Climatic conditions, which are seen as the fundamental influence for form generation in the design of any project; understanding the site and its context, which is essential at the beginning of every sustainable design project; optimizing orientation and compactness to help reduce the city district's heat gain or losses; achieving a city with minimized environmental footprint by working with the existing landscape, topography, and resources particular to the site, and the existing micro-climate of the immediate surroundings. Maintaining complexity in the system is always desirable (be it biodiversity, eco-system, or neighborhood layout), and a high degree of complexity is always beneficial for society. Enhancing the opportunities offered by topography and natural setting leads to a city well adapted to the local climate and its eco-system. We can use the buildings' envelope to filter temperature, humidity, light, wind, and noise. Due to the different characteristics of every location, each city district has to develop its own methods and tailored strategies to reach sustainability and capture the spirit of the place. Each site or city is different, and the drivers for re-engineering existing districts will need to understand how to take full advantage of each location's potential and fine-tune the design concept to take advantage of local circumstances. As an aim, all urban development must be in harmony with each location's specific characteristics, various site factors, and advantages and be appropriate to its societal setting and contexts (cultural, historical, social, geographical, economical, environmental, and political). In the future, all buildings should have climate-adapted envelope technologies with fully climate-responsive facades.

Renewable Energy for Zero CO_2 Emissions

The various aspects of this principle include: Energy supply systems and services, as well as energy-efficient use and operation, promoting increased use of renewable power, and perhaps natural gas as a transition fuel in the energy mix, but always moving quickly away from heavy fossil fuels such as coal and oil; and the transformation of the city district from an energy consumer to an energy producer, with local solutions for renewables and the increasing de-carbonizing of the energy supply. The oil supply will last shorter than the life expectancy of most buildings. The local availability of a renewable energy source is the first selection criteria for deciding on energy generation. Generally, a well-balanced combination of energy sources can sensibly secure future supply. A necessary aim is to have a distributed energy supply through a decentralized system, utilizing local renewable energy sources. This will transform city districts into local power stations of renewable energy sources, including solar PV, solar thermal, wind (on- and off-shore), biomass, geothermal power, mini-hydro energy, and other new technologies. The most promising technologies are building-integrated PV, urban wind turbines, micro CHP, and solar cooling. That is to say, there should be on-site electrical generation and energy storage in combination with a smart grid, which integrates local solar and wind generation, utilizing energy efficiency in all its forms. Solar hot water systems would be compulsory. Cogeneration technology utilizes waste heat through CHP combined-heat-and-power plants. Energy-efficiency programs are not enough. Too often, we find that a rise in energy use absorbs savings from energy efficiency programs. Genuine action on climate change means that coal-fired power stations cease to operate and are replaced by renewable energy sources. Eco-districts will need to operate on renewable energy sources as close to 100 percent as possible. At least 50 percent of on-site renewable energy generation should be the aim of all urban planning, where the energy mix comes from decentralized energy generation and takes into account the locally available resources, as well as the cost and availability of the technology. The energy balance can be optimized using exchange, storage, and cascading (exergy) principles. Therefore, the fossil-fuel-powered energy and transportation systems currently supporting our cities must be rapidly turned into systems supplied by renewable energy sources. High building insulation, high energy-efficiency standards, and smart metering technology are essential. If a part of an office building is not in use, the intelligent building management system will shut down lights and ventilation.

Zero-Waste

Sustainable waste management means turning waste into a resource. All cities should adopt nature's zero-waste management system. Zero-waste urban planning includes reducing, recycling, reusing, and composting waste to produce energy. All material flows need to be examined and fully understood, and special attention needs to be given to industrial waste and e-waste treatment. We need to plan for recycling centers, zero landfill, and ‘eliminating the concept of waste’ and better understand nutrient flows. Ecodistricts are neighborhoods where we reuse and recycle materials and significantly reduce the volume of solid waste and toxic chemical releases. All construction materials and the production of goods (and building components) need to be healthy and fully recyclable.

Waste prevention is always better than the treatment or cleaning up after waste is formed. Some other systems that need to be put in place are: the remanufacturing of metals, glass, plastics, and paper into new products needs to be a routine (without down-grading the product); waste-to-energy strategies are needed for residual waste; and an `extended producer responsibility’ clause is needed for all products. In this context of waste, better management of the nitrogen cycle has emerged as an important topic: to restore the balance to the nitrogen cycle by developing improved fertilization technologies and technologies in capturing and recycling waste. Controlling agriculture’s impact on the global nitrogen cycle is a growing challenge for sustainable development. Essentially, we need to become (again) a recycling society, where it is common that around 60 to 90 percent of all waste is recycled and composted.

Water

The various aspects of this principle include, in general, reducing water consumption, finding more efficient uses for water resources, ensuring good water quality, and the protection of aquatic habitats. The city can be used as a water catchment area by education using wastewater recycling and stormwater harvesting techniques. Stormwater and flood management concepts need to be adopted as part of the urban design, including stormwater run-offs, improved drainage systems, and wastewater treatment (Figure 2).

Figure 2. Description of Rainwater Harvesting Techniques (1) and a Sample Dual-Flush Water-Efficient Toilet (2) at a Rio de Janeiro Hardware Store.

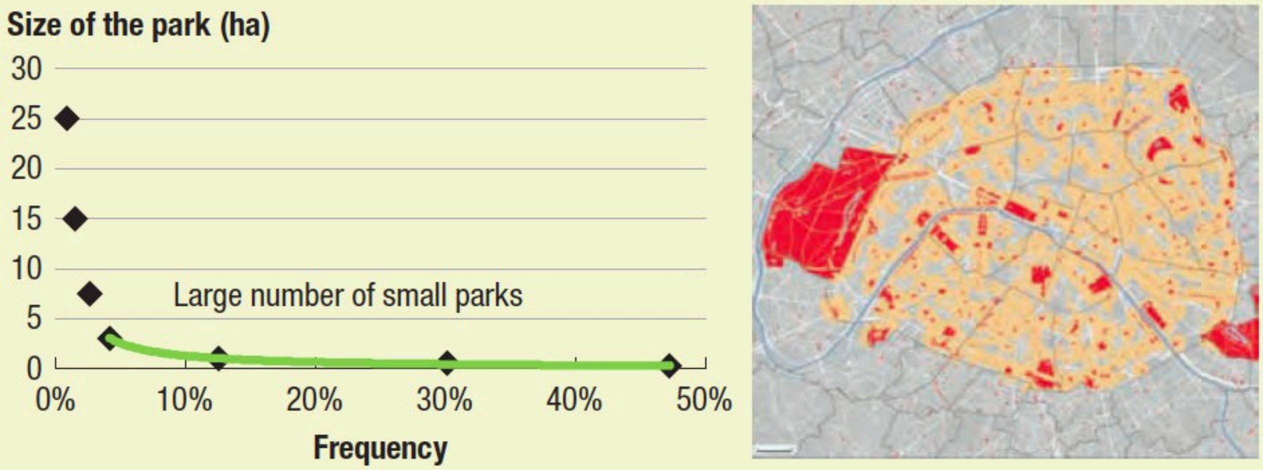
As part of the eco-districts, adequate and affordable health care provisions must ensure safe water and sanitation supply. This includes algae and biofiltration systems for grey water and improving the quality of our rivers and lakes so they are fishable and swimmable again. An integrated urban water cycle planning and management system that includes a high-performance infrastructure for sewage recycling (grey and black water recycling), stormwater retention, and harvesting the substantial run-off through storage must be routine in all design projects. On a household level, we need to collect rainwater and use it sparingly for washing and installing dual-water systems and low-flush toilets. On a food production level, we need to investigate the development of crops that need less water and are more drought resistant.

Landscape, Gardens, and Urban Biodiversity

A sustainable city takes pride in its many beautiful parks and public gardens (Figure 3). This pride is best formed through a strong focus on local biodiversity, habitat and ecology, wildlife rehabilitation, forest conservation, and the protection of regional characteristics. Ready access to these green spaces (Figure 4): public parks and gardens, with opportunities for leisure and recreation, are essential components of a healthy city, as is arresting the loss of biodiversity by enhancing the natural environment and landscape and planning the city using ecological principles based on natural cycles (not on energy-intensive technology) as a guide, and increasing urban vegetation. A city that preserves and maximizes its open spaces, natural landscapes, and recreational opportunities is more healthy and resilient. The sustainable city must also introduce inner-city gardens, **urban farming**, and **green roofs** in all its urban design projects (using the city for food supply).

Figure 3. Urban Farming in Chicago. Some new crops were being started, protected by shade cloth barriers to the west.

It needs to maximize the resilience of the ecosystem through urban landscapes that mitigate the `urban heat island' (UHI) effect, using plants for air purification and urban cooling. Further, narrowing roads, which calms traffic and lowers the UHI effect, allows for more (all-important) tree planting. Preserving green space, gardens, and farmland, maintaining a green belt around the city, and planting trees everywhere (including golf courses), as trees absorb CO_2, is an important mission.



Left: Long tail distribution of parks in Paris, with the long tail of small parks in green.
Right: Numerous small parks in Paris ensure 5 minute walk accessibility to parks (red) to 80% of the people.

Figure 4. Comparison of green space in Paris, France. Green spaces are an essential feature of energy-efficient and livable cities. However, many urban policies concerning green spaces in emerging countries' cities boil down to a predetermined percentage of green space. What really matters is access and proximity of green spaces with diversified social activities instead of proportion only. The spatial distribution of green spaces in Paris results from policies and regulations that have ensured that every citizen lives less than 400 m from a public park, square, or garden. This target has been reached, whereas green spaces only represent 5 percent of the urban area. A few large parks allow a wide range of activities for residents and a large number of very successful pocket parks for daily family activities and inter-generational mix (300 green spaces less than 6 ha). As a comparison, green spaces in Beijing represent 30 percent of the urban area. Most green spaces are very big parks, and the long tail of small parks is lacking. As a result, residents live more than 3 km away from public parks on average.

As is conserving natural resources, respecting natural energy streams, and restoring stream and river banks, maximizing species diversity. At home, we need to de-pave the driveway or tear up parking lots. In all urban planning, we need to maintain and protect the existing ecosystem that stores carbon (e.g., through a grove or a park) and plans to create new carbon storage sites by increasing the amount of tree planting in all projects. The increase in the percentage of green space as a share of total city land will be combined with densification activities.

Sustainable Transport and Good Public Space: Compact and Poly-Centric Cities

Good access to basic transport services is crucial, as it helps to reduce automobile dependency, as does reducing the need to travel. We need to see integrated non-motorized transport, such as cycling or walking, and, consequently, bicycle/pedestrian-friendly environments with safe bicycle ways, free rental bike schemes, and pleasant public spaces. Identifying the optimal transport mix that offers interconnections for public transport and integrating private and public transport systems is important.

Some ideas include eco-mobility concepts and smart infrastructure (electric vehicles), integrated transport systems (bus transit, light railway, bike stations), improved public space networks and connectivity, and a focus on transport-oriented development. It is a fact that more and wider roads result in more car and truck traffic and CO emissions. Also, it allows for sprawling development and suburbs that increase electricity demand and provides less green space. The transport sector is responsible for causing significant greenhouse-gas emissions (over 20 percent). To combat this effect, we need to change our lifestyles by, for example, taking public transport, driving the car less, or car-pooling. Alternatively, we can bike or walk if the city district has been designed for it. Personal arrangements have the potential to reduce commuting and boost community spirit. We want a well-connected city district for pedestrians, a city with streetscapes that encourage a healthy, active lifestyle, and where residents travel less and less by car.

Density and Retrofitting of Existing Districts

The various aspects of this principle include: encouraging the densification of the city center through mixed-use urban infill (Figure 5), center regeneration and green transit-oriented development (TOD); increasing sustainability through density and compactness; promoting business opportunities around green transit-oriented developments; optimizing the relationship between urban planning and transport systems; retrofitting inefficient building stock and systematically reducing the city district's carbon footprint.

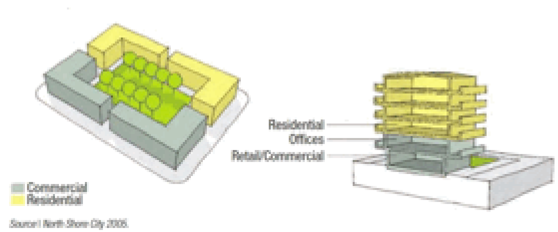


Figure 5. Mixed Use on the Block and Building Scale.

Consideration will need to be given to better land-use planning to reduce the impact of urban areas on agricultural land and landscape; to increase urban resilience by transforming city districts into more compact communities and designing flexible typologies for inner-city living and working. Special strategies for large metropolitan areas and fast-growing cities are required. Here, examples of rapid development are being provided by Asian cities. Special strategies are also needed for small and medium-sized towns due to their particular milieu, and creative concepts are needed for the particular vulnerabilities of Small Island States and coastal cities. Public space upgrading through **urban renewal** programs will bring people back to the city center. This will need some strategic thinking about using brownfield and greyfield developments and the adaptive reuse of existing buildings. Remodeling and re-energizing existing city centers to bring about diverse and vibrant communities requires people to move back into downtown areas. This can be achieved through mixed-use urban infill projects, building the "city above the city" by converting low-density districts into higher-density communities and revitalizing underutilized land for community benefit and affordable housing.

Green Buildings and Districts, Using Passive Solar Design Principles

The various aspects of this principle include low-energy, zero-emission designs, applying best practices for **passive solar design principles** (Figure 6) for all buildings and groups of buildings; dramatically reducing building energy use, introducing compact solar architecture, and renovating and retrofitting the entire building stock. New design typologies need to be developed at a low cost, and we need to produce functionally neutral buildings that last longer.

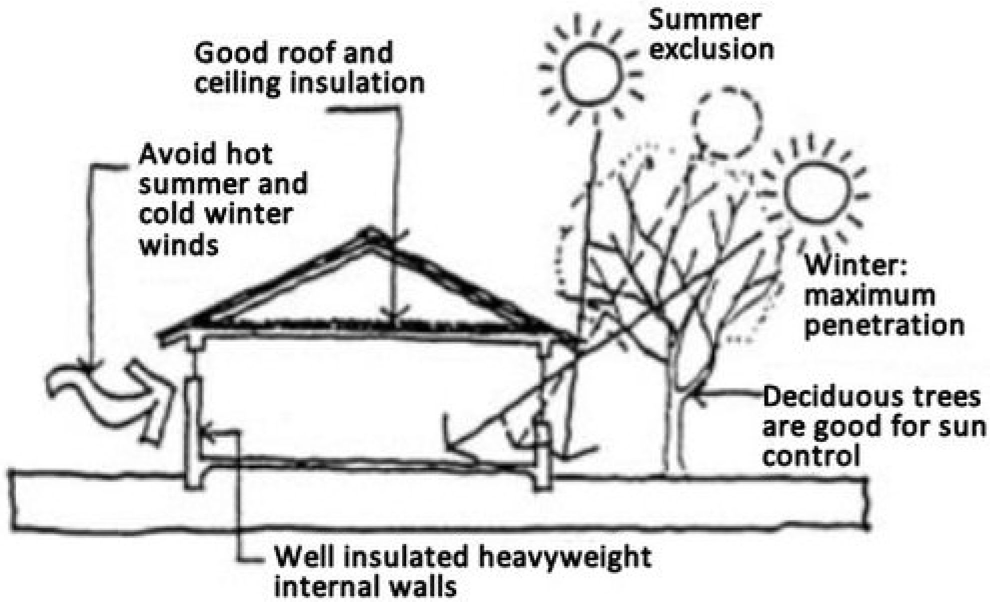


Figure 6. Passive Solar Design

We need to apply facade technology with responsive building skins for bio-climatic architecture to take advantage of cooling breezes and natural cross-ventilation, maximizing cross-ventilation, day-lighting, and opportunities for night-flush cooling; we need to focus on the low consumption of resources and materials, including the reuse of building elements and design for disassembly. Other ideas include mixed-use concepts for compact housing typologies; adaptive reuse projects that rejuvenate mature estates; solar architecture that optimizes solar gain in winter and sun shading technology for summer, catching the low winter sun and avoiding too much heat gain in summer. It is important to renew the city with energy-efficient green architecture, creating more flexible buildings of long-term value and longevity. Flexibility in a plan leads to a longer life for buildings. Technical systems and services have a shorter life cycle. First, this means applying technical aids sparingly and making the most of all passive means provided by the building fabric and natural conditions. Buildings that generate more energy than they consume, and collect and purify their own water, are achievable. We need to acknowledge that the city as a whole is more important than any individual building.

Local and Sustainable Materials with Less Embodied Energy

The various aspects of this principle include advanced materials technologies, using opportunities for shorter supply chains, where all urban designs focus on local materials and technological know-how, such as regional timber in common use. Affordable housing can be achieved through modular prefabrication. **Prefabrication** (Box below) has come and gone several times in modern architecture. Still, this time, with closer collaboration with manufacturers of construction systems and building components in the design phase, the focus will be sustainability. We need to support innovation and be aware of sustainable production and consumption, the embodied energy of materials, and energy flow in closing life cycles. We must emphasize green manufacturing and an economy of means, such as process-integrated technologies that reduce waste. Using lightweight structures, enclosures, and local materials with less embodied energy is more environmentally friendly, requiring minimal transport. We need improved material and system specifications, supported by research in new materials and technological innovation, and reduced material diversity in multi-component products to help facilitate the design for resource recovery, disassembly, value retention, and the possibility of reusing entire building components. Success in this area will increase the long-term durability of buildings, reduce waste and minimize packaging.

In April 2010, a prototype AQUA house for low-income families was exhibited in São Paulo. It measures 40 square meters and has a construction cost of R$45,000 (11,000 USD). Some of the sustainable solutions adopted include a rainwater reuse system consisting of a cistern and permeable soil; a solar water heater; fiber-cellulose shingles; and soil-cement bricks, which are dimensioned and prefabricated to allow for faster assembly and do not use mortar, thereby reducing costs. A sloped roof with skylights was designed to take advantage of natural light and ventilation. The house's interior also includes environmentally friendly products such as cement board made from mineralized wood, which does not require finishing, and recycled Tetra Pak packaging on some walls. The house has a dual-flush toilet, which reduces water usage, and fluorescent light bulbs. The Casa AQUA construction takes 30-60 days to complete.

Livability, Healthy Communities, and Mixed-Use Programs

Land use development patterns are the key to sustainability. A mixed-use (and mixed-income) city delivers more social sustainability and inclusion and helps repopulate the city center. Demographic changes, such as age, are a major issue for urban design. It is advantageous for any project to maximize the diversity of its users. Different sectors in the city can take on different roles over a 24-hour cycle; for example, the Central Business District is used for more than just office work. In general, we want

connectivity (Figure 8), compact communities for a livable city, applying mixed-use concepts and strategies for housing affordability, and offering different typologies for housing needs.

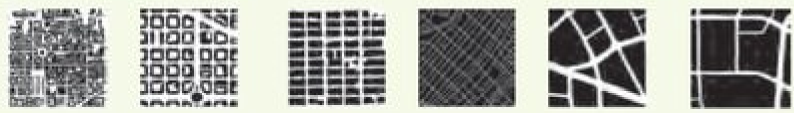
	Turi, Estonia	Barcelona, Spain	Paris, France	Ginza, Tokyo	Pudong in Shanghai, China	Towers North in Beijing, China
						
Intersections per km^2	152	103	133	211	17	14
Distance between intersections (m)	80	130	150	43	280	400

Figure 8. The Absence of Connectivity and Fine Grain in Chinese Urban Developments. The pictures illustrate the size of blocks and their impacts on the connectivity of a series of cities in Europe, Japan, and China. It shows the absence of connectivity and increased average distances between intersections in recent urban developments in China.

To this end, we need affordable and livable housing and new flexible typologies for inner-city living. These mixed-use neighborhoods (of housing types, prices, and ownership forms) have to avoid gentrification and provide affordable housing with districts inclusive for the poor and the rich, young and old, and workers of all walks of life, and also provide secure tenure (ensuring ‘aging in place’). Mixed land uses are particularly important as it helps reduce traffic. Master plans should require all private developments to contain 40 to 50 percent of public (social) housing and integrate it with private housing. Higher densities should center on green TODs. These changes will introduce more sustainable lifestyles, with jobs, retail, housing, and a city campus nearby. IT and telecommuting (Figure 9) from home significantly help reduce travel.

Figure 9. Telecommuting

By integrating a diverse range of economic and cultural activities, we avoid mono-functional projects, which generate a higher demand for mobility. Green businesses would be supported through ethical investments to generate funding.

Local Food and Short Supply Chains

The various aspects of this principle include local food production; regional supply; an emphasis on urban farming and agriculture, including `eat local' and `slow food' initiatives. The sustainable city provides adequate land for food production, a return to the community, and the allotment gardens of past days, where roof gardens become an urban market. We must bridge the urban-rural disconnect and move cities towards models that deal with natural ecosystems and healthy food systems.

The people of the eco-city would garden and farm locally, sharing food, creating compost with kitchen scraps and garden clippings, and growing `community' vegetables. Buying and consuming locally will be necessary to cut down on petrol-based transport. Such things as reusing bags and glass containers, paper recycling, and the cost of food processing will need reconsideration. We will need to reduce our consumption of meat and other animal products, especially shipped-in beef, as the meat cycle is very intensive in energy and water consumption, and herds create methane and demand great quantities of electricity. Perhaps as much as 50 percent of our food will need to be organically produced, without using fertilizers or pesticides made from oil, and grown in local allotments.

Cultural Heritages, Identity, and Sense of Place

All sustainable cities aim for air quality, health, and pollution reduction, to foster resilient communities, and to have strong public space networks and modern community facilities. This is the nature of sustainable cities. However, each city has its own distinct environment, whether by the sea, a river, in a desert, or a mountain; whether its climate is tropical, arid, temperate, etc., each situation is unique. The city's design will consider all these factors, including materials, history, and population desires. The essence of a place is the up-swelling of grassroots strategies, the protection of its built heritage, and the maintenance of a distinct cultural identity, e.g., by promoting locally owned businesses and supporting creativity and cultural development. New ideas require affordable and flexible studio space in historic buildings and warehouses. Cities will grow according to the details and unique qualities of localities, the demographic qualities of the populace, and the creativity of the authorities and citizens. A city aims to support its residents' health, activities, and safety. It is, therefore, incumbent on city councils to protect the city by developing a master plan that balances heritage with conservation and development, fostering distinctive places with a strong sense of place, where densities are high enough to support basic public transit and walk-to retail services.

Urban Governance, Leadership, and Best Practice

Good urban governance is extremely important to transform existing cities into sustainable compact communities. It has to provide efficient public transport, good public space and affordable housing, and high urban management standards; change will not happen without political support. City councils need strong management and political support to realize their urban visions. They need strong support for a strategic direction to manage sustainability through coherent combined management and governance approaches, which include evolutionary and adaptive policies linked to a balanced review process, and to help public authorities overcome their unsustainable consumption practices and change their methods of urban decision-making. A city that leads and designs holistically that implements change harmoniously, and where decision-making and responsibility are shared with the empowered citizenry is a city that is on the road to sustainable practices. In balancing community needs with development, public consultation exercises and grassroots participation are essential to ensuring people are sensitive to urban design and to encouraging community participation. Citizens need to participate in community actions aimed at governments and big corporations by writing letters and attending city-council hearings. Empowering and enabling people to be actively involved in shaping their community and urban environment is one of the hallmarks of a democracy. Cities are a collective responsibility. As far as bureaucratic urban governance and best practice is concerned, and authorities could consider many of the following: updating building code and regulations; creating a database of best practices and worldwide policies for eco-cities; revising contracts for construction projects and integrating public management; raising public awareness; improving planning participation and policy-making; creating sustainable subdivisions, implementing anti-sprawl land-use and growth boundary policies; legislating for controls in density and supporting high-quality densification; arriving at a political decision to adopt the Principles of Green Urbanism based on an integrated Action Plan; measures to finance a low-to-no-carbon pathway; implementing environmental emergency management; introducing a program of incentives, subsidies, and tax exemptions for sustainable projects that foster green jobs; eliminating fossil-fuel subsidies; developing mechanisms for incentives to accelerate renewable energy take-up; implementing integrated land-use planning; having a sustainability assessment and certification of urban development projects.

Education, Research, and Knowledge

The various aspects of this principle include technical training and up-skilling, research, exchange of experiences, and knowledge dissemination through research publications about ecological city theory and sustainable design. Primary and secondary teaching programs need to be developed for students in such subjects as waste recycling, water efficiency, and sustainable behavior. Changes in attitude and personal lifestyles will be necessary. The city is a hub of institutions, such as galleries, libraries, and museums, where knowledge can be shared. We must provide sufficient access to educational opportunities and training for the citizenry, thus increasing their chances of finding green jobs. Universities can act as `think tanks' for transforming their cities. We also need to redefine the education of architects, urban designers, planners, and landscape architects. Research centers for sustainable urban development policies and best practices in eco-city planning could be founded, where assessment tools to measure environmental performance are developed, and local building capacity is studied.

Strategies for Cities in Developing Countries

Developing and emerging countries have their needs and require particular strategies, appropriate technology transfers, and funding mechanisms. Cities in the developing world cannot have the same strategies and debates as cities in the developed world. Similarly, particular strategies for emerging economies and fast-growing cities are required, as is the problem of informal settlements and urban slums and slum upgrading programs. Cooperation with poverty reduction programs, low-cost buildings, and mass housing typologies for rapid urbanization is required. We must train local people to empower communities, create new jobs, and diversify job structures to not focus on only one segment of the economy (e.g., tourism). Achieving more sustainable growth for Asian metropolitan cities is a necessity. Combating climate change, mainly caused by the emissions by industrialized nations and which is having its worst effect in poorer countries in Africa, Asia, and Latin America, with a focus on the Small Island States, is a priority.

Across the globe, municipalities and their communities are responding to the sustainability transition challenges. Two of these, Chattanooga (Figure 1) and Curitiba (Figure 2), illustrate the differences in motivation that can impel cities in differing locations and conditions to innovate. Chattanooga was driven to change by the economic, social, and health impacts of chokingly high levels of industrial pollution. Within ten years, the city turned from being the 'most polluted city' in the USA to becoming its 'sustainable development capital.' This story has a powerful 'demonstration effect' on other cities. But if Chattanooga was a city that was forced to react, Curitiba is an example of a proactive city. This administration planned for change rather than being overtaken by change. Neither city is sustainable in the full sense of the word: they both have large ecological footprints, there is still racial division and urban sprawl in Chattanooga, and poor sanitation and squatter settlements in Curitiba. But both cities are unlearning old ways and learning new ways in partnership with their communities, and this is the essence of the sustainability challenge.

Chattanooga, Tennessee: Belle of the Sustainable Cities Ball

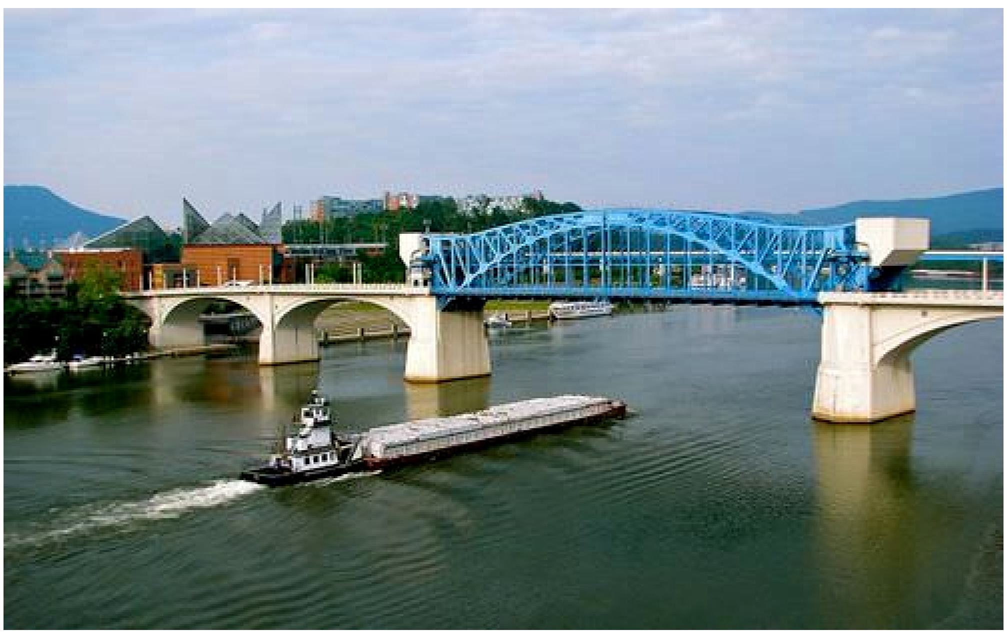


Figure 1. The John Ross Bridge, in Chattanooga, Tennessee.

Fifty years ago, the US government labeled Chattanooga, Tennessee, the dirtiest city in America. Today, the President's Council on Sustainable Development hailed the city as a sustainability success story. Chattanooga's turnaround has inspired communities worldwide, and the former manufacturing center is now selling itself as a world leader in the sustainable cities movement. In a matter of decades, the city of 150,000 has transformed its city center into a prime job center and bustling tourist attraction (with a state-of-the-art aquarium); created a revitalized waterfront to which birds are now returning; re-used a former Army facility, once the largest producer of TNT worldwide, as a manufacturing site for electric buses; is attracting clean industry through the development of an eco-industrial park; and is experimenting with 'zero-emission' manufacturing processes. The secret of Chattanooga's success lies in visionary civic leaders, a committed and engaged local population, public-private partnerships, and adventurous financial investors willing to fund a series of environmental innovations. The process began in 1984 when city residents ‘responded to a planning initiative by saying they wanted more than a strong local economy. They wanted to go fishing without driving out of town and to be able to eat the fish they caught without worrying about their health. This led to a visioning process, Vision 2000, which brought together city residents from all walks of life to identify the city’s problems — and find solutions. Forty goals were set, ranging from affordable housing to river clean-up. Pre-existing urban revitalization initiatives fed into, and were transformed by, this process of ecology-based urban renewal. The experimentations continue, and the city has adopted sustainable development as its motto — expressed in the shorthand ‘equity, environment and economy.’ This has become its unique selling point. While Chattanooga’s gains are impressive, whether its performance can live up to its marketing claims over time remains to be seen. Like most U.S. cities, the city still suffers from chronic urban sprawl and the loss of habitat and agricultural land.

Curitiba, Brazil: A Laboratory for Sustainable Urban Development

Figure 2. Curitiba, Brazil: A Laboratory for Sustainable Urban Development

Curitiba is one of the fastest-growing industrial cities in Brazil, with a population of over 2.1 million. Yet, compared to other cities its size, Curitiba has significantly less pollution, no gridlocked city center, a slightly lower crime rate, and a higher educational level among its citizens. The city is held up as an example of far-sighted and unconventional planning. For example, its ‘design with nature strategy’ has increased the amount of green space per capita (during a period of rapid population growth), and its mass transit strategy has cut total travel time by a third for its citizens and contributed to the city having one of the lowest rates of ambient pollution in the country. Curitiba’s success lies in the gradual institutionalisation (over a period of 30 years) of urban development policies explicitly favoring: public transport over private automobiles; appropriate rather than high-tech solutions; innovation with citizen participation instead of master planning; incentive schemes to induce changes in business, household and individual behavior; and labor-intensive approaches rather than mechanization and massive capital investment. Such policies were officially adopted in the 1970s by Jaime Lerner, a visionary mayor who was also an architect and planner who helped pre-empt the usual growth-related problems that comparable cities face. Among Curitiba's innovative features are: ·

- transport — an express bus-based transportation system designed for speed and convenience which is also self-financing, affordable, wheelchair-accessible, and offers balanced routes;
- solid waste — a garbage-purchase program that pays low-income families in bus tokens or food in exchange for waste; more than 70% of households also sort recyclable materials for collection;
- housing — a low-income housing program with ready access to jobs in Curitiba's Industrial City (which generates one-fifth of all jobs in the city; polluting industries are not allowed).
- incentives — provision of public information about the land to fight land speculation;
- environmental education — free, practical short courses for workers and residents on the environmental implications of their work are offered by Curitiba's Free University for the Environment.

Summary

Urbanization is the study of the social, political, and economic relationships in cities. There are three prerequisites for the development of a city. First, a good environment with fresh water and a favorable climate; second, advanced technology, producing a food surplus to support non-farmers; and third, strong social organization to ensure social stability and a stable economy. Urbanization levels are affected by two things – migration and natural increase. Global urbanization reached the 50 percent mark in 2008, meaning that more than half of the global population lived in cities compared to only 30 percent 50 years ago. Access to basic services— clean water, sanitation, electricity, and roads—are some of the main urbanization challenges facing the developing world. Long commute times, observed in sprawling metropolitan areas, are unsustainable in many aspects. Various negative health and environmental consequences related to these development trends can be identified. Green urbanism is a conceptual model that seeks to transform and reengineer existing city districts and regenerate the post-industrial city center. It promotes the development of socially and environmentally sustainable city districts. The principles of green urbanism offer practical steps on the path to sustainable cities, harmonizing growth and usage of resources.

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Chapter Attributions:

ABIOTIC
nonliving components of an ecosystem

ACCLIMATION
to become accustomed to a new climate or environment; to physically adapt

AGENT ORANGE
an herbicide used by the U.S. military to defoliate forests during the Vietnam War

AGRO-ECOSYSTEM
The area of land that is influenced by or that supports agricultural activity; land used for crops, pasture, and livestock, the adjacent uncultivated land that supports other vegetation and wildlife and the associated atmosphere, the underlying soil, ground and water, irrigation channels, and drainage networks

AIR QUALITY INDEX (AQI)
a numerical index used by government agencies to inform the public of air quality levels

ALGAL BLOOM
a rapid increase of accumulation in the population of algae (typically microscopic) in an aquatic system

ALKYLPHENOL
a commonly accepted marker of industrial and urban pollution; a family of organic compounds used in the production of detergents and other cleaning products

ALLUVIUM
a deposit of sand, mud, or other sediment formed by flowing water

ANADROMOUS
a species which migrates from the sea to freshwater to reproduce

ANNUAL CROPS
crops that grow, produce seeds, and die in a year and must be replanted each season

ANTHROPOGENIC
caused by or related to human action; originating in human activity

AQUACULTURE
Farming of aquatic organisms (plant or animal) in any water environment (ocean, pond, or river)

AQUEDUCT SYSTEM
a series of pipes, ditches, canals, tunnels, and supporting structures used to transport water from its source to its main distribution point

AQUIFER
an underground layer of permeable rock or soil that is saturated with water; a geological formation containing ground water

ARID
a region characterized by a severe lack of available water to the extent of hindering or preventing the growth and development of plant and animal life

ATMOSPHERE
the layer of gases surrounding Earth and held by Earth's gravity

ATMOSPHERIC RIVERS
regions of intense moisture over oceans that transport moisture from lower altitudes to higher altitudes

ATOLL
a region characterized by a severe lack of available water to the extent of hindering or preventing the growth and development of plant and animal life

BACTERIA
a single-celled, prokaryotic organisms that lacks a nuclei
BALLAST WATER
water taken into the haul of a shipping vessel to provide stability
BIODIVERSITY
the variety of life on Earth or in a particular habitat or ecosystem
BIOLOGICAL CONTROL
biocontrol, a management practice that involves introducing a predator to an area to regulate the population of a pest
BIOMAGNIFICATION
the increased level of substances within the tissue of predators as a result of consuming organisms that contain bio-accumulated substances such as mercury
BIOMASS
material from plants and animals that can be used for energy
BIOTIC
the living or organic components of an ecosystem
BIRTH DEFECT
structural or functional abnormalities present at birth that cause physical or mental disability
BRINE
water saturated with salt; a liquid with high salinity
BROADCAST
to uniformly distribute fertilizer on a soil surface without working it into the soil
BYCATCH
a non-target organism that is caught unintentionally when harvesting a target species
CALCIUM CARBONATE
CaCO3; a common chemical compound composed of three main elements calcium, carbon and oxygen
CANCER
a type of disease characterized by unregulated cell growth
CARBON CREDITS
a permit that represents carbon removed from the atmosphere, which companies or governments can purchase to offset the carbon emissions they generate
CARBON SINK
a process or material in an environment that removes carbon dioxide from the atmosphere
CARCINOGENIC
cancer-causing
CARRYING CAPACITY
the population size that an area can support indefinitely
CESIUM-137
one of the common fission products of uranium nuclear power plants
CLEAN AIR ACT
U.S. law that authorizes the EPA to set standards for dangerous air pollutants and enforce those standards
CLEAN WATER ACT
U.S. federal legislation that regulates the release of point source pollution into surface waters and sets water quality standards for those waters
CLIMATE
long-term weather conditions in a particular region

CLIMATE CHANGE
a change in global climate patterns such as rainfall and average regional temperature
CLIMATOLOGY
the scientific study of Earth's climates, climate variability, climate change, and effects of climate on the biosphere
COLIFORM BACTERIA
type of bacteria that are universally found in the feces of warm-blooded animals; commonly used as a water quality indicator
COLONIES
refers to individual organisms of the same species living closely together
COLONY COLLAPSE DISORDER (CCD)
a disorder in honey bees categorized by sudden loss of worker bees, lack of dead bodies, and delayed invasion from attackers
COMMODITY
a physical substance that is uniform in quality and can be bought and sold
CONDENSE
to change from a gas to a liquid
CONDUCTOR
a material that easily permits the flow of electrons, often an electric current
CONSERVATION
a political, environmental, and social movement to help protect natural resources and wildlife from exploitation
CONTAMINATION
to make something dangerous, dirty, or impure by adding something harmful or undesirable to it
CONTRACEPTION
a technique used to prevent pregnancy
CORAL BLEACHING
the expulsion of the algae living within coral's tissues causing it to die
CORRELATION
a statistical relationship involving the dependence of two or more variables
CRITICALLY ENDANGERED
a species that is facing a very high risk of extinction
CRITTERCAM
a camera that is attached to a wild animal with intent of studying the animal's behavior and ecology
CROP YIELD
the amount of product a crop produces per unit of land in a given time
CULLING
a method of population control that involves the killing of an entire family unit
DEFORESTATION
removal of forest areas by humans for non-forest use, often for agriculture
DESALINATION
the removal of salt from a water source to convert it to fresh water, often used with seawater
DESERTIFICATION
the increased degradation of drought-affected areas, causing them to become deserts
DIABETES
a metabolic disorder defined by high blood sugar and insulin resistance

DIOXINS
a group of chemically related compounds that are classified as environmental pollutants
DISRUPTIVE STIMULI
chemical, light, or audio repellents used to try and deter organisms
DISTILLATION
the process of separating substances in a mixture
DNA
deoxyribonucleic acid; found in all living organisms and contains genetic information
DROUGHT
an extended amount of time with little to no precipitation
ECOLOGICAL SOCIETY OF AMERICA
a nonpartisan, nonprofit organization of scientists founded to promote, conduct, and disseminate studies in the ecological sciences
ECOSYSTEM
all of the organisms in a given area interacting in a physical environment
EDNA
Environmental DNA; genetic material left behind by a species
EFFLUENT
liquid waste discharged into a body of water; outflow from a sewage treatment plant that is rich in nutrients
ELECTRIC FISH BARRIER
a tool that sends low-level electric currents into a body of water to cause discomfort in fish and cause them to move away from the affected area; used to regulate the movement of fish
EMERALD ASH BORER
a green beetle that was accidentally transported from Asia to North America in the 1990s and has caused widespread destruction of ash trees in the United States and Canada
EMISSIONS
the production and discharge of a gas
ENDANGERED
a species that is threatened with extinction
ENDOCRINE DISRUPTOR
a chemical that interferes with the endocrine system, typically mimicking a hormone or preventing a hormone from having effect
ENDOCRINE SYSTEM
the system cells, glands, and tissue within an organism that is responsible for secreting hormones into the bloodstream
ENTRAINMENT
the loss of fish during water diversion often occurs when fish enter irrigation systems and become isolated when diversion ends
ENVIRONMENTAL PROTECTION AGENCY (EPA)
a federal agency in the United States tasked with implementing legislation concerning the protection of the environment
ENVIRONMENTAL SUSTAINABILITY INDEX
a measure of a country's overall progress toward environmental sustainability
ENZYME
a molecular protein that acts as a catalyst and facilitates complex biological reactions
EROSION

the process by which something is gradually worn away by natural forces (wind, water, or other natural agents)

EUROPEAN UNION

economic and political union of 28 member states that are located primarily in Europe

EUTROPHICATION

the process by which a body of water is enriched with nutrients (nitrogen and phosphorus), stimulating excessive growth of photosynthetic organisms like algae. Human activities can accelerate the process.

EXTINCTION

the complete loss of a species

EXTIRPATION

describes a species that is locally extinct in one or more areas within its historical range

FALLOUT

airborne radioactive particles that gradually fall back to Earth after a nuclear blast

FECUNDITY

related to fertility; the actual reproductive rate of an organism

FIELD TRIALS

small, controlled fields of genetically modified plants used to conduct research

FLOY TAG

a small piece of plastic attached to live fish as part of scientific studies; a company that produces tags used to identify live fish as part of studies specifically

FOLSOM LAKE

a reservoir in Northern California formed by the Folsom Dam that provides flood control, drinking water, hydroelectricity, and water for irrigation to the surrounding communities

FOOD AND DRUG ADMINISTRATION (FDA)

a federal agency of the United States government found within the Department of Health and Human Services, which is responsible for protecting the public health by assuring the safety, efficacy and security of human and veterinary drugs, biological products, medical devices, food supply, cosmetics, and products that emit radiation

FOSTERING

when a female cares for and raises an orphaned juvenile in addition to her own offspring or after the death of her biological offspring

FOUL BROOD DISEASE

a disease in bees in which bacteria attack larvae and kill them before they mature

FRACKING FLUID

a combination of sand, liquids, and chemicals used in the hydraulic fracturing process, which is pumped underground to break away natural gasses from permeable rock layers

FUNCTIONAL EXTINCTION

when a population becomes so reduced that it no longer plays an important role in the way an ecosystem functions

FUNGUS

a diverse group of eukaryotic single-celled or multicelled organisms that live by decomposing organic material

GAME RESERVATION

a controlled area used for wildlife conservation which sometimes allows regulated hunting

GENE

the hereditary material of an organism that directs the production of a particular protein and influences an individual’s traits

GENETIC DIVERSITY
the hereditary variability among individuals of a single population or within a species

GENETIC MARKER
a gene or short sequence of DNA used to identify a chromosome or to locate other genes on a genetic map

GENETIC MUTATION
a heritable change in the DNA sequence

GENOTYPE
the complete genetic content of an organism

GHOST TOWN
a human settlement, such as a town, that has few or no remaining inhabitants

GLOBAL WARMING
a scientifically observed and ongoing rise in the biosphere's average temperature that is contributing to climate change

GMO
a genetically modified organism; an organism whose DNA has been altered with a gene from another species to produce a desired trait

GOLDEN RICE
a variety of rice that has been genetically modified to produce beta-carotene, a precursor of vitamin A

GRAPHITE MODERATOR
a nuclear reactor that uses carbon as a neutron moderator, which allows un.enriched uranium to be used as nuclear fuel

GREENHOUSE GASES
water vapor, carbon dioxide, methane, nitrous oxide, and ozone; gases that contribute the greenhouse effect and global climate change

GROSS DOMESTIC PRODUCT (GDP)
the total value of goods and services provided in a country during a one-year period

GROUNDWATER
the water beneath the surface of the ground, consisting largely of surface water that seeped into the ground

HABITAT
the environment in which an animal or plant species resides

HALLIBURTON LOOPHOLE
a provision included in the U.S. Energy Policy Act of 2005 that gave natural gas drilling and extraction companies exemptions from the Safe Drinking Water Act

HAULING OUT
leaving the water to stay on land between periods of foraging

HEGEMONY
a form of government where one state or group has cultural, economic, and military dominance over all others

HERBICIDE
a substance used to exterminate or slow the growth of plants

HIBERNATION
cessation from or slowing of activity during the winter

HIGH PRESSURE RIDGE
a region where the atmospheric pressure at the surface of the planet is greater than its surrounding environment

HOME RANGE
the area where an organism lives and travels

HYDRAULIC FRACTURING
aka fracking; the process of breaking up subsurface rock formations through the use of high-pressure liquids usually mixed with sand and chemicals to extract gas and oil

HYDROGEOLOGY
the study of the distribution and movement of water through the Earth

HYDROGRAPH
a graph showing the rate by which water flows past a specific point in a river over time, or a chart that displays a hydrologic variable over time

HYPOXIA
a condition in which a body of water contains inadequate amount of oxygen, compromising the health of aquatic organisms

IMMUNOCONTRACEPTION
a type of contraceptive technique that uses immunochemistry as opposed to hormones to prevent pregnancy

INACTIVE INGREDIENT
an ingredient that does not increase or affect the intended action or purpose of a formulated product, drug, or pesticide

INFRASTRUCTURE
the physical and organizational structures and facilities needed for a functioning society

INHOSPITABLE
an environment where organisms cannot grow or live easily

INSECTICIDE
chemicals used to kill insects

INVASIVE SPECIES
a nonnative species whose introduction is likely to cause environmental or economic harm; a nonnative species that disrupt the local ecosystem

IODINE-131
heavy radioactive isotope of iodine with a half-life of 8 days; a major product produced by uranium plutonium nuclear power plants

ISOTOPE
an atom of a given element that differs in the number of neutrons in its nucleus

IVORY
mammalian teeth or tusk composed of mostly dentin, the desirable white material in which elephant tusks are made

KEYSTONE SPECIES
a species whose presence in its ecosystem is necessary to prevent the system from collapse

LACTATION
when mammary glands (breast tissue) secretes milk, often occurring after a female has given birth and is supporting offspring

LANDSAT
a satellite imagery program first launched in 1972

LARVAE
the immature and often wormlike feeding form that hatches from the egg of many insects that have a metaphoric lifecycle

LETHAL CONTROL

a method of controlling wildlife populations that result in the death of individuals from the target population

LIMITING NUTRIENT

a nutrient in limited supply relative to others that when exhausted prevents further growth of an organism

MACRONUTRIENT

in the case of plants, phosphorus, nitrogen, and potassium; a nutrient needed in large amounts for normal growth to occur

MATRIARCH

the female who is the leader of a family unit

MICROORGANISM

an organism that cannot be seen with the human eye

MICROSCOPY

the practice of using a microscope to study objects

MIDDLE EAST

geographic region northeast of Africa and southwest of Asia that contains the country Syria

MIOCENE AGE

the first geological epoch of the Neogene period and extends from about 23.03 to 5.332 million years ago, this time period had a warmer global climate

MISSISSIPPI RIVER BASIN

the area covering much of the central United States that includes tributaries that drain into the Mississippi River

MOBBING

when more than one adult male attempts to mount a female in heat; often leads to serious injury and has been linked to a boost in testosterone and uneven distribution of gender in a population

MODIS IMAGES

Moderate Resolution Imaging Spectroradiometer; a satellite imaging instrument that views the entire Earth's surface every 1-2 days

MONOCROP

a single crop produced year after year on the same land that is economically efficient but ultimately damaging to soil ecology

MONSANTO

an American multinational chemical and agricultural biotechnology company; the leading producer of genetically engineered seeds

MUSTH

a period in which a bull (male) elephant is ready to mate, characterized by increased aggression and a surge of reproductive hormones – mainly testosterone

NATIONAL ACADEMY OF SCIENCES

a non-profit society established by the U.S. congress in 1863 to provide independent and objective consultation on matters related to science and technology

NATIONAL PARKS

an area of land set aside by the national government of a country specifically to safeguard nature and wildlife biodiversity

NATIONAL TIGER RECOVERY PROGRAM

a conservation program enacted in 2011 by the Ministry of Forestry in Indonesia to double the number of wild Sumatran tigers by 2022

NATURAL GAS

a combustible mixture of gaseous hydrocarbons consisting mostly of methane

NEBRASKA SANDHILLS

a region of mixed-grass prairie on grass-stabilized sand dunes, it is the largest sand dune formation in the western hemisphere

NO-TILL

growing crops without disturbing the soil through tilling or plowing to increase soil organic matter and decrease soil erosion

NOBLE GAS

any of the gaseous elements helium, neon, argon, krypton, xenon, and radon, occupying Group 0 (18) of the periodic table that is believed to be unreactive

NON-GMO PROJECT

a non-profit organization that verifies non-GMO products and educates consumers

NON-LETHAL CONTROL

a method of controlling wildlife populations through actions that do not harm the health of the target population

OCEAN ACIDIFICATION

the decrease of pH levels in the ocean due to the uptake of carbon dioxide from the atmosphere

OGALLALA AQUIFER

an aquifer located on the High Plains in the United States, it is composed of clay, sand, silt, and gravel

OZONE LAYER

a region of Earth's atmosphere that absorbs most of the Sun's ultraviolet (UV) radiation

PAPAYA RINGSPOT VIRUS (PRSV)

a virus that infects papayas and is transmitted by aphids. Infested papayas exhibit yellowing, leaf distortion, and severe mosaics. The papaya fruit will have bumps and a "ringspot."

PARTICULATE MATTER

pieces of matter small enough to remain suspended in the air for long periods of time

PATHOGEN

a bacterial, viral, or fungal agent of disease

PESTICIDE

a substance that is used to prevent or kill animals or insects that damage plants or crops

PETROLEUM HYDROCARBONS

the primary molecular constituent in oil, gasoline, diesel, and other petroleum products; the simplest of organic compounds containing only carbon and hydrogen atoms

PHOTOSYNTHESIS

the conversion of sunlight, carbon dioxide, and water into glucose and oxygen by organisms for use as energy

PLANKTON

microscopic organisms that float freely in marine and fresh bodies of water PM10 particulate matter less than 10 micrometers in diameter

PM10

particulate matter less than 10 micrometers in diameter

POACHING

the illegal hunting, killing, or capturing of wild animals

POLLINATE

the transfer of pollen from the anther to the stigma of a plant often from one plan to another

POLYCHLORINATED BIPHENYLS (PCBS)

a broad range of man-made chemicals used as a coolant and flame retardant; a chemical known to be carcinogenic, neurotoxic, and cause developmental and reproductive disorders

POLYMER SHEET
a chemical compound or mixture of compounds formed by polymerization and consisting essentially of repeating structural units

POLYMERASE CHAIN REACTION (PCR)
a method to amplify copies of DNA using many cycles of DNA denaturation, primer annealing, and DNA polymerization

POLYP
the individual base of a coral; sedentary form of a coelenterate

POPULATION
a group of organisms that are of the same species, which reside in the same general geographic location and can interact and breed

PRECIPITATION
weather activity in the form of rainfall, hail, or snowfall

PRESERVE
a protected area set aside for the refuge and safety of plants and animals

PRIMARY FOREST
mature forests of native trees that have not been affected by deforestation

PROPAGANDA
use of communications to try and influence a person or group of people with often biased information

QUANTIFIABLE
the ability to be expressed or measured in terms of quantity

QUARANTINE
a state of enforced isolation, often imposed when a human or animal has been exposed to an infectious disease

RADIOACTIVE
atoms that spontaneously emit subatomic particles and/or energy; emitting ionizing radiation when decaying

RADIONUCLIDE
atoms with an unstable nucleus, characterized by the availability of excessive energy; can be naturally occurring or artificially produced

RANCH HAND
a U.S. Military Operation during the Vietnam War that involved spraying millions of liters of herbicide to rid Vietnam of crops and vegetation to expose roads and trails used by the Viet Cong

REDUCING EMISSIONS FROM DEFORESTATION AND FOREST DEGRADATION (REDD)
a mechanism to mitigate climate change through reducing net greenhouse gas emissions; under negotiation by the United Nations

RESERVOIR
a natural or artificial body of water that is used to store water

REVERSE OSMOSIS
a process by which a solvent passes through a porous membrane in the direction opposite to that for natural osmosis when subjected to a hydrostatic pressure greater than the osmotic pressure

RNA
ribonucleic acid; a molecular structure present in all living cells that carries and transmits commands to build proteins

ROTOR

the non-stationary part of a rotary motor or generator; contains electromagnets which are used by the generator to induce an electrical current

ROUNDTABLE ON SUSTAINABLE PALM OIL (RSPO)

a non-profit organization that aims to transform markets towards sustainable palm oil

RUNOFF

the portion of precipitation on land that is not absorbed by the ground but instead flows into nearby waterways; waste products that are carried by rain into surface waters

RUST BELT

referring to economic decline in a region of the United States surrounding the Great Lakes

SAFE DRINKING WATER ACT

Federal law setting standards for water quality across the United States to be enforced primarily by the U.S. Environmental Protection Agency

SALMONIDS

a fish belonging to the family Salmonidae which includes the salmon, trout, and whitefish

SANCTUARY

a protected area set aside for the refuge and safety of plants and animals

SECONDARY PRODUCTION

the rate at which primary consumer organisms convert food into their own biomass

SEDIMENT

a solid material that moves and settles in a different location, often from erosion

SHOAL

a piece of land where moving water promotes sediment deposition, such as a sandbar

SNOWPACK

a layer of compacted snow on the ground that often accumulates in high altitudes for long periods of time

STAND

a contiguous area that contains a number of relatively homogeneous trees or have a common set of characteristics.

STATOR

the stationary part of a rotary motor or generator; contains conductors on which electric current is induced by the rotation of the rotor

SYMBIOTIC RELATIONSHIP

a close relationship between two organisms in which they mutually benefit

THERMAL PROCESS

a process by which phosphate rock is heated to create phosphorus pentoxide, which is then dissolved in dilute phosphoric acid to form very pure phosphoric acid

THYROID CANCER

cancer originating in the thyroid gland, which is located in the front of the neck

TOPOGRAPHY

surface features or an area or a region on a map

TRANSLOCATION

immobilizing and transporting one or more individuals of a population from an area of high population density to an area of lower population density where they will have less of an environmental impact

TROPICAL STORM

a localized, powerful storm that forms in tropical areas

TSUNAMI

a series of high sea waves caused by an earthquake, submarine landslide, or other disturbance

TURBIDITY

a measure of the amount of suspended solids in water

VASCULAR

of or relating to a channel for the conveyance of a body fluid (as blood of an animal or sap of a plant)

VIRUS

an acellular particle containing a genome that can replicate only inside a cell; a noncellular pathogen

WATER STRESS

a lack of sufficient water resources available to meet the demands of water usage

WATER TABLE

the planar level at which water-saturated soil or rock meets unsaturated ground

WEANING

a period in which young mammals transition to sources of food other than their mother's milk

WESTERLIES

consisting of the winds that blow from the west towards the east; a belt of major air currents in the mid-latitudes of the northern and southern hemispheres

WET ACID PROCESS

a process by which phosphate rock is dissolved in sulfuric acid forming phosphoric acid and waste products

WORLD HEALTH ORGANIZATION (WHO)

an agency of the United Nations that promotes health and control of diseases around the world

Congratulations, you made it to the end of the text!

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