

Environmental Biology

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and Matthew R. Fisher

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Introduction



Photo above taken in the mid-Coastal Mountain range of Oregon, CC BY 4.0 Matthew R. Fisher

Environmental Biology is a free and open textbook that enables students to develop a nuanced understanding of today's most pressing environmental issues. 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 is a collaboration between various authors and organizations that are committed to providing students with high quality and affordable textbooks. Particularly, this text draws from the following open sources, in addition to new content from the editor, Joni Baumgarten:

- [Biology](#) by [OpenStax](#) is licensed under [CC BY 3.0](#)
- [Sustainability: A Comprehensive Foundation](#) by Tom Theis and Jonathan Tomkin, Editors, is licensed under [CC BY 3.0](#)
- [Essentials of Environmental Science](#) by Kamala Doršner is licensed under [CC BY 4.0](#)
- [Environmental Biology, 1st ed.](#) by Matthew R. Fisher is licensed under [CC BY 4.0](#)
Matthew R. Fisher is Biology Faculty at Oregon Coast Community College.

Special Note to Instructors:

Lecture slides for all chapters are available via [Environmental Biology Lecture Slides](#).

Note: Currently these are from the first edition of the textbook. Updates to the slides are planned for June thru August, 2023.

Publication and on-going maintenance of this textbook is possible due to grant support from Open

Oregon Education Resources. Every time that you use this textbook, please email the editor, Joni Baumgarten, and Open Oregon Educational Resources (jbaumgart1@brynmawr.edu and <https://openoregon.org/contact/>) and provide the course title and the number of 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 prior to adopting this textbook to see if any substantial revisions or additions are pending.

Major Updates, Spring 2023

The clone of the original textbook was created and edited by Joni Baumgarten between December, 2022 and March 15, 2023. The major changes are now complete. Minor editing to Chapters 8-10 may occur until April 1, 2023. The final completion of this edition will include more comprehensive updates to the “Chapter Resources” sections and questions, as well as the addition of new slide decks for teaching; completion is anticipated for September 1, 2023.

Updates include:

- The addition of “Section Goals” at the top of all sub-sections
- Reorganization of Chapter 1; Additional information added to the environmental ethics section; the addition of the section “Science in the Media”
- Additional detail added to Chapter 2
- Reorganization of Chapter 3
- Major changes in the structure of Chapter 4 and updates to the introduced ecological principles
- Reorganization of Chapter 5 (including renaming the chapter title and section titles) to highlight the connection between biodiversity and evolution
- Additional detail added to Chapter 6. Addition of a section: Pollution and Sustainability.
- Additional detail added to Chapter 7. Section 7.1 reworked to focus on water in the environment (some details moved to section 7.2). Section 7.2 reworked to focus on human use of water.
- Substantial detail added to Chapter 8. Sections 8.2 Global Food Systems and 8.4 Genetically Modified Crops added.
- Detail added to Chapter 9, including how specifically plant roots acquire nutrients from the soil, the topic of the Green Revolution, organic certification of products and additional details about specific practices associated with organic farming can be used to improve farm and ecosystem health even if a farm is not officially certified as organic.
- Substantial detail added to Chapter 10. Section 10.4 split into two sections.
- Substantial detail added to Chapter 11. Sections 11.4 and 11.5 added.

Chapter 1: Environmental Science



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Learning Outcomes

After studying this chapter, you should be able to:

- Define environmental science
- Understand why it is important to study environmental science
- Explain the concept of sustainability and its social, political, and cultural challenges
- Understand the process of scientific inquiry
- Compare inductive reasoning with deductive reasoning
- Describe the goals of basic science and applied science
- Evaluate the main points of environmental ethics
- Understand the Tragedy of the Commons and be able to apply this concept to other examples
- Describe the concept of environmental justice
- Think about bias in the media presentation of science

Chapter Outline

- 1.1 The Earth, Humans, and the Environment

- 1.2 The Process of Science
- 1.3 Environment and Sustainability
- 1.4 Environmental Ethics and Environmental Justice
- 1.5 Science in the Media
- 1.6 Chapter Resources – Environmental Science

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1.1 The Earth, Humans, & the Environment

Section Goals:

1. Understand environmental science and sustainability.

Why Study Environmental Science?

Environmental science is the dynamic, interdisciplinary study of the interaction of living and non-living parts of the environment, with special focus on the impact of humans on the environment. The study of environmental science includes circumstances, objects, or conditions by which an organism or community is surrounded and the complex ways in which they interact.

The need for equitable, ethical, and sustainable use of Earth's resources by a global population that nears the carrying capacity of the planet requires us not only to understand how human behaviors affect the environment, but also the scientific principles that govern interactions between the 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.

The Earth, Humans, and the Environment

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. Even in geological history, where there are examples of changes in atmospheric conditions similar to what we see now, the periods of high carbon dioxide are associated with unfriendly conditions to living organisms; meaning the fossil record shows mass extinctions. It's alarming.

Humans cannot exist outside of the natural systems of the Earth, and humans have been changing the Earth at unprecedented levels. The interconnection of **the environment**, defined below, with human populations and the earth as a whole is an essential part of environmental biology (and this textbook).

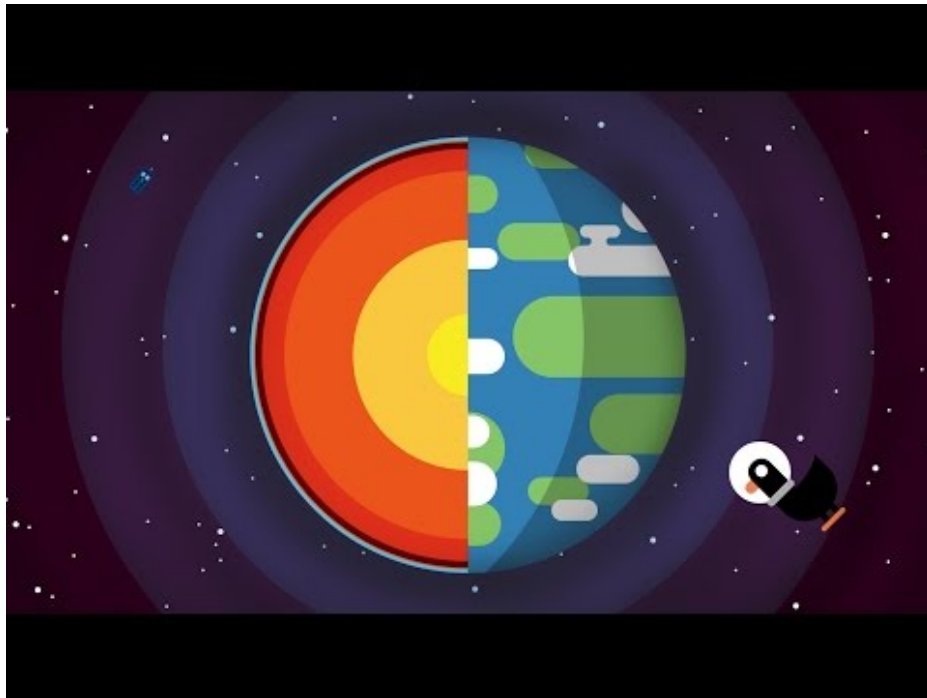
The Environment: The complete range of external conditions, physical and biological, in which an organism lives. Environment includes social, cultural, and (for humans) economic and political considerations, as well as the more usually understood features such as soil, climate, and food supply.

Oxford Dictionary of Ecology, 4th edition

Our challenge is to acquire an improved understanding of 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.

Perspectives: A brief history of planet Earth:



7-minute video about everything you need to know about planet earth.

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1.2 The Process of Science

Section Goals:

1. Understand the process of science, including the scientific method and hypothesis testing.

The Nature of Science



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 methods of science 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 and some science is dedicated to practical applications, such as the prevention of disease (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.

Biology is a science, but what exactly is science? What does the study of biology share with other scientific disciplines? **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 taken place 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 a method of 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 an 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. Scientific theory is the foundation of scientific knowledge. In addition, in many scientific disciplines (less so in biology) there are **scientific laws**, often expressed in mathematical formulas, which describe how elements of nature will behave under certain specific conditions, but they do not offer explanations for why they occur.



Figure 2: Biologists 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. In this micrograph, the bacterium is visualized using a scanning electron microscope and digital colorization. (credit: Eric Erbe; digital colorization by Christopher Pooley, USDA-ARS)

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 of 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 a biologist makes observations and records them. These data can be qualitative (descriptive) or quantitative (consisting of numbers), and the raw data can be supplemented with drawings, pictures, photos, or videos. From many observations, the scientist can infer conclusions (inductions) based on evidence. Inductive reasoning involves formulating generalizations inferred from careful observation and the analysis of 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 pattern of thinking moves in the opposite direction as 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 is evidence that the climate change conclusion is a valid one.

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, while **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 forms of study 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 Mlodinow, in The Grand Design (2010), Bantam Books

Hypothesis Testing

Biologists study the living world by posing questions about it and seeking science-based responses. This approach is common to other sciences as well 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. The scientific method is not exclusively used by biologists but can be applied to almost anything as a logical problem-solving method.



Figure 3: Sir Francis Bacon is credited with being the first to document the scientific method. (Image is Public Domain).

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. One Monday morning, a student arrives at class and quickly discovers that the classroom is too warm. That is an observation that also describes a problem: the classroom is too warm. The student then asks a question: "Why is the classroom so warm?"

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, and therefore other hypotheses may be proposed. A second hypothesis might be, "The classroom is warm because there is a power failure, and 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." There is no experiment that 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 in proofs like mathematics. If an experiment fails to disprove a hypothesis, then we find support for that explanation, but this is not to say that down the road a better explanation will not be found, 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, with the exception 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 that don't receive the drug (but they might receive a placebo, such as 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 the growth of algae in freshwater ponds. A series of artificial ponds are filled with water and half of them are treated by adding phosphate each week, while the other half are treated by adding a non-nutritional mineral that is not used by algae. The experimental variable here is presence/absence of a nutrient (phosphate). One potential controlled variable would be the volume of water in each tank. The amount of water that algae have access to may influence the results, thus researchers want to *control* its influence on the results by making sure all test subjects get the same amount. The control group consists 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.

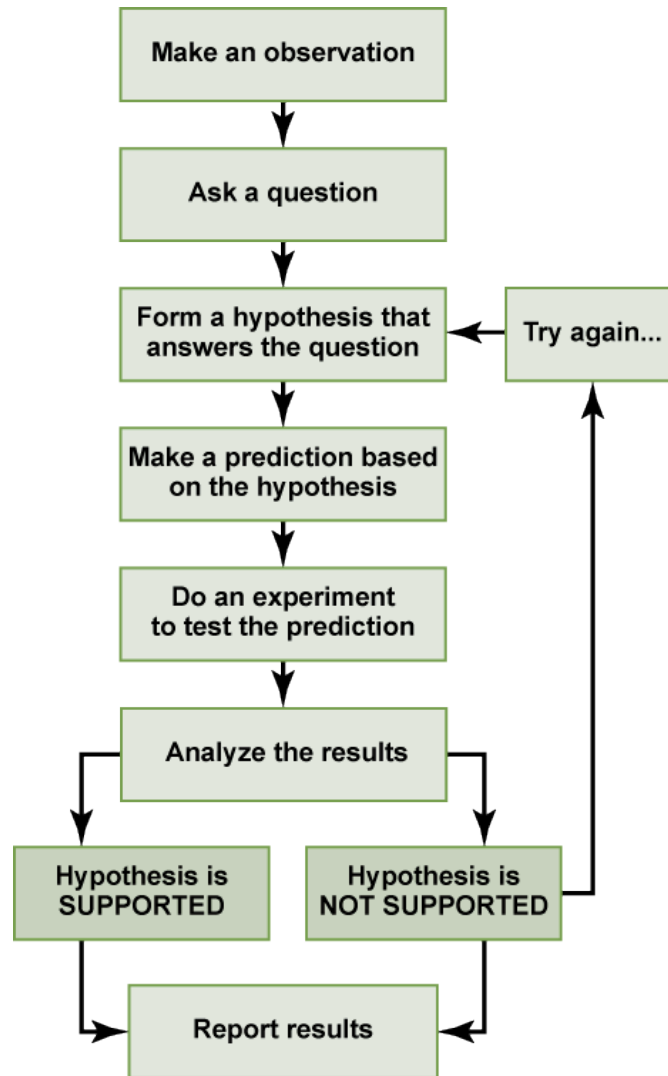


Figure 4: The scientific method is a series of defined steps that include experiments and careful observation. If a hypothesis is not supported by data, a new hypothesis can be proposed.

In the example below, the scientific method is used 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.

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. Many times, science does not operate in a linear fashion; instead, 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 for the sake of simply gaining knowledge, 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, find a cure for a particular disease, or save animals threatened by a natural disaster. In applied science, the problem is usually defined for the researcher.

Some individuals 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?” A careful look at the history of science, however, 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 that it is time to move on from basic science and instead to find solutions to actual problems. Both approaches are valid. It is true that there are problems that 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 the discovery of 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, where they provide the instructions necessary for life. During DNA replication, new copies of DNA are made, shortly before a cell divides to form new cells. Understanding the mechanisms of DNA replication (through basic science) enabled scientists to develop laboratory techniques that are now used to identify genetic diseases, pinpoint individuals who were 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 & Open to Critique

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 the limited few who are present. Instead, most scientists present their results in peer-reviewed articles that are 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 process of peer review helps to 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 process of peer review? 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.](https://www.businessinsider.com/5-of-albert-einsteins-thought-experiments-that-revolutionized-science-2016-7)" *Business Insider*. <<https://www.businessinsider.com/5-of-albert-einsteins-thought-experiments-that-revolutionized-science-2016-7>>

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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)

1.3 Environment & Sustainability

Section Goals:

1. Begin to understand the impact of humans on the environment.
2. Understand the concept of sustainability as it relates to the earth and a global community of human populations.

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 with its roughly 200,000-year history barely merits attention. As the American novelist Mark Twain once remarked, if our planet's history were to be 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 in terms of our recent planetary impact. 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 being used to satisfy human demand. Human appropriation of such natural resources is having a profound impact upon the wide diversity of other species.

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. 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, humans — *Homo sapiens* — have upset this balance to the degree that the rate of species extinction is now estimated at 10,000 times the rate of species renewal. Though humans have manipulated the natural world ever since the nomadic, gatherer-hunter ways of life were abandoned for settled societies some 12,000 years ago, the rate, scale, and the nature of human-induced global change in the post-industrial period is unprecedented in the history of life on Earth.

There are three primary reasons for this:

Firstly, mechanization of both industry and agriculture in the last century resulted in vastly improved labor productivity which enabled the creation of goods and services. Since then, scientific advance and

technological innovation — 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, has generated material flows of an unprecedented scale. The [Wuppertal Institute](#) estimates that humans are now responsible for moving greater amounts of matter across the planet than all natural occurrences (earthquakes, storms, etc.) put together.

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, coupled with rising material expectations in a world of limited resources, has catapulted the issue of distribution 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 patterns of production and consumption are unsustainable for a global population that is projected to reach between 12 billion by the year 2050. If ecological crises and rising social conflict are to be countered, the present rates of over-consumption by a rich minority, and under-consumption by a large majority, will have to be brought into balance.

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 do 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 alterations in the environment, the effects of which are only slowly manifesting themselves, and the full scale of which is beyond calculation. CFCs and PCBs are but two examples of the approximately 100,000 chemicals currently in global circulation. (Between 500 and 1,000 new chemicals are being added to this list annually.) The majority 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 the Idea of Sustainability

Given the challenge presented by the global human footprint, sustainability is one umbrella solution to balance the impact. Where does the modern understanding of sustainability come from? *Our Common Future* (1987), the report of the World Commission on Environment and Development, is widely credited with having popularized 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 the technological development, and institutional change are made consistent with future as well as present needs.

But, the intellectual history of the concept of sustainability can be traced back to the terms ‘stationary’ or ‘steady-state economy’ used by 19th century political economists. For John Stuart Mill, the 19th-century political economist, ‘stationary’ was not a static concept but referred to a balance between production and natural resources implying equality of access to natural resources for successive generations.

Even more relevant to this question because of the recent uptick (post 1950’s) in the pressure

from modern societies on the earth's resources is the understanding of sustainability found in the oral histories of indigenous cultures. For example, the principle of intergenerational 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 to be undertaken its potential consequences on the seventh generation had to be considered. That other cultures have based their decision-making systems on time scales of many decades (7 generations is approximately 300 years) seems inconceivable in the current political climate. The additional fact that this understanding of sustainability has been downplayed and even ignored is a result of colonialism, which will be further addressed in section 1.4

Environmental Equity

An important subset of sustainable development is the massive inequity in resource distribution. Currently, just one-fifth of the global population is consuming 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 the standard of living (and also resource consumption/waste emission) of the industrialized countries.

Countries such as China, Brazil, India, and Malaysia are, however, catching up fast. In such a situation, global consumption of resources and energy needs to be drastically reduced to a point where it can be repeated by future generations. But who will do the reducing? Poorer nations want to produce and consume more. Yet so do richer countries: their economies demand ever greater consumption-based expansion. Parallel conflicts of interest can also be found at the local and national level. Such stalemates have prevented any meaningful progress towards equitable and sustainable resource distribution at the international level. These issues of fairness and distributional justice remain unresolved.

Other Important Concepts in Sustainability

Ecological Footprint

The **ecological footprint** (EF), developed by Canadian ecologist and planner William Rees, is basically an accounting tool that uses 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 and 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

Figure 1:
Global Consumption Inequality
24 % of the global population — mostly in the high-income countries — accounts for:



92% cars
70% CO₂ emissions
86% copper and aluminium
81% paper
80% iron and steel
48% cereal crops
60% artificial fertilizer

Figure 1: 24% of the global population accounts for most of the resource consumption.

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. Calculated 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.

Connectivity

We live in a world characterized by **connectivity**, that is, by complex chains linking our everyday lives to distant strangers and ecosystems in far flung regions of the earth. This connectivity is expected to increase in the coming years. This connectivity has been crucial to building a relatively stable global food supply, which also ties to the improvement in agricultural methods during what is called the "Green Revolution" in the late 1960s^[1]. Despite the benefits of a globally connected food supply system, there is also overwhelming scientific evidence that there will be rapidly increasing strains on our systems of food, water, and energy provision as well as on the seasonable weather to which we have adapted our agricultural and urban regions. For example, a long-term drought in India might sharply bring the reality of aquifer depletion or climate change home to thousands of people driven from their land, but can also impact other countries through the limitations of agricultural production caused by the drought.

Precautionary Principle

The **precautionary principle** is an important concept in environmental sustainability. A 1998 consensus statement characterized the precautionary principle this way: "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 the sake of safety, that the chemical may have potential 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

Organizations such as the World Commission on Environment and Development, the Millennium Ecosystem Assessment, and several others including the Intergovernmental Panel on Climate Change, the Organization for Economic Cooperation and Development, and the National Academy Report to Congress have all issued reports on various aspects of the state of society and the environment. The

members of these groups are among the best experts available to assess the complex problems facing human society in the 21st century (e.g., Figure 2), and all have reached a similar conclusion: absent the enactment of new policies and practices that confront the global issues of economic disparities, environmental degradation, and social inequality, the future needs of humanity and the attainment of our aspirations and goals are not assured.



Figure 2: Deforestation and increased road-building in the Amazon Rainforest in Bolivia cause significant concern because of increased human encroachment upon wild areas, increased resource extraction and further threats to biodiversity.

Credit: Planet Labs, Inc. – <https://www.planet.com/gallery/sugarcane-deforestation/> (direct link) with NC license. Archived version: <https://web.archive.org/web/20200219014658/https://www.planet.com/gallery/sugarcane-deforestation/> – with CC-BY-SA license. This license cannot be revoked., CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=57172203>

Nine specific challenges are listed below:

Forests — Deforestation remains a main issue. 1 million hectares of forest were lost every year in the decade 1980-1990. The largest losses of forest area are taking place 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. There is increasing concern about the decline in forest quality associated with 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). In order to maintain current per capita consumption of fish, global fish harvests must be increased; much of the increase might come through aquaculture which is a known source of water pollution, wetland loss and mangrove swamp destruction.

Biodiversity — Biodiversity is increasingly coming under threat from development, which destroys or degrades natural habitats, and from pollution from a variety of sources. The first comprehensive global assessment of biodiversity 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 are having a discernible influence on global climate. CO₂ emissions in most industrialized countries have risen during the past few years and countries generally failed to stabilize their greenhouse gas emissions at 1990 levels by 2000 as required by the Climate Change convention.

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 levels of toxicity and persistence in the environment.

Hazardous wastes — Pollution from heavy metals, especially from their use in industry and mining, is also creating serious health consequences in many parts of the world. Incidents and accidents involving uncontrolled radioactive sources continue to increase, and particular risks are posed by the legacy of contaminated areas left from 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, it is highly likely that waste generation will double during the next decade. The level of awareness regarding the health and environmental impacts of inadequate waste disposal remains rather poor; poor sanitation and waste management infrastructure is still one of the principal causes of death and disability for the urban poor.

Attribution

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1.4 Environmental Ethics & Environmental Justice

Section Goals:

1. Understand social concepts of ethics that relate to human interactions with the ecosystem.
2. Understand what the tragedy of the commons is and to relate it to larger societal challenges.
3. Begin to understand environmental racism.

1.4.1 Ethics shape human interactions with the land

The ways in which humans interact with the land and its natural resources are determined by ethical attitudes and behaviors. 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. In this section, the focus is on the intersection of ethics with attitudes specifically about the earth, environment, and ecosystem, which will be identified by the term **ecosystem ethics**. Historically, ecosystem ethics of the Western world have been human-centered and related to the beliefs of colonialism. A more modern frame, though still limited by the context of a colonial society, is that of an environmental ethic which includes humans as part of the natural community rather than managers of it. Other cultures which have been subsumed by colonial structures have a completely different way of conceptualizing relationships between humans and land.^[1]

Sustainable Ethic

A **sustainable ethic** is an ecosystem 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 in a manner that allows 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 in a way that is consistent with a sustainable ethic? The solutions might include finding new ways to conserve oil or developing renewable energy alternatives. A sustainable ethic attitude in the face of such a problem would be that if drilling for oil damages the ecosystem, then that damage will affect the human population as well. A sustainable ethic can be either anthropocentric (human-centric) or biocentric (life-centered). An advocate for conserving oil resources may consider all oil resources as the property of humans. Using oil resources wisely so that future generations have access to them is an attitude consistent with an anthropocentric ethic. Using resources wisely to prevent ecological damage is in accord with a biocentric ethic.

Frontier Ethic

While this textbook strives to show the questionability of the **frontier ethic**, the history of this assumption has dramatically shaped our world. Early European settlers in North America rapidly consumed the natural resources of the land through colonialism. 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, for only the needs of humans are considered.

Most industrialized societies experience and understand population and economic growth that are based upon this frontier ethic because of the foundation of many societies in colonialism. There is the assumption that infinite resources exist to support continued growth indefinitely. In fact, 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, for good reason.

Land Ethic

Another important historical ecosystem ethic is that of Aldo Leopold, an American wildlife natural historian and philosopher, advocated a biocentric ethic in his book, *A Sand County Almanac*. He suggested that humans had always considered land as property, just as ancient Greeks considered slaves as property. He believed that mistreatment of land (or of slaves) 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 of it. 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 group that regards the soil as a commodity and the other that regards the land as biota, with a broad interpretation of its function. If we apply this idea

to the field of forestry, the first group of conservationists would grow trees like cabbages, while the second group would strive to maintain a natural ecosystem. Leopold maintained that the conservation movement must be based upon more than just economic necessity. Species with no discernible economic value to humans may be an integral part of 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)

Some conservation activities that are motivated by the land ethic are misaligned with respecting and supporting the struggles of marginalized or indigenous groups.

Case study: 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, 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 good of the public). The other faction, led by John Muir, advocated 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, but 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 supply of water. 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 to be derived from it's 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 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 the sake of 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 continue to debate whether we should be guided by preservationism or conservationism.

The Tragedy of the Commons

Related to the understanding of ecosystem ethics as drivers of human/land interactions, the concept of the tragedy of the commons gives context to individual versus societal motivation in the use of land (when it’s considered a resource... *see M. Liboiron for more context on this statement*).^[1] In economics and in an ecological context, the **tragedy of the commons** is a situation in which individual users, who have open access to a resource unhampered by shared social structures or formal rules that govern access and use,^{[2][3]} act independently according to their own self-interest and, contrary to the common good of all users, cause depletion of the resource through their uncoordinated action in case there are too many users related to the available resources.^[4]

A central element of the concept originated in an essay written in 1833 by the British economist William Forster Lloyd,^[5] who used a hypothetical example of the effects of unregulated grazing on common land, also known as “the commons” (in Anglo-Saxon law) in Great Britain and Ireland.^{[6][7]} In embryonic form the idea can also be found at Aristotle: “That which is common to the greatest number gets the least amount of care. Men pay most attention to what is their own: they care less for what is common.”^[8] The theory became widely known as the “tragedy of the commons” after an essay with this title was published in *Science* written by Garrett Hardin in 1968.^[9]

Hardin describes in this early essay that common use will only work reasonably satisfactorily as long as the number of man and beast stay well below the carrying capacity of the land (carrying capacity is described in [Section 4.2](#)). The availability of resources and the amount of people depending on it should therefore be kept in balance. However, as a result of discussions carried out in the decade after publication, Hardin suggested a better wording of the central idea: “Under conditions of overpopulation, freedom in an unmanaged commons brings ruin to all.”^[8] Finally, in 1991, faced with evidence of historical and existing commons, Hardin retracted his original thesis and wrote “The Tragedy of the ‘Unmanaged’ Commons”.^[10]

Critical scholars note that although taken as a hypothetical example by Lloyd, the historical demise of the commons of Britain and Europe resulted not from misuse of long-held rights of usage by the commoners, but from the commons’ owners enclosing and appropriating the land, abrogating the commoners’ rights.^[11]

Although open-access resource systems may collapse due to overuse (such as in overfishing), many examples have existed and still do exist where members of a community with regulated access to a common resource co-operate to exploit those resources prudently without collapse.^{[12][13]} Elinor Ostrom

was awarded the 2009 [Nobel Memorial Prize in Economic Sciences](#) for demonstrating this concept in her book *Governing the Commons*,^[14] which included examples of how local communities were able to do this without top-down regulations or privatization. On the other hand, Dieter Helm argues that these examples are context-specific and the tragedy of the commons “is not generally solved this way. If it were, the destruction of nature would not have occurred.”^[19] Though the original understanding by Hardin is not universally true, that will be the definition utilized in this text because of how the concept relates to climate change.

In a modern global economic context, “commons” is taken to mean any open-access and unregulated resource such as the atmosphere, oceans, rivers, ocean fish stocks, or even an office refrigerator. With this context, the “Tragedy of the Commons” is applicable to what is arguably the most consequential environmental problem: global climate change. The atmosphere is a commons into which countries are dumping carbon dioxide from the burning of fossil fuels. Although we know that the generation of greenhouse gases will have damaging effects upon the entire 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.

1.4.2 Environmental Justice

Environmental Justice is defined as the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. 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 in which to live, learn, and work.

“**Environmental racism**” was a term coined in 1982 by Benjamin Chavis, previous executive director of the United Church of Christ (UCC) Commission for Racial Justice. In a speech opposing the placement of hazardous polychlorinated biphenyl (PCB) waste in the Warren County, North Carolina landfill, Chavis defined the term as:

Racial discrimination in environmental policy making, the enforcement of regulations and laws, the deliberate targeting of communities of color for toxic waste facilities, the official sanctioning of the life-threatening presence of poisons and pollutants in our communities, and the history of excluding people of color from leadership of the ecology movements.

Recognition of environmental racism catalyzed the environmental justice movement that began in the 1970s and 1980s with influence from the earlier civil rights movement. Grassroots organizations and campaigns brought attention to environmental racism in policy making and emphasized the importance of minority input. While environmental racism has been historically tied to the environmental justice movement, throughout the years the term has been increasingly disassociated. Following the events in Warren County, the UCC and US General Accounting Office released reports showing that hazardous waste sites were disproportionately located in poor minority neighborhoods. Chavis and Dr. Robert D. Bullard pointed out institutionalized racism stemming from government and corporate policies that led to environmental racism. These racist practices included redlining, zoning, and colorblind adaptation planning. Residents experienced environmental racism due to their low socioeconomic status, lack of political representation and mobility. Expanding the definition in “The Legacy of American Apartheid and Environmental Racism”, Dr. Bullard said that environmental racism:

... refers to any policy, practice, or directive that differentially affects or disadvantages (whether intended or unintended) individuals, groups, or communities based on race or color.

Though environmental racism is a clear problem, the decisions in citing hazardous waste facilities are generally made on the basis of economics, geological suitability and the political climate, which can be both impacted by structural racism or can have aspects that are independent of structural racism. For example, a site must have a soil type and geological profile that prevents hazardous materials from moving into local aquifers.

In an ideal world, there would be no hazardous waste facilities, but we do not live in an ideal world. Unfortunately, we live in a world plagued by rampant pollution and dumping of hazardous waste. Our industrialized society has produced wastes during the manufacture of products for our basic needs and colonial attitudes mean that society assumes that land can be used to deal with such waste^[16]. 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 the selection of future hazardous waste sites. All humans who help produce hazardous wastes must share the burden of dealing with those wastes, not just the poor and minorities.

Indigenous People

This topic is much more nuanced than can be addressed here. Please be responsible about researching this topic further with the detail needed for your specific geographical location if it applies to your situation.

Since the end of the 15th century, most of the world's frontiers have been claimed and colonized by established nations. Invariably, these conquered frontiers were home to people indigenous to those regions. Some were wiped out or assimilated by the invaders, while others survived while trying to maintain their unique cultures and way of life. The United Nations officially classifies **indigenous people** as those "having an 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. The main objective of this proclamation, according to the United Nations, 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 identity, 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. 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, claim that drilling in the region would devastate their way of life. Thousands of years of culture would be destroyed for a few months’ supply of oil. 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. Because they own considerable amounts of land adjacent to the refuge, they would potentially reap economic benefits from the development of the region.



Figure 2: An Inupiaq woman, Nome, Alaska, c. 1907. Credit: [This work](#) is in the [Public Domain, CC0](#)

The heart of most environmental conflicts faced by governments usually involves what constitutes proper and sustainable levels of development. For many indigenous peoples, sustainable development constitutes 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.

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Suggested Supplementary Reading

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 Liboiron, Max. 2021. *Pollution is Colonialism*. Duke University Press. <https://www.dukeupress.edu/pollution-is-colonialism>
 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>>

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 Wikipedia. “Environmental racism”. Accessed December 27, 2022. Licensed by [CCA-SA 3.0](#) https://en.wikipedia.org/wiki/Environmental_racism Modified by Joni Baumgarten.

Wikipedia. "Tragedy of the Commons". Accessed December 26, 2023. Licensed by [CCA-SA 3.0](https://creativecommons.org/licenses/by-sa/3.0/) https://en.wikipedia.org/wiki/Tragedy_of_the_commons#cite_note-garretthardinsociety.org-7
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1.5 Science in the Media

Section Goals:

1. Have a basic understanding of science in the media.

Media Bias

A common concern in the modern era, where information is very accessible via the internet, is the bias in the information that individuals see. Part of the rise in the bias in the media in the USA is attributed to the **fairness doctrine**, which was abolished in 1987.

The fairness doctrine had two basic elements: It required broadcasters to devote some of their airtime to discussing controversial matters of public interest, and to air contrasting views regarding those matters. Stations were given wide latitude as to how to provide contrasting views: It could be done through news segments, public affairs shows, or editorials. The doctrine did not require equal time for opposing views but required that contrasting viewpoints be presented. The 1987 repeal of the fairness doctrine enabled the rise of talk radio that has been described as “unfiltered” divisive and/or vicious. Prior to 1987, people who used much less controversial verbiage than the notable example of Rush Limbaugh (who received a nationwide syndication contract in 1988) had been taken off the air due to violations of the fairness doctrine.

The abolishment of the fairness doctrine may not entirely explain the complexity of the news industry today, which also has been undermined by funding issues^[1] and competition between traditional news providers and internet sources. Clickbait, where revenue is generated based on the number of clicks an article receives^[2], is an example of how repercussions of the challenges facing the media industry affect the individual reader.

Finding Reliable References

The first step to understanding if an internet resource is reliable is to look at the publishing information including the author, the organization that owns or hosts the website, the organization that sponsored the content (which may be different than the website host). There are websites that obscure this information, which should be a warning that the website might be untrustworthy.

A common occurrence in science media is to summarize other articles, or even repost the original article on a secondary website. Reposted articles should be identified in the header or the footer of the article, and the original article should be linked. Summary articles may link to the relevant original resource in hyperlinks in the text, but usually have them listed at the end. Find the relevant reference link for the fact or story of interest, go to that resource and see if it says the same thing and if there are any additional and relevant details. When citing facts in your own work, use the original articles instead of a summary article.

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Wikipedia. “FCC fairness doctrine”. https://en.wikipedia.org/wiki/FCC_fairness_doctrine. Accessed December 25, 2022. Licensed by [CCA-SA 3.0](#). Modified by Joni Baumgarten.

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2. Wikipedia. “Clickbait”. Accessed December 26, 2022. https://en.wikipedia.org/wiki/Clickbait#cite_note-18

Further reading

Interactive Media Bias Chart®. [Interactive Chart | Ad Fontes Media](#)

1.6 Chapter Resources

Summary

Science attempts to describe and understand the nature of the universe in whole or in part. Science has many fields; those fields related to the physical world and its phenomena are 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. The primary goal of applied research, however, 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 ways in which humans interact with the land and its natural resources are determined by what we term ecosystem ethical attitudes and behaviors. A frontier ethic assumes that the earth has an unlimited supply of resources. Sustainable ethic assumes that the earth's resources are not unlimited and that humans must use and conserve resources in a manner that allows their continued use in the future.

Tragedy of the commons is an important theme of environmental science that relates the actions of the individuals to the overall negative impact on a shared resource.

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.

Review Questions

1. Scientific research that produces knowledge without any immediate practical use is specifically known as...
 - A. Basic science
 - B. Applied science
 - C. Hypothesis-based science

- D. Descriptive science
- E. Retrospective science

2. Which one of the following fulfills the definition of a hypothesis?

- A. Removing invasive species will result in greater biodiversity.
- B. Introducing invasive species will harm an ecosystem.
- C. Invasive species are non-native species that alter ecosystems.
- D. Introducing invasive species will decrease biodiversity by displacing native species
- E. Ecosystem productivity will decrease when invasive species are introduced.

3. Which one of the following is consistent with the frontier ethic?

- A. Expanding the area covered by a wildlife sanctuary
- B. Protecting a natural area as a national park
- C. Sustainable logging of a forest
- D. Transferring ownership of forestland from private ownership to the federal government
- E. Extracting copper ore from mineral-rich deposit in a landscape rich in biodiversity

4. Which one of the following suggests that when the effects of a human activity are poorly understood, we must presume that some level of harm may exist to the environment, and thus must proceed with that activity carefully?

- A. Sustainability ethic
- B. Precautionary principle
- C. Environmental harm dictum
- D. Environmental injustice
- E. Presumptive principle

5. Which one of the following demonstrates the concept of the “tragedy of the commons”?

- A. Competing companies log as many trees as possible for financial gain until no trees are left
- B. Public forest land is sold to a privately-owned investor group
- C. Logging forests is dangerous work and ends up killing or injuring many workers
- D. A careless hiker accidentally starts a wildfire that destroys hundreds of acres of forest
- E. Government regulations lead to conditions that increase the risk of forest fire on public lands

6. The equal sharing of Earth’s resources is specifically known as...

- A. Environmental justice
- B. Sustainability
- C. Environmental equity
- D. Ecological footprinting
- E. Mutualism

7. John Muir’s position on the proposed development in the Hetch Hetchy Valley of California in the early 1900s would best match which one of the following?

- A. Frontier ethic
- B. Sustainable ethic
- C. Land ethic
- D. Ethos ethic

E. Darwinian ethic

8. Which one of the following is an example of inductive reasoning?

- A. Every lion you've seen on TV hunts gazelles, therefore all lions hunt gazelles.
- B. All tigers are mammals. All mammals are vertebrates. Therefore, tigers are vertebrates.
- C. Every lake contains water; therefore, Crater Lake contains water.
- D. Only plants have flowers. Tulips are a plant because they have flowers.
- E. The sun emits energy in the form of photons. Visible light is made of photons and thus light is a type of energy.

9. The fair treatment and meaningful involvement of all people regarding enforcement and implementation of environmental regulations and policies is known as what?

- A. *Quid pro quo*
- B. Environmental justice
- C. Environmental equity
- D. *Habeas corpus*
- E. Ecologic inclusiveness

10. People and their culture that have existed continuously dating back to a time before their land was invaded or colonized by other societies are known as...

- A. Endemic
- B. Indigenous
- C. Exotic
- D. Incunable
- E. Invidious

See Appendix for answers

Attributions

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Chapter 2: Matter, Energy, & Life



This sage thrasher's diet, like that of almost all organisms, 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

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2.1 Matter

Section Goals:

1. Link the underlying concepts about matter to the larger patterns that define ecosystems.
2. Understand water, its chemistry, and its importance.
3. Identify macromolecules and their major function in multicellular organisms.

2.1.1 Atoms, Molecules, & 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 based on its atomic number. These unique properties allow elements to combine and to 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 it 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 together to form molecules. In multicellular organisms, such as animals, molecules interact to form cells, cells combine to form tissues, tissues make up organs, all contained in one individual organism. The key point is that basic properties of life are regulated by the molecular structure of the elements that are within the cell.

Molecule are chemicals made from two or more atoms bonded together. Some molecules are very simple, like O₂, which is comprised of 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), which is 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 has 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, which has a net zero charge.

Each element contains a different number of protons and neutrons, giving it its own atomic number and mass number. The **atomic number** of an element is equal to the number of protons that element contains. If an atom loses or gains a proton, it becomes a different element. **The number of protons** is what defines an element. 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 that have 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 isotope of carbon, 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. Isotopes are important in research methods; measuring the carbon isotope ratio of an organism or of fossils is a well-trusted technique in a number of scientific fields (see Box 1).

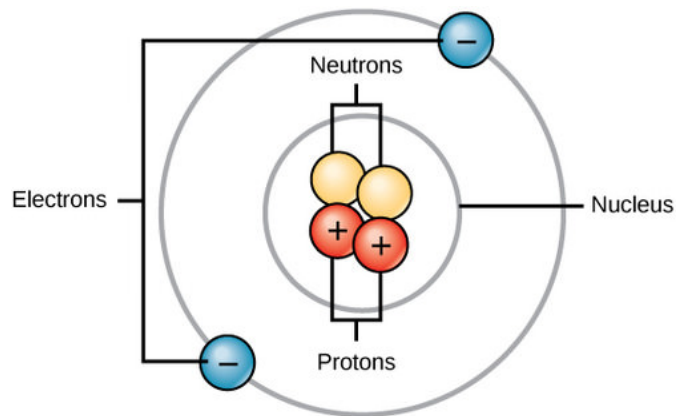


Figure 1: Atoms are comprised of protons and neutrons located within the nucleus, and electrons surrounding the nucleus. The nucleus of an atom should not be confused with the nucleus of a cell. This image shows Helium (He), with two protons, two neutrons, and two electrons.

Box 1: EVOLUTION IN ACTION**Carbon dating**

Carbon-14 (^{14}C) is a naturally occurring radioisotope that is created in the atmosphere by cosmic rays. This is a continuous process, so more ^{14}C is always being created. As a living organism develops, the relative level of ^{14}C in its body is equal to the concentration of ^{14}C in the atmosphere. When an organism dies, it is no longer ingesting ^{14}C , so the ratio will decline. ^{14}C decays to nitrogen-14 (^{14}N) 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 ^{14}C will have been converted to ^{14}N . 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 ^{14}C is long, it is used to age formerly living objects, such as fossils. Using the ratio of the ^{14}C concentration found in an object to the amount of ^{14}C 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 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. Through the use of 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)

Essential elements

There are four elements that are common in all organisms.

In the human body, these four elements compose about 96% of the weight, with major minerals and trace elements making up the remainder. Two additional elements make up the six **essential elements**: Phosphorus and Sulfur (Figure 3). Comparing the top four elements (Table 1) from humans to the atmosphere highlights an important concept that will be covered later: The limitation of nitrogen availability (see [Section 3.4](#)).

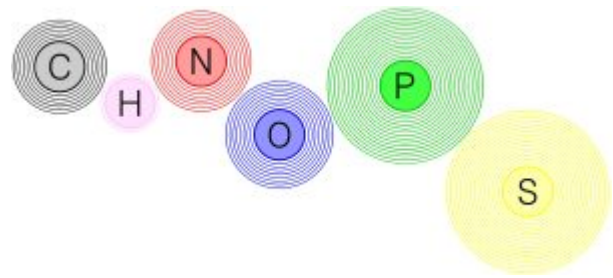


Figure 3: The six essential elements with their relative atomic size displayed.

Table 1:

Element	Life (humans)	Atmosphere
Oxygen (O)	65%	21%
Carbon (C)	18%	trace
Hydrogen (H)	10%	trace
Nitrogen (N)	3%	78%

Chemical Bonds

How elements interact with one another depends on the **number of electrons** and how they are arranged. Electrons move in predictable patterns called **orbitals**, or shells, around the nucleus of an atom. Because the nucleus is positively charged, there is potential energy contained in electrons based on their attraction to the nucleus. Most atoms are more stable energetically when they have eight electrons in their **valence shell**, the outermost electron shell (with the exception of hydrogen [H] and helium [He] which have a full valence shell with two electrons). Therefore, the atoms without a full valence shell tend to form bonds with other atoms that result in both atoms having a full valence shell. **Molecules** are simply two or more atoms chemically bonded together, with covalent or ionic bonds.

There are two strong bonds between atoms that form molecules: Covalent bonds and ionic bonds. These bonds hold atoms together in a relatively stable state. An additional way that molecules interact is a less strong, but still important, is the attraction called a hydrogen bond.

Ionic bonds cannot be understood without understanding ions. 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 will have 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**. Atoms that have one or two electrons in their valence shell tend to lose electrons to become cations. Atoms with six or seven electrons in their valence shell tend to gain electrons and become anions. These elements are located in the first two columns or the 16th and 17th columns of the periodic table (Figure 4).

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. Because ionic bonds are held together by charge, if the charge gets

disrupted in some way (the primary example being dissolution in water), the molecule will no longer hold together. Therefore, ionic bonds are considered to be weaker than covalent bonds.

Covalent bonds form when electrons are shared between two atoms. Each atom shares one of their electrons, which then orbits the nuclei of both atoms, holding the two atoms together. If atoms share more than one electron, the bond is stronger. There are common examples of double bonds (O_2) and triple bonds (N_2). 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.

An additional complexity to covalent bonds is whether the molecule formed has a **partial charge**. Therefore, covalent bonds can be divided into two varieties: polar and non-polar. A non-polar covalent bond occurs when electrons are shared equally between the two atoms, so no partial charge exists. Polar covalent bonds form when the electrons are shared unequally, and a partial charge exists. Why does this occur? Each element has a known **electronegativity**: a measure of their 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, 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 5). 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 it were not for hydrogen bonding, water would be a gas rather than a liquid at room temperature.

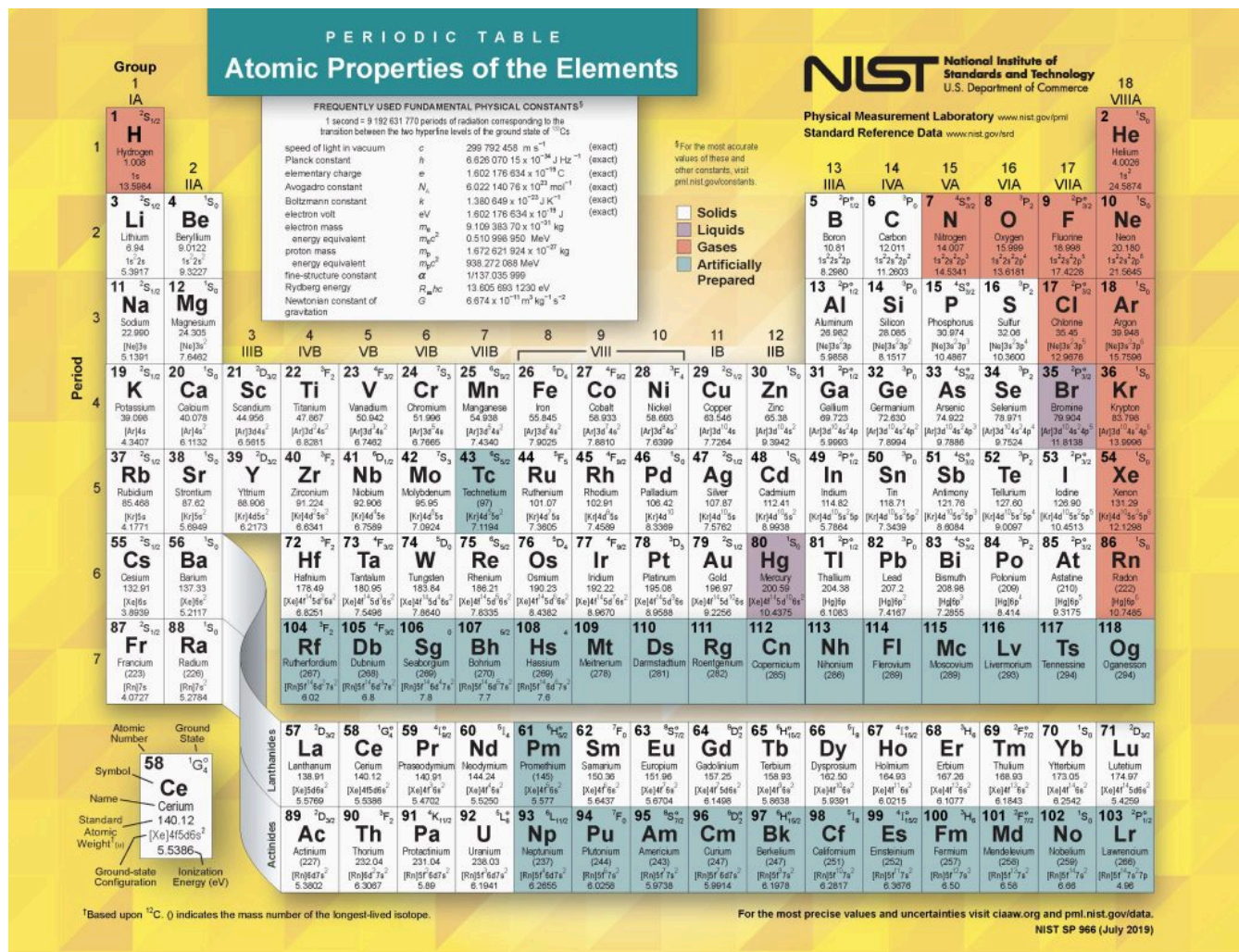


Figure 4: Periodic table of elements. Elements like Na and Mg tend to lose electrons and become cations. Elements like S and Cl tend to gain electrons and become anions.

2.1.2 Water is Crucial for Maintaining Life

Do you ever wonder why scientists spend time looking for water on other planets? It is because 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 simply would not exist. There are four defining properties of water:

1. **Water is polar.** As just noted, the hydrogen and oxygen atoms within water molecules form polar covalent bonds. The shared electrons spend more time associated with the oxygen atom than they do 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 of one molecule are attracted to the slightly negative oxygen atom of another molecule. Water also attracts other polar molecules (such as sugars); these molecules dissolve easily in water and are referred to as hydrophilic (“water-loving”).
2. **Water stabilizes temperature.** The hydrogen bonds in water allow it to absorb and release heat energy more slowly than many other substances. This is most easily understood with the example of water changing to water vapor (aka, boiling): As a liquid, there are a lot of hydrogen bonds between the molecules. To break those bonds takes extra “oomph”, thus water can absorb a lot of energy while it is boiling but will not change temperature because the energy is going into breaking the hydrogen bonds of the molecules that are released from the liquid and turned into gas. More generally, increased energy that goes into liquid water disrupts the hydrogen bonds between water molecules. But, those bonds can be created and disrupted rapidly, so water can absorb a relatively high amount of energy with only minimal temperature changes. What these molecular-level details mean at larger scales is that water moderates temperature changes within organisms, and water moderates air temperature at the ecosystem scale. Both facts help life survive.

Note that temperature is a measure of the motion (kinetic energy) of molecules. As the motion increases, energy is higher and thus temperature is higher.

3. **Water is an excellent solvent.** Because water is polar, with slight positive and negative charges, ionic compounds and polar molecules can readily dissolve in it. Water is, therefore, what is referred to as a universal solvent. A solvent is a substance capable of dissolving another substance. Any charged particle that mixes with water will quickly attract the opposite-partial-charge of water molecules, the water molecules will form a dense shell or

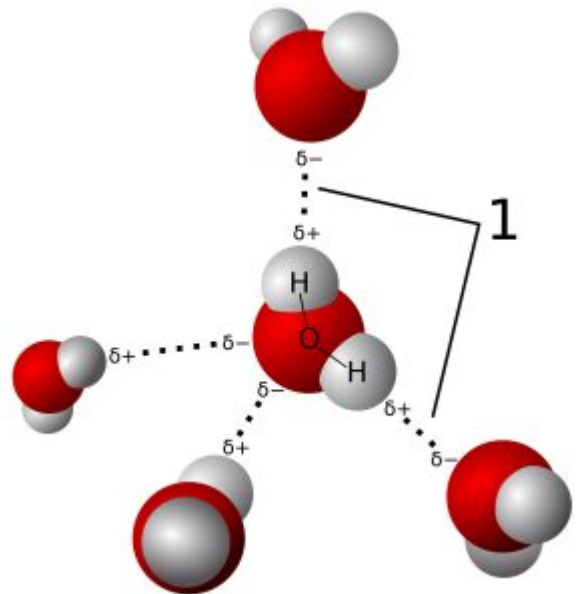


Figure 5: Model of hydrogen bonds (1) between molecules of water

cloud around the particle, thus breaking a large substance into individual molecules surrounded by water molecules: dissolution!

4. **Water is cohesive.** Have you ever filled up a glass of water to the very top and then slowly added a few more drops? Before it overflows, the water actually 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. Cohesion gives rise to surface tension, the capacity of a substance to withstand rupture when placed under tension or stress. 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 that is created by the water molecules. It is even possible to “float” a steel needle on top of a glass of water if you place it gently, without breaking the surface tension. A similar property is **adhesion**, 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 to be higher on the sides of the straw than in the middle. This is because the water molecules are attracted to the straw and therefore adhere to it. Cohesive and adhesive forces are important for sustaining life. For example, because of these forces, water can flow up from the roots to the tops of plants to feed the plant.

Buffers, pH, Acids, and Bases

pH is introduced here because of the importance of water as a solvent, and the fact that water molecules can split into the ions that contribute to acidity and alkalinity.

The **pH** of a solution is a measure of its **acidity** or **alkalinity**. The pH scale ranges from 0 to 14 (Figure 6). A change of one unit on the pH scale represents a change in the concentration of hydrogen ions by a factor of 10, 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, and a change from 4.0 to 6.0 is a 10x larger change than a change in pH from 5.0 to 6.0. 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 (from 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 = 1.0 to 2.0). 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 is it that we can ingest or inhale acidic or basic substances and not die? **Buffers** are the key. Buffers readily absorb excess H^+ or OH^- , keeping the pH of the body 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 the 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.

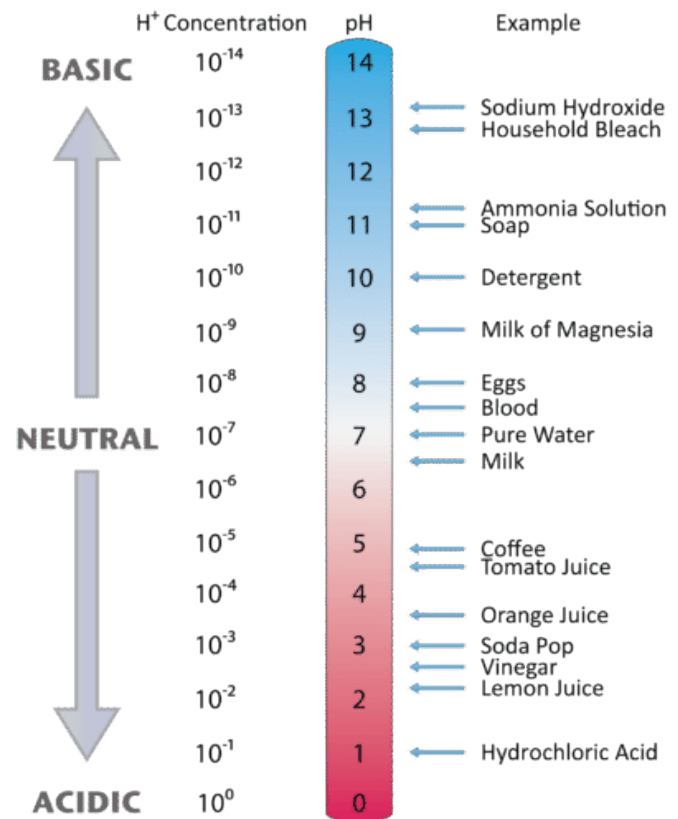


Figure 6: pH scale with the logarithmic H^+ concentration listed. Common substances like soap and coffee are also noted at their average pH. Credit: CK-12 Foundation

2.1.3 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 of the 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. It is the bonding properties of carbon atoms that are responsible for its important role: Carbon has four electrons in its valence shell, thus it can form four covalent bonds with other atoms or molecules.

1. **Carbohydrates** include what are 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 names (e.g., starch).

2. **Lipids** include a diverse group of compounds that are 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. 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.
3. **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 there are 20 different chemically distinct amino acids that form long chains, and the amino acids can be in any order. Proteins can function as enzymes, hormones, contractile fibers, cytoskeleton rods, and much more. **Enzymes** are vital to life because they act as catalyst in biochemical reactions (like digestion). Each enzyme is specific for the substrate (a reactant that binds to an enzyme) upon which it acts. Enzymes can function to break molecular bonds, to rearrange bonds, or to form new bonds.

4. **Nucleic acids** are very large molecules that are important to the continuity of life. 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 is made up of three components: a nitrogenous base, a pentose (five-carbon) sugar, and a phosphate. DNA has a beautiful double-helical structure (Figure 7).

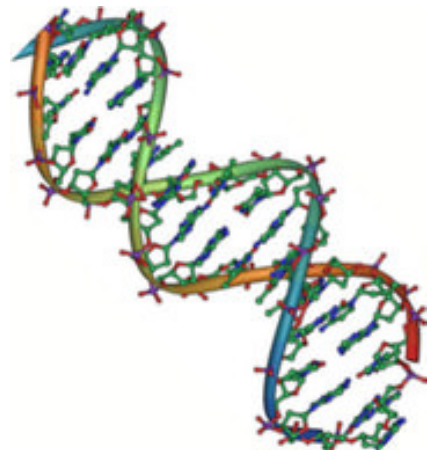


Figure 7: The double-helix model shows DNA as two parallel strands of intertwining molecules.

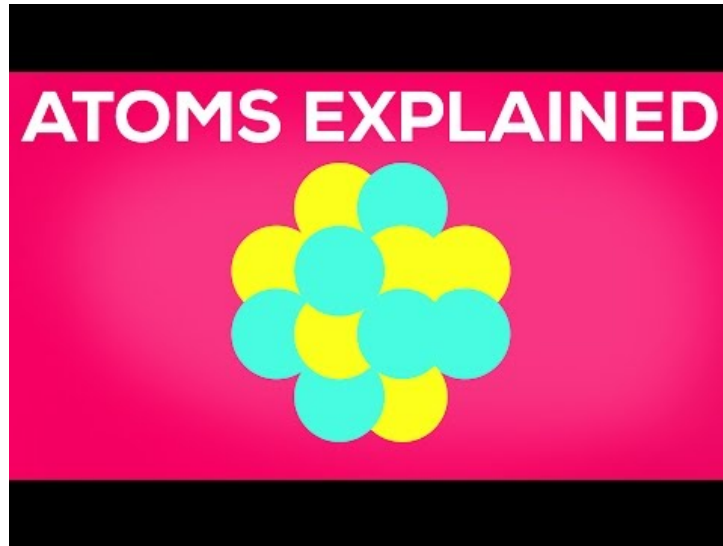
Additional Resources:

Figure 8: A video that provides some wicked-awesome information about atoms.

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2.2 Energy

Section Goals:

1. Understand the two laws of thermodynamics.
2. Understand kinetic and potential energy.

Energy

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 for the synthesis and breakdown of molecules, as well as the transport of molecules into and out of cells. In addition, processes such as ingesting and breaking down food, exporting wastes and toxins, and movement of the cell all require 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 of 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.

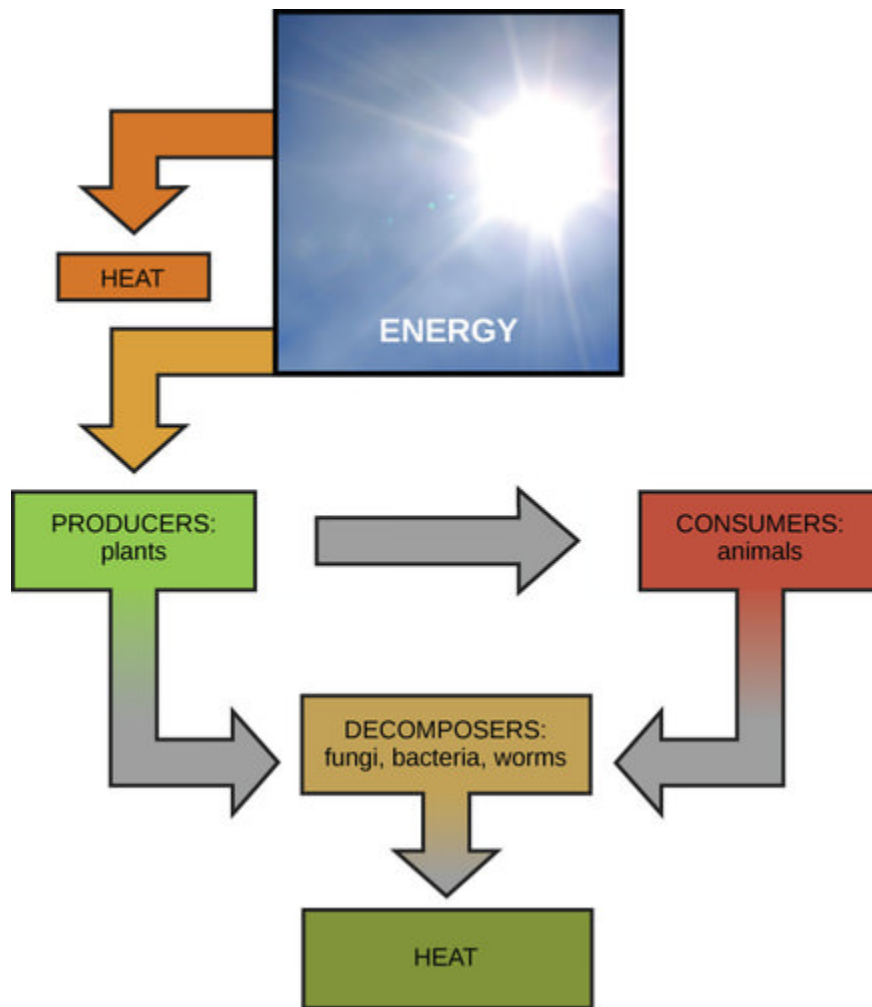


Figure 1: Ultimately, most life forms get their energy from the sun. Plants use photosynthesis to capture sunlight, and herbivores eat the plants to obtain energy. Carnivores eat the herbivores, and eventual decomposition of plant and animal material contributes to the nutrient pool.

Thermodynamics

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. The stovetop system is open because heat can be lost to the air. A **closed system** cannot exchange energy with its surroundings. How would you describe the system that is the entire Earth? How about a human body?

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 the way energy flows into and out of biological systems, it is important to understand two of the physical laws that govern 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 the most biologically useful energy transformations on earth: that of converting the energy of sunlight to chemical energy stored within organic molecules.

The challenge for all living organisms is to obtain energy from their surroundings in forms that are 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 a series of cellular chemical reactions into energy within molecules of **ATP** (adenosine triphosphate). Energy in ATP molecules is easily accessible to do work because the energy stored in a bond between the three phosphate groups can be easily broken to release energy and re-connected to store energy (converting into **ADP** with the loss of a phosphate group [Figure 2]). 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.

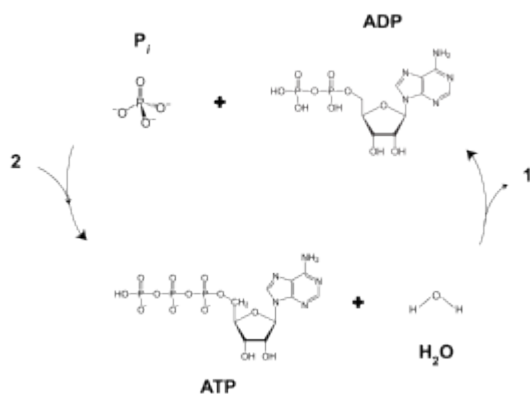


Figure 2: ATP is the “energy currency” of cells. Image is Public Domain.

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 a form that is unusable. 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 of the energy being converted from electrical energy into 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. Living things are highly ordered, requiring constant energy input to be maintained in a state of low entropy.

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**. A speeding bullet, a walking person, and the rapid movement of molecules in the air all have kinetic energy. Now 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 that was required to lift the wrecking ball did not disappear, but is now stored in the wrecking ball by virtue of its position and the force of gravity acting on it. This type of energy is called **potential energy** (Figure 3). 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 examples of potential energy include the energy of water held behind a dam or a person about to skydive out of an airplane.

Potential energy is not only associated with the location of matter, but also with the structure of matter. 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 that has potential energy. The fact that energy can be released by the breakdown of certain chemical bonds implies that those bonds have potential energy. In fact, there is potential energy 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.



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)

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2.3 A Cell is the Smallest Unit of Life

Section Goals:

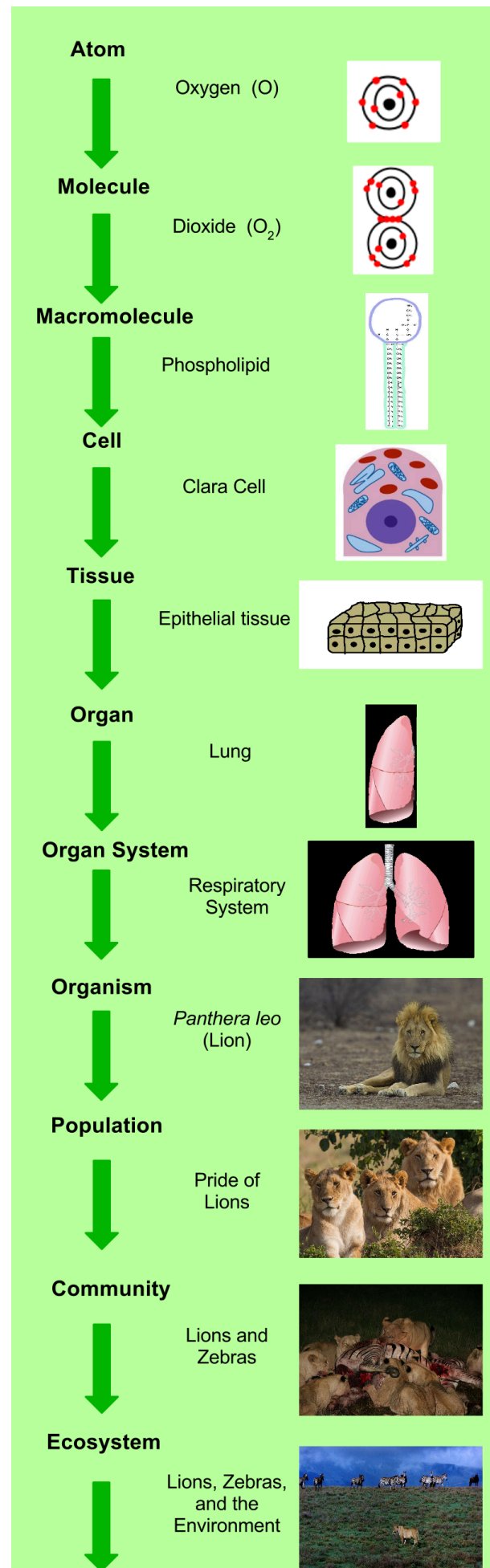
1. Understand the levels of biological organization.
2. Understand cells as fundamental units of life and differentiate eukaryotic and prokaryotic cells.
3. Understand the two major eukaryotic organelles: chloroplasts and mitochondria.

2.3.1 Levels of Biological Organization

Living things are highly organized and structured, following a hierarchy of scale 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. The chemical properties of molecules affect how they assemble into cells. All living things are made of one or more cells. In plants, animals, and other eukaryotic organisms, before the hierarchical level of cells, molecules come together in specific ways to create structures called organelles, which perform specific functions. Details of organelles and cells are discussed in more detail in the section 2.3.2.

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.

The levels of biology from organism to the biosphere are also called the ecological levels of organization. All the individuals of a species living within a specific area are collectively called a population. A community is the set of different populations inhabiting a common area. For instance, all of the trees, flowers, insects, and other populations in a forest 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, and it represents the zones of life on Earth. It includes land, water, and portions of the atmosphere. The biosphere is divided into **biomes**,



which are discussed in more detail in sections [3.2](#) and [3.3](#).

Each level in the hierarchy represents an increase in organizational complexity, and is primarily composed of the previous level's basic unit. E.g., a eukaryotic cell is primarily composed of organelles and molecules, the levels lower than that of "cell". The basic principle behind the organization is the concept of *emergence*—the properties and functions found at a hierarchical level are not present and are even irrelevant at the lower levels.

Figure 1: Levels of biological organization. The simplest unit in this hierarchy is the atom, like oxygen. Two or more atoms is a molecule, like a dioxide. Many small molecules may combine in a chemical reaction to make up a macromolecule, such as a phospholipid. Multiple macromolecules form a cell, like a club cell. A group of cells functioning together as a tissue, for example, Epithelial tissue. Different tissues make up an organ, like a lung. Organs work together to form an organ system, such as the Respiratory System. All of the organ systems make a living organism, like a lion. By Mikala14 – Own work, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=26262662>

2.3.2 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 kinds of cells, each specialized for a specific purpose. Just as a home is made from a variety of building materials, the human body is constructed from many cell types. For example, cells of the immune system fight invading bacteria, and red blood cells carry oxygen throughout the body. Each of these cell types plays a vital role during the growth, development, and day-to-day maintenance of the body. In spite of 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 who had great skill in crafting lenses. Despite the limitations of his now-ancient lenses, van Leeuwenhoek observed the movements of single-celled organism 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 that lacks 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). Prokaryotes are divided into two domains of life: Bacteria and Archaea (see more in [Section 5.1](#)). Most of our current knowledge of prokaryotes is derived from studying bacteria. Note that the composition of the cell membrane and cell wall are different among the larger groupings of organisms (meaning archaea vs. bacteria vs. eukaryotic cells).

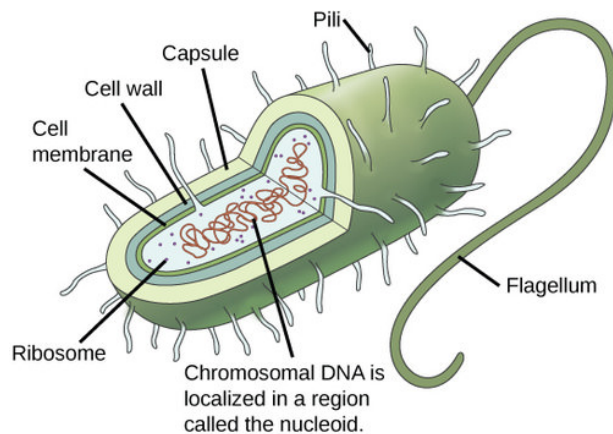


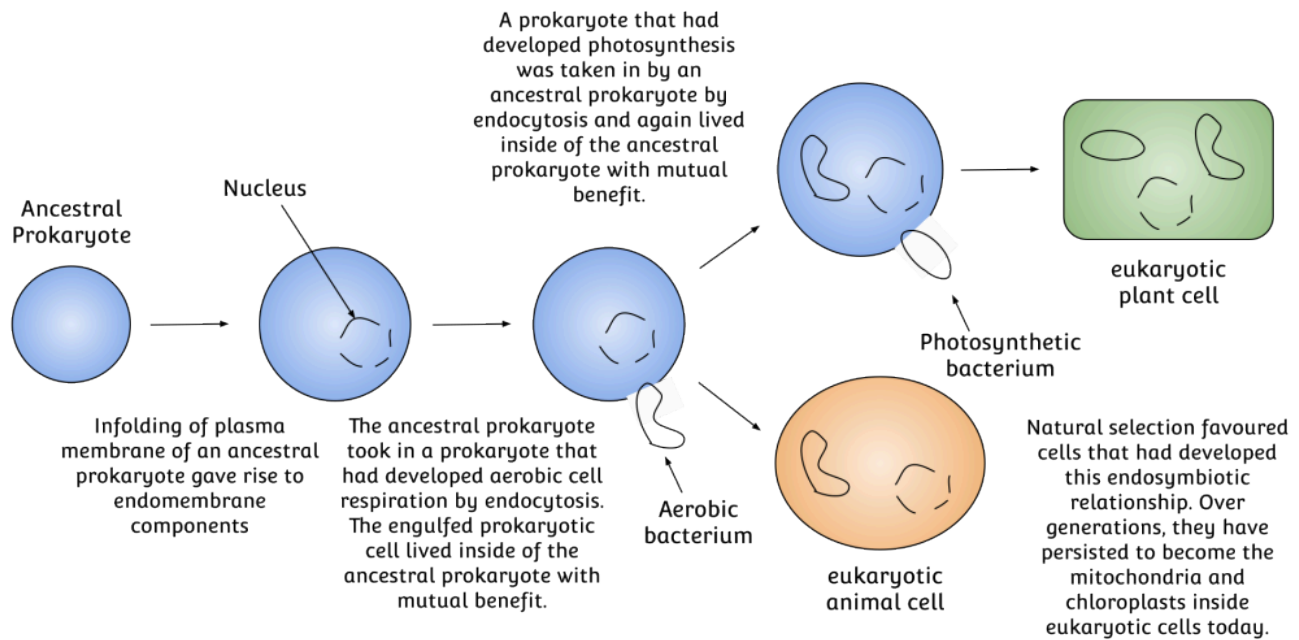
Figure 2: This figure shows the generalized structure of a prokaryotic cell.

All bacteria have a cell wall in addition to their cell membrane with the specific compound called peptidoglycan (molecules comprised of sugars and amino acids) and many have a polysaccharide capsule outside the cell wall. The cell wall acts as an extra layer of protection, helps the cell maintain its shape, and prevents dehydration. The capsule typically enables the cell to attach to surfaces in its environment, and can be the specific feature that bothers the human immune system. 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**. Organelles are either separately enclosed within their own lipid bilayers (also called membrane-bound organelles) or are spatially distinct functional units without a surrounding lipid bilayer (non-membrane bound organelles). The word “organelle” means “little organ,” and, as already mentioned, organelles have specialized cellular functions, just as the organs of your body have specialized functions (see Figure 5 and 6). The word eukaryotic means “true kernel” or “true nucleus,” alluding to the presence of the membrane-bound nucleus in these cells.

Two specific organelles in eukaryotes are thought to have originated through **symbiogenesis**: mitochondria and chloroplasts. The symbiogenesis theory proposes that these organelles evolved from certain types of bacteria that early eukaryotic cells engulfed through phagocytosis (Figure 3). These cells and the bacteria trapped inside them entered an endosymbiotic relationship, meaning that the bacteria took up residence and began living exclusively within the eukaryotic cells. Mitochondria and chloroplasts both have double membranes and separate DNA from that in the cell’s nucleus.



Chloroplast and Mitochondrial Evidence

- They have double membranes
- They can only be produced by division of pre-existing mitochondria and chloroplasts
- They have their own DNA which is naked and circular
- They have ribosomes which are 70S in size

Figure 3: There is evidence that the precursor to mitochondria and chloroplasts were bacterium specialized in aerobic respiration and photosynthesis, respectively.

By Eosmanov – Own work, CC BY-SA 4.0.

Cell Size

In general, cell size is limited because volume increases much more quickly than does cell surface area. As a cell becomes larger, 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. At 0.1–5.0 μm in diameter, most prokaryotic cells are significantly smaller than eukaryotic cells, which have diameters ranging from 10–100 μm (Figure 4). The small size of prokaryotes allows ions and organic molecules that enter them to quickly spread to other parts of the cell. Similarly, any wastes produced within a prokaryotic cell can quickly move out. Larger eukaryotic cells have evolved different structural adaptations to enhance cellular transport with the most basic functions being to bring energy-providing molecules and to carry away waste products. Indeed, the large size of these cells would not be possible without these adaptations.

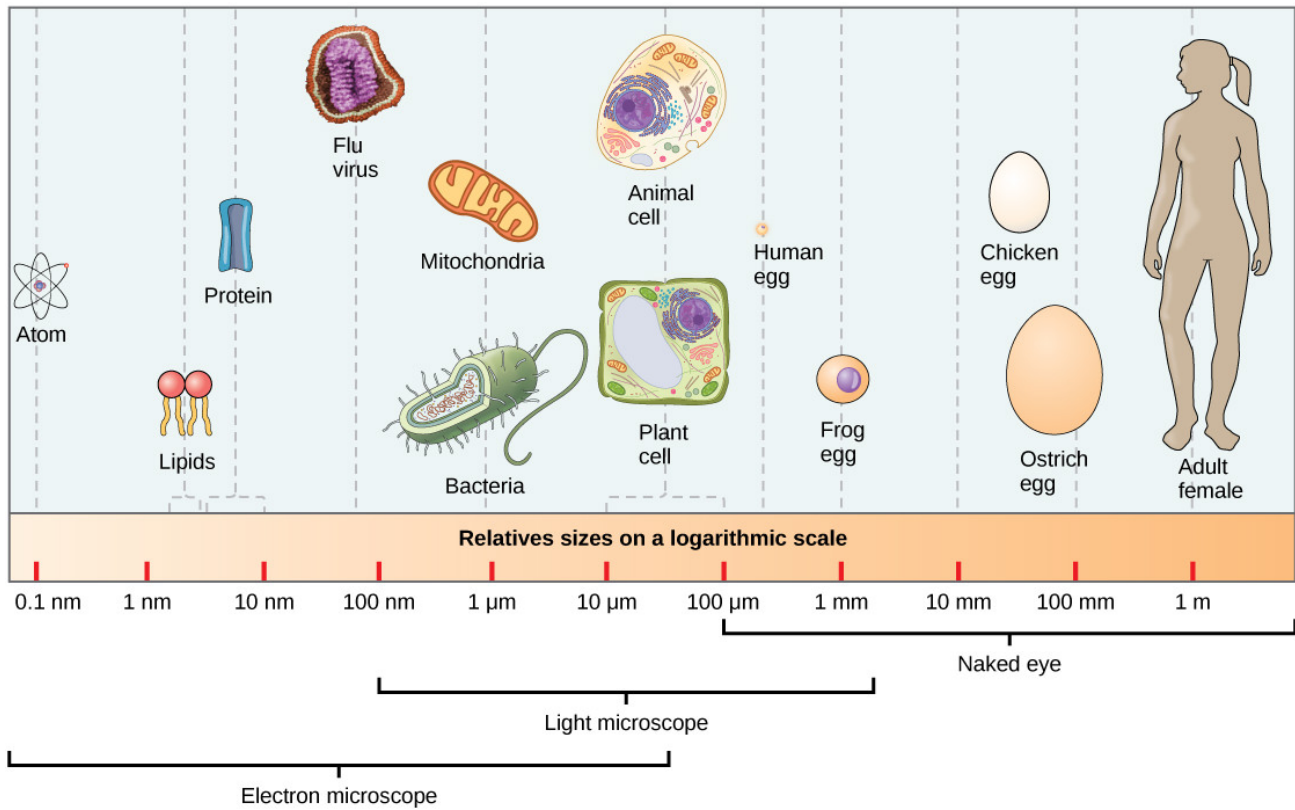


Figure 4: This figure shows the relative sizes of different kinds of cells and cellular components. An adult human is shown for comparison.

2.3.3 Chloroplasts and Mitochondria

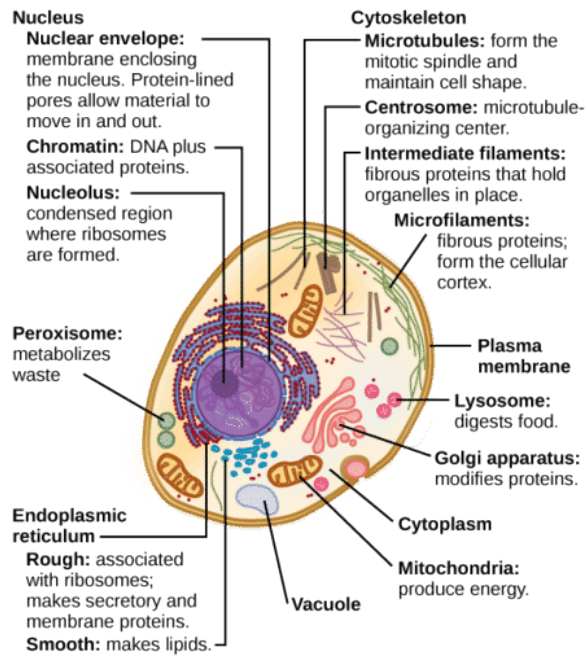


Figure 5: An example of a typical animal cell.

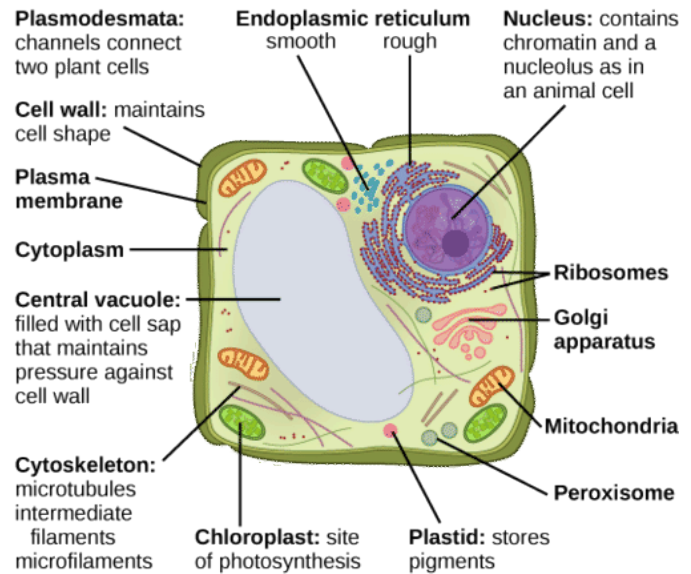


Figure 6: An example of a typical plant cell.

Despite their fundamental similarities, there are some striking differences between animal and plant cells (Figures 5 and 6). 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. These fundamental differences in cell membrane and cell wall connect to larger concepts like the digestibility of food.

Chloroplasts

One major difference between algae/plants and animals is that plants/algae are able to make their own food, like glucose, whereas animals must obtain food by consuming other organisms. Which leads us to this topic and subsection.

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 (some prokaryotic cells can also perform photosynthesis, but the majority of photosynthesis is performed by eukaryotic cells and organisms). During photosynthesis, carbon dioxide, water, and light energy are used to make glucose and molecular oxygen.

Chloroplasts have outer and inner membranes, but within the space enclosed by a chloroplast's inner membrane is a set of interconnected and stacked, fluid-filled membrane sacs called thylakoids (Figure 7). 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. The inner membranes help organize

the reactions that are part of photosynthesis, and moving electrons across the inner membrane is a fundamental way that energy is transformed from solar energy into chemical energy.

A few common themes in biology are demonstrated in chloroplasts. First is that form and function are interrelated. Each structure within the chloroplast has an important function, which is enabled by its particular shape. For example, the membrane-rich stacks of the thylakoids provide ample surface area to embed the proteins and pigments that are vital to photosynthesis. Second is the importance of surface area in organization of organisms.

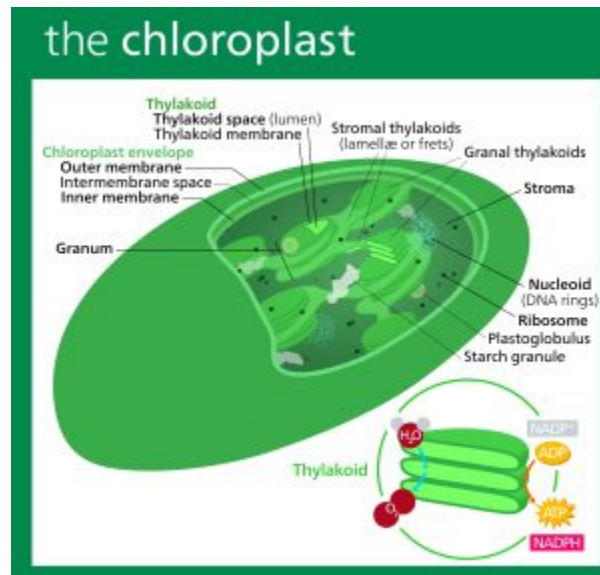


Figure 7: An image of a chloroplast organelle. The subset image of the thylakoid highlights the importance of the thylakoid (and associated membranes) in splitting water into oxygen during the light portion of photosynthesis. This image by Kelvinsong is licensed CC BY 3.0

Mitochondria

Most eukaryotic cells, both plants and animals, have **mitochondria** that function as a “powerhouse” to provide the cell with enough energy in the form of ATP to function. Mitochondria are important organelles thought to originate as separately living prokaryotic cells (like chloroplasts). Similar to chloroplasts, mitochondria have a high amount of membrane surface area regulating the interior of the mitochondria (Figure 8). These membranes control the movement of ions—most importantly, electrons and H⁺ cations—that allow the aerobic respiration reactions to break down complex carbon molecules like glucose into simple carbon dioxide molecules and transform the energy from one chemical bond to a different one (held in ATP).

In the next section, we will see these two chemical reactions in more detail: photosynthesis and aerobic respiration.

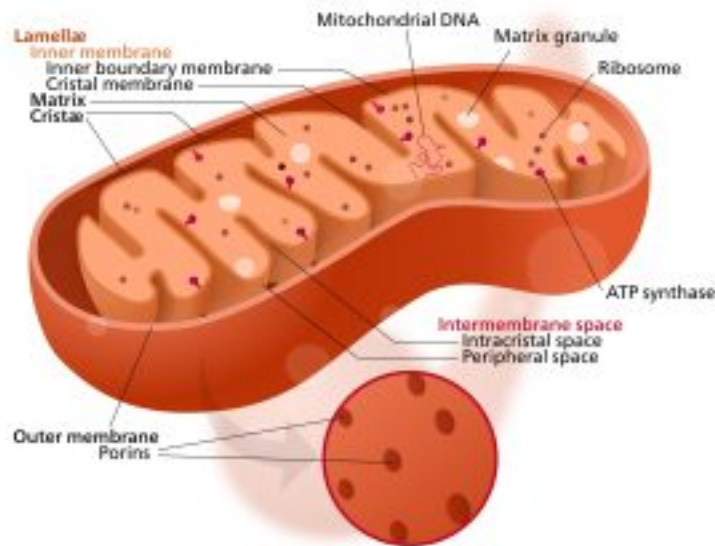


Figure 8: An image of the mitochondria organelle. Image highlights the highly folded intermembrane with intermembrane space between it and the outer membrane of the mitochondria. This image originally by Kelvinsong; modified by Sowlos; is licensed CC BY-SA 3.0

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2.4 Energy Enters Ecosystems Through Photosynthesis

Section Goals:

1. Understand the connection between energy and biological food webs.
2. Understand photosynthesis and cellular respiration.
3. Understand the link between photosynthesis, cellular respiration, and climate change.

Solar Energy Drives Ecosystems

All cells perform cellular respiration, which runs on the chemical energy. The fundamental unit of chemical energy is found in carbohydrate molecules, and the majority of carbohydrate molecules are produced by one process: photosynthesis. The energy stored in the bonds to hold carbohydrate molecules together is released when an organism breaks down food. Cells then use this chemical energy to perform work, such as movement. The energy that is harnessed from photosynthesis enters the ecosystems of our planet continuously and is transferred from one organism to another. Therefore, directly or indirectly, the process of 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, to eat and breathe humans depend almost entirely on the organisms that carry out photosynthesis.

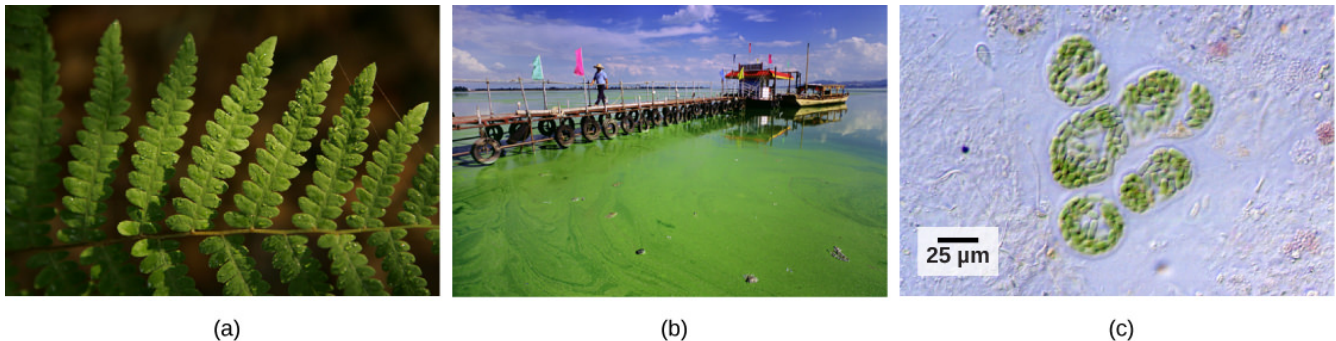


Figure 1: (a) Plants, (b) algae, and (c) certain bacteria, called cyanobacteria, are photoautotrophs that can carry out photosynthesis. Algae can grow over enormous areas in water, at times completely covering the surface. (credit a: Steve Hillebrand, U.S. Fish and Wildlife Service; credit b: “eutrophication&hypoxia”/Flickr; 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) “feeder” (troph). Plants are the best-known autotrophs, but others exist, including certain types of bacteria and algae (Figure 1). Oceanic 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.

Heterotrophs are organisms that 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 the process of 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.



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

Summary of Photosynthesis

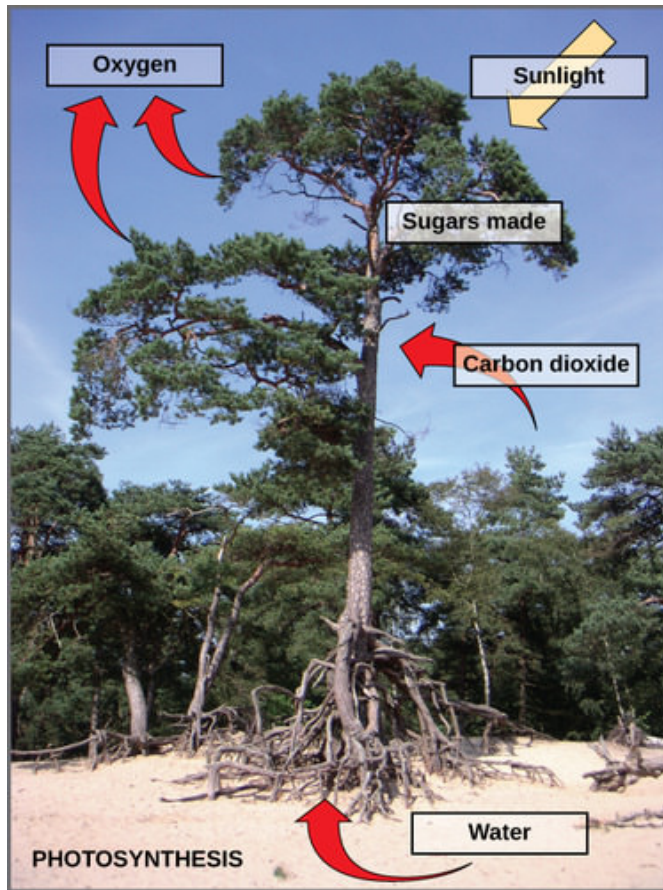


Figure 3: Photosynthesis uses solar energy, carbon dioxide, and water to release oxygen and to produce energy-storing sugar molecules.

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 complex reactions of photosynthesis can be summarized by the chemical equation shown in Figure 4 below.

Although the equation looks simple, the many steps that take place during photosynthesis are actually 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		Sugar + Oxygen
6CO_2		$6\text{H}_2\text{O}$		$\text{C}_6\text{H}_{12}\text{O}_6$ + 6O_2

Figure 4: This equation means that six molecules of carbon dioxide (CO_2) combine with six molecules of water (H_2O) in the presence of sunlight. This produces one molecule of glucose ($\text{C}_6\text{H}_{12}\text{O}_6$) and six molecules of oxygen (O_2).

The Two Parts of Photosynthesis

Photosynthesis takes place in two stages: the light-dependent reactions and the Calvin cycle. In the **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 from the splitting of

water. In the **Calvin cycle**, the chemical energy derived from the light-dependent reactions drives both the capture of carbon in carbon dioxide molecules and the subsequent assembly of sugar molecules.

The Global Significance of Photosynthesis

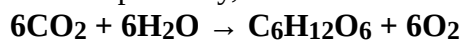
The process of photosynthesis is crucially important to the biosphere for the following reasons:

1. It creates O₂. The molecular oxygen in Earth's atmosphere was created by photosynthetic organisms; without photosynthesis there would be no O₂ to support cellular respiration 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 a diversity of present-day photosynthesizing organisms, Earth's atmosphere is currently about 21% O₂. Also, this O₂ is vital for the creation of the ozone layer (see [Section 10.2](#)), which protects life from harmful ultraviolet radiation emitted by the sun. Ozone (O₃) is created from the breakdown and reassembly of O₂.
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. Though photosynthesis captures only about 1% of total incoming solar radiation, that is enough energy to support entire biomes! 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 CO₂ 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 CO₂ used by photosynthetic organisms (see [Section 3.1](#) for more information on food webs).

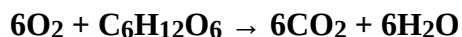
Cellular respiration

Carbohydrates are storage molecules for energy in all living things. Living things access energy by breaking down carbohydrate molecules. This fundamental process is **cellular respiration**. You may wonder: if plants make carbohydrate molecules, do they also need to break them down? Yes! Carbohydrates are much more stable and efficient reservoirs for chemical energy and it the way energy is transferred between cells. ATP is the form of chemical energy that can be used locally to power chemical reactions within a cell. Photosynthetic organisms must also carry out the reactions of respiration to harvest the energy that they have stored in carbohydrates and convert it into ATP; plants have mitochondria in addition to chloroplasts.

Most importantly, notice that the overall reaction for photosynthesis:



is the reverse of the overall reaction for cellular respiration:



Photosynthesis produces **oxygen** as a byproduct, and respiration produces **carbon dioxide** as a byproduct. In nature, there is no such thing as waste. Every single atom of matter is conserved, recycling indefinitely. Substances change form or move from one type of molecule to another, but never disappear. CO₂ is no more a form of waste produced by respiration than oxygen is a waste product of photosynthesis. Both are byproducts of reactions that move on to other reactions. Photosynthesis absorbs energy to build carbohydrates in chloroplasts, and aerobic cellular respiration releases energy by using oxygen to break down carbohydrates. Photosynthesis and cellular respiration function in a biological cycle, allowing organisms to access life-sustaining energy that originates millions of miles away in a star.

Carbon dioxide, photosynthesis, and climate change

This concept will be revisited in more detail in future sections, but the key point is highlighted here:

All life produces carbon dioxide as a result of living (via cellular respiration), and requires carbon to build body tissue. Photosynthesis turns carbon dioxide into organic carbon molecules. This balance and feedback between photosynthesis and cellular respiration is a crucial part of the overall geochemical cycles that allow the earth to support life. Photosynthesis is the opposite of cellular respiration, and vice versa. It is undeniable that global carbon dioxide concentrations are rising. Thus, as a natural opposite reaction to cellular respiration, photosynthesis is a buffer to climate change caused by rising carbon dioxide levels.

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2.5 Chapter Resources

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, and covalent bonds. Hydrogen bonds form between partially charged portions of molecules like water and other partially charged molecules. 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 such 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, the process of 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, to eat and breathe, humans depend almost entirely on the organisms that carry out photosynthesis.

Review Questions

1. You analyze a sample of carbon and determine that 6% of the carbon atoms in your sample have a mass number (atomic mass) greater than 12, (12 is the normal atomic mass of carbon). Based on these results, which of the following can you reasonably conclude?
 - A. 6% of the carbon sample is a different element
 - B. 6% of the sample is comprised of carbon isotopes
 - C. 6% of the sample is comprised of carbon ions
 - D. 94% of the sample is comprised of carbon radioisotopes
 - E. 94% of the sample contains covalent bonds
2. An atom that has an electrical charge due to having a number of electrons unequal to the number of protons is considered a(n)...
 - A. Isotope
 - B. Ion
 - C. Element
 - D. Molecule
 - E. Acid

3. The atomic number for the element fluorine is 9 and its mass number is 19. How many neutrons does a normal atom of fluorine have?
- A. 0
 - B. 9
 - C. 10
 - D. 19
 - E. Impossible to determine with the information given
4. Which one of the following is not one of the four major classes of organic compounds?
- A. Nucleic acids
 - B. Water
 - C. Proteins
 - D. Carbohydrates
 - E. Lipids
5. You are working as an astrobiologist for NASA and are asked to analyze the first ever samples returned to Earth from Mars. How would you recognize if organic molecules were present in the samples?
- A. Test for isotopes of carbon
 - B. Look for the presence of hydrogen bonds
 - C. Search for chemicals with carbon to hydrogen bonds
 - D. Analyze the percentage of molecules with covalent bonds
 - E. Measure the pH of the samples
6. A micro-organism is viewed through a microscope and is determined to be made of a single cell that lacks organelles. From this information, which of the following can you conclude?
- A. The organism belongs to Domain Bacteria
 - B. The organism belongs to Domain Eukarya
 - C. The organism belongs to Domain Archaea
 - D. The cell is prokaryotic
 - E. The cell is eukaryotic
7. Which one of the following terms describes the complete set of chemical reactions that occur within cells?
- A. Metabolism
 - B. Cellular respiration
 - C. Calvin Cycle
 - D. Bioenergetics
 - E. Thermodynamics
8. Which one of the following is most strongly associated with kinetic energy?
- A. Atomic force
 - B. Static position in a gravitational field
 - C. Chemical energy
 - D. Movement

E. Covalent bonds

9. Which one of the following would help remove more CO₂ from the atmosphere?

- A. Planting more trees
- B. Burning less fossil fuels
- C. Increase the number of heterotrophs
- D. Decrease the number of autotrophs
- E. All of the above.

10. Water is essential to life because it has many special properties. Which one of the following is a special property of water?

- A. It is able to covalently bond to other water molecules
- B. It is good at dissolving other substances
- C. It easily heats up.
- D. It easily cools.
- E. It has a low surface tension

See Appendix for answers

Additional Materials:

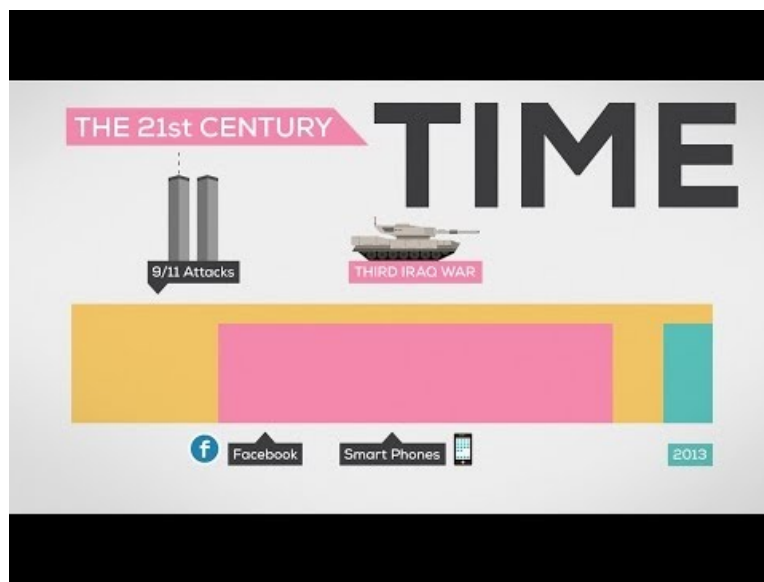


Figure 1. A video that provides some perspective about time, history, life, the universe, and everything.

Attributions

- CK12. (2014). *Biology*. Retrieved from <http://www.ck12.org/user%3AZ3JlZ29yLmRpZXRIcmxlQGhvcml6b25jbGMub3Jn/book/CK-12-Biology/r1/>. Available under Creative Commons Attribution-NonCommercial 3.0 Unported License. (CC BY-NC 3.0). Modified from Original.
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[%3A%3Aof%3A%3A-MS-Cell-Functions-%3A%3Aof%3A%3A-CK-12-Life-Science-For-Middle-School/](#). Available under Creative Commons Attribution-NonCommercial 3.0 Unported License. ([CC BY-NC 3.0](#)). Modified from Original.

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Chapter 3: Ecosystems and the Biosphere



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:

- Differentiate between food chains and food webs and recognize the importance of each
- Describe how organisms acquire energy in a food web and in associated food chains
- Describe the basic types of ecosystems on Earth
- 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

- 3.2 Terrestrial Biomes
- 3.3 Aquatic Biomes
- 3.4 Biogeochemical Cycles
- 3.5 Chapter Resources

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3.1 Energy Flow through Ecosystems

Section Goals:

1. Define broad categories of ecosystem.
2. Understand food chains and food webs.
3. Understand how organisms get the required energy to live.
4. Connect food webs to the movement of substances through ecosystems.

Ecosystems

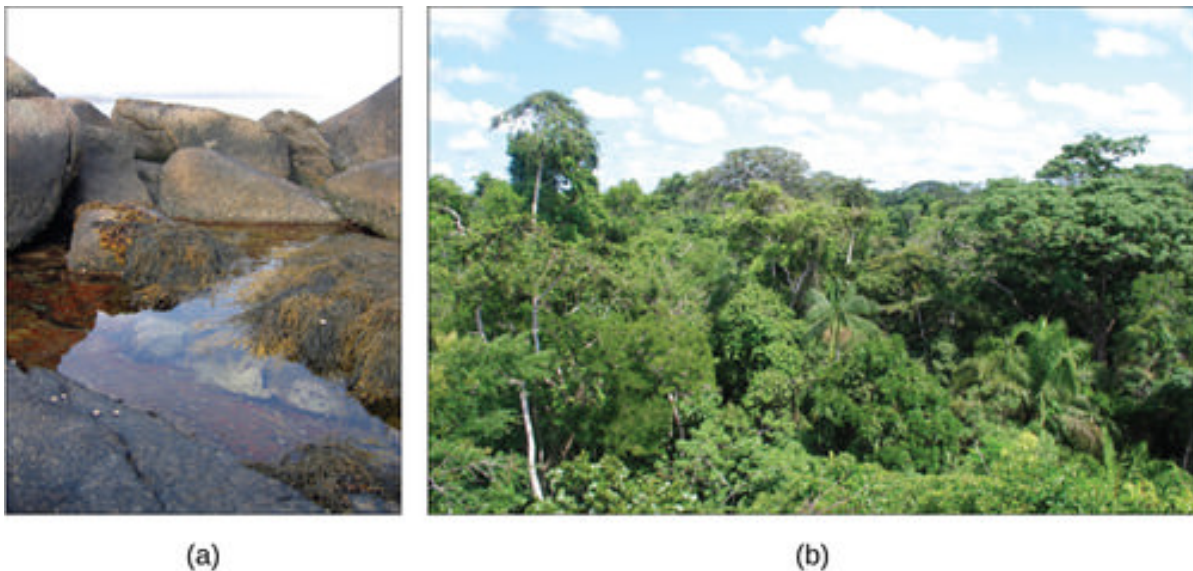


Figure 1: A (a) tidal pool ecosystem in Matinicus Island, Maine, is a small ecosystem, while the (b) Amazon rainforest in Brazil is a large ecosystem. (credit a: modification of work by Jim Kuhn; credit b: modification of work by Ivan Mlinaric)

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. Within 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 tundra. 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 gigantea*) 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).



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)

Food Chains and Food Webs

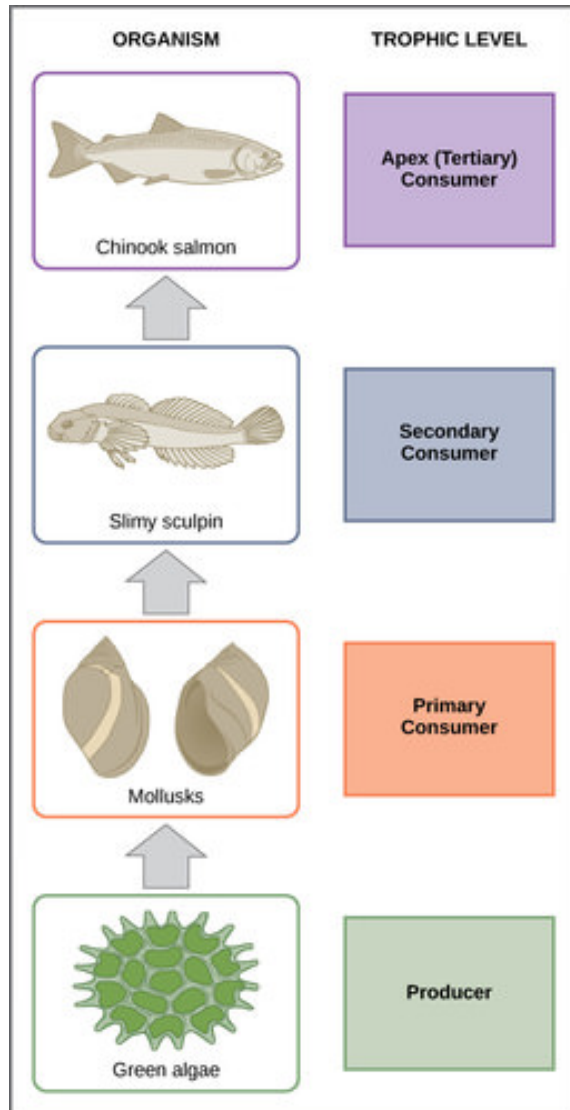


Figure 3: These are the trophic levels of a food chain in Lake Ontario at the United States–Canada border. Energy and nutrients flow from photosynthetic green algae at the base to the top of the food chain: the Chinook salmon. (credit: modification of work by National Oceanic and Atmospheric Administration/NOAA)

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. 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 base, or foundation, of the food chain consists of photosynthetic organisms (mainly 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.

One major factor that limits the number of steps in a food chain is energy. 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. What happens to this “missing” energy? It is lost as heat. Remember, all living organisms have a metabolism and require a consistent input of energy.

There is a problem when using food chains to describe an 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—which includes all the interactions between different species and their complex interconnected relationships with each other and with 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).

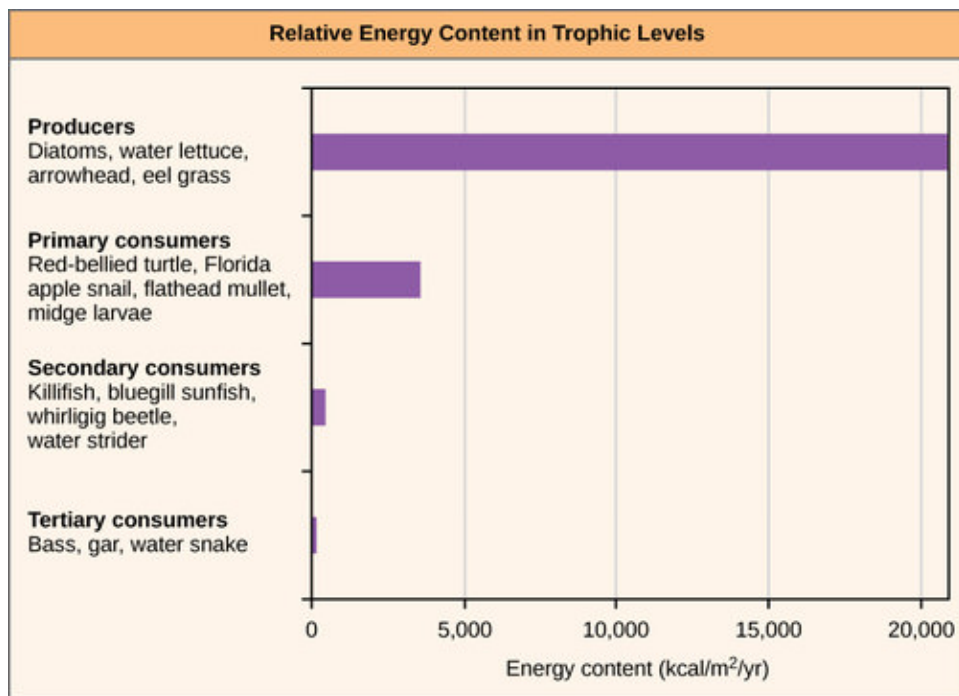


Figure 4: The relative energy in trophic levels in a Silver Springs, Florida, ecosystem is shown. Each trophic level has less energy available, and usually, but not always, supports a smaller mass of organisms at the next level.

So far, only one general type of food web has been described: a **grazing food web** that has plants or other photosynthetic organisms at its base. There is a second general type of food web: a detrital food web. A **detrital food web** consists of a base of organisms that feed on decaying organic matter (AKA detritus or dead organisms), including **decomposers**, which break down dead and decaying organisms, and **detritivores**, which consume detritus. Decomposers are typically bacteria and fungi. Detritivores are typically invertebrate animals (like insects and earthworms) that recycle organic material back into the biotic part of the ecosystem through their excrement and as they themselves are consumed by other organisms.

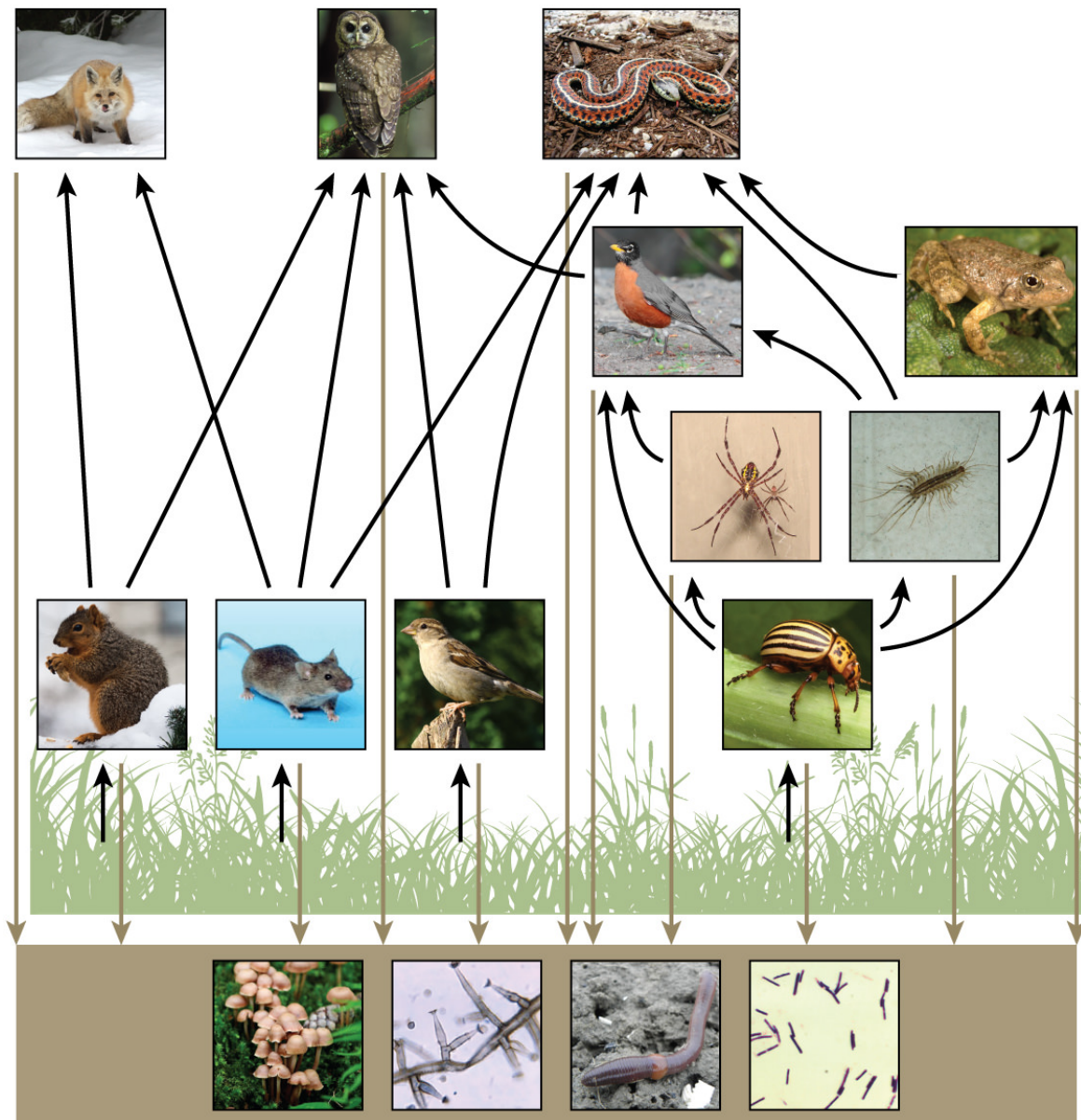


Figure 5: This food web shows the interactions between organisms across trophic levels. Arrows point from an organism that is consumed to the organism that consumes it. All the producers and consumers eventually become nourishment for the decomposers (fungi, mold, earthworms, and bacteria in the soil). (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

All living things require energy in one form or another. At the cellular level, chemical energy is used in most metabolic pathways (usually in the form of ATP [Section 2.2]), especially those responsible for building large molecules from smaller compounds; these large molecules include the 4 categories of macromolecule (proteins, lipids, nucleic acids, and carbohydrates [Section 2.1]). Living organisms would not be able to assemble complex organic molecules without a constant energy input. The assembling of macromolecules from smaller molecules is an example of an important cellular-level energy transfer, and thus by definition, some energy is lost as heat in the transformation.

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



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 to 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.

Photosynthetic and chemosynthetic organisms are autotrophs, which are organisms capable of synthesizing their own food (more specifically, capable of 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.

Chemoautotrophs are primarily bacteria and archaea that are found in rare ecosystems where sunlight is not available, 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), which is 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.

Consequences of Food Webs: Biological Magnification

One of the most important consequences of ecosystem dynamics in terms of human impact is biomagnification. **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 were 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 substance that biomagnifies is polychlorinated biphenyl (PCB), which was used as coolant liquids 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 is otherwise exists at low concentrations in the environment. As illustrated in a study performed by the NOAA in the Saginaw Bay of Lake Huron of the North American Great Lakes (Figure 7), 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 that are at least ten times higher than those found in the lake fish.

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 the food we eat.

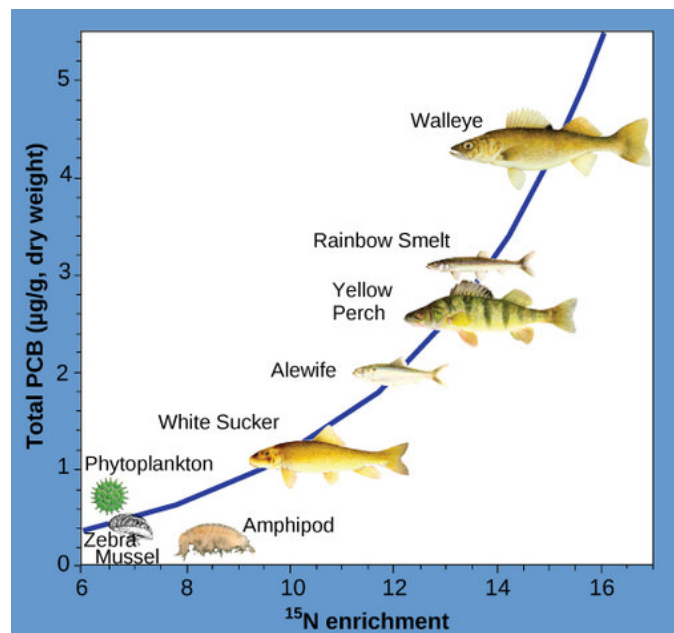


Figure 7: This chart shows the PCB concentrations found at the various trophic levels in the Saginaw Bay ecosystem of Lake Huron. Notice that the fish in the higher trophic levels accumulate more PCBs than those in lower trophic levels. (credit: Patricia Van Hoof, NOAA)

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3.2 Terrestrial Biomes

Section Goals:

1. Understand the patterns of the world's major terrestrial biomes.

Eight Terrestrial Biomes

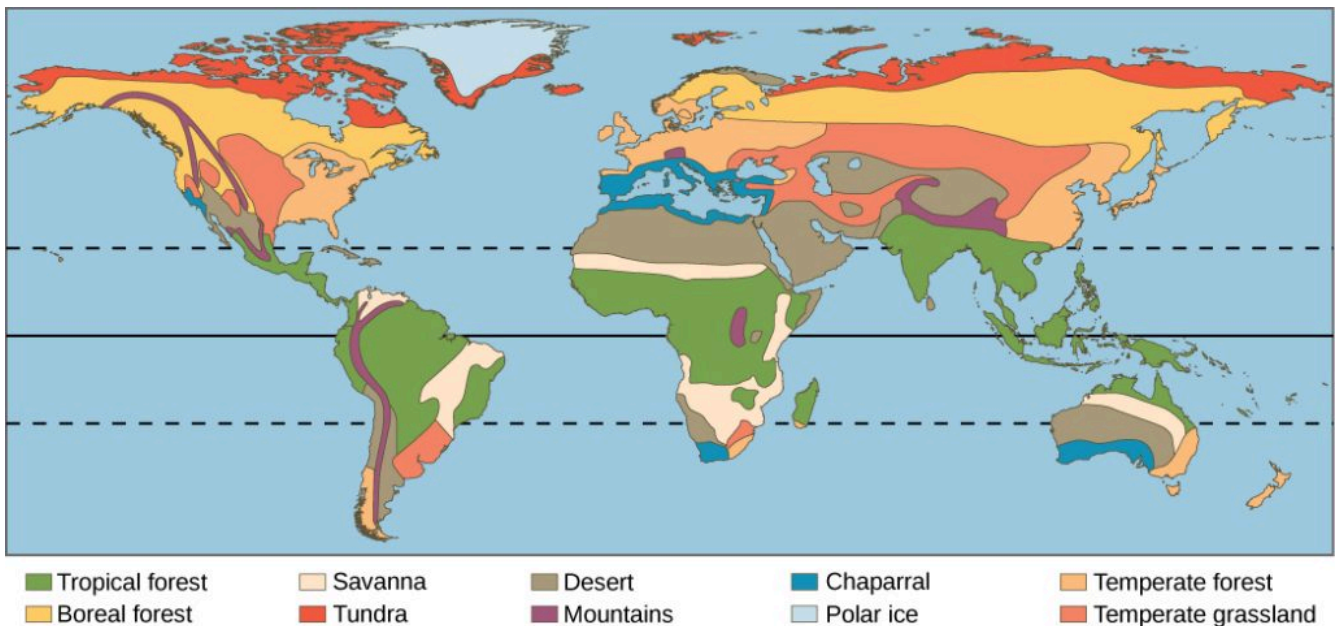


Figure 1: Each of the world's eight major biomes is distinguished by characteristic temperatures and amount of precipitation. Polar ice caps and mountains are also shown.

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 that are distinguished by characteristic temperature ranges and amounts of precipitation. Thus, biomes tend to follow latitudinal gradients. The two variables (temperature and precipitation) primarily affect the types of vegetation that can grow in an area, since plants cannot locomote. But the variables also affect animal life directly. Simultaneously, climate affects animal life indirectly through the vegetation that makes up the diets of the herbivores at the base of the food web. 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, found in equatorial regions, 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 that is 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.

The temperature and sunlight profiles of tropical rainforests are stable in comparison to other terrestrial biomes, with average temperatures ranging from 20°C to 34°C (68°F to 93°F). Month-to-month temperatures are relatively constant in tropical rainforests, in contrast to forests farther from the equator. 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, as well as dry months in which there are fewer 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 leaches nutrients from the soils of these forests, which causes challenges to farms that try to establish in these biomes.

Tropical rainforests are characterized by vertical layering of vegetation and the formation of distinct habitats for animals within each layer. On the forest floor is a sparse layer of plants and decaying plant matter. 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 the variety of plants, animals, and other organisms. Many species of animals use the variety of plants and the complex structure of the tropical wet forests for food and shelter. Some organisms live several meters above ground, rarely descending to the forest floor.

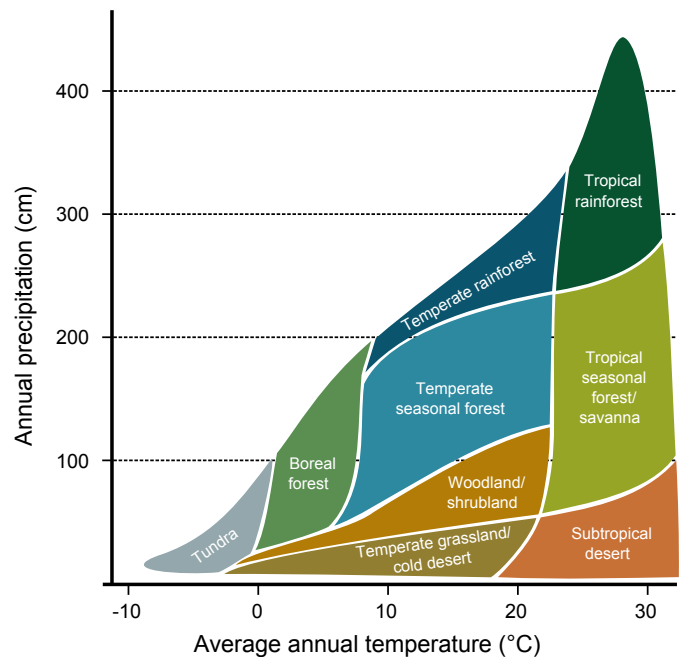


Figure 2: Precipitation and temperature are the two most important climatic variables that determine the type of biome in a particular location. Credit: “Climate influence on terrestrial biome” by Navarras is in the Public Domain, CC0

Savannas are grasslands with scattered trees and are found in Africa, South America, and northern Australia. Savannas are hot, tropical areas with temperatures averaging from 24°C –29°C (75°F –84°F) and an annual rainfall of 51–127 cm (20–50 in). Savannas have an extensive dry season and consequent fires. As a result, there are relatively few trees 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 resprout after a fire.



Figure 3: A MinuteEarth video about how trees create rainfall, and vice versa.

Subtropical deserts exist between 15° and 30° 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°C (140°F) and nighttime temperatures approaching 0°C (32°F). Subtropical deserts are characterized by low annual precipitation of fewer than 30 cm (12 in) with little monthly variation and 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 they die. Perennial plants in deserts are characterized by adaptations that conserve water: deep roots, reduced foliage, and water-storing stems (Figure 4). 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 4: A MinuteEarth video about the global climate patterns which lead to subtropical deserts.

In addition to subtropical deserts there are **cold deserts** that 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.

The **chaparral** is also called scrub forest and is found in California, along the Mediterranean Sea, and along the southern coast of Australia. The annual rainfall in this biome ranges from 65 cm to 75 cm (25.6–29.5 in) and the majority 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 behind 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, where they are also known as prairies, and in Eurasia, where they are known as steppes. 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 for those found growing along rivers or streams. The dominant vegetation tends to consist of grasses. The treeless condition is maintained by low precipitation, frequent fires, and grazing. The vegetation is very dense and the soils are fertile because the subsurface of the soil is packed with the roots and rhizomes (underground stems) of these grasses. The roots and rhizomes act to anchor plants into the ground and replenish the organic material (humus) in the soil when they die and decay.

Fires, which are 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 fire is suppressed in temperate grasslands, the vegetation eventually converts to scrub and dense forests. Often, the restoration or management of temperate grasslands requires the use of controlled burns to suppress the growth of trees and maintain the grasses.

Temperate forests are the most common biome in eastern North America, Western Europe, Eastern Asia, Chile, and New Zealand. This biome is found throughout mid-latitude regions. Temperatures range between -30°C and 30°C (-22°F to 86°F) and drop to below freezing on an annual basis. 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 the 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 reduced leaching of nutrients by rainfall. 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 their predators.

The **boreal forest**, also known as **taiga** or **coniferous forest**, is found roughly between 50° and 60° north latitude across most of Canada, Alaska, Russia, and northern Europe. 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 takes the form of 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, which 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-leaved 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.

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, during this time, there are almost 24 hours of daylight 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 12). There is little species diversity, low net primary productivity, and low above-ground biomass. The soils of the Arctic tundra may remain in a perennially frozen state referred to as 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](https://www.hhmi.org/biointeractive/biomeviewer). [Interactive Website]. Howard Hughes Medical Institute.
<<https://www.hhmi.org/biointeractive/biomeviewer>>

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3.3 Aquatic Biomes

Section Goals:

1. Understand the difference between terrestrial and aquatic biomes.

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 (there are no suspended particles), water still absorbs light. As one descends into a deep body of water, there will eventually be a depth which the sunlight cannot reach. While there are some abiotic and biotic factors in a terrestrial ecosystem that 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 both 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 (rates of heating and cooling) 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.

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.

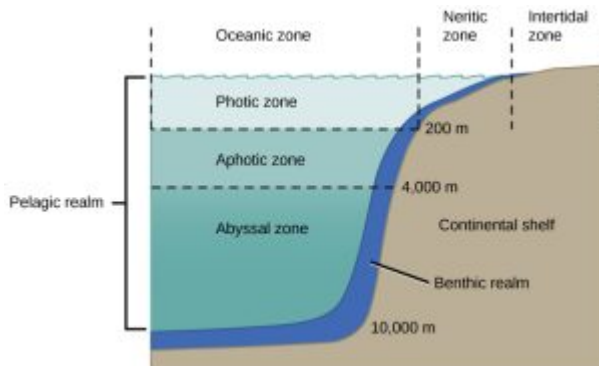


Figure 1: Availability of sunlight is a major control of marine biomes. The ocean biome is divided into zones based primarily on the availability of sunlight.

The ocean is categorized by 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**, which is the portion of the ocean 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.

The Ocean Biome

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.



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

The **intertidal zone**, which is the zone between high and low tide, is the oceanic region that is closest to land (Figure 2). Generally, most people think of this portion of the ocean 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 underwater most of the time, 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.

The **neritic zone** 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 type of free-floating marine seaweed) provide a habitat for some sea life found 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**. Within the oceanic zone there is thermal stratification where warm and cold waters mix because of ocean currents. Abundant plankton serve 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**, which is at depths of 4000 m or greater. The abyssal zone is very cold and has very high pressure, high oxygen content, and low nutrient content. There are a variety of invertebrates and fishes 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**, essentially the ocean floor, which is 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 upper layers of the ocean. Because of this high level of nutrients, a diversity of sponges, sea anemones, marine worms, sea stars, fishes, and bacteria exist.

The Coral Reef Biome

Coral reefs are characterized by high biodiversity and the structures created by invertebrates that live in warm, shallow waters within the photic zone of the ocean. 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 the energy they require. The waters in which these corals live are nutritionally poor and, without this mutualism, it would not be possible for large corals to grow.



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)

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.

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. As global warming due to fossil fuel emissions raises ocean temperatures, coral reefs are suffering. 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 loss of the symbiotic zooxanthellae is prolonged.

Rising levels of atmospheric carbon dioxide further threaten the corals in other ways; as CO₂ 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.

The Estuary Biome: Where the Ocean Meets Fresh Water

Estuaries are biomes that occur 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 a diluted (brackish) saltwater (Figure 4). 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 rate of flow of its 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 that the plant absorbs. Other plants are able to 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 (in which they use 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.



Figure 4: An estuary is where fresh water and salt water meet, such as the mouth of the Klamath River in California, shown here. (credit: U.S. Army Corps of Engineers)

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, therefore, connected with abiotic and biotic factors influencing these terrestrial biomes.

Lakes and Ponds



Figure 5: The uncontrolled growth of algae in this lake has resulted in an algal bloom. (credit: Jeremy Nettleton)

Lakes and ponds can range in area from a few square meters to thousands of square kilometers. Temperature is an important abiotic factor affecting living things found 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.

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), the growth of algae skyrockets, resulting in a large accumulation of algae called an **algal bloom**. Algal blooms (Figure 5) 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 then more likely to die, and resulting dead zones are found across the globe. Lake Erie and the Gulf of Mexico represent freshwater and marine habitats where phosphorus control and storm water runoff pose significant environmental challenges.

Rivers and Streams

Rivers and streams are continuously moving bodies of water that carry large amounts of water from the source, or headwater, to a lake or ocean (Figure 6). The largest rivers include the Nile River in Africa, the Amazon River in South America, and the Mississippi River in North America.



Figure 6: Rivers can range from narrow and fast moving (a) to wide and slow moving (b).

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 at 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 that are growing on rocks; the swift current inhibits the growth of phytoplankton. An additional input of energy can come from leaves or other organic material that falls into the river or stream from trees and other plants that border the water. When the leaves decompose, the organic material and nutrients in the leaves are returned to the water. 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 be found burrowing 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 in which the soil is either 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 that are rooted in the soil but have portions of leaves, stems, and flowers extending above the water's surface. There are several types of wetlands including marshes, swamps, bogs, mudflats, and salt marshes (Figure 7).



Figure 7: 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)

Suggested Supplemental Materials

[Video](https://oceanexplorer.noaa.gov/edu/oceanage/03etnoyer/welcome.html) about research in coral reefs. NOAA. <<https://oceanexplorer.noaa.gov/edu/oceanage/03etnoyer/welcome.html>>

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3.4 Biogeochemical Cycles

Section Goals:

1. Name the important elements that have biogeochemical cycles.
2. Understand the water cycle, the carbon cycle, the nitrogen cycle, the phosphorus cycle, and the sulfur cycle.
3. Describe similarities between these biogeochemical cycles.

Matter is recycled through ecosystems

Energy flows directionally through ecosystems, entering as sunlight (or inorganic molecules for chemoautotrophs) and leaving as heat. In contrast, the matter that makes up organisms is conserved and recycled within ecosystems. The six most common elements associated with organic molecules—carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur—take a variety of chemical forms and may exist for long periods in the atmosphere, on land, in water, or beneath Earth's surface. This recycling of inorganic matter (or essential nutrients) between living organisms and their nonliving environment is called **biogeochemical cycling**. Geologic processes, such as weathering, erosion, water drainage, and the subduction of the continental plates, all play a role in the cycling of elements on Earth. The name biogeochemical cycles reflects the importance of geology and chemistry in the study of these processes.

The six aforementioned elements (C, H, N, O, P, S) are used by organisms in a variety of ways. Hydrogen and oxygen are found in water and organic molecules, both of which are essential to life. Carbon is found in all organic molecules. 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, especially when water plays an active role. For example, the movement of water is critical for the leaching of both sulfur and phosphorus into rivers, lakes, and oceans. Similarly, all of these elements are crucial for the function of all organisms. To again highlighting interconnection, organisms can and will uptake multiple nutrients simultaneously.

The Water Cycle

Since water regulates portions of the biogeochemical cycles of all six elements, and relates directly to the cycling of hydrogen and oxygen, we will cover the water cycle first. 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 (Figure 1). Of the remaining water, more than 99 percent is groundwater or ice. Thus, less than one percent of freshwater is present in lakes and

ivers. Many organisms are dependent on this small percentage, a lack of which can have negative effects on ecosystems. Humans, of course, 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, the supply of fresh water continues to be a major issue in modern times.

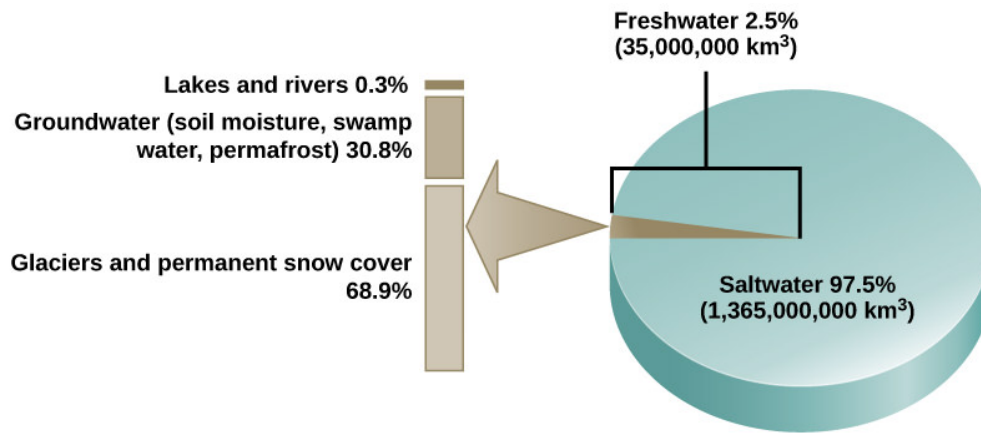


Figure 1: Only 2.5 percent of water on Earth is fresh water, and less than 1 percent of fresh water is easily accessible to living things.

The **water cycle** is driven by the Sun's energy. The various processes that occur during the cycling of water are illustrated in Figure 2. The processes include the following:

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

The Sun's energy 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 and eventually leads to **precipitation** (rain, snow, hail), which returns 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 a heavy rainfall. Water in the soil can be taken up by plant roots. 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, but 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 and evaporates, or transpires, through the stomata (small microscope openings) of the leaves. Ecologists combine transpiration and evaporation into a single term that describes water returned to the atmosphere: **evapotranspiration**. Water in the soil that is not taken

up by a plant and that does not evaporate is able to percolate into the subsoil and bedrock where it forms 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. **Aquifers**, the official term for groundwater reservoirs, are a crucial source of drinking or irrigation water drawn up through wells in most areas of the world. Unfortunately, in many cases these aquifers are being depleted faster than they are being replenished by water percolating down from above, presenting a challenge for long-term water availability.

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

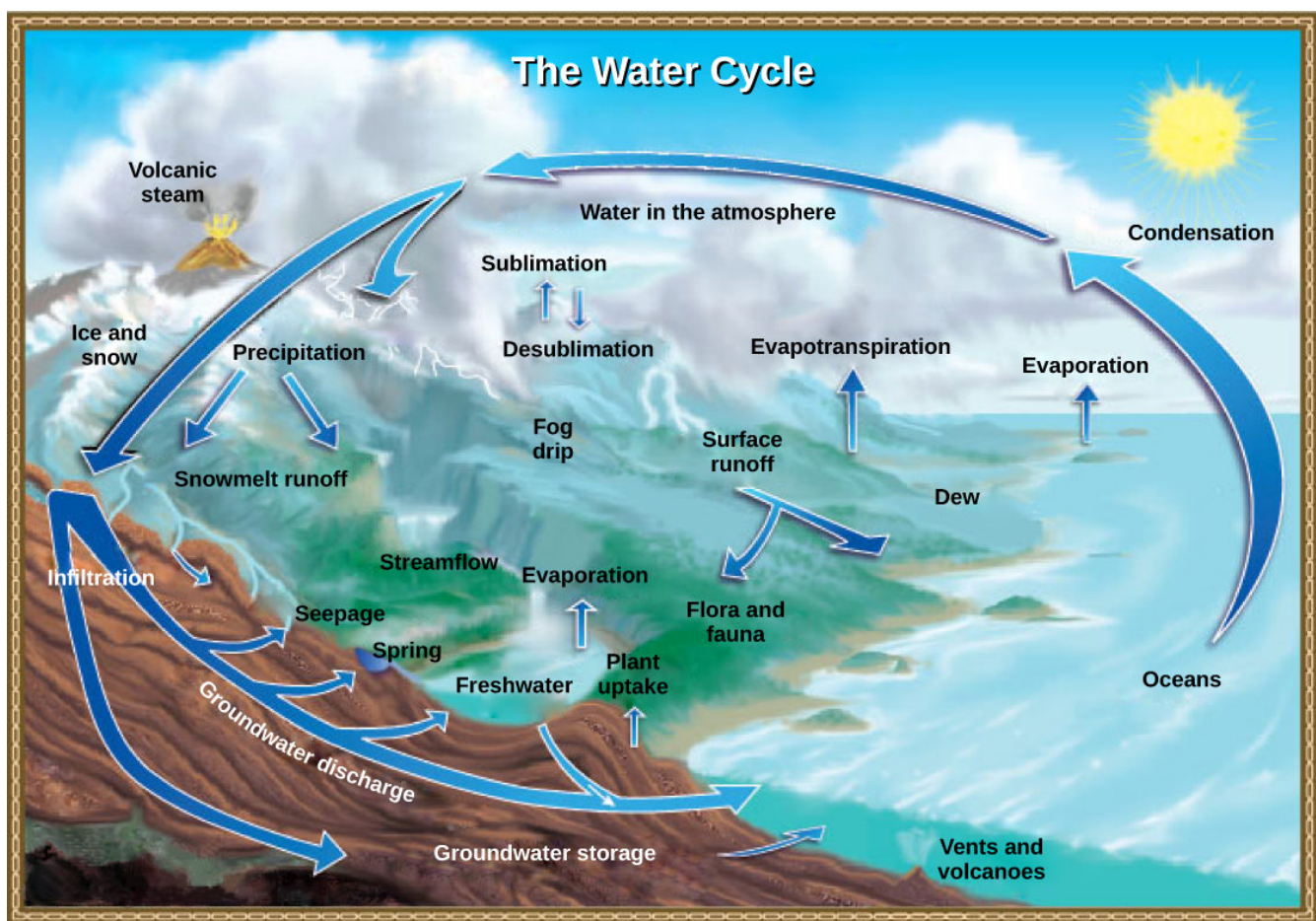


Figure 2: Water from the land and oceans enters the atmosphere by evaporation or sublimation, where it condenses into clouds and falls as rain or snow. Precipitated water may enter freshwater bodies or infiltrate the soil. The cycle is complete when surface or groundwater reenters the ocean. (credit: 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, critical in both food sources for heterotrophs and for society: **fossil fuels** are compounds derived from dead plants and algae that have fossilized over millions of years. 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 drastically increase. 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.

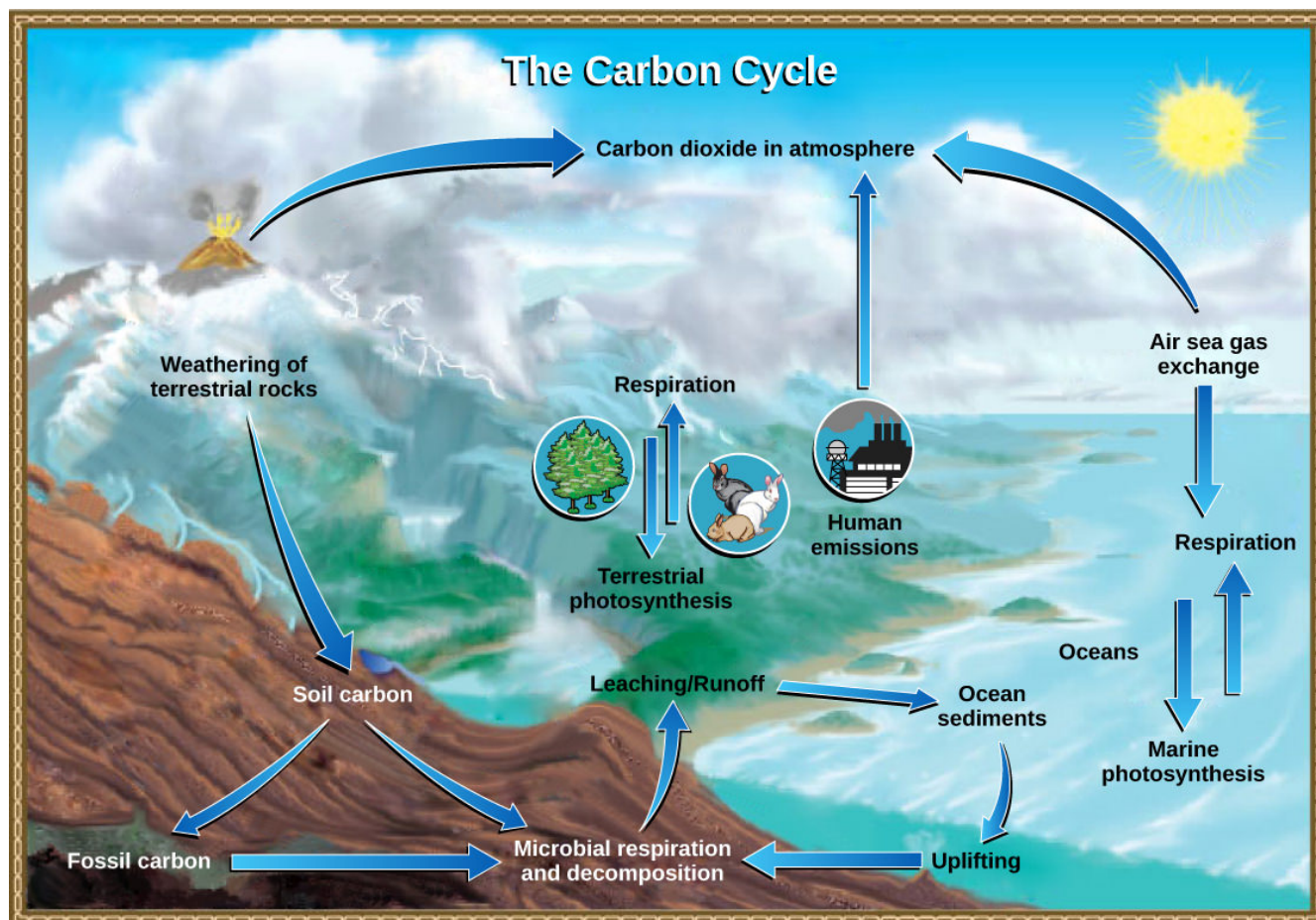


Figure 3: Carbon dioxide gas exists in the atmosphere and is dissolved in water. Photosynthesis converts carbon dioxide gas to organic carbon, and respiration cycles the organic carbon back into carbon dioxide gas. Long-term storage of organic carbon occurs when matter from living organisms is buried deep underground and becomes 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. A good example of this connection is the exchange of carbon between heterotrophs and autotrophs by way of atmospheric carbon dioxide. Carbon dioxide (CO_2) is the basic building block that autotrophs use to build high-energy compounds such as glucose. The energy harnessed from the Sun is used by these organisms to form the covalent bonds that link carbon

atoms together, converting the solar energy into chemical energy. 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 up 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, organisms are performing respiration, a process in which organic molecules are broken down to release energy (recall [Section 2.4](#)). 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. This completes the balance and the biological portion of the carbon cycle: CO_2 that is consumed by producers during photosynthesis makes organic molecules; when these molecules are broken down during respiration, the carbon once again enters the atmosphere as CO_2 . Carbon exchange like this connects all organisms on Earth. The carbon in your DNA was once part of plant; millions of years ago perhaps it was part of dinosaur.

The Biogeochemical Carbon Cycle

The slow movement of carbon through land, water, and air is complex, and notably, 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 reservoir of carbon in the form of carbon dioxide that is essential to the process of photosynthesis. The level of carbon dioxide in the atmosphere is greatly influenced by the reservoir of carbon in the oceans. The exchange of carbon 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 as a result of 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 rate of formation. A **non-renewable resource** is either regenerated very slowly or not at all.

Another way for carbon to enter the atmosphere from land (including land beneath the surface of the ocean) is by the eruption of volcanoes and other geothermal systems. In connection to the volcanic activity is the deep reservoir of carbon that enters the depths of the earth through the process of **subduction**; the movement of one tectonic plate beneath another which carries with it carbon sediments from the ocean floor. This carbon is only released as carbon dioxide when a volcano erupts or from volcanic hydrothermal vents.

The Nitrogen Cycle

The dominant feature of the nitrogen cycle is that getting nitrogen into living organisms is difficult.

The largest reservoir of nitrogen is in the atmosphere, where it exists as tightly bonded, triple covalent N_2 . Plants and phytoplankton are not equipped to incorporate atmospheric nitrogen, even though it comprises approximately 78 percent of the atmosphere. Nitrogen mainly enters the living world through bacteria (both free-living and symbiotic), which use specialized biochemical processes to break the triple-bond. Certain species of bacteria are able to perform **nitrogen fixation**, the process of converting nitrogen gas into ammonia (NH_3), which spontaneously becomes ammonium (NH_4^+). Ammonium is converted by other species of bacteria into nitrites (NO_2^-) and then nitrates (NO_3^-). At this point, the nitrogen-containing molecules are able to be used by plants and other producers to make organic molecules such as DNA and proteins. Once incorporated into the living tissue of producers, the nitrogen becomes available to consumers.

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

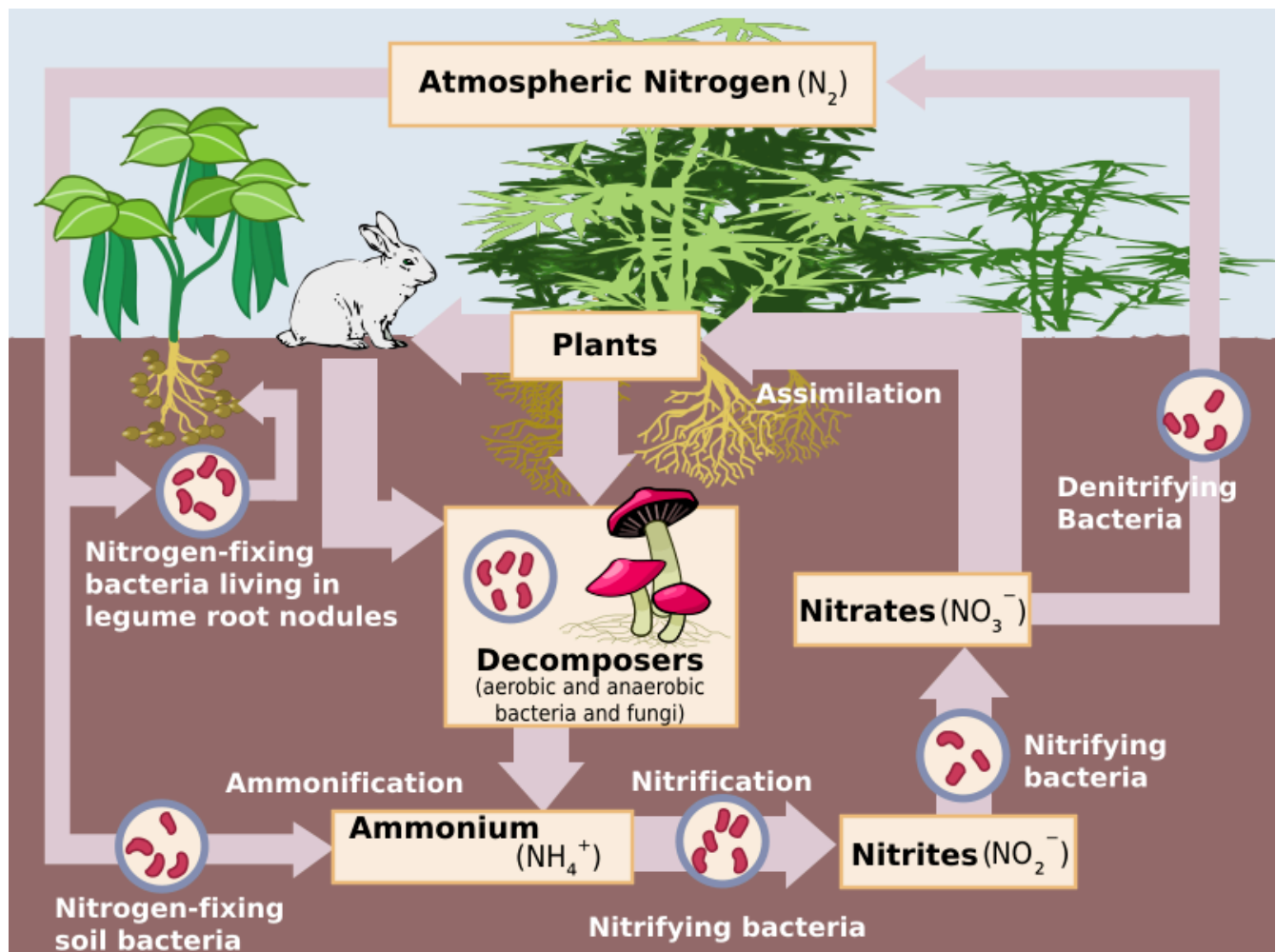


Figure 4: Nitrogen enters the living world from the atmosphere via nitrogen-fixing bacteria. This nitrogen and nitrogenous waste from animals is then processed back into gaseous nitrogen by soil bacteria, which also supply terrestrial food webs with the organic nitrogen they need. (credit: "[Nitrogen 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 nitrogen oxides, and by the use of artificial fertilizers (which contain nitrogen and phosphorus compounds) 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 from fertilizer runoff is **eutrophication** in both saltwater and freshwater systems. Eutrophication is a process where nutrient runoff causes the overgrowth of algae, leading to the depletion of oxygen, and death of aquatic fauna. The algal bloom is the most obvious response to excess nutrients, because algae are able to quickly reproduce when these excess nutrients become available.

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

The Phosphorus Cycle

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

Phosphorus occurs in nature as the phosphate ion (PO_4^{3-}) held in rocks. This rock has its origins in the ocean. Phosphate-containing ocean sediments form primarily from the bodies of ocean organisms and from their excretions. This sediment then is moved to land over geologic time by the uplifting of Earth's surface (Figure 5). Then, bio-available phosphorus enters the ecosystem through natural weathering of phosphate-containing rock into soil. A major concern for the phosphorus cycle is phosphate runoff as a result of human activity (e.g., fertilization). Volcanic ash, aerosols, and mineral dust may also be significant phosphate sources.

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.

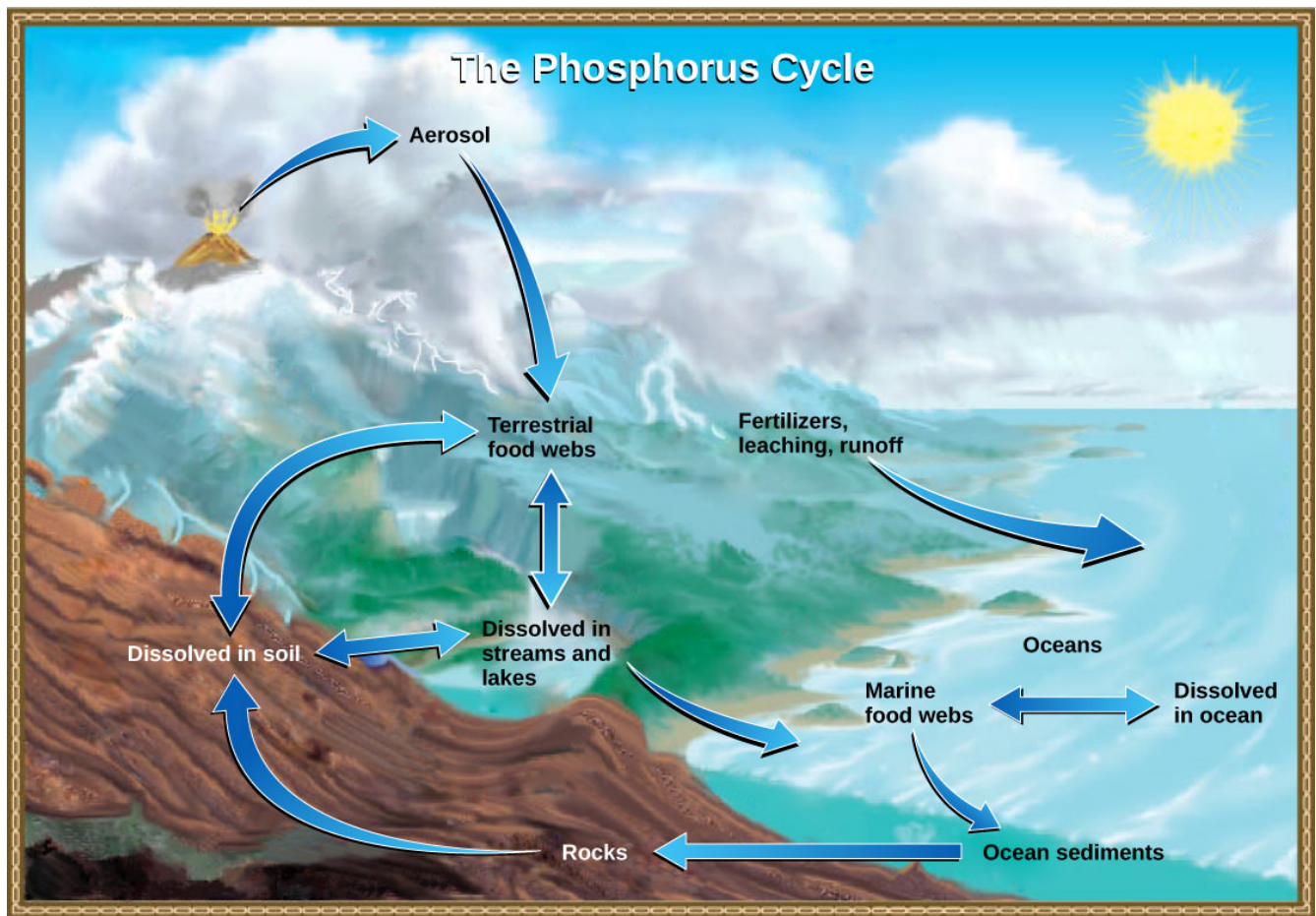


Figure 5: In nature, phosphorus exists as the phosphate ion (PO_4^{3-}). Weathering of rocks and volcanic activity releases phosphate into the soil, water, and air, where it becomes available to terrestrial food webs. Phosphate enters the oceans in surface runoff, groundwater flow, and river flow. Phosphate dissolved in ocean water cycles into marine food webs. Some phosphate from the marine food webs falls to the ocean floor, where it forms sediment. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

Excess phosphorus and nitrogen that enter these ecosystems from fertilizer runoff and from sewage cause excessive growth of algae. The subsequent death and decay of these organisms depletes 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, which often occur during the summer months (Figure 6).

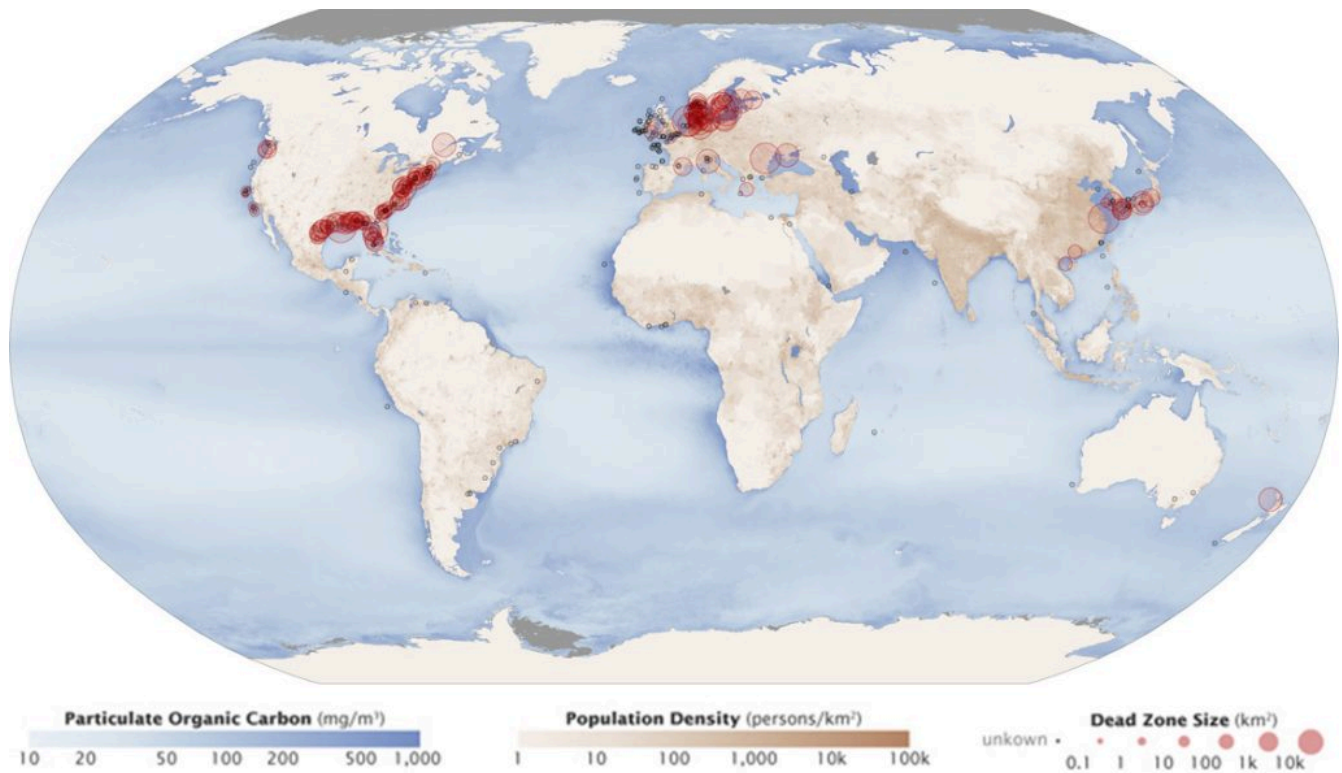


Figure 6: Dead zones occur when phosphorus and nitrogen from fertilizers cause excessive growth of microorganisms, which depletes oxygen and kills fauna. Worldwide, large dead zones are found in coastal areas of high population density. (credit: NASA Earth Observatory)

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, dumping 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.

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 the formation of proteins. As shown in Figure 7 below, sulfur cycles between the oceans, land, and atmosphere. Atmospheric sulfur is found in the form of sulfur dioxide (SO₂), 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.

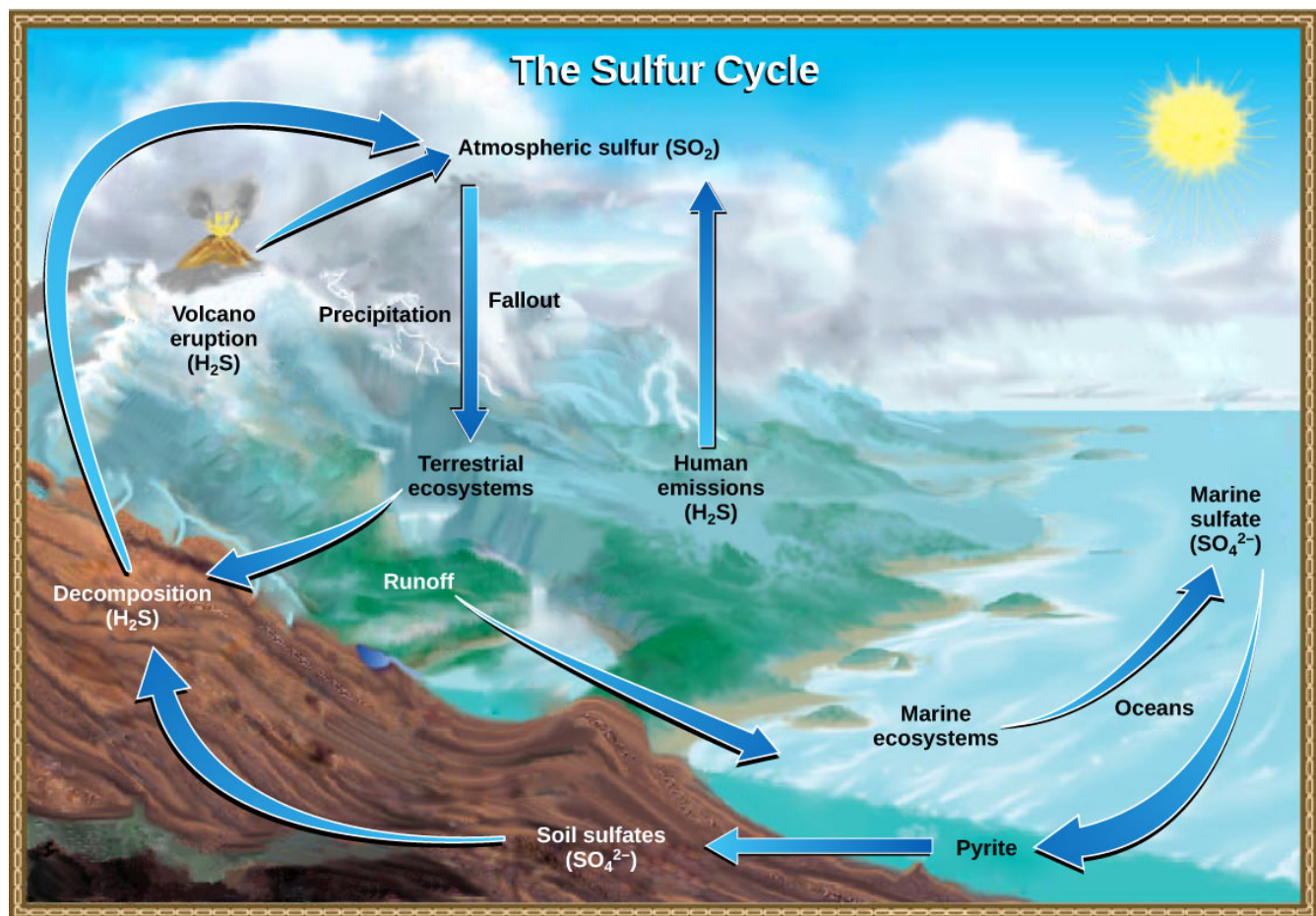


Figure 7: Sulfur dioxide from the atmosphere becomes available to terrestrial and marine ecosystems when it is dissolved in precipitation as weak sulfuric acid or when it falls directly to Earth as fallout. Weathering of rocks also makes sulfates available to terrestrial ecosystems. Decomposition of 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 make use of 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 back into the atmosphere as hydrogen sulfide (H_2S) gas.

Sulfur enters the ocean in runoff from land, from atmospheric fallout, and from 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. The burning of large quantities of fossil fuels, especially from coal, releases larger amounts of 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 of the 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 over the years. 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](https://serc.carleton.edu/microbelife/topics/deadzone/index.html). [Website] <<https://serc.carleton.edu/microbelife/topics/deadzone/index.html>>

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3.5 Chapter Resources

Summary

Ecosystems exist underground, on land, at sea, and in the air. Organisms in an ecosystem acquire energy in a variety of 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.

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 and precipitation, and variations in both, are key abiotic factors that shape the composition of animal and plant communities in terrestrial biomes. Sunlight is an important factor in bodies of water, especially those that are very deep, because of the role of photosynthesis 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.

Mineral nutrients are cycled through ecosystems and their environment. Of particular importance are water, carbon, nitrogen, phosphorus, and sulfur. All of these cycles have major impacts on ecosystem structure and function. Ecosystems have been damaged by a variety of human activities that alter the natural biogeochemical cycles due to pollution, oil spills, and events causing global climate change. The health of the biosphere depends on understanding these cycles and how to protect the environment from irreversible damage.

Review Questions

1. Secondary consumers would eat which one following?
 - A. Producers
 - B. Plants
 - C. Herbivores
 - D. Carnivores
 - E. Tertiary consumers
2. If you are concerned about biomagnification of toxins, which one of the following would you most want to avoid eating?
 - A. Tuna (tertiary consumer)
 - B. Seaweed (producer)
 - C. Urchin (primary consumer)
 - D. Sculpin (secondary consumer)
 - E. Any photoautotroph
3. Which one of the following is not a biogeochemical cycle?

- A. Energy cycle
 - B. Nitrogen cycle
 - C. Carbon cycle
 - D. Phosphorus cycle
 - E. Water cycle
4. Which one of the following would not increase the amount of water in the atmosphere?
- A. Evaporation
 - B. Transpiration
 - C. Sublimation
 - D. Infiltration
 - E. Evapotranspiration
5. Which one of the following processes would remove nitrates from contaminated water by converting it into nitrogen gas?
- A. Nitrification
 - B. Nitrogen fixation
 - C. Denitrification
 - D. Assimilation
 - E. Ammonification
6. What do deserts and chaparral have in common?
- A. Dry and hot summers
 - B. Dominated by abundant evergreen shrubs
 - C. Both can exist as either the hot or cold variety
 - D. Very small amounts of rainfall consistently throughout the year
 - E. Very low biodiversity
7. Which one of the following would most likely live within the benthic realm of the ocean?
- A. Squid
 - B. Tuna
 - C. Phytoplankton
 - D. Marine worm
 - E. Shark
8. What two variables most strongly contribute to the type of biome that exists in a particular area?
- A. Precipitation levels and temperature
 - B. Type of producers and density of herbivores
 - C. Amount of sunlight and annual rainfall
 - D. Soil type and amount of O_2
 - E. Distance from ocean and elevation
9. The conversion of nitrogen gas (N_2) into ammonia (NH_3) happens during which specific process?
- A. Ammonification
 - B. Denitrification
 - C. Nitrification

- D. Nitrogenous cycling
- E. Nitrogen fixation

10. Use your knowledge of the relative energy content among trophic levels to answer the following question: A larger human population could be supported if all humans derived their food from which trophic level?

- A. Producers
- B. Primary consumers
- C. Secondary consumers
- D. Tertiary consumers
- E. Quaternary consumers

See Appendix for answers

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Chapter 4: Community & Population Ecology



Asian carp jump out of the water in response to electrofishing. (credit: modification of work by USGS)

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 the presence of Asian carp. This fish—actually 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 disrupts ecological community structure to the point of threatening 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.

Learning Outcomes

After studying this chapter, you should be able to:

- Describe how ecologists measure population size and density
- Describe three different patterns of distribution within or between populations
- 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 Community Ecology
- 4.2 Population Dynamics and Demographics
- 4.3 Population Growth & Regulation
- 4.4 The Human Population
- 4.5 Chapter Resources

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4.1 Community Ecology

Section Goals:

1. Understand how communities fit within ecosystems and biomes.
2. Understand common species-to-species interactions.
3. Relate important types of species to community structure.

4.1.1 Community Properties

Communities are Within Biomes

We just learned about the major biomes of the world. Any land within a single type of biome will have a similar climate no matter what continent the land is located on, yet that does not mean that the organisms within the biome are the same across such a wide diversity of physical space. Communities bridge the difference between the abstract concept of a biome and the concrete scale of organisms that we see on an average day. Ecological communities are discussed here in order to understand individual species and populations, which are discussed in the next section.

Communities are a tangible way to envision the study of ecosystems because we see communities in our daily lives and can easily differentiate separate communities we encounter when traveling. No organism lives in isolation from other species. A **community** is defined as multiple populations of different species that interact within a given habitat. 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 cannot be accurately assessed. Scientists study ecology at the community level to understand how species interact with each other and compete for the same resources. A community does not include the abiotic resources of an area, while an ecosystem would include the community and the abiotic factors. There are multiple ecosystems and communities within a biome.

Characteristics of Communities

Communities are complex systems that can be 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 untangle the impact of humans on ecosystem and then to minimize human impacts on ecosystems to (hopefully) sustainably manage the ecological communities we benefit from.

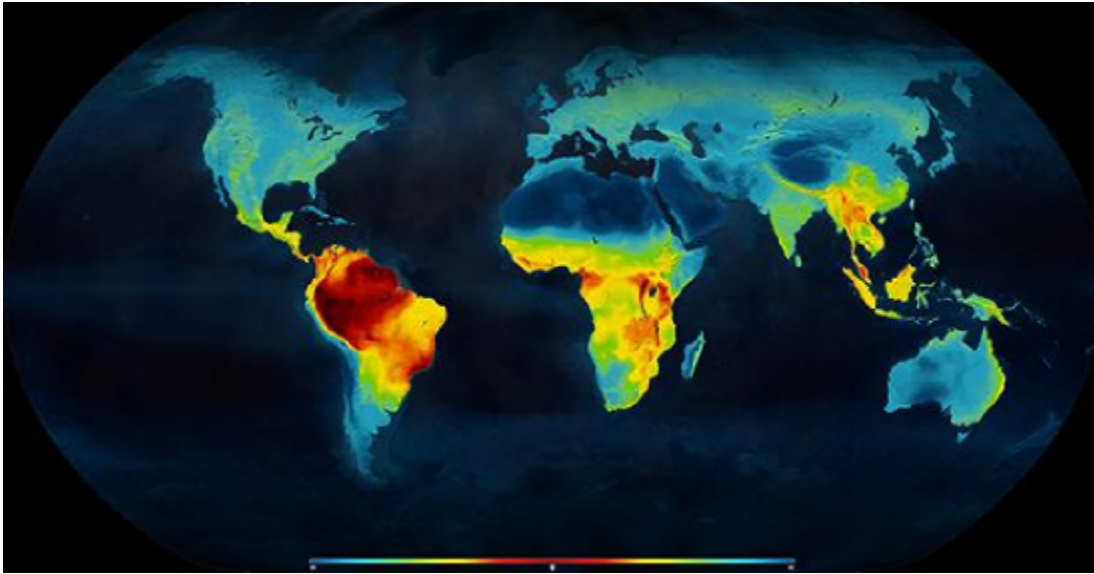


Figure 1: Distribution of living terrestrial vertebrate species, highest concentration of diversity shown in red in equatorial regions, declining polewards (towards the blue end of the spectrum)
 By Mannion, P. D. 2014. Patterns in Palaeontology: The latitudinal biodiversity gradient.
 Palaeontology Online, Volume 4, Article 3, 1-8., CC BY 3.0, <https://commons.wikimedia.org/w/index.php?curid=64316329>

Ecologists have extensively studied one of the fundamental characteristics of communities: **biodiversity**. In most average conversations and in the media, *biodiversity* means species richness. **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 1). Species richness is related to latitude: the greatest species richness occurs near the equator and the lowest richness occurs near the poles (e.g., Figure 2). 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; which in non-island settings would be comparable to habitat size and distance from other equivalent habitats. In general, a higher number of species in a particular area tends to be associated with a healthier ecosystem, and common measure of the strength of a disruption to an ecosystem is measured by the impact on total species richness.

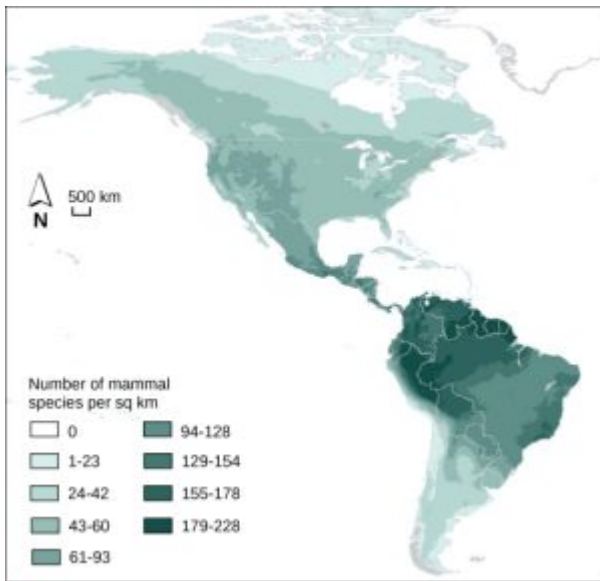


Figure 2: The greatest species richness for mammals in North America is associated in the equatorial latitudes. (credit: modification of work by NASA, CIESIN, Columbia University)

Another measure of biodiversity is **relative abundance** (sometimes called evenness). Relative abundance is the number individuals in a species relative to the total number of individuals in all species within a system. A habitat is expected to be more ecologically stable if the relative abundance of the species is evenly distributed between species. If one species is very dominant over the others, any disruption to that single species could devastate a community. In comparison, a community with multiple species should have more flexibility and be able to respond and recover from different types of disruption. The **Shannon Index** is a common measure of biodiversity that combines species richness with relative abundance by calculating the proportion of the total for each species and then summing the value for each species together. A higher Shannon Index correlates with a healthier ecological community.

Resource use Regulates Community Structure

A fundamental concept in understanding communities is that resources are often limited within a habitat and multiple species may compete to obtain them. Ecologists have come to understand that all species have an **ecological niche**: the unique set of resources used by a species, which includes its interactions with other species (e.g., Figure 3).

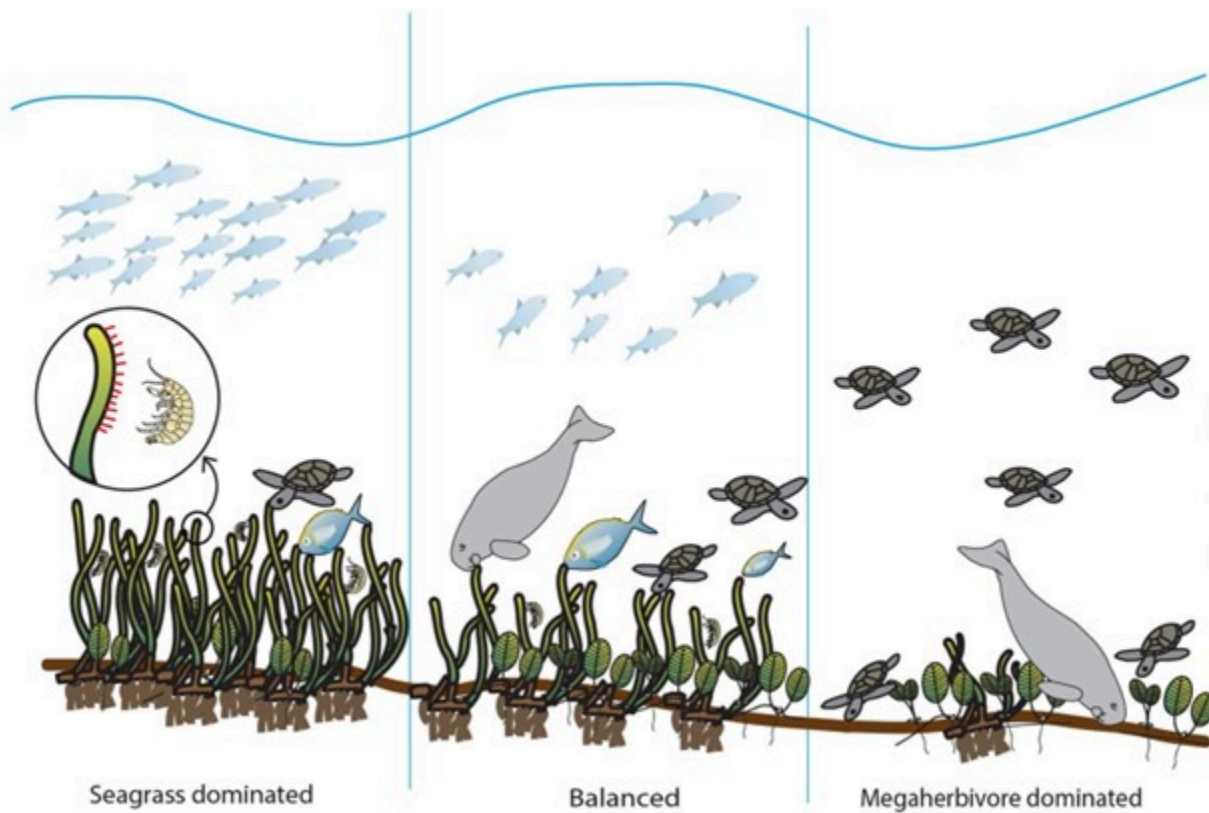


Figure 3: Different states of a potential community highlight different niches provided by the plants. In the first option, the tall seagrass provides excellent hiding space for certain organisms. In the second option, the community is balanced between the four types of herbivore (the manatee, two types of fish, and the turtle), thus there are niches for each herbivore. In the third scenario, the manatee eats the seagrass so much that the hiding niches for smaller organisms provided by the plant community are completely different than in the first scenario and there would not be enough biomass to support the other herbivores, reducing those niches to zero.

Modified image from original file by Abigail L. Scott, Paul H. York, Clare Duncan, Peter I. Macreadie, Rod M. Connolly, Megan T. Ellis, Jessie C. Jarvis, Kristin I. Jinks, Helene Marsh and Michael A. Rasheed. Images: Catherine Collier, Diana Kleine, Tracey Saxby and Dieter Tracey Integration and Application Network, University of Maryland Center for Environmental Science (<http://ian.umces.edu/imagelibrary/>). – <https://www.frontiersin.org/articles/10.3389/fpls.2018.00127/full>, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=91948742>

A theoretical niche could also be mapped out on a graph (Figure 4), with each niche for different species resulting in a different configuration on the graph. In this theoretical example, the five variables are graphed based on their relative importance for the species by calculating the impact of the factor on both the whole population and on an individual, with larger circles representing more impact. The species in Figure 4a is more impacted by competition and food compared to the species in Figure 4b which is more impacted by mutualism and water.

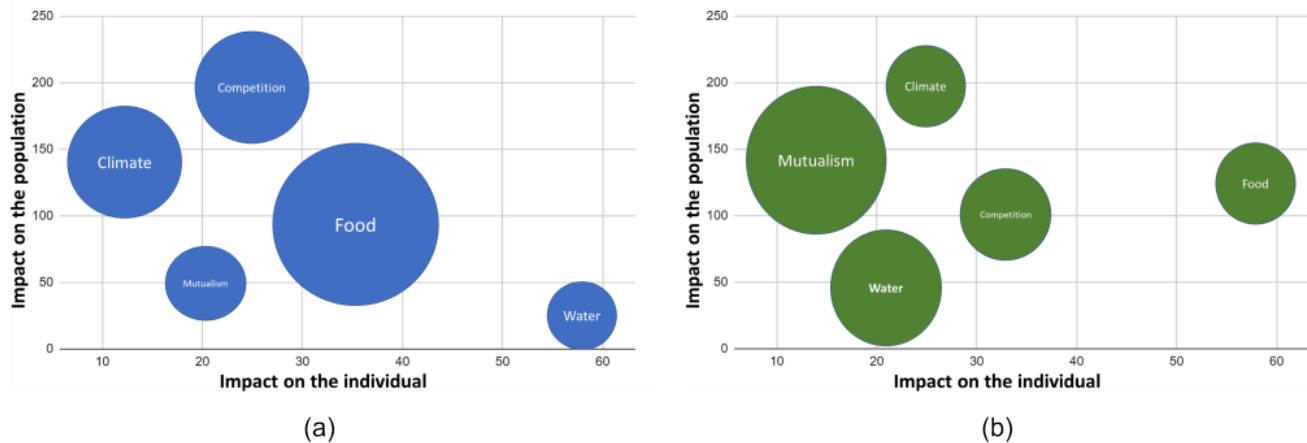


Figure 4: Theoretical niches for two different species (a) and (b). The importance of a factor like competition or mutualism with other species could be plotted (here, species (a) is more impacted by Competition, species (b) is more impacted by Mutualism). Factors like food, climate and water could be concretely measured or graphed based on importance. The idea is that different species will map out differently, and the map relates to the habitat niche of the species. Credit: Joni Baumgarten

Competitive Exclusion Principle

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 if they are competing for all the same resources. It is important to note that competition is bad for both competitors because it wastes energy. In this precise scenario, the species that most efficiently exploits the resource will drive the other species to extinction, thus the “exclusion” part of the concept. In reality, when there is competition between two species for the exact same resources, natural selection favors traits in both species that lessen reliance on the shared resource, thus reducing competition. In different words, each species’ niche shifts slightly away from the centerpoint of competition. An experimental example of this principle is shown in Figure 5 with two protozoan species: *Paramecium aurelia* and *Paramecium caudatum*. When grown individually in the laboratory, they both thrive. But when they are placed together in the same test tube (habitat), *P. aurelia* outcompetes *P. caudatum* for food, leading to the latter’s eventual extinction. Note that when *P. caudatum* is alive, there is a lower number of *P. aurelia*.

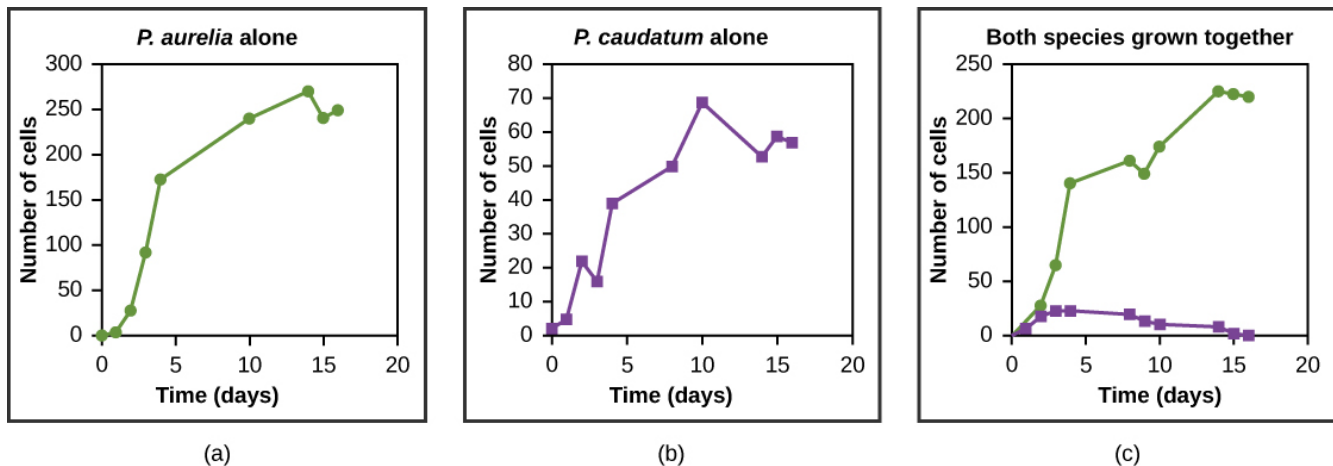


Figure 5: *Paramecium aurelia* and *Paramecium caudatum* grow well individually, but when they compete for the same resources, the *P. aurelia* outcompetes the *P. caudatum*.

4.1.2 Types of Species-to-Species Interactions

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 6: 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 or is harmed. Birds nesting in trees provide an example of a commensal relationship (Figure 5). 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 type of symbiotic relationship is called **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 7a). The termite benefits from the ability of the

protists to digest cellulose. However, the protists are able to 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 are a mutualistic relationship between a fungus and photosynthetic algae or cyanobacteria (Figure 7b). The glucose produced by the algae provides nourishment for both organisms, whereas 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 of the fungal partners are unable to live on their own.



Figure 7: (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 host is usually weakened by the parasite as it siphons resources the host would normally use 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 are able to 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 disease in humans when contaminated and under-cooked meat such as pork, fish, or beef is consumed. The tapeworm can live inside the intestine of the host 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 in order to complete its life cycle.

Predation and Herbivory

Predation and herbivory are interactions where one organism benefits at the expense of the second organism, with predation typically causing the death of the second organism. 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 8). This cycling of predator and prey population sizes has a period of 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, there is more food available for the lynx, allowing the lynx population to increase as well. When the lynx population grows to a threshold level, however, they kill so many hares that hare numbers begin to decline, followed by a decline in the lynx population because of scarcity of food. When the lynx population is low, the hare population size begins to increase due, in part, to low predation pressure, starting the cycle anew.

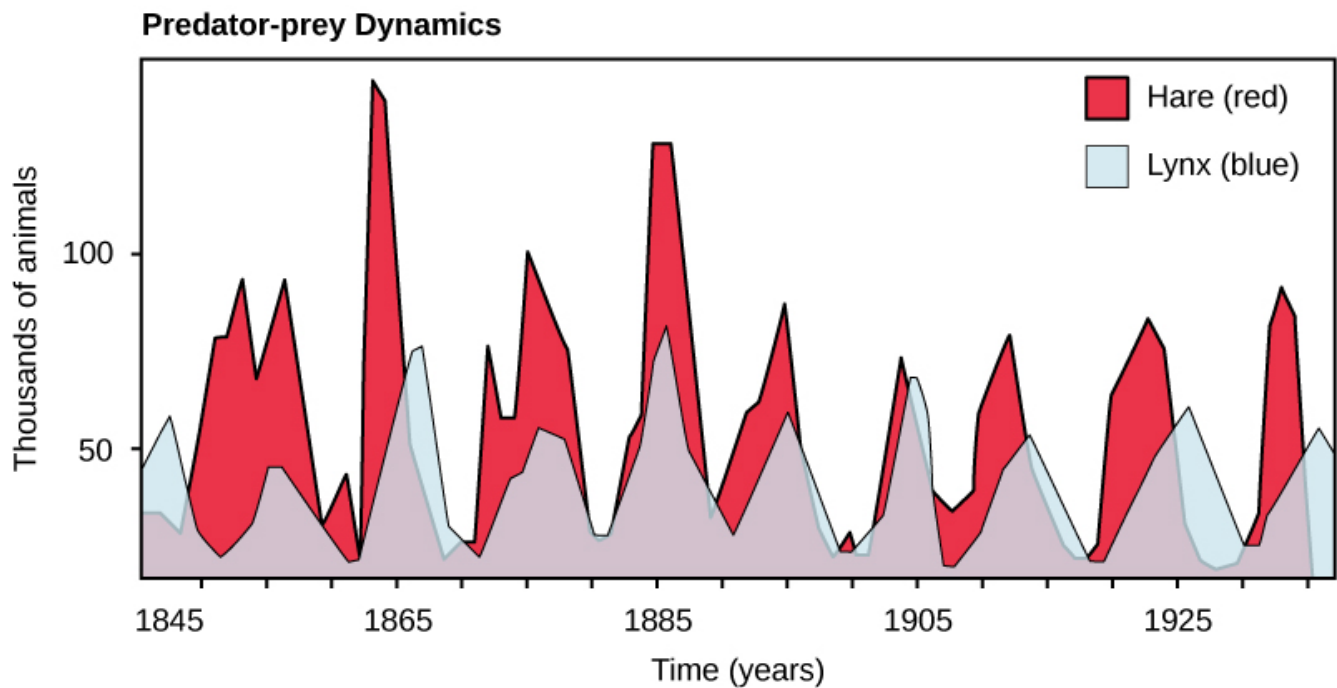


Figure 8: The cycling of snowshoe hare and lynx populations in Northern Ontario is an example of predator-prey dynamics.

Defense Mechanisms against Predation and Herbivory

Predation and predator avoidance are strongly influenced by natural selection (see more on evolution in [Section 5.2](#)). Any heritable character that allows an individual of a prey population to better evade its predators 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 that are 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 9a). 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 9b). (Biomedical scientists have repurposed the chemical produced by foxglove as a heart medication, which has saved lives for many decades.)



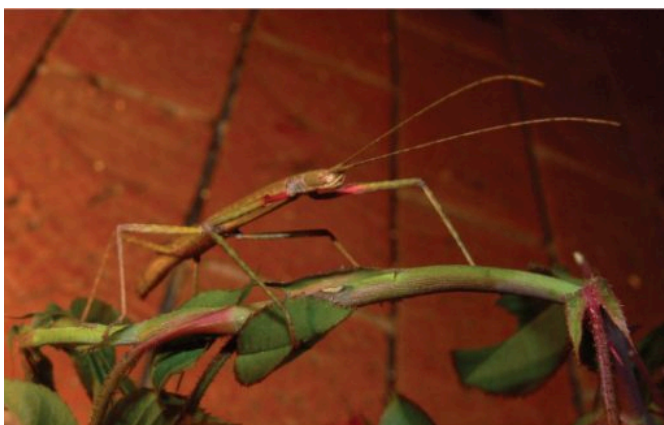
(a)



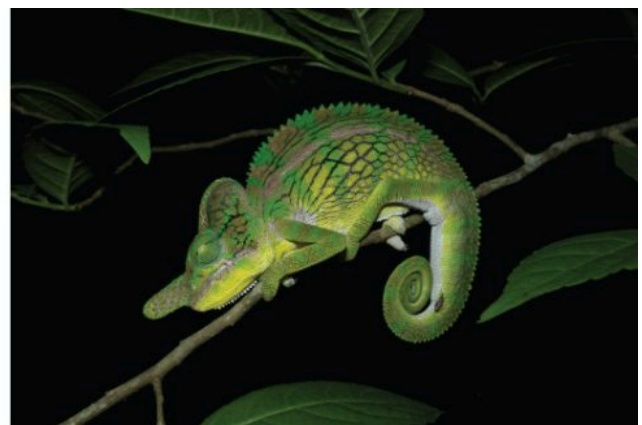
(b)

Figure 9: 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 the coloration and body shape of a twig, which makes it very hard to see when it is stationary against a background of real twigs (Figure 10a). In another example, the chameleon can change its color to match its surroundings (Figure 10b).



(a)



(b)

Figure 10: (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 as a way of warning 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 is also able to pass the sequestered toxins on to the adult monarch, which is also dramatically colored black and red as a warning to potential predators.



Figure 11: 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)

Fire-bellied toads produce toxins that make them distasteful to their potential predators (Figure 11). 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.



(a)



(b)

Figure 12: 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)

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 12).



Figure 13: 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 the potential predators. Figure 13 shows a variety of foul-tasting butterflies with similar coloration.

Species that Structure Communities

There are two types of species that are critically important to understanding community structure because of their impact.

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 an abundant organism. For example, kelp, a species of brown algae, is a foundation species that forms the basis of the kelp forests off the coast of California.



Figure 14: Coral is the foundation species of coral reef ecosystems. (credit: Jim E. Maragos, USFWS)

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 14). The exoskeletons of living and dead coral make up most of the reef structure, which protects many other species from waves and ocean currents.

A **keystone species** is one whose presence has 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 15). Studies have shown that when this organism is removed from communities, mussel populations (their natural prey) increase, which completely alters the



Figure 15: This sea star functions as a keystone species of the intertidal zone.

species composition and reduces biodiversity. Another keystone species is the banded tetra, a fish in tropical streams, which supplies 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.

BIOLOGY IN ACTION

Invasive species are non-native organisms that, when introduced to an area out of its 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 proliferations 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 by 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 and 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, which is 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 have the Chicago channel permanently cut off 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.

4.1.3 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 said to be 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 16: 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 when the soil and all life is 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. From this process, approximately 32 acres of land are added to the Big Island each year. 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 that is 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, which are collectively known as **pioneer species** (Figure 16) because they are the first to appear. These species help to further break down the mineral-rich rock into 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 by clearcut logging (Figure 17). Wildfires will burn most vegetation, and 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, there is a soil ecosystem present that provides a foundation for rapid recolonization.

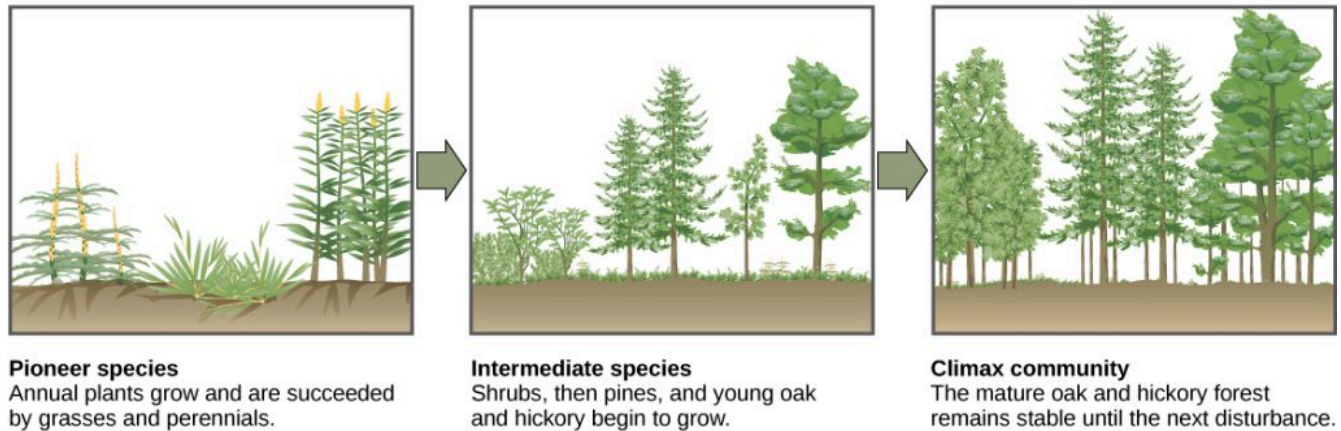
Secondary Succession of an Oak and Hickory Forest

Figure 17: Secondary succession is seen in an oak and hickory forest after a forest fire. A sequence of the community present at three successive times at the same location is depicted.

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 also 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 plants 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, over many years, shrubs emerge along with small trees. These organisms are called intermediate species. Eventually, over 150 years or more, the forest will reach its equilibrium point and resemble the community before the fire. This equilibrium state is referred to as 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 it is attained, the equilibrium is a dynamic one with constant changes in abundance and sometimes species identities.

Suggested Supplemental Resources

More examples of [mimicry](https://bugguide.net/node/view/116283) on BugGuide, by Iowa State University. <<https://bugguide.net/node/view/116283>>

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4.2 Population Demographics & Dynamics

Section Goals:

1. Connect community concepts to population concepts.
2. Understand ways that populations are regulated.
3. Understand two population growth models.

Populations are the Foundational Unit of a Species

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

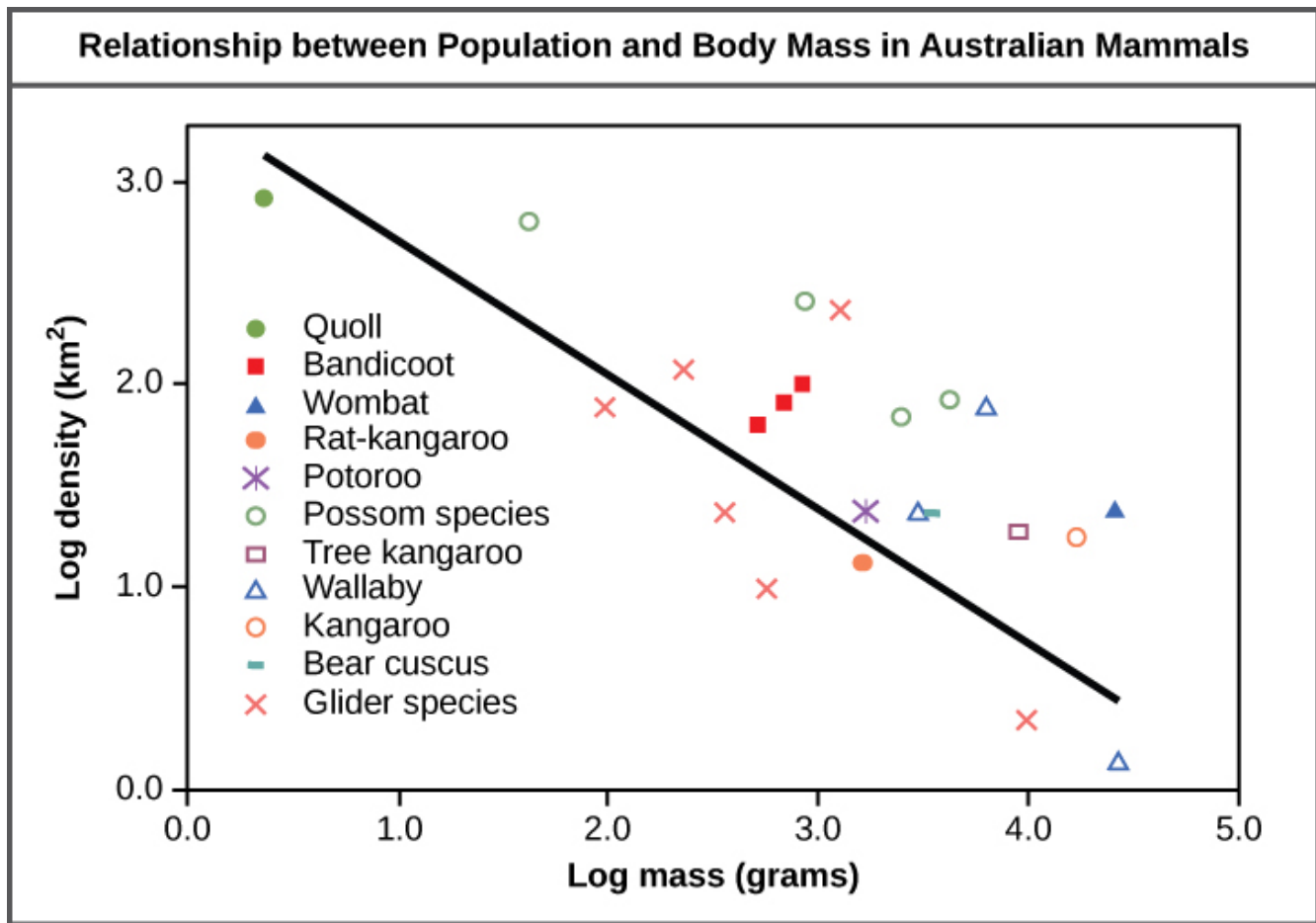


Figure 1: Australian mammals show a typical inverse relationship between population density and body size. As this graph shows, population density typically decreases with increasing body size. Why do you think this is the case?

Population Size and Density

Populations are characterized by their population size (total number of individuals) and their 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 potential for adaptation because it affects the amount of genetic variation present in the population. Density can have effects on interactions within a population such as competition for food and the ability of individuals to find a mate. Smaller organisms tend to be more densely distributed than larger organisms (Figure 1).

Estimating Population Size

The most accurate way to determine population size is to count all of the 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. For immobile organisms such as plants, or for very small and slow-moving organisms, a

quadrat may be used. 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 in 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 of the 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:

$$N = (\text{number marked first catch} \times \text{total number of second catch}) / \text{number marked second catch}$$

Using our example, the equation would be:

$$(80 \times 100) / 20 = 400$$

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 point in time—broad categories of patterns are used to describe them.

Individuals within a population can be distributed at random, in groups, or equally spaced apart (more or less). These are known as **random, clumped, and uniform distribution patterns**, respectively (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 that have wind-dispersed seeds that germinate wherever they happen to 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. The territorial defensive behaviors of each individual create a regular pattern of distribution 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 does 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.

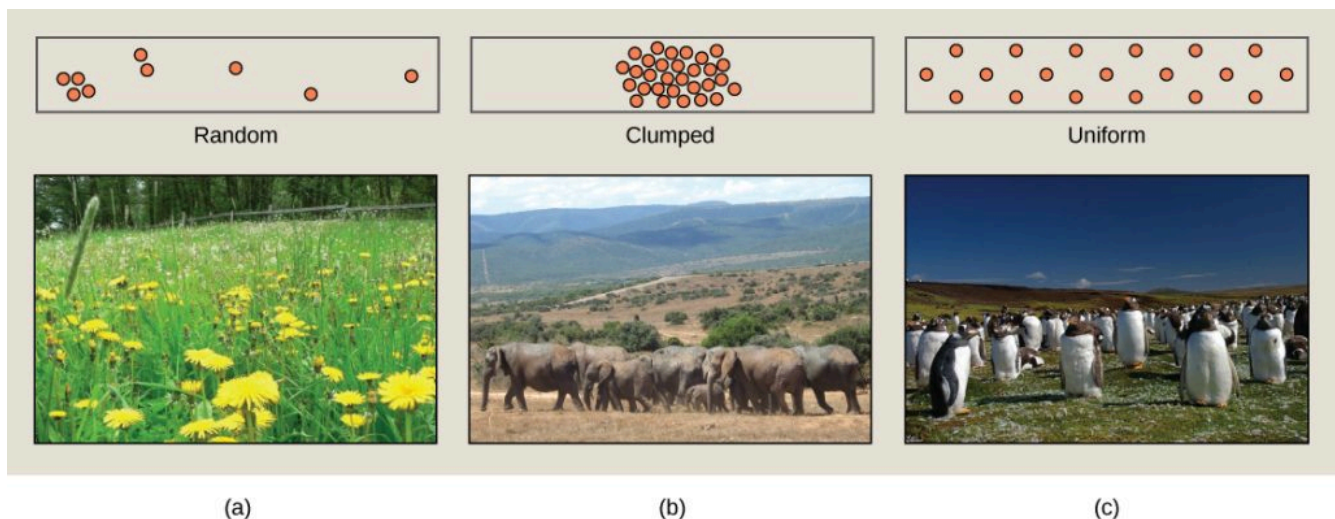


Figure 2: Species may have a random, clumped, or uniform distribution. Plants such as (a) dandelions with wind-dispersed seeds tend to be randomly distributed. Animals such as (b) elephants that travel in groups exhibit a clumped distribution. Territorial birds such as (c) penguins tend to have a uniform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

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 were to survive 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.

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 Sheep¹

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 used by population ecologists is a **survivorship curve**, which is 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 the likelihood of their survival. Humans and most mammals exhibit a type I survivorship curve. In type II curves, mortality is relatively constant throughout the entire life span, 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, but those that do make it to an old age are more likely to survive for a relatively long period of time.

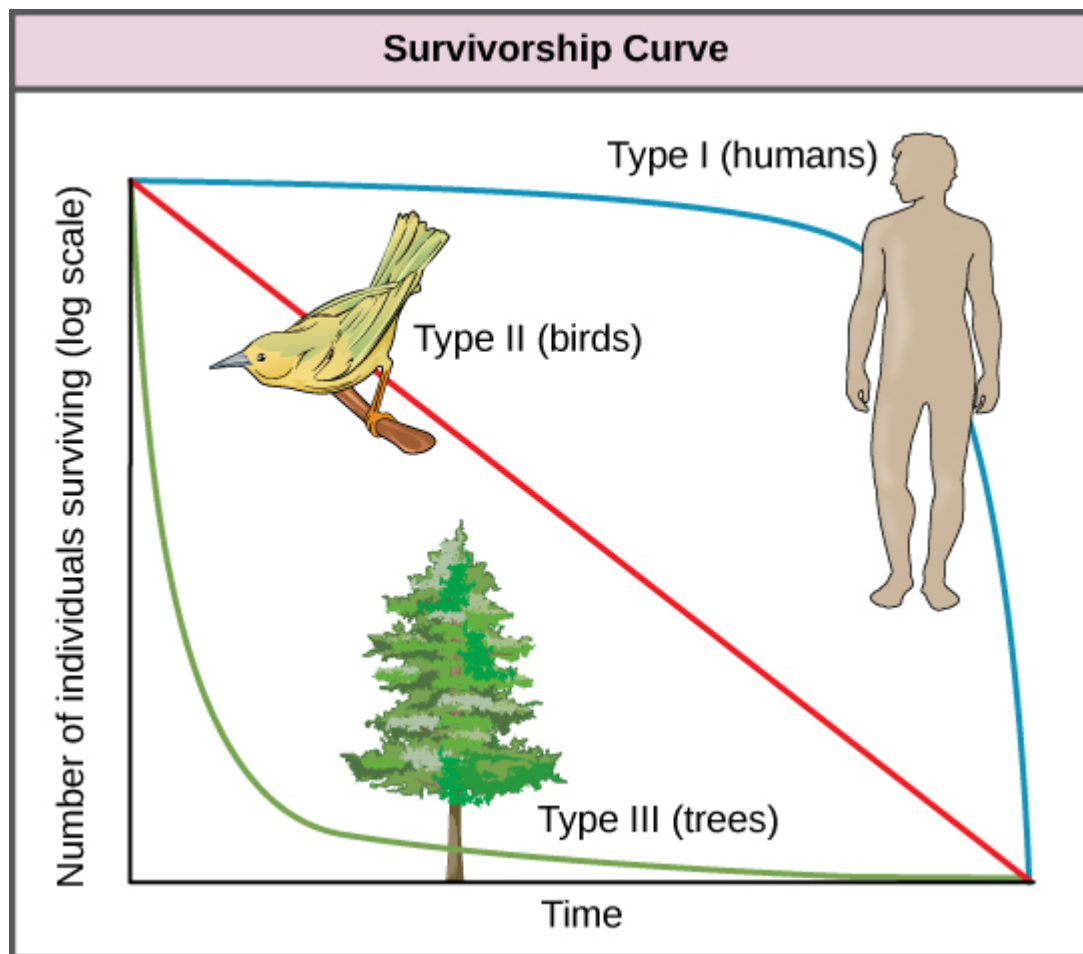


Figure 3: Survivorship curves show the distribution of individuals in a population according to age. Humans and most mammals have a Type I survivorship curve, because death primarily occurs in the older years. Birds have a Type II survivorship curve, as death at any age is equally probable. Trees have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

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4.3 Population Growth and Regulation

Section Goals:

1. Model population growth.
2. Understand carrying capacity.

Population Growth

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.

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**, describes 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

Charles Darwin, in developing his theory of natural selection, 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. In another hour, each of the 2000 bacteria will divide, 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 of these cycles, the population would have increased from 1000 to more than 16 billion bacteria. When the population size, N , is plotted over time, a J-shaped growth curve is produced (Figure 1).

The bacteria-in-a-flask example is not truly representative of 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 the case 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). To model the reality of limited resources, population ecologists developed the logistic growth model.

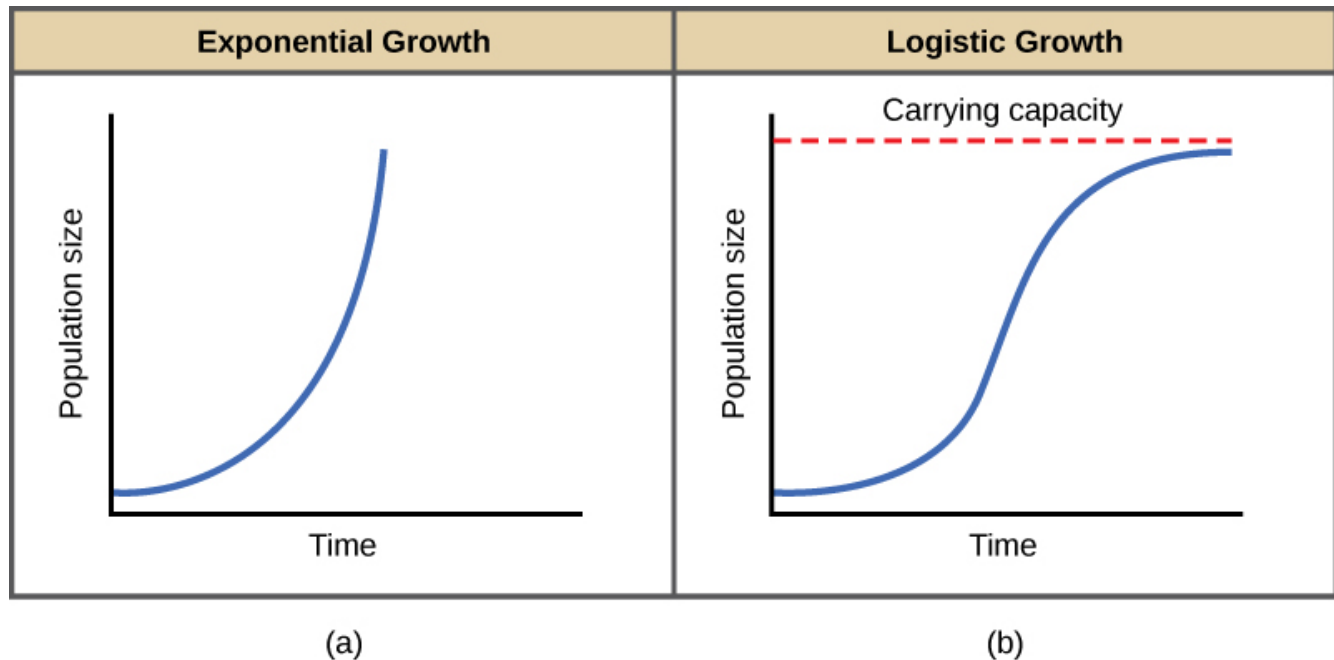


Figure 1. When resources are unlimited, populations exhibit (a) exponential growth, shown in a J-shaped curve. When resources are limited, populations exhibit (b) logistic growth. In logistic growth, population expansion decreases as resources become scarce, and it levels off when the carrying capacity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

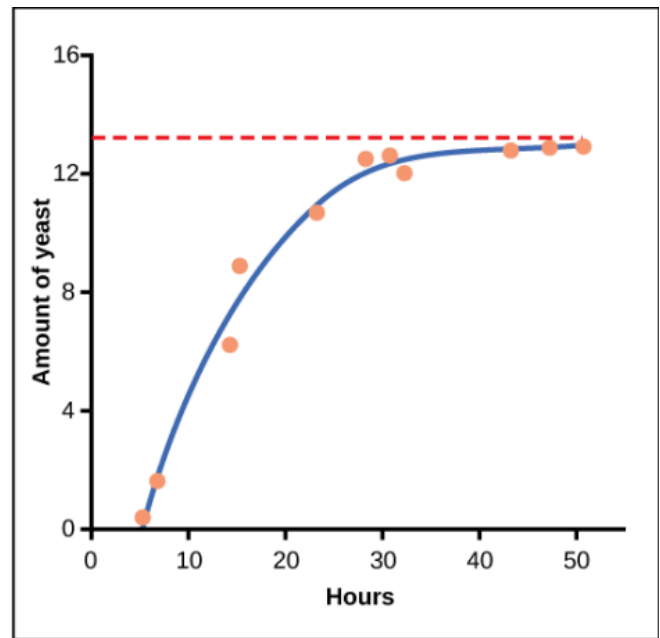
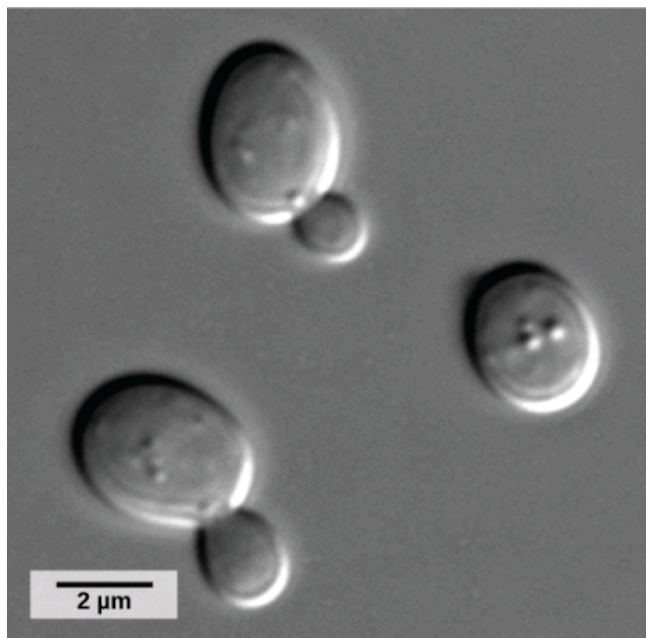
Carrying Capacity and the Logistic Model

In the real world, with its limited resources, exponential growth cannot continue indefinitely. Exponential growth may occur in environments where there are few individuals and plentiful resources, but 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.

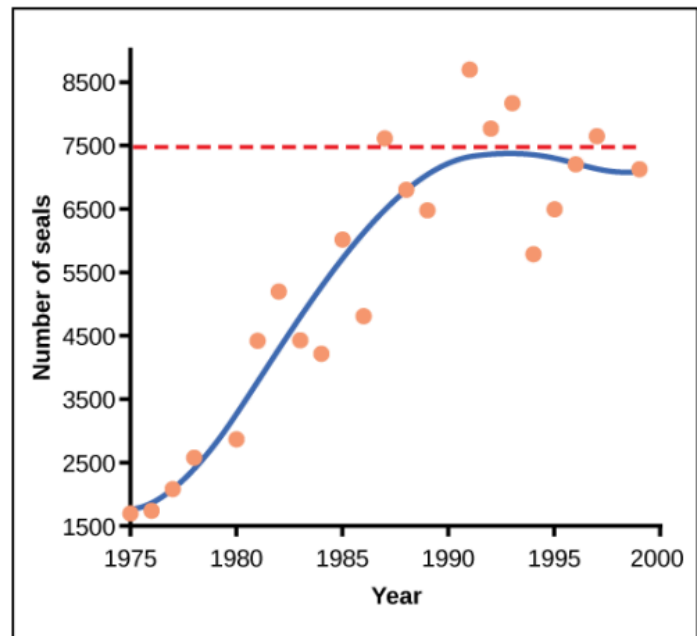
A graph of logistic growth yields the S-shaped curve (Figure 1). It is a more realistic model of population growth than exponential growth. There are three different sections to an S-shaped curve. Initially, growth is exponential because there are few individuals and ample resources available. Then, as resources begin to become limited, the growth rate decreases. Finally, the growth rate levels off at the carrying capacity of the environment, with little change in population number over time.

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 that are necessary for its growth. In the real world, however, there are variations to this idealized curve. Examples in 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 afterwards. 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.



(a)



(b)

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)

Population Growth and Regulation

The logistic model of population growth, while valid in many natural populations and a useful model, is a simplification of real-world population dynamics. Implicit in the model is that the carrying capacity of the environment 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 the winter is much lower than it is during the summer. Also, natural events such as earthquakes, volcanoes, and fires can alter an environment and hence 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.

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 just 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. Animals that are *r*-selected do not provide a lot of resources or parental care to offspring, and 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, but can evolve independently of each other, so each species may have some characteristics that trend toward one extreme or the other.

Density-independent Regulation and Interaction with Density-dependent Factors

Many factors that are typically physical in nature cause mortality of a population regardless of its density. These factors include weather, natural disasters, and pollution. An individual deer will be killed in a forest fire regardless of how many deer happen to be in that area. Its chances of survival are the same whether the population density is high or low. The same holds true for cold winter weather.

In real-life situations, population regulation is very complicated and density-dependent and independent factors can interact. A dense population that suffers mortality from a density-independent cause will be able to recover differently than a sparse population (Figure 3). For example, a population of deer affected by a harsh winter will recover faster if there are more deer remaining to reproduce.

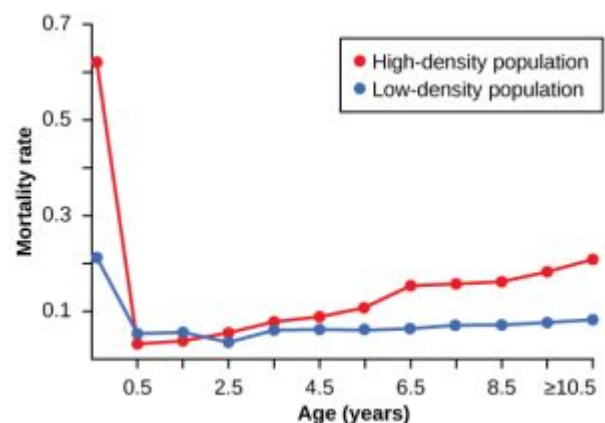


Figure 3: This graph highlights density-dependent factors that affect population growth by looking at the rate of mortality in two populations of wild donkeys. The high-density population has a higher rate of mortality in nearly all age categories.

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 4). 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.



Figure 4: The three images include: (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)

It is commonly thought that climate change and human hunting led to their extinction. A 2008 study estimated that 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 also 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 reduction of habitat, 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.

The maintenance of 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.

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4.4 The Human Population

Section Goals:

1. Apply population growth models to the current global population.
2. Understand how age structure of a population relates to predicted future population size.
3. Consider population growth in different countries.

The Human Population

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, have the ability to alter their environment to increase its carrying capacity, sometimes to the detriment of other species. Earth's human population and their 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. Please note that there is an uncomfortable and often ignored history of overconcern from members of “upper” society with the populations of people viewed as “less-than”, e.g., the people who believed in eugenics. Therefore, this topic is one where careful thought and additional reading are highly encouraged to ensure that structural inequalities are not perpetuated as we as a global society deal with the consequences of climate change.

Human technologies, most particularly our harnessing of the energy contained in fossil fuels, have caused unprecedented changes to Earth's environment, altering ecosystems to the point where some may be in danger of collapse. There is overwhelming scientific consensus on this fact. Human-caused changes on a global scale including depletion of the ozone layer, desertification and topsoil loss, and global climate change. These challenges will be addressed more directly in the second half of this textbook (starting with [Chapter 6](#)). Because the way societies use resources is linked to individual choice, the fact that the population has accelerated since 1960 (Figure 2) is of note.

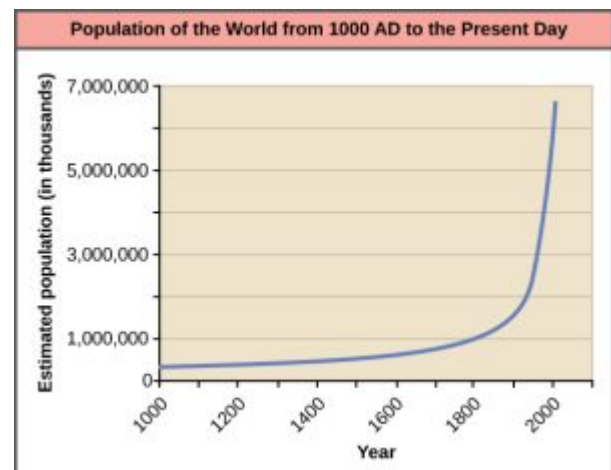


Figure 1: Human population growth has been exponential since 1000 AD.

Human Population Growth

The fundamental cause of the acceleration of growth rate for humans 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 sewage has drastically improved health in areas where it is implemented. Also, medical innovations such as the use of antibiotics and vaccines have decreased the ability of infectious disease 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 and reduced the overall world population by as many as one hundred million people. Naturally, infectious disease continues to have an impact on human population growth. For example, life expectancy in sub-Saharan Africa, which was increasing from 1950 to 1990, began to decline after 1985 largely as a result of HIV/AIDS mortality.

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. The increase in agricultural yields and the stability of the global food system since the widespread implementation of inorganic fertilizers, called the Green Revolution, also have contributed to human population growth by supporting the growth (see [Chapter 8](#)).

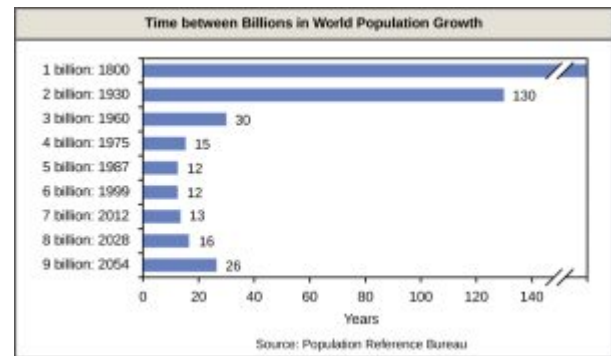


Figure 2: The time between the addition of each billion human beings to Earth decreases over time. (credit: modification of work by Ryan T. Cragun)

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 that incorporate age structure allow better prediction of population growth, plus the ability to associate this growth with the level of economic development in a region. 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 there is 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.

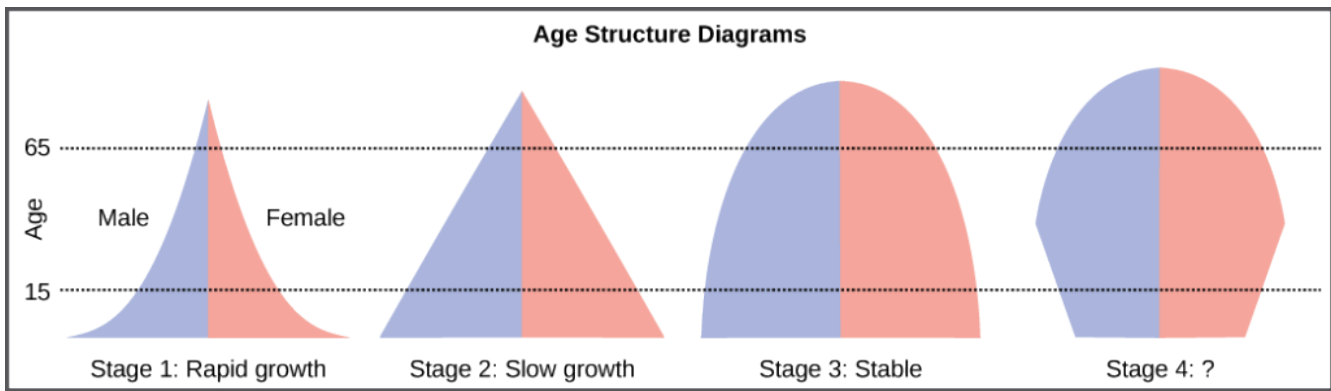


Figure 3: Typical age structure diagrams are shown. The rapid growth diagram narrows to a point, indicating that the number of individuals decreases rapidly with age. In the slow growth model, the number of individuals decreases steadily with age. Stable population diagrams are rounded on the top, showing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

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 will starve to death in spite of any crash programs embarked upon now. At this late date nothing can prevent a substantial increase in the world death rate."

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 who have more than one child. Due to the fact that 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 having occurred in some of the more rural areas of the country. These results are not the goal. However, the United Nations estimates the future world population size to be 11.2 billion people by the year 2100. It is hard to imagine how that number of individuals will be supported at full health given the challenges we already see happening.

Another consequence of population growth that can be avoided without direct control of human population 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 the interaction of human population growth with the environmental impact predicted should less developed countries consume resources at a rate similar to that in the United States.

The actual growth rates in different countries are shown in Figure 4, with the highest rates tending to

be in the less economically developed countries of Africa and Asia. Again, to reiterate the point at the beginning of this section: This topic has a history steeped in judgmental views (e.g., white supremacy). Please do not use this figure to judge or to perpetuate simplified perceptions of people.

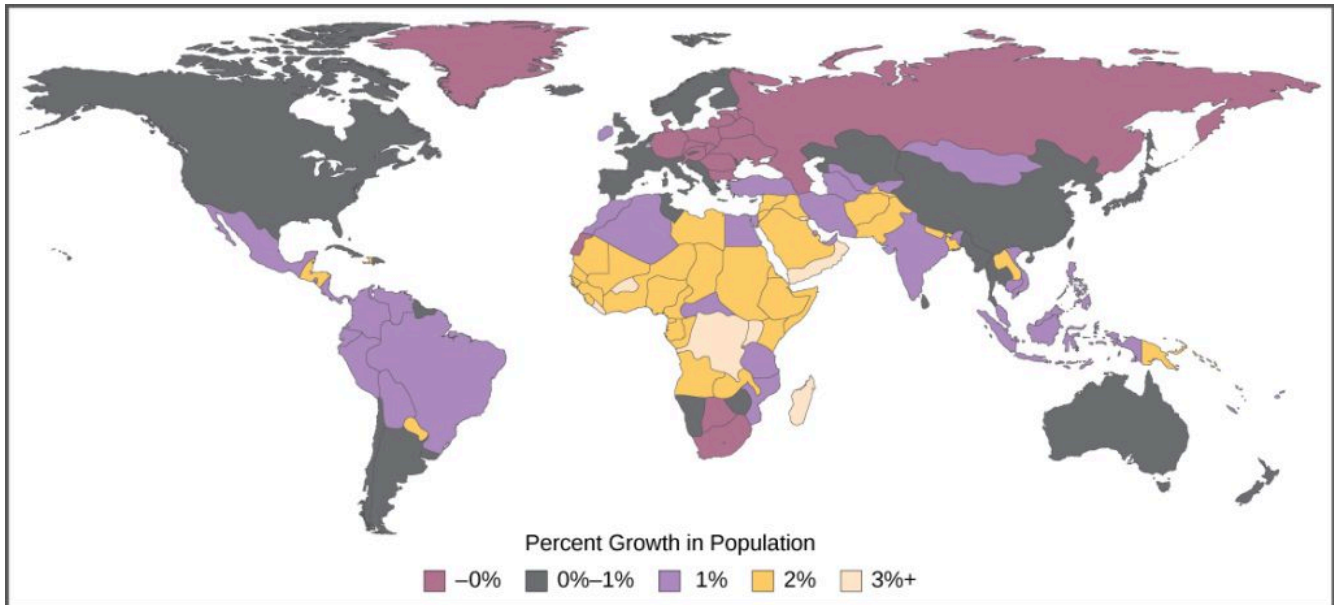


Figure 4: The percent growth rate of population in different countries is shown.

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4.5 Chapter Resources

Summary

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. Community structure is described by its foundation and keystone species. Communities respond to environmental disturbances by succession: the predictable appearance of different types of plant species, until a stable community structure is established.

Populations are individuals of a species that live in a particular habitat. Ecologists measure characteristics of populations: size, density, and distribution pattern. Life tables are useful to calculate 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 limiting, populations follow a logistic growth curve in which population size will level off 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, especially if resource use per individual rises to the level of the average use in the United States.

Review Questions

1. You are working as a biologist and perform the “mark and recapture” technique to estimate the number of endangered lemurs living within a particular habitat. You initially capture 37 lemurs, marking them all before releasing them. Two months later, you capture 49 lemurs, of which 11 are those originally captured and marked. What is the estimated size of the lemur population, rounded to the nearest whole number?
 - A. 60
 - B. 86
 - C. 97
 - D. 165
 - E. 407
2. Which one of the following measuring techniques would best enable you to determine the distribution pattern of a population of zebra?
 - A. Track how many and which individuals use a central watering hole
 - B. Use a drone to capture aerial photographs of their habitat range
 - C. Employ a camera trap in the middle of their habitat
 - D. Use the mark-recapture method
 - E. Collect and analyze DNA from hair samples collected at 2 locations

3. A species that you are studying has a type III survivorship curve. Which one of the following describes this type of curve?

- A. Survivorship rates are lowest during early parts of its lifecycle
- B. Survivorship rates are lowest during the late parts of its lifecycle
- C. Survivorship rates are highest during early parts of its lifecycle
- D. Survivorship rates are consistent through the lifecycle
- E. Survivorship rates are highest in the early and middle parts of its lifecycle

4. A population has unlimited resources and exhibits rapid and sustained population growth. This type of growth would be best described by which one of the following?

- A. Exponential
- B. Logistic
- C. Sigmoidal
- D. Parabolic
- E. Inverse

5. What single factor has most strongly contributed to the rapid population growth in the human population witnessed over the last 150 years?

- A. Increased fertility rates
- B. Reduced death rates
- C. Longer life spans
- D. Economic growth
- E. Increased morbidity

6. Which one of the following age groups would most likely to lead to rapid population growth in the future if it contained the greatest relative abundance within that population?

- A. 0-15 years old
- B. 16-30 years old
- C. 31-45 years old
- D. 46-60 years old
- E. 61 years old and greater

7. Two species have the same ecological niche. If they lived in the same habitat, both would compete until one species became predominant and the other became locally extinct. This process is summarized by which one of the following?

- A. Niche warfare
- B. Competitive exclusion principle
- C. Species selection principle
- D. Exclusion through competition theorem
- E. Exclusive ecological fractioning

8. Which form of symbiosis benefits one member of the interaction, but neither benefits nor harms the other member?

- A. Parasitism
- B. Commensalism

- C. Sequentialism
- D. Mutualism
- E. Natural selection

9. Biologists examined the effects of reintroducing wolves into Yellowstone National Park of the United States. They found that by preying on elk, wolves altered the foraging behavior of the elk; the elk spent less time browsing near streambanks. This allowed the regrowth of important vegetation, which had large positive impacts on the ecosystem at large. When a relatively small number of individuals, like wolves, have disproportionate impacts on the ecosystem, they are referred to as a...

- A. Foundation species
- B. Portal species
- C. Keystone species
- D. Cornerstone species
- E. Pivotal species

10. The 1980 volcanic explosion of Mt. St. Helens in the United States devastated the north side of the mountain and its forests. The forests were demolished and replaced with volcanic debris that formed the new soil, free of any remnants of the previous ecosystem (such as seeds stored in the soil). Such an event would lead to which one of the following processes?

- A. Primary succession
- B. Secondary succession
- C. Tertiary succession
- D. Quaternary succession
- E. Pioneering succession

See Appendix for answers

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Chapter 5: Evolution, Biodiversity & Conservation



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:

- Explain how Darwin's theory of evolution differed from the current view at the time
- Describe how the present-day theory of evolution was developed
- Describe the four basic causes of evolution
- Describe the definition of species and how species are identified as different
- 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

- 5.1 Introduction to Biodiversity and Evolution
- 5.2 Mechanisms of Evolution
- 5.3 Speciation
- 5.4 Origin and Importance of Biodiversity
- 5.5 Threats, and Preserving Biodiversity
- 5.6 Chapter Resources

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5.1 Introduction to Biodiversity

Section Goals:

1. Define biodiversity in relation to evolution.
2. Understand the three domains of life.
3. Relate biodiversity to taxonomic classification.

Three Domains are Used to Describe All Life on Earth

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, and are thus referred to as **unicellular**. Organisms containing more than one cell are said to be **multicellular**. Despite the wide range of organisms, there exists only two fundamental cell plans: prokaryotic and eukaryotic. The main difference these two cell plans is that eukaryotic cells have internal, membrane-bound structures called organelles (see [Section 2.3](#)). Thus, if you were to microscopically analyze the cells of any organism on Earth, you would find either prokaryotic or eukaryotic cells depending on the type of organism. The theory of evolution states that life originated once, as a prokaryotic-type cell, and the rest of the diversity we see today evolved through time. This is why the phylogenetic tree in Figure 1 has a single line representing the origin of life.

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. 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.

Phylogenetic Tree of Life

★ = You are here

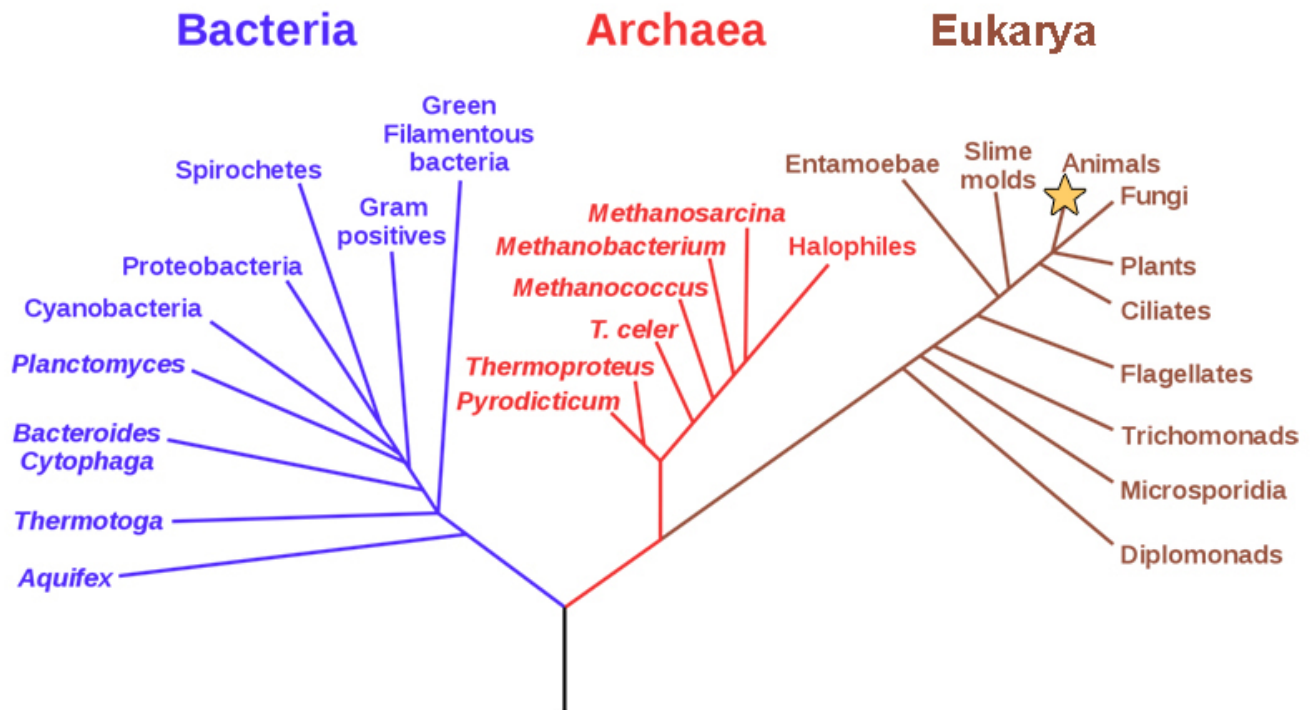


Figure 1: All life as we know it originated from a common ancestor, which then led to the three Domains of life: Bacteria, Archaea, and Eukarya. Credit: OpenStax <<https://openstax.org/books/concepts-biology/pages/12-1-organizing-life-on-earth>>

Domain Bacteria

Domain Bacteria includes prokaryotic, unicellular organisms (Figure 2). They are incredibly abundant and found in nearly every imaginable type of habitat, including your body. While many people view bacteria only as disease-causing organisms, most species are actually either 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 of cells. Many species of bacteria are **autotrophs**, meaning they can create their own food source without having to eat other organisms. Most autotrophic bacteria do this by using photosynthesis, a process that converts light energy into chemical energy that can be utilized by cells. A well-known and ecologically-important group of photosynthetic bacteria is **cyanobacteria**. These are sometimes referred to blue-green algae, but this name is not appropriate because, as you will see shortly, algae are organisms that belong to domain Eukarya. Cyanobacteria play important roles in food webs of aquatic systems, such as lakes.

Other species of bacteria are **heterotrophs**, meaning that they need to acquire their food by eating other organisms. This classification includes the bacteria that cause disease in humans (*during an infection, the bacteria is eating you...*). However, most heterotrophic bacteria are harmless to humans. In fact, 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.

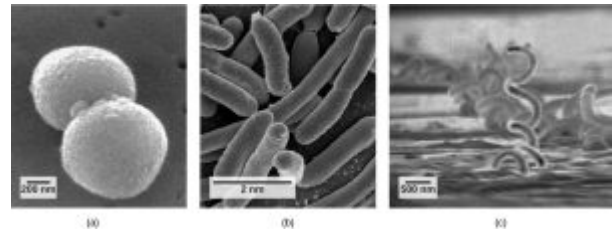


Figure 2: Many prokaryotes fall into three basic categories based on their shape: (a) cocci, or spherical; (b) bacilli, or rod-shaped; and (c) spirilla, or spiral-shaped. (credit a: modification of work by Janice Haney Carr, Dr. Richard Facklam, CDC; credit c: modification of work by Dr. David Cox, CDC; 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**. Note 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, in addition to unicellular species. The domain is characterized by the presence of eukaryotic cells. For this domain, you will be introduced to several of its kingdoms. **Kingdom** is the taxonomic grouping immediately below domain.

Kingdom Animalia is comprised of multicellular, heterotrophic organisms that can move at at least one stage of their life. This kingdom includes humans and other primates, insects, fish, reptiles, and many other types of animals.

Kingdom Plantae includes multicellular, autotrophic organisms. Except for 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 mildews, which are commonly seen on rotting food. Lastly, **yeast** are unicellular fungi. Many species of yeast are important to humans, especially baker's and brewer's yeast. Through their metabolism, these yeast produce CO₂ gas and alcohol. The former makes bread rise and the latter is the source for all alcoholic beverages.

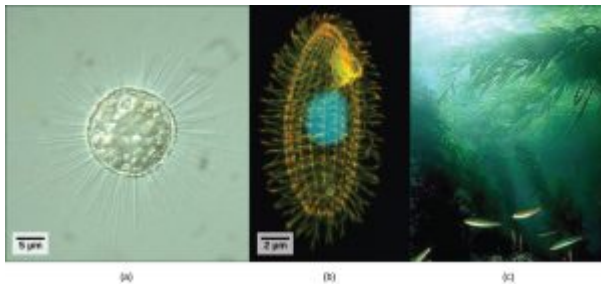


Figure 4: Protists range from the microscopic, single-celled (a) *Acanthocystis turfatea* and the (b) ciliate *Tetrahymena thermophila* to the enormous, multicellular (c) kelps (*Chromalveolata*) that extend for hundreds of feet in underwater “forests.” (credit a: modification of work by Yuiuji Tsukii; 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](#)



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 in to 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 (which kills hundreds of thousands of people every year despite efforts to prevent and treat the disease).

Taxonomic Categories

Taxonomy (which literally means “arrangement law”) is the science of classifying organisms to construct internationally shared classification systems with each organism placed into increasingly more inclusive groupings. Think about a grocery store’s organization. One large space is divided into departments, such as produce, dairy, and meats. Then each department further divides into aisles, then each aisle into categories and brands, and then finally a single product. We call this organization from larger to smaller, more specific categories a hierarchical system.

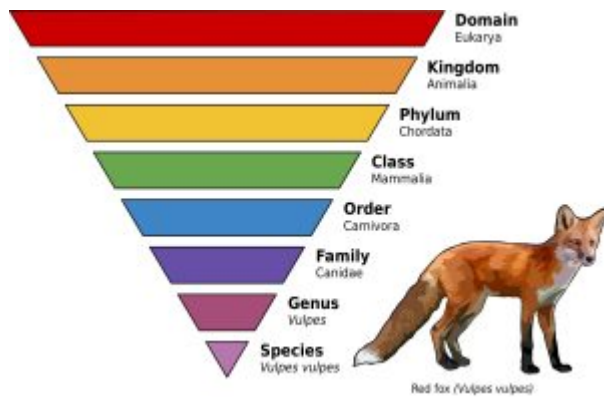


Figure 5: The hierarchical arrangement of taxonomic groups. By Annina Breen – Own work
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The taxonomic classification system (also called the Linnaean system after its inventor, Carl Linnaeus, a Swedish botanist, zoologist, and physician) uses a hierarchical model. Moving from the point of origin, the groups become more specific, until one branch ends as a single species. For example, after the common beginning of all life, scientists divide organisms into three large categories called domains: Bacteria, Archaea, and Eukarya. Within each domain is a second category called a kingdom. After kingdoms, the subsequent categories of increasing specificity are: phylum, class, order, family, genus, and species (Figure 5). At each sublevel, the organisms become more similar because they are more closely related. So, species within the same genus would be more similar to each other than species in a

second genus. The same applies with each group; everything within a family will be more similar to the in-group species compared to species within a different family.

Conclusion

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 the myriad ways they interact with each other, with us, and with their environment. Thus, it is wise to value biodiversity and take measures to conserve it.

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5.2 Origin of Biodiversity

Section Goals:

1. Define evolution.
2. Understand how evolution relates natural selection and to species diversity.

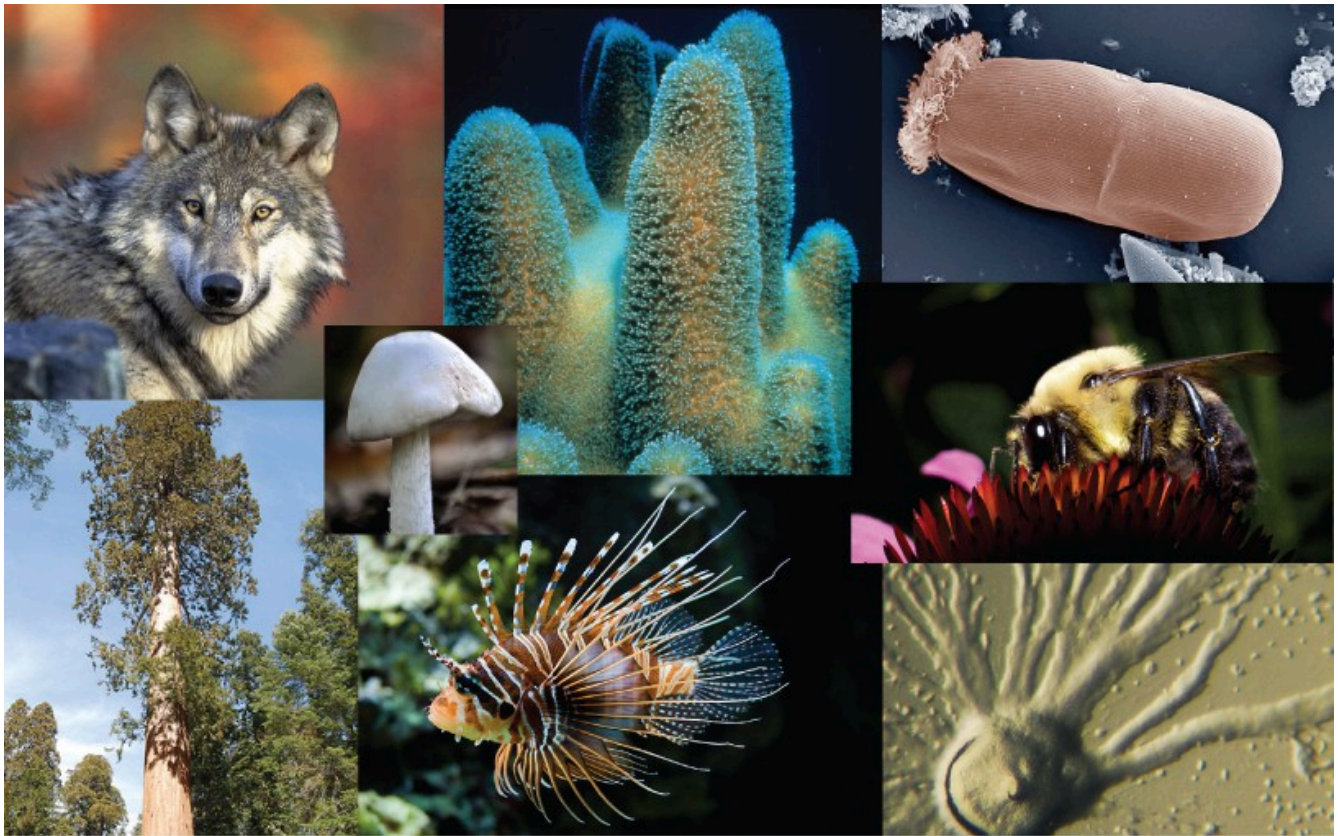


Figure 1: The diversity of life on Earth is the result of evolution, a continuous process that is still occurring. (Original photo credits: credit “wolf”: modification of work by Gary Kramer, USFWS; credit “coral”: modification of work by William Harrigan, NOAA; credit “river”: modification of work by 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) The [combined image](https://uen.pressbooks.pub/biology1010revision/part/evolution-and-its-processes/) credit: Biology and the Citizen by Colleen Jones and Elisa Taylor is licensed [CC BY 4.0](https://creativecommons.org/licenses/by/4.0/) <<https://uen.pressbooks.pub/biology1010revision/part/evolution-and-its-processes/>>

What biological process is responsible for biodiversity?

All species—from the bacteria on our skin to the birds outside—evolved from a historically different species. 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

Natural selection describes a mechanism for how species can change over time. It is part of the theory of evolution. Though Darwin is the name most associated with evolution, the concept that species change was suggested and debated well before Darwin. For instance, the view that species were unchanging was grounded in the writings of Plato, yet there were ancient Greeks that disagreed and expressed evolutionary ideas.

In the eighteenth century, ideas about the evolution of animals were reintroduced by the various naturalists. James Hutton, the Scottish naturalist and geologist, observed that processes that shape the soil and rock outcrops slowly but surely in his own lifetime. He proposed that all geological change occurred gradually by the accumulation of small changes from processes (over long periods of time), just like those he observed on shorter timescales. This contrasted with the predominant view that the geology of the planet was a consequence of catastrophic events occurring during a relatively brief past. Hutton’s view was later popularized by the geologist Charles Lyell in the nineteenth century. Lyell became a friend to Darwin and his ideas were very influential on Darwin’s thinking. Like Hutton, Lyell also argued that Earth must be very old, given the slow rate of current geological events. His theory of the gradual building and shifting of the Earth’s crust, published as *Principles of Geology*, connected directly to Darwin’s argument for gradual changes occurring over that geological time period in species (published in *On the Origin of Species*).

Charles Darwin and Natural Selection

Natural selection as a mechanism for evolution was independently conceived of 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 expeditions to the tropics. From 1831 to 1836, Darwin traveled around 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 to 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 that each had a unique beak shape (Figure 2). He observed both that these finches closely resembled another finch species on the mainland of South America and that the group of 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 species 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."

Wallace and Darwin both observed similar patterns in other organisms and independently conceived a mechanism to explain how and why such changes could take place. 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, and these traits are inherited, or passed from parent to offspring. Second, more offspring are produced than are able to survive; in other words, resources for survival and reproduction are limited. And lastly, there is a 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 change in populations over generations in a process that Darwin called "**descent with modification.**" In sum, we can define **natural selection** as a process that causes beneficial traits to become more common in a population over time, causing the population to evolve.

Papers by Darwin and Wallace presenting the idea of natural selection were read together in 1858 before the Linnaean Society in London. The following year Darwin's book, *On the Origin of*

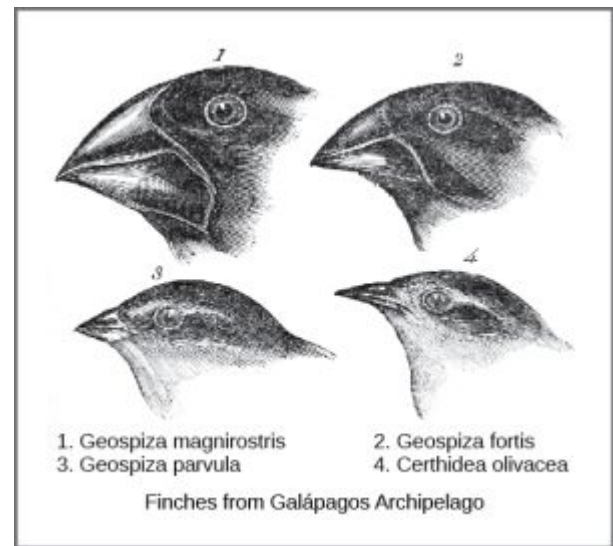


Figure 2: Darwin observed that beak shape varies among finch species. He postulated that the beak of an ancestral species had adapted over time to equip the finches to acquire different food sources. This illustration shows the beak shapes for four species of ground finch: 1. *Geospiza magnirostris* (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).

Species, was published, which outlined in considerable detail his arguments for evolution by natural selection.

Natural selection can only take place if there is **variation**, or differences, among individuals in a population. Importantly, these differences must have some genetic basis, otherwise natural selection would not lead to change in 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. However, the underlying rate of mutation for any given strand of DNA is slow. Sexual reproduction is a way to get genetic diversity in offspring *if* it already exists in the parents. Without variation in traits, nature would not be able to select the traits that are 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 it has been directly observed by scientists. How does this happen? Imagine a person that has a bacterial infection: their body is being attacked by billions of bacteria. Because there is 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 had a trait that was beneficial and thus nature selected for it. The surviving population will all be resistant to the drug and continue to reproduce, multiple, and pass down that beneficial trait to all offspring. The population has now 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 is reliant upon genetic variation that was already present. Without that variation, there is nothing for nature to select for. The rise and spread of antibiotic resistant bacteria is an emerging environmental issue and will be discussed in a later chapter.

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5.3 Importance of Biodiversity

Section Goals:

1. Understand current estimates of global biodiversity.
2. Relate current rates of species extinction to historical averages.
3. Understand alternate ways to conceptualize diversity.
4. Contextualize the importance of biodiversity to its impact on human health.

The Biodiversity Crisis

Biologists 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 biodiversity of the planet 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 biologists have not yet discovered. Most of these “invisible” species that will become extinct currently live in tropical rainforests like those of 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 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 is occurring in tropical rainforests like the one pictured in Figure 1, which are very high in biodiversity but are being cleared for timber and agriculture. This is likely to have dramatic effects on human welfare through the collapse of ecosystems.

Biologists recognize that human populations are embedded in ecosystems and are dependent on them, just as is every other species on the planet. Agriculture began after early hunter-gatherer societies first settled in one place and heavily modified their immediate environment. This cultural transition has made it difficult for humans to recognize their dependence on



Figure 1: This tropical lowland rainforest in Madagascar is an example of a high biodiversity habitat. This particular 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)

living things other than crops and domesticated animals on the planet. Today our technology smooths

out the harshness of existence and allows many of us to live longer, more comfortable lives, but ultimately the human species cannot exist without its surrounding ecosystems. Our ecosystems provide us with food, medicine, clean air and water, recreation, and spiritual and aesthetical inspiration.

Types of Biodiversity

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 taking into account both the number of species and the number of individuals of each species (see [Section 4.1](#)). However, biologists are using different measures of biodiversity, including genetic diversity, to help focus efforts to preserve the biologically and technologically important elements of biodiversity.

As previously described in Section 4.1, the 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 10 equally common species of trees is more diverse than a forest that has 10 species of trees wherein just one of those species makes up 95 percent of the trees. Biologists have also identified alternate measures of biodiversity, some of which are important in planning how to preserve biodiversity.

There are four types of diversity that can be targeted for conservation: Genetic diversity, Taxonomic diversity, Ecosystem diversity, and Functional diversity.

Genetic diversity is an important alternate concept of biodiversity because it links to the fundamental diversity that matters for evolution: the genetic material that is passed from parent to offspring. **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. As we just learned, evolution only acts on variations that already exist.

Taxonomic diversity uses taxonomic classification, like species, genus, or family, to measure diversity. Looking at the species level is a subcategory of taxonomic diversity.

Another useful alternative diversity concept for conservationists is **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 is able to create. An example of a largely extinct ecosystem in North America is the prairie ecosystem (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 of the species survive, but the hugely productive ecosystem that was 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. Ecosystem diversity is useful when considering the placement of preserves such as parks. If possible, we should ensure that all existing ecosystems today have portions of them that are protected, and by preserving this ecosystem diversity, we hopefully preserve some resilience of our Earth.



Figure 2: The variety of ecosystems on Earth—from coral reef 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)

Finally, **functional diversity** looks at the role of a species within an ecosystem. Multiple evolutionarily distinct species are able to pollinate flowers (e.g., bats and bees). In some cases, ensuring that each important function within an ecosystem exists is a way to aim to preserve ecosystem health. Some examples of functions are: decomposition (fungi and bacteria), carrion eaters, pollinators, and seed eaters.

Current Species Diversity

Despite considerable effort, knowledge of the species that inhabit the planet 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 biologists agree that science has only just begun to catalog 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 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 Species¹ 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 biologists determine an organism's unique characteristics and whether or not that organism belongs to any other described species. It allows biologists 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 to our ecosystems. Without a name and description, a species cannot be studied in depth and in a coordinated way by multiple scientists.

Patterns of Biodiversity

Biodiversity is not evenly distributed on the planet. Lake Victoria contained almost 500 species of cichlids (just one family of fishes that are present in the lake) before the introduction of an exotic species in the 1980s and 1990s caused a mass extinction. All of 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 to explain biodiversity patterns on Earth.

Biogeography is the study of the distribution of the world's species both in the past and in the present. The work of biogeographers is critical to understanding our physical environment, how the environment affects species, and how changes in 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. Conservation biogeography, on the other hand, is focused on the protection and restoration of species based upon the known historical and current ecological information.

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 3).

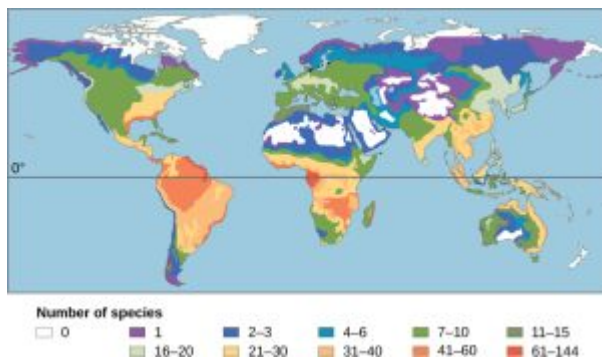


Figure 3: This map illustrates the number of amphibian species across the globe and shows the trend toward higher biodiversity at lower latitudes. A similar pattern is observed for most taxonomic groups.

It is not yet clear why biodiversity increases closer to the equator, but 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 has impacts on 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 a diverse group of 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. Examples of significant medicines derived from plant compounds include aspirin, codeine, digoxin, atropine, and vincristine. 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 natural plant ingredients are replaced by synthetic versions of the plant compounds. 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 drugs are being used in other countries. Other toxins under investigation come from mammals, snakes, lizards, various amphibians, fish, snails, octopuses, and scorpions.

Aside from representing billions of dollars in profits, these medications improve people's lives. Pharmaceutical companies are actively 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 and that 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 that suggest 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 that has been 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 loss of the crop led to famine, death, and mass emigration. Resistance to disease is a chief benefit to maintaining crop biodiversity and lack of diversity in contemporary crop species carries similar risks. Seed companies, which are 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 in crop improvement. Maintaining the genetic diversity of wild species related to domesticated species ensures our continued supply of food.



Figure 4: The Svalbard Global Seed Vault is a storage facility for seeds of Earth's diverse crops. (credit: Mari Tefre, Svalbard Global Seed Vault)

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 (Figure 4), located on Spitsbergen island, Norway, began storing seeds from around the world 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, but 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.

Although crops are largely under our control, our ability to grow them is dependent 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 in the soil that 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, as a result of the diverse metabolic activities of the organisms living there, but they provide benefits to 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 per year; 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 been suffering large losses caused by a syndrome known as colony collapse disorder, a new phenomenon with an unclear cause. Other pollinators include

a diverse array of 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, but these are costly and lose their effectiveness over time as pest populations adapt. They also lead to collateral damage by killing non-pest species as well as 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 do damage to other ecosystems like streams, lakes, and even the ocean. Ecologists believe that the bulk of the work in removing pests is actually done by predators and parasites of those pests, but the impact has not been well studied. A review article found that in 74 percent of studies that looked for an effect of landscape complexity (forests and fallow fields near to 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) increased the yield of alfalfa significantly. This study shows that a diversity of enemies is more effective at control than one single enemy. Loss of diversity in pest enemies will inevitably make it more difficult and costly to grow food. 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 are managed sustainability.

Fishery extinctions rarely lead to 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 ways that are difficult or impossible to predict. The collapse of fisheries has dramatic and long-lasting effects on local human populations that work in the fishery. In addition, the loss of 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.

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5.4 Threats to Biodiversity

Section Goals:

1. Name specific threats to species diversity.
2. Understand how humans contribute to loss of biodiversity.

Species Diversity is Being Threatened

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. Global climate change worsens the impact of human-driven threats to biodiversity. These human-driven threats to biodiversity are: habitat loss, overharvesting, and introduction of exotic species. The first two of these are a direct result of human population growth and resource use. The third results from increased mobility and trade. Global climate change is also a consequence of human population needs for energy and the use of fossil fuels to meet those needs (Figure 1). Environmental issues, such as toxic pollution, also have specific targeted effects on species, which for some areas causes an impact at the magnitude of the other threats.

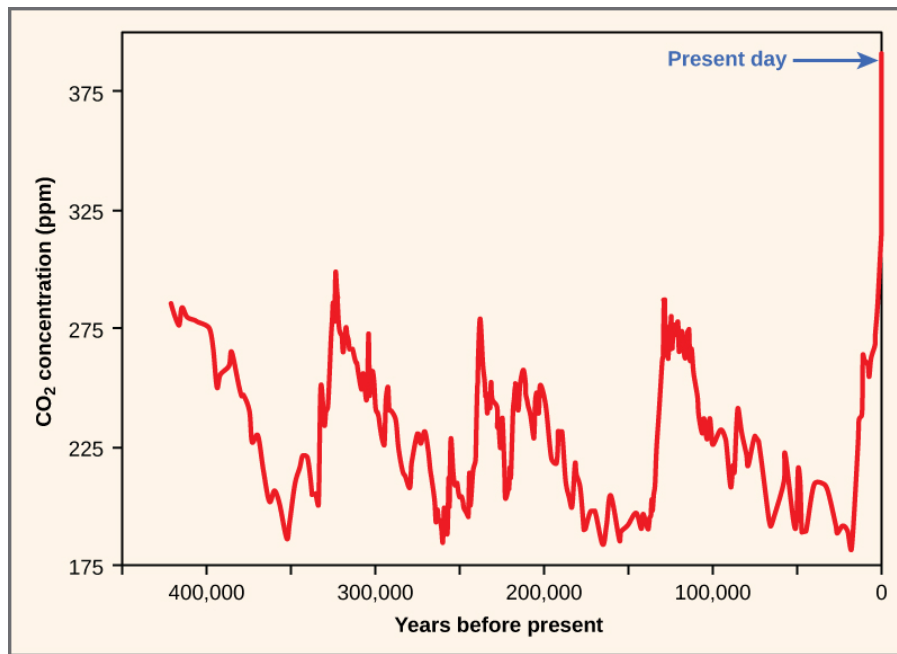


Figure 1: Atmospheric carbon dioxide levels fluctuate in a cyclical manner. However, the burning of fossil fuels in recent history has caused a dramatic increase in the levels of carbon dioxide in the Earth's atmosphere, which have now reached levels never before seen on Earth. Scientists predict that the addition of 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. Most other species cannot do this. Elimination of 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 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 the other species of orangutan, has lost a similar area of forest. 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), but 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 for the years 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: Left and right images show palm oil plantations in Indonesia (right) and Malaysia (Left). The inset picture shows an oil palm stem, weighing about 10 kg (22 lb), with some of its fruits picked. Photo credits: By Achmad Rabin Taim from Jakarta, Indonesia – P3260481, CC BY 2.0, <<https://commons.wikimedia.org/w/index.php?curid=5616589>> By Craig – Own work, Public Domain, <<https://commons.wikimedia.org/w/index.php?curid=1899947>> By T.K. Naliaka – Own work, CC BY-SA 4.0, <<https://commons.wikimedia.org/w/index.php?curid=48045694>>

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 that are adapted to seasonal changes in flow. 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 both 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 a variety of possible reasons.

BIOLOGY IN ACTION: Preventing Habitat Destruction with Wise Wood Choices

Most consumers do not imagine that the home improvement products they buy might be contributing to habitat loss and species extinctions. 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, which is the world's largest consumer of wood products, is illegally logged. In 2006, this amounted to \$3.6 billion in wood products. Most of the 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 even 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 questions about where a wood product came from and how the supplier knows that it was harvested legally.

Overharvesting

Overharvesting is a serious threat to many species, but particularly to aquatic species. There are many examples of regulated fisheries (including hunting of marine mammals and harvesting of crustaceans and other species) monitored by fisheries scientists that 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 led to it becoming 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 when technology gives fishers the ability to overfish. In a few fisheries, it is more profitable to continue overfishing than to wait for the fishery to recover. In these cases—whales are an example—economic forces will drive toward fishing the population to extinction.

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 is known to have been driven extinct by the pet trade, there are studies showing that populations of some species 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 throughout the world, 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 are not being met from agriculture. Species threatened by the bush meat trade are mostly mammals including many monkeys and the great apes living 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 have been intentionally or unintentionally introduced by humans 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 that are well beyond the capacity of the species 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 the species that exist there. When this happens, the exotic species also becomes an **invasive species**. Invasive species can threaten other species through competition for resources, predation, or disease.

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 as a means to migrate; one was even found on an aircraft arriving in Corpus Christi, Texas. Constant vigilance on the part of 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 make up a

large area of land on the globe, but they do contain a disproportionate number of endemic species because of their isolation from mainland ancestors.



Figure 4: Two destructive, invasive snakes. Photo on right shows the brown tree snake, *Boiga irregularis*. It is an exotic species that has caused numerous extinctions on the island of Guam since its accidental introduction in 1950 (credit: NPS). Photo on left shows a Florida Park Ranger holding the tail of a Burmese Python, *Python bivittatus*. This species has caused drastic reduction of native species in the Everglades National Park. (credit: United States Geological Survey).

Many introductions of aquatic species, both marine and freshwater, 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 then 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 prior to 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 also benefited some species, such as smallmouth bass. The mussels are filter feeders and have dramatically improved water clarity, which in turn has allowed aquatic plants to grow along shorelines, providing shelter for young fish where it 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 with resulting increases in the prey species of those native crabs.

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 part, caused by the fungus *Batrachochytrium dendrobatidis*,



Figure 5: This little brown bat in Greeley Mine, Vermont, March 26, 2009, was found to have white-nose syndrome. (credit: modification of work by Marvin Moriarty, USFWS).

which causes the disease chytridiomycosis. There is evidence that the fungus is native to Africa and may have been spread throughout the world by transport of a commonly used laboratory and pet species: the African clawed frog, *Xenopus laevis*. It may well be that biologists themselves are responsible for spreading this disease worldwide. The North American bullfrog, *Rana catesbeiana*, which has also 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.

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 a point of origin in western New York State (Figure 5). The disease has decimated bat populations and threatens 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 on clothes or equipment from Europe.

Climate Change

Climate change, and 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 and is due to past and continuing emission of greenhouse gases, primarily carbon dioxide and methane, into the atmosphere caused by the burning of fossil fuels and deforestation. Scientists overwhelmingly agree the present warming trend is caused by humans 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.

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

Other shifts in range have been observed. For example, one study indicates that European bird species ranges have moved 91 km (56.5 mi) northward, on average. 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 trend to decreasing sea ice coverage 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 6: 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 a glacier 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 have an effect on 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 by the widespread distribution of poison. An alternate approach is genetic engineering in the form of a “gene drive”, an emerging technique that could be better – or worse – for the environment.

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5.5 Preserving Biodiversity

Section Goals:

1. Define biodiversity as the balance between speciation rates and extinction rates.
2. Name specific conservation strategies, including the Endangered Species Act.
3. Understand examples of successful conservation and restoration.

Preserving Biodiversity

Preserving biodiversity is an extraordinary challenge that must be met by greater understanding of biodiversity itself, changes in human behavior and beliefs, and various preservation strategies. Successful conservation efforts rely on knowledge from evolution, ecology, and understanding human societies.

Change in Biodiversity through Time

The number of species on the planet, or in any geographical area, is the result of an equilibrium of two evolutionary processes that are ongoing: speciation and extinction. When speciation rates begin to outstrip extinction rates, the number of species will increase. Likewise, the reverse is true when extinction rates begin to 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).

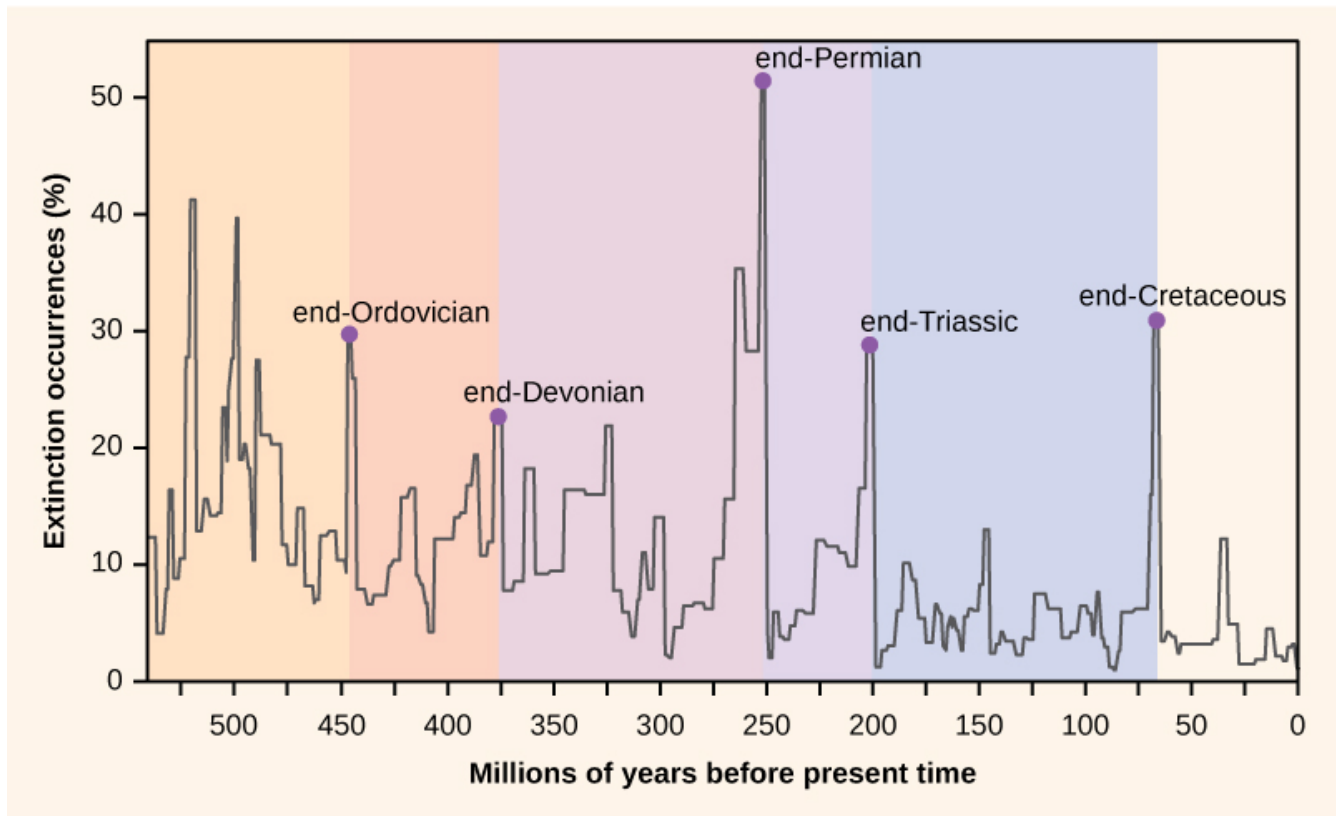


Figure 1: Extinction intensity as reflected in the fossil record has fluctuated throughout Earth's history. Sudden and dramatic losses of biodiversity, called mass extinctions, have occurred five times.

Paleontologists have identified five layers in the fossil record that appear to show sudden and dramatic losses in biodiversity. These are called **mass extinctions** and are characterized by more than half of all species disappearing from the fossil record. There are many 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 dinosaurs 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 biologists say that we are currently experiencing a sixth mass extinction and it mostly has to do with the activities of humans. There are numerous recent extinctions of individual species that are recorded in human writings. Most of these are coincident with the expansion of the European colonies 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).

Another example is Steller's sea cow, which 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 extinction of the species. The last Steller's sea cow was killed in 1768. A final example is the passenger pigeon. 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 of the 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 not complete, but it describes 380 vertebrates that became extinct after 1500 AD, 86 of which were driven extinct by overhunting or overfishing.

Estimates of Present-day Extinction Rates

Estimates of extinction rates are hampered by the fact that most extinctions are probably happening without being observed. The extinction of a bird or mammal is often noticed by humans, especially if it has been hunted or used in some other way. But there are many organisms that are less noticeable to humans (not necessarily of less value) and many that 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, then we would expect 10 of those 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 the year 1500. For birds alone, this method yields an estimate of 26 E/MSY, 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.



Figure 2: The dodo bird was hunted to extinction around 1662. (credit: Ed Uthman, taken in Natural History Museum, London, England)

Taking these factors into account raises the estimated extinction rate to nearer 100 E/MSY. The predicted rate by the end of the century is 1500 E/MSY.

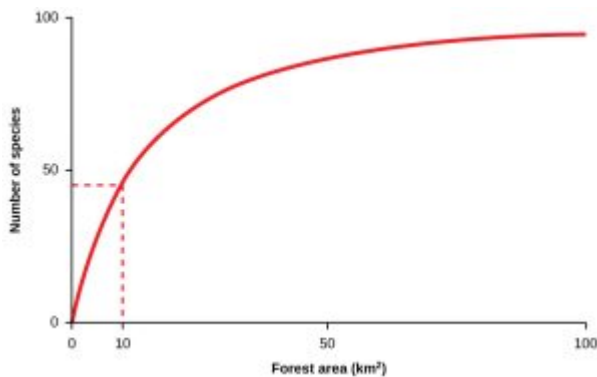


Figure 3. A typical species-area curve shows the cumulative number of species found as more and more area is sampled. The curve has also been interpreted to show the effect on species numbers of destroying habitat; a reduction in habitat of 90 percent from 100 km² to 10 km² reduces the number of species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

have led to estimates of present-day species extinction rates of about 1000 E/MSY and higher.

Conservation of Biodiversity

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

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, provides 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 international movement of organisms or their parts. It is also limited by various countries’ ability or willingness to enforce the treaty and supporting legislation. The illegal trade in organisms and their parts is probably a market in the hundreds of millions of dollars.

Within many countries there are laws that protect endangered species and that regulate hunting and fishing. In the United States, the **Endangered Species Act (ESA)** was enacted in 1973. When an at-risk species is listed by the Act, the U.S. Fish & Wildlife Service is required by law to 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 to get an effective management plan in place once a species is listed.

The **Migratory Bird Treaty Act** (MBTA) is an agreement between the United States and Canada that was 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 that came out of the United Nations Framework Convention on Climate Change that committed countries to reducing 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.

Conservation in Preserves



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

Establishment of 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 boundaries of the preserve. In 2003, the IUCN World Parks Congress estimated that 11.5 percent of Earth's land surface was covered by preserves of various kinds. 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 purpose of the concept was to identify important locations on the planet for conservation efforts, a kind of conservation triage. By protecting hotspots, governments are able to protect a larger number of species. The original criteria for a hotspot included the presence of 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 large numbers of endemic species, which include half of Earth's endemic plants.

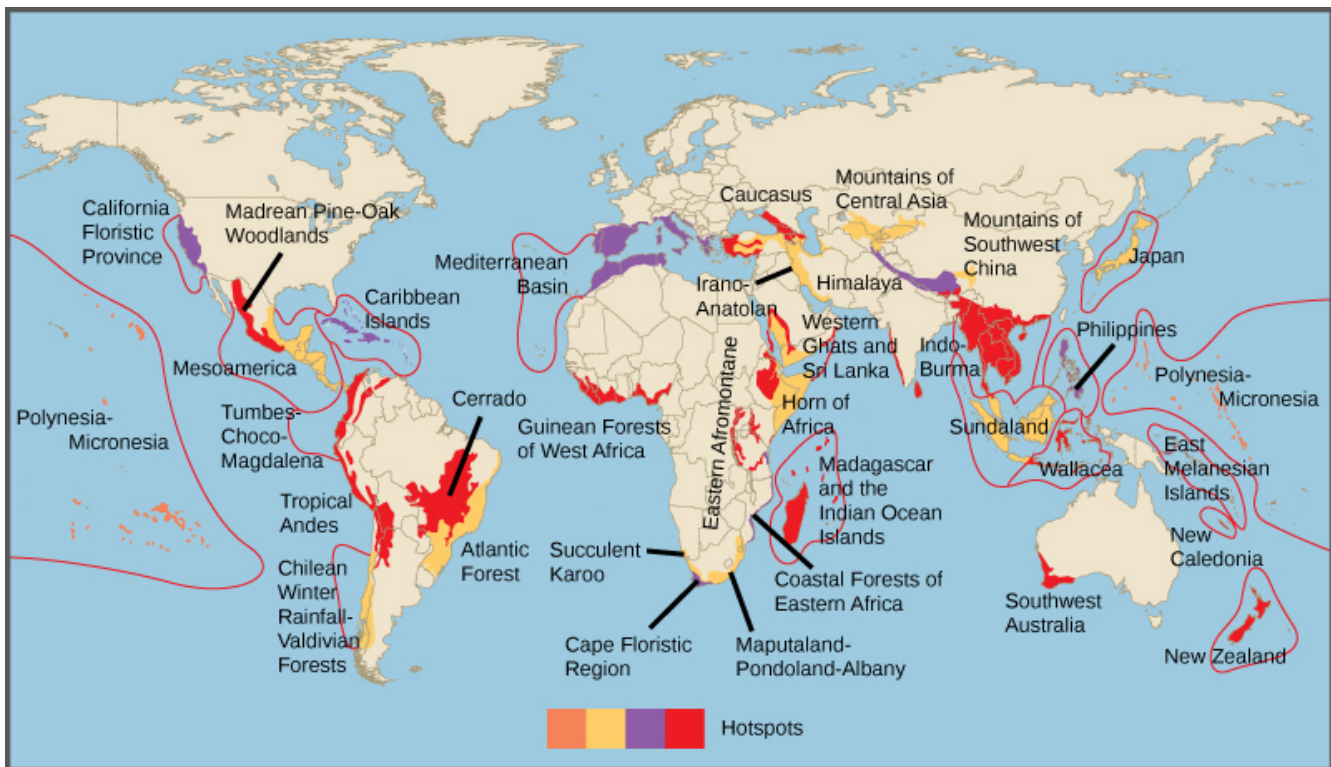


Figure 5: Conservation International has identified 34 biodiversity hotspots. Although these cover only 2.3 percent of the Earth's surface, 42 percent of the terrestrial vertebrate species and 50 percent of the world's plants are endemic to those hotspots.

There has been extensive research into optimal preserve 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 can be seen as “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 area 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 same reason, preserves in the shape of a square or circle will be better than a preserve with many thin “arms.” If preserves must be smaller, then providing **wildlife corridors** (narrow strips of protected land) between two preserves is important so that species and their genes can move between them. All of these factors are taken into consideration 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 can include anything from timber extraction, mineral extraction, regulated hunting, human habitation, and nondestructive human recreation. Many of the decisions to include these other uses are made 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 habitat of the preserve 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 do damage to 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.

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 function to suppress elk and coyote populations and provide more abundant resources to the detritivores. Reducing elk populations and behavioral modification of the elk has allowed revegetation of riparian (the areas along the banks of a stream or river) areas, which has increased the diversity of species in that habitat (Figure 6). Reduction of coyote populations by wolves has increased the prey species previously suppressed by coyotes. In this habitat, the wolf is a **keystone species**, meaning a species that is instrumental in maintaining 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 have the effect of restoring biodiversity in the community. Ecologists have argued for the identification of keystone species where possible and for focusing protection efforts on these species. It makes sense to return the keystone species to the ecosystems where they have been removed.

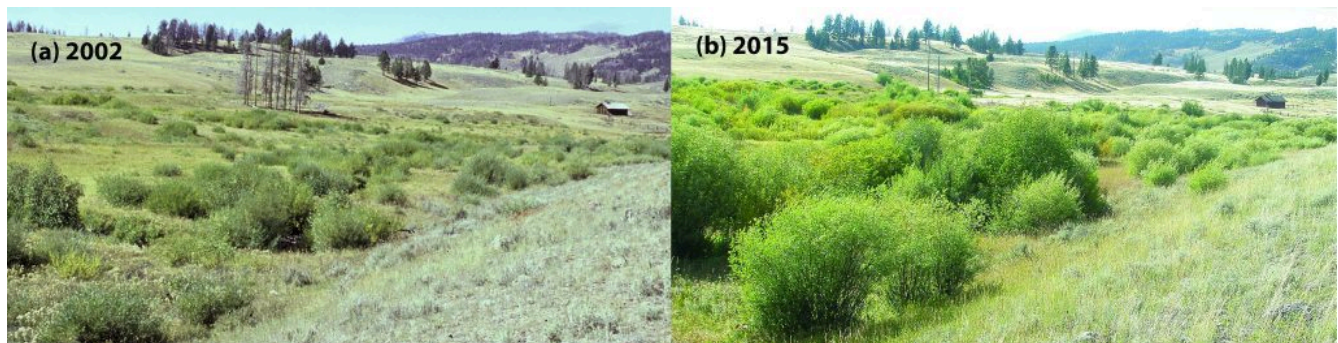


Figure 6: Reintroduction of wolves to Yellowstone National Park resulted in different browsing patterns by large herbivores, which cascaded to the health of the riparian zones of streams: vegetation regrew where it had previously been eaten bare. Credit: By Oregon State University (photographs) Self – arrangement – File:Fig. 1 -Riparian willow recovery (26485120926).jpg, from Fig. 1 -Riparian willow recovery, CC BY-SA 2.5, <https://commons.wikimedia.org/w/index.php?curid=68479968>

Other large-scale restoration experiments underway involve dam removal. In the United States, since the mid-1980s, many aging dams are being 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 that are born in fresh water, live most of their lives in salt water, and return to fresh water 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 Elwha Dam on the Olympic Peninsula of Washington State. The large-scale ecological experiments that these removal projects constitute will provide valuable data for other dam projects slated either for removal or construction.

The Role of Zoos and Captive Breeding

Zoos have sought to play a role in conservation efforts both through captive breeding programs and education. The transformation of the missions of zoos from collection and exhibition facilities to organizations that are dedicated to conservation is ongoing. In general, it has been recognized that, except in some specific 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 numbers of species that are now at risk. Education, on the other hand, is a potential positive impact of zoos on conservation efforts, particularly given the global trend to urbanization and the consequent reduction in contacts 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.

Suggested Supplemental Reading:

Paterniti. 2017. [Should we Kill Animals to Save Them?](#) *National Geographic*. October.
Quammen. 2019. [Saving Africa's Parks](#). *National Geographic*. December

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5.6 Chapter Resources

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 numbers 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.

Loss of biodiversity 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 be a significant cause of extinction in the coming century. 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. In the United States, the Endangered Species Act protects listed species 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 in some way. Habitat restoration has the potential to restore ecosystems to previous biodiversity levels before species become extinct. Examples of restoration include reintroduction of keystone species and removal of dams on rivers.

Review Questions

1. Bacteria that feed upon decaying organic matter in the soil would best be described as which one of the following?

- A. Eukaryotic
- B. Autotrophic
- C. Fungi
- D. Cyanobacteria
- E. Heterotrophic

2. As Darwin recognized, populations evolve through natural selection when which of the following condition(s) are met?

- A. Variation of traits among individuals
- B. Competition for limited resources
- C. More offspring are produced than can survive
- D. All of the above

3. You are the world's foremost expert on lizards. You have traveled the world extensively and have found that a particular species of lizard is found only in one desert near of the Chilean Andes. Which of following terms, with regard to its distribution, can be definitively applied to this species?

- A. Endangered
- B. Prokaryotic
- C. Endemic
- D. Disbursed
- E. Clustered

4. Which one of the following is not a major cause of biodiversity loss?

- A. Habitat loss
- B. Climate change
- C. Invasive Species
- D. Zoonotic diseases
- E. Overharvesting

5. Which one of the following statements is false?

- A. There have been five mass extinctions preserved in the fossil record
- B. Some bacteria are autotrophs
- C. Current rates of extinction are higher than background extinction rates
- D. Speciation is the process of creating new species
- E. All living things can be classified into one of four taxonomic domains

6. During the middle of the 19th century, which scientist independently derived and proposed a theory of evolution that was similar to Darwin's?

- A. Gregor Mendel
- B. Alfred Wallace
- C. Isaac Newton
- D. Rachel Carson
- E. Niels Bohr

7. The study of the distribution of the world's species both in the past and in the present is known by what term?

- A. Geology
- B. Biogeography
- C. Biodiversity
- D. Biogeomorphology
- E. Ecological Succession

8. Which one of the following would be described as anthropogenic?

- A. Water backing up behind a beaver dam
- B. The dinosaurs going extinct
- C. Logging a forest
- D. A mudslide burying a stream
- E. A volcanic eruption

9. By definition, what are you most likely to find in a biodiversity hotspot?

- A. A large abundance of endangered species
- B. A large number of endemic species
- C. Mostly eukaryotic species
- D. Extremophiles
- E. Heat-loving microbes

10. You are working as a biologist for a team surveying biodiversity in the Amazon rainforest. You find a non-motile organism that grows in the soil, has eukaryotic cells, and is heterotrophic. Which one of the following could potentially describe this species?

- A. Fungus
- B. Animal
- C. Bacteria
- D. Plant
- E. Archaea

See Appendix for answers

Attributions

OpenStax College. (2013). *Concepts of biology*. Retrieved from <http://cnx.org/contents/b3c1e1d2-839c-42b0-a314-e119a8aafbdd@8.10>. OpenStax CNX. Available under Creative Commons Attribution License 3.0 ([CC BY 3.0](#)). Modified from Original.

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Chapter 6: Environmental Hazards & 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:

- Link pollution to its impact on sustainable production goals
- Define environmental health
- Categorize environmental health risks
- Classify environmental contaminants
- Summarize the principles of environmental toxicology
- Explain the concept of emerging diseases

Chapter Outline

- 6.1 Pollution and Sustainability
- 6.2 The Impacts of Environmental Conditions
- 6.3 Environmental Health
- 6.4 Environmental Toxicology
- 6.5 Bioremediation
- 6.6 Case Study: The Love Canal Disaster
- 6.7 Chapter Resources

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6.1 Pollution and Sustainability

Joni Baumgarten

Section Goals:

1. Conceptualize how pollution is a concept of our society.
2. Define common pollutants.
3. Understand cradle-to-grave analysis of impact.

Pollution as a Concept

As a person who lives in the built environment in the United States, it is easy to take for granted the concept of pollution and ideas of disposing of pollution on land or remediating land polluted with industrial chemicals. **Pollution** is the introduction of contaminants into the natural environment that cause adverse change. Pollution can take the form of any substance (solid, liquid, or gas) or energy (such as radioactivity, heat, sound, or light). Pollutants, the components of pollution, can be either foreign substances/energies or naturally occurring contaminants. Although environmental pollution can be caused by natural events, the word pollution generally implies that the contaminants have an anthropogenic source – that is, a source created by human activities.

To protect the environment from the adverse effects of pollution, many nations worldwide have enacted legislation to regulate various types of pollution as well as to mitigate the adverse effects of pollution.

Pollution control is a term used in environmental management. It means the control of emissions and effluents into air, water or soil (e.g., Figure 1 and Figure 2). Without pollution control, it has been the case that the waste products from overconsumption, heating, agriculture, mining, manufacturing, transportation and other human activities, degraded the environment. Ideally, pollution prevention and waste minimization are more desirable than pollution control.



Figure 1: A dust collector in Pristina, Kosovo. By Kristoferb at English Wikipedia, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=10784144>



Figure 2: Air pollution control system, known as a thermal oxidizer, decomposes hazard gases from industrial air streams at a factory in the United States. By Combustion2016 – Own work, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=52028818>

The concept that natural lands and waters can act as filters, and that we can dispose of contaminants at levels that do not reach dangerous levels can be tied to specific scientific studies, such as the work of H. W. Streeter, a sanitary engineer, and Earle B. Phelps, a consultant for the U.S. Public Health Service. In 1925, working in the Ohio River, Streeter and Phelps developed an equation to measure the impact of contaminants based on how the contaminant reduced the total oxygen availability in the river. The **Streeter–Phelps equation** is used in the study of water pollution as a water quality modelling tool. Specifically, the model describes how dissolved oxygen decreases in a river or stream along a certain distance due to the oxygen demand of microbes degrading the biochemical. Based on this equation, acceptable limits of contamination can be calculated; below a threshold, the waters will act as a filter and the contaminants will not reduce the oxygen in the river to levels that would result in the death of most aquatic

organisms (e.g., fish).

Types of Pollution

Various definitions of pollution exist, which may or may not recognize certain types such as noise pollution or greenhouse gases. The United States Environmental Protection Administration defines pollution as “Any substances in water, soil, or air that degrade the natural quality of the environment, offend the senses of sight, taste, or smell, or cause a health hazard. The usefulness of the natural resource is usually impaired by the presence of pollutants and contaminants.” In contrast, the United Nations considers pollution to be the “presence of substances and heat in environmental media (air, water, land) whose nature, location, or quantity produces undesirable environmental effects.”

The major forms of pollution are listed below along with the particular contaminants relevant to each of them:

- **Air pollution** is the release of chemicals and particulates into the atmosphere. Common gaseous pollutants include carbon monoxide, sulfur dioxide, chlorofluorocarbons (CFCs) and nitrogen oxides produced by industry and motor vehicles. Photochemical ozone and smog are created as nitrogen oxides and hydrocarbons react to sunlight. Particulate matter, or fine dust is characterized by their micrometer size PM_{10} to $PM_{2.5}$. $PM_{2.5}$ particulates are particularly dangerous due to their ability to penetrate deep into the lungs and enter the blood streams, causing health problems including cardiovascular disease, respiratory disease, and premature death.
- **Electromagnetic pollution** is the overabundance of electromagnetic radiation in their non-ionizing form, such as radio and television transmissions, Wi-fi etc. Although there is no demonstrable effect on humans there can be interference with radio-astronomy and effects on safety systems of aircraft and cars.

- **Light pollution** includes light trespass, over-illumination and astronomical interference (which causes the night sky to become lighter, blocking views of the stars, planets, etc.).
- **Littering** is the criminal throwing of inappropriate man-made objects, unremoved, onto public and private properties.
- **Noise pollution** encompasses roadway noise, aircraft noise, industrial noise as well as high-intensity sonar.
- **Plastic pollution** involves the accumulation of plastic products and microplastics in the environment that adversely affects wildlife, wildlife habitat, or humans.
- **Soil contamination** occurs when chemicals are released by spill or underground leakage. Among the most significant soil contaminants are hydrocarbons, heavy metals, herbicides, pesticides and chlorinated hydrocarbons.
- **Radioactive contamination** results from 20th century activities in atomic physics, such as nuclear power generation and nuclear weapons research, manufacture, and deployment.
- **Thermal pollution** is a temperature change in natural water bodies caused by human influence, such as use of water as coolant in a power plant.
- **Visual pollution** can refer to the presence of overhead power lines, motorway billboards, scarred landforms (as from strip mining), open storage of trash, municipal solid waste or space debris.
- **Water pollution** is caused by the discharge of water which enters a local waterway; it includes industrial wastewater from commercial and industrial waste (intentionally or through spills) into surface waters; discharges of untreated sewage and chemical contaminants, such as chlorine, from treated sewage; and releases of waste and contaminants into surface runoff flowing to surface waters (including urban runoff and agricultural runoff, which may contain chemical fertilizers and pesticides, as well as human feces from open defecation).

Triple Bottom Line and Life-Cycle Assessment

One way that Western Society has responded to the challenge of industrial pollution and the increased awareness of environmental damage and climate change is to analyze industry and development through a sustainability lens. This idea of sustainable development (as a modern term) is linked to the 1960s and 1970s, when people became more and more aware of environmental pollution.

Sustainability is a societal goal that relates to the ability of people to safely co-exist on Earth over a long time. Specific definitions of sustainability are difficult to agree on and have varied with literature, context, and time. However, sustainability is commonly described as having three dimensions (or pillars): environmental, economic, and social.

Sustainable development can be understood through the concept of a triple bottom line, which differs from traditional industry concern for just “the bottom line”, aka net income. The Triple Bottom Line, also known as TBL or 3BL, was first proposed in 1997 by John Elkington to expand the traditional financial reporting framework so as to capture a firm’s social and environmental performance. Elkington also used the phrase *People, Planet, Profit* to explain the three focuses of triple bottom line reporting.

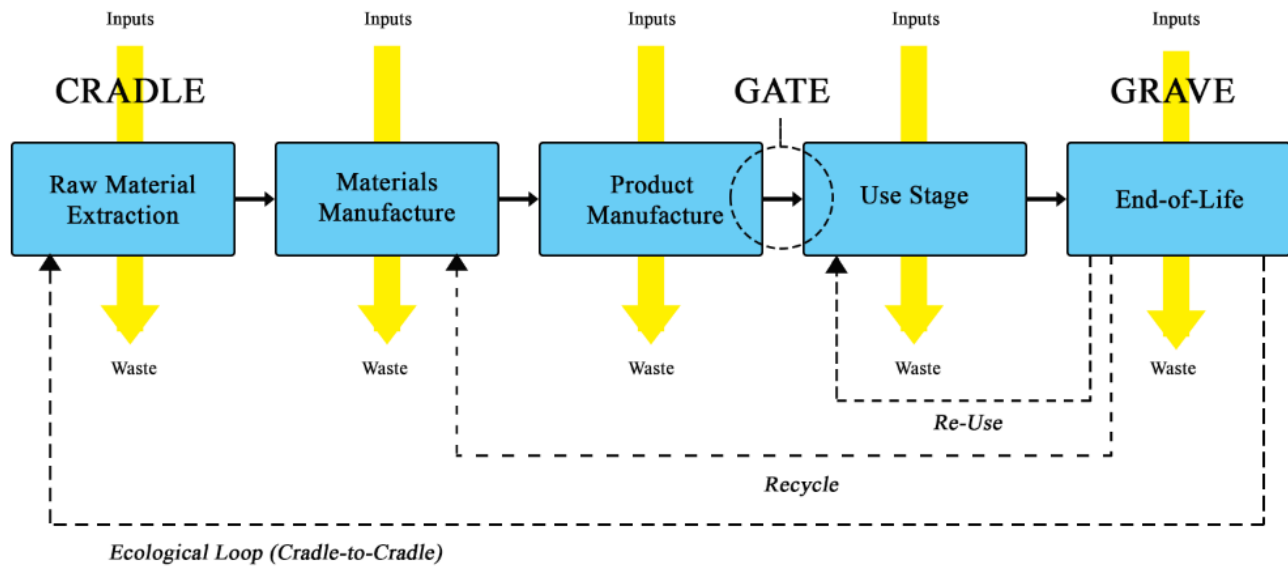
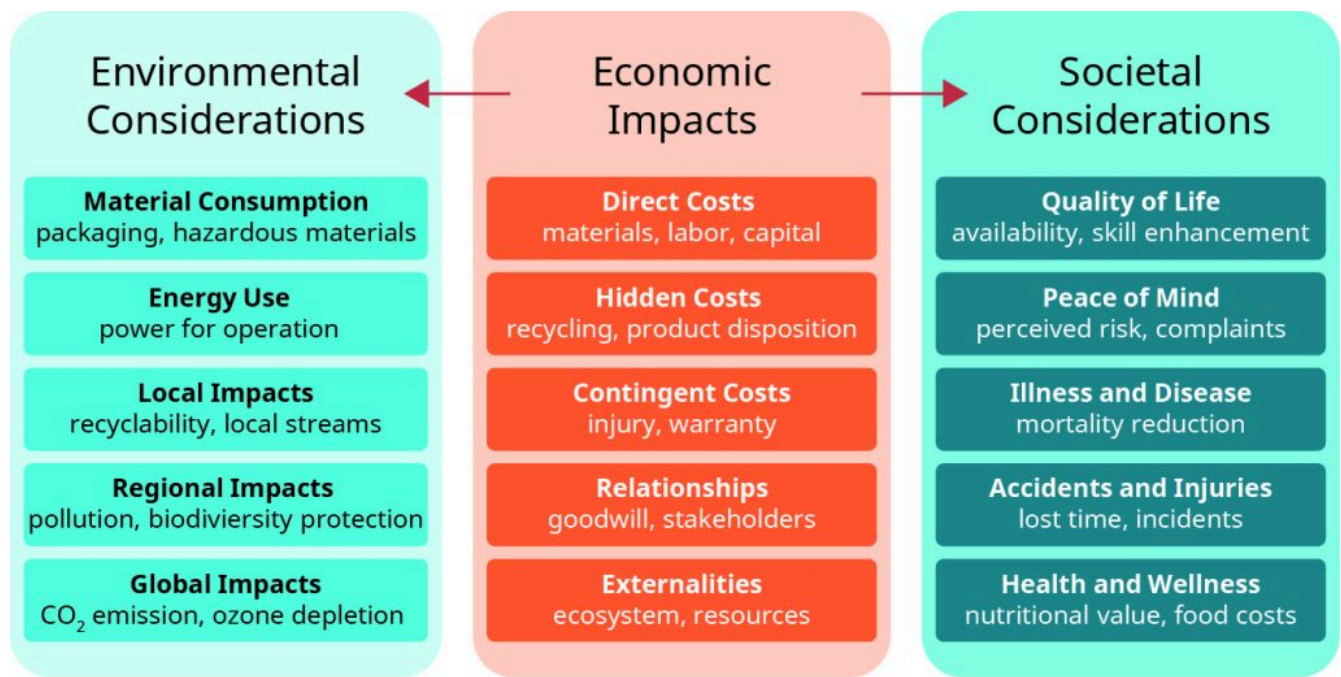


Figure 3: A model of the cradle to grave concept. By MtW17 – Own work, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=97566700>

Another innovation of this societal concern was life-cycle accounting. This reporting method took a **“cradle to grave”** approach to costing that put a price on the disposal of products at the end of their lives and then considered ways to minimize these costs by making adjustments in the design phase (Figure 3). This method also incorporated potential social, environmental, and economic costs (*externalities* in the language of economics) to attempt to identify all of the costs involved in production. For example, one early adopter of **life-cycle accounting**, Chrysler Corporation, looked the material costs, hidden manufacturing expenses, and liabilities associated with disposal of a newly-developed oil filter. They found that the option with the lowest *direct* costs had hidden disposal costs that meant it was not the cheapest overall mode of production.

Early study into the *hows* of sustainability reporting led researchers to suggest that some performance indicators could be quantified. Figure 4 shows the sustainable product indicators identified by Fiskel and colleagues (1998) with suggestions on how each element of economic output might also be measured from an environmental or societal stance.



Source: Fiksel, J., J. McDaniel, and D. Spitzley. "Measuring Product Sustainability." *The Journal of Sustainable Product Design*. July 1998 (6): 7–18.

Figure 4: Sustainable Product Indicators. There are a number of approaches to dealing with economic costs from an environmental and/or social impact perspective. (attribution: Copyright Rice University, OpenStax, under CC BY-NC-SA 4.0 license)

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[Streeter-Phelps Equation](#) by Wikipedia is licensed [CCA-SA 3.0](#). Accessed February 19, 2023. Modified by Joni Baumgarten.

6.2 The Impacts of Environmental Conditions

Section Goals:

1. Understand examples of how ecosystem health and human health are linked.
2. Introduce the concept of biomagnification.

The Health of Earth's Ecosystems Affects Human Health

Ecosystems have always played a role in human habitats and health. For most of human history, biological agents were a dominant factor in human health, with the distribution of the biological agents relating to ecosystem boundaries. Currently, 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 health of the earth's ecosystems, and this degradation ultimately affects the health and well-being of human populations.

As just stated, **biological agents** were the most significant factor in health for most of human history. These included pathogenic (disease causing) organisms such as bacteria, viruses, protozoa, and internal parasites. While other causes of death (cardiovascular diseases, cancer, and accidents) have risen higher than biological causes in modern times and in industrialized countries, infectious diseases still cause about 22 million deaths a year. These diseases include: tuberculosis, malaria, pneumonia, influenza, whooping cough, dysentery and Acquired Immune Deficiency Syndrome (AIDS). Most of those affected are children in non-industrialized countries. 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 factors such as drug-resistant pathogens, insecticide resistant carriers, and overpopulation. Overuse of antibiotics have 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 now reversed that trend. Another example is malaria. The insecticide DDT (a chemical called 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.

Case Study: Biomagnification of Chemicals

Chemical agents are a more modern concern which 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. All of them **biomagnify**; they become more concentrated in species at higher trophic levels because the chemical does not cycle out of organisms, rather it builds up at each level of the food chain. For example, mercury from polluted water can accumulate in swordfish to levels toxic

to humans. When toxic heavy metals get into the human body, they continue to accumulate in tissues and may eventually cause sickness or death. Studies show that people with above-average lead levels in their bones have an increased risk of developing attention deficit disorder and aggressive behavior. Lead can also damage brain cells and affect muscular coordination.



Figure 1. DDT was a commonly-used pesticide. [“This work”](#) by OpenStax is licensed under [CC BY 4.0](#).

ecological impact.

Case Study: ENVIRONMENTAL PERSISTENCE OF DDT

The pesticide DDT was 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—meaning that the levels of DDT in animal tissue greatly increase at each level of the food chain.

Populations of bird species at the top of the food chain, e.g., eagles and pelicans, accumulate DDT in their tissue through consumption of animals that also have DDT in their tissue. Because DDT does not break down in their bodies, DDT concentrations grow through time. 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 made noticeable recoveries, including the iconic bald eagle.

In some parts of the world, the use of DDT has been approved with limitations because it is such an effective pesticide, and if the environmental spread is limited, the benefits to human health by reducing insect vectors like mosquitos outweighs the risk of

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6.3 Environmental Health

Section Goals:

1. Define environmental health.
2. Discuss the interconnection between poverty and health, which is a major impact on child health and survival.
3. Discuss emerging diseases as a part of environmental health.
4. Highlight the importance and risk of antibiotic resistance.

Environmental Health

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 health care 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 that of modern health hazards by 10 times in Africa, 5 times in Asian countries (except for China), and 2.5 times in Latin America and 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 5 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 in each year.

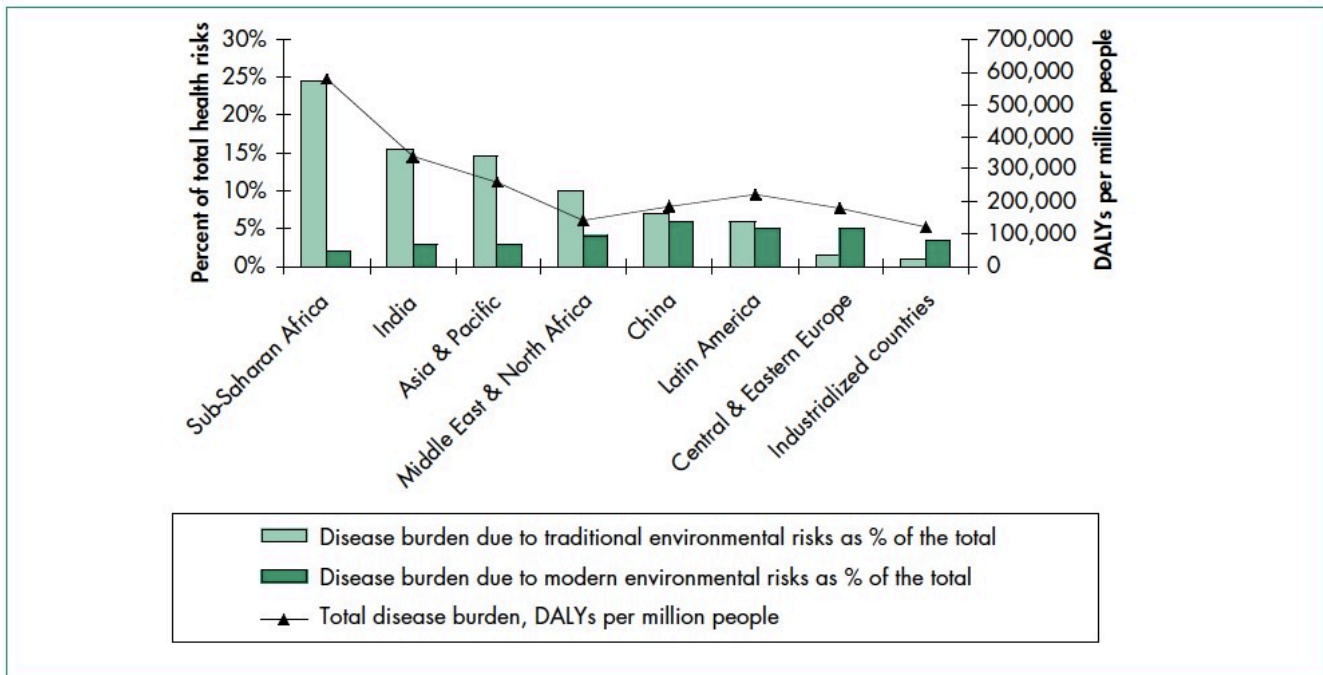


Figure 1: Traditional environmental health hazards prevail in developing countries but modern risks are also significant.

Modern hazards, caused by technological development, prevail in industrialized countries where exposure to traditional hazards is low. 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

Worldwide, the top killers of children under five are acute respiratory infections (from 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. Four specific examples are highlighted here: Malnutrition, Poor Sanitation, Indoor Air Pollution, and Malaria.

Malnutrition

Malnutrition (the condition that occurs when 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 in fact caused by inadequate water and sanitation provision and poor hygienic practices.



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

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 the age of five. 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 combined with 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 per year and for 2.7% of global burden of disease. 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 subsequently, 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 as a result of 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 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.

A variety of environmental factors may contribute to 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 of these environmental and/or social factors to allow optimal conditions for transmission of the disease.

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. There were a small number of cases reported in Nigeria and Mali and a single case 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. Each day, approximately 14,000 new infections occur, more than half of them among young people below age 25. Over 95 percent of PLWHA (People Living With HIV/AIDS) are in low- and middle- income countries. More than 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 10 years in several nations.

It seems likely that a wide variety of infectious diseases have affected human populations for thousands of years emerging when the environmental, host, and agent conditions were favorable. Expanding human populations have increased the potential for transmission of infectious disease as a result of close human proximity and increased likelihood for humans to be in “the wrong place at the right time” for disease to occur (e.g., natural disasters or political conflicts). Global travel increases the potential for a carrier of disease 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, together called antimicrobial agents, have been used for the last 70 years to treat patients who have 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 the drugs less

effective. **Antibiotic resistance** occurs when bacteria change in a way that reduces 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.

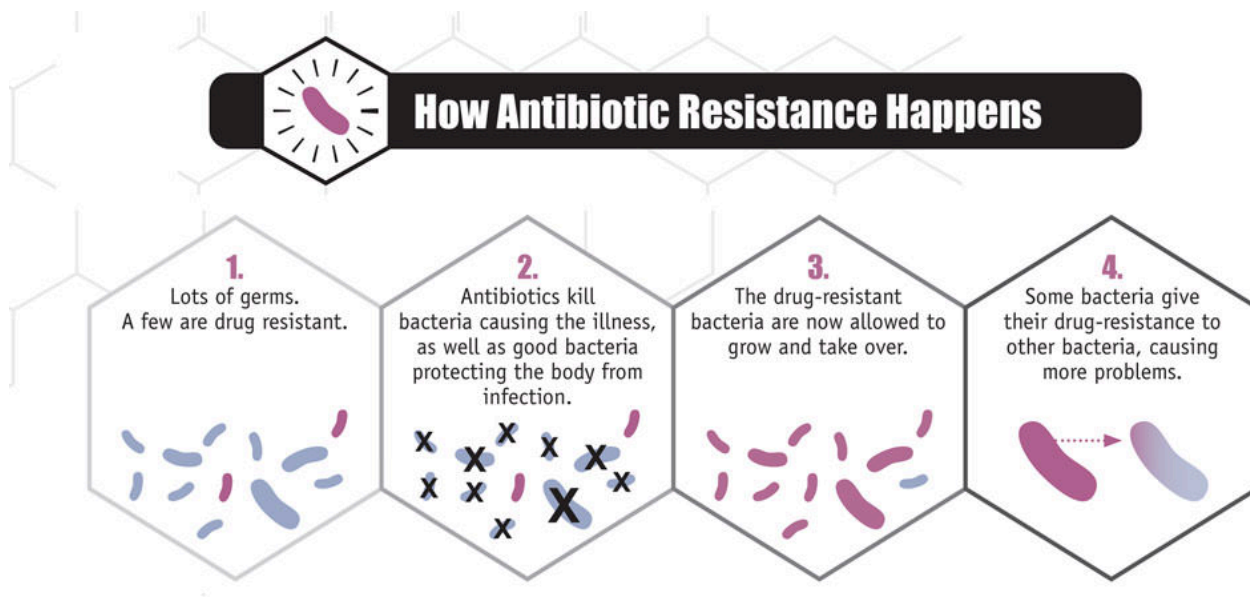


Figure 3: Antibiotic resistance is of increasing concern to medical professionals.

New forms of antibiotic resistance can cross international boundaries and spread between continents with ease. Many forms of resistance spread with remarkable speed. Each year in the United States, at least 2 million people acquire serious infections with bacteria that are resistant to one or more of the antibiotics designed to treat those infections. At least 23,000 people die each year in the US as a direct result of 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, but up to 50% of all the antibiotics prescribed for people are not needed or are not optimally effective as prescribed.

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



Figure 4: [Click here for a video link to an experiment done at Harvard Medical school, where they show bacteria adapting 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

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6.4 Environmental Toxicology

Section Goals:

1. Understand the routes of exposure for different chemicals.
2. Define LD-50 and ED-50.
3. Understand the risks of some common contaminants.

Environmental toxicology

Environmental toxicology is the scientific study of the health effects associated with 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.

Table 1. The [ATSDR](#) 2013 Substance Priority List. The table below lists 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 a combination of 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

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 dusts that are in the air.
- Skin or eye contact: Getting chemicals on the skin, or in 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, beads, 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.

What Forms do Chemicals Take?

Chemical substances can take a variety of forms. They can be in the form of solids, liquids, dusts, 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 that 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 effect** 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.

For centuries, scientists have known that just about any substance is toxic in sufficient quantities. 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 dose and the response of the individual. **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 in order to give a measure of their toxicity. A dose that causes 50% of a population to exhibit any significant response (e.g., hair loss, stunted development) is referred to as the **effective dose-50%** or **ED-50**. Some toxins have a threshold amount below which there is no apparent effect on the exposed population. However, there are also toxins where any dose is dangerous, and there is no threshold value that can be calculated (this is one of the challenges in regulating chemicals).

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 a variety of residential, commercial, and industrial sources. Sometimes harmful environmental contaminants occur biologically, such as mold or a toxic algae bloom.

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 which 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 variety 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 that is 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 surface of the land for hundreds of years as a long-term source of exposure. Wood that has been treated with chromated copper arsenate (CCA) is commonly found in decks and railing in existing homes and outdoor structures such as playground equipment. Some underground aquifers are located in rock or soil that has 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 around the world, 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 which 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 eat fish high in mercury on a regular basis run the risk of 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.

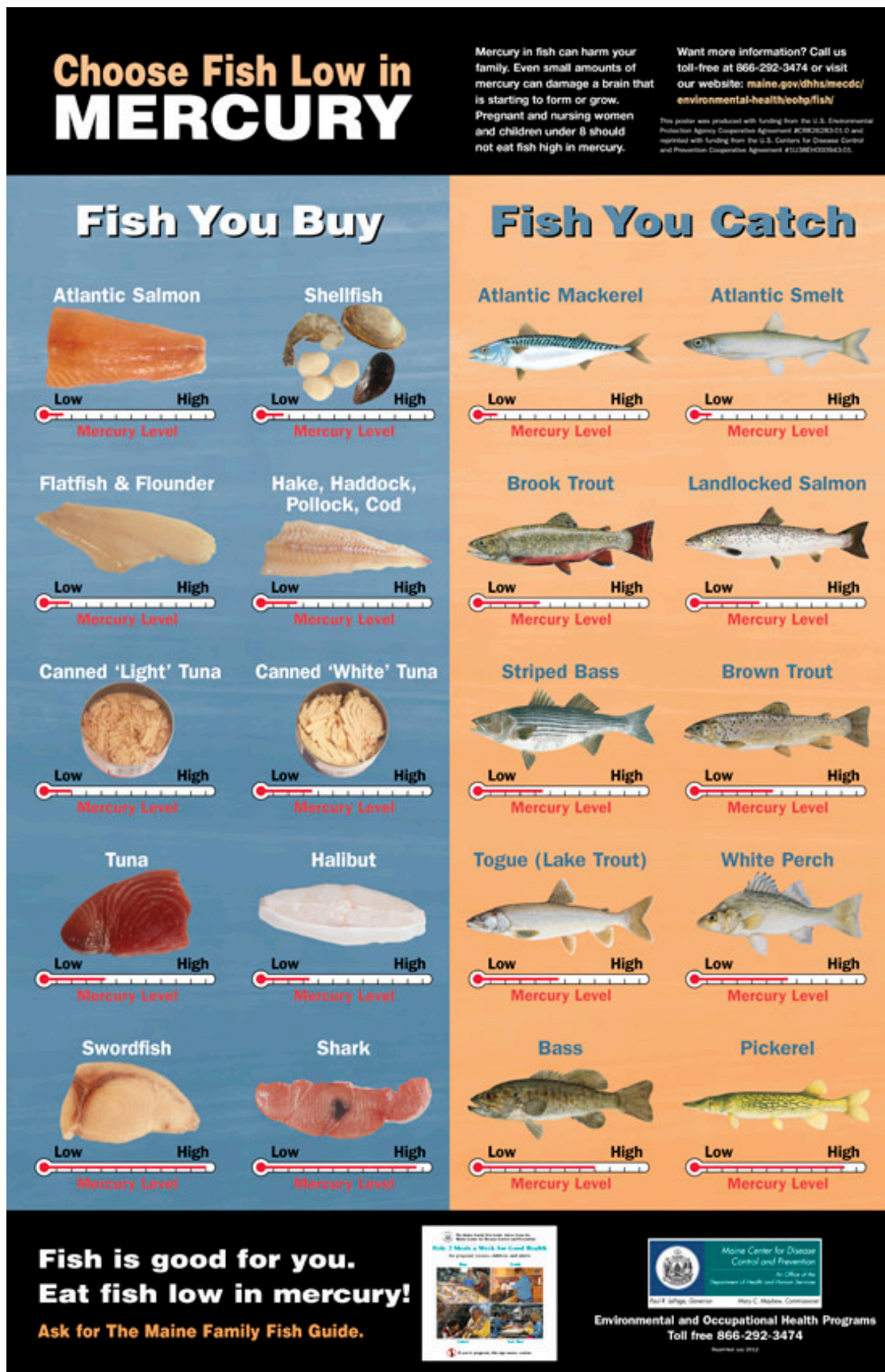


Figure 1: Mercury concentrations in fish can reach potentially dangerous levels (published by the

[Maine Center for Disease Control & Prevention](#)).

Bisphenol A (BPA) is a chemical synthesized in large quantities for use primarily in the production of polycarbonate plastics and epoxy resins. Polycarbonate plastics have many applications including use in some 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 from 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 exposures of their infants and children to BPA:

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

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 from burning fossil fuels such as coal, oil, gasoline, and natural gas; mining; and manufacturing. Lead has no distinctive taste or smell. The chemical symbol for elemental lead is Pb. Lead is used to produce 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; from solder used on water pipes in 1986; from gasoline in 1995; from solder used on food cans in 1996; and

from tin-coated foil on wine bottles in 1996. The U.S. Food and Drug Administration has set a limit on 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 levels of lead for 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 that has 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). Formaldehyde levels in outdoor air range from 0.001 to 0.02 ppm in urban areas.

Radiation is energy given off by atoms and is all around us. We are exposed to radiation every day from natural sources like soil, rocks, and the sun. We are also exposed to radiation from man-made sources like medical X-rays and smoke detectors. We’re even exposed to low levels of radiation 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 up through the ground and into the home through cracks in floors, walls and foundations. It can also be released from building materials or from 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.

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6.5 Bioremediation

Section Goals:

1. Review examples of events that require remediation.
2. Compare bioremediation with other types of remediation.
3. Understand what types of organisms contribute to bioremediation.

Examples of Remediation

There are thousands of examples of places where accidental, purposeful, or mismanaged actions caused contamination of soils, waters, or ecosystems. Contamination from petroleum products, due to their hydrophobic nature and natural contaminants contained within them, are unfortunately common at local scales (like underground storage tanks leaking) and massive scales; stark examples such as the Exxon Valdez spill in Alaska, the Deepwater Horizon Spill, and the long-term leak at a oil platform owned by Taylor Energy, both in the Gulf of Mexico, highlight the extensive damage that can occur. Heavy metal contamination is another category of contamination that causes major health concerns, most specifically due to bioaccumulation. Top metal pollutants in the United States of America include arsenic, lead, mercury, cadmium, and chromium. The most common treatment for metal-contaminated sites is to remove the contaminated material, and landfill it somewhere else. Though this method is immediate, it is also ecologically disruptive, costly, and the contaminant is still located somewhere, just theoretically in a place that poses less danger to human health.

Bioremediation

Bioremediation is a waste management technique that involves the use of 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 in situations that may not seem worthy of “remediation”; such as to treat human sewage and to remove agricultural chemicals (pesticides and fertilizers) that leach from soil into groundwater. Certain toxic metals, such as selenium and arsenic compounds, can also be removed from water by bioremediation. Mercury is an example of a toxic metal that can be removed from an environment by bioremediation. Mercury is an active ingredient of 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.

Probably one of the most useful and interesting examples of the use of prokaryotes for bioremediation purposes is the cleanup of oil spills. The importance of prokaryotes to petroleum bioremediation has

been demonstrated in several oil spills, 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). To clean up these spills, bioremediation is promoted by adding inorganic nutrients that help bacteria already present in the environment to grow.



(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)

Specific ways that bacteria mitigate oil spills include breaking the oil down into smaller, inorganic components, and degrading the oil fully to carbon dioxide. 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, inasmuch as there are oil-consuming bacteria in the ocean prior to the spill. Under ideal conditions, it has been reported that up to 80 percent of the nonvolatile components in oil can be degraded within 1 year of the spill.

Researchers have genetically engineered other bacteria to consume petroleum products; indeed, the first patent application for a bioremediation application in the U.S. was for a genetically modified oil-eating bacterium.

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 bioremediation of hydrocarbons also has the advantage of breaking down contaminants at the molecular level, as opposed to simply chemically dispersing the contaminant.

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6.6 Case Study: The Love Canal Disaster

Section Goals:

1. Understand the combination of environmental injustices and complexity of chemical contaminants that contributed to the Love Canal tragedy.

The Superfund Federal Program

One of the most famous and important examples of groundwater pollution in the U.S. 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 U.S.

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) that was 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 both 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 or so homes along the canal banks and another 1,000 in the neighborhood (Figure 1). During construction, the canal's clay cap and walls were breached, damaging some of the metal barrels.

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



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

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 studies by the New York State Health Department 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, which was funded by Superfund and completely 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 Federal Emergency Management Association for the relocation of 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 in the process of being cleaned.

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6.7 Chapter Resources

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 health care 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 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 per year and for 2.7 percent of global burden of disease.

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 a variety of residential, commercial, and industrial sources.

Often, contaminated sites are treated with traditional remediation efforts which includes the total removal of the contaminated material (e.g., soil). However, bioremediation is an alternative that may be less ecologically damaging, less costly, and actually transform the contaminant into a less-toxic form.

The Love Canal disaster is an important example to remember because it led to the formation of the Superfund, and the original company that caused the damage was held responsible for the required remediation.

Review Questions

1. The pesticide DDT is an example of which one of the following?
 - A. Biological agent
 - B. Atomic agent
 - C. Chemical agent
 - D. Capricious agent
 - E. Inorganic agent

2. From the perspective of human health, malnutrition is important because it...
 - A. Causes the majority of birth defects
 - B. Is the primary source of teratogens for most children
 - C. is an important contributor to child mortality
 - D. Is the second leading cause of death from emerging disease
 - E. Increases the occurrence of infectious cancers
3. Antibiotic resistance in organisms is the result of what process?
 - A. Differentiation
 - B. Evolution
 - C. Emergence
 - D. Succession
 - E. Fixation
4. Which one of the following is an example of an emerging disease?
 - A. Malaria
 - B. Ebola
 - C. Cancer
 - D. Heart disease
 - E. Leukemia
5. “Effective dose – 50%” describes which one of the following?
 - A. The dose that results in 50% mortality
 - B. The dose the results in 50% survival
 - C. The dose that is 50% less than the lethal dose
 - D. The dose that results in a significant response in 50% of subjects
 - E. The dose that is 50% more than the minimal dose
6. You are working as an environmental toxicologist for the government. Your results indicate that a particular chemical causes birth defects. Which one of the following best describes the effects of this chemical?
 - A. Teratogen
 - B. Carcinogen
 - C. Mutagen
 - D. Endocrine disruptor
 - E. Neurotoxicant
7. Which one of the following is most directly associated with radon?
 - A. Radiation
 - B. Endocrine disruption
 - C. Birth defects
 - D. Biological agents
 - E. Biomagnification
8. Which one of the following is an example of bioremediation?

- A. Adding chemical dispersants following an oil spill
 - B. Growing large colonies of bacteria to produce antibiotic chemicals
 - C. Mimicking the processes of natural in a laboratory or industrial context
 - D. Removing invasive species that are overpopulating an ecosystem
 - E. Using plants to remove toxic metals from soils following a mining operation
9. Which one of the following is not a naturally-occurring element that may be hazardous to human health?
- A. Lead
 - B. Radon
 - C. Phthalate
 - D. Mercury
 - E. Arsenic
10. Which one of the following is not true regarding the “Love Canal Disaster”?
- A. It involved the improper storage of chemical waste
 - B. It was one of several incidents that led to the creation of the Superfund
 - C. A school was built on the contaminated site
 - D. Many homes had to be evacuated due to contamination from various biological agents
 - E. Many people living in the year reported serious health problems

See Appendix for answers

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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

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7.1 Water Cycle and Fresh Water Supply

Section Goals:

1. Understand the abundance of different types of water.
2. Describe the different fresh water reservoirs.
3. Understand watersheds and the water table.

Water is Essential

Water, air, and food are the most important natural resources to people. 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 breakdown water and use it to create oxygen during the process of 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 and 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 (km^3) (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 clean water to all people. 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 climate 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 water pollution have compounded significantly the water crisis that exists today. Hundreds of millions of people lack access to safe drinking water, and billions of people lack access to improved sanitation as simple as a pit latrine. As a result, nearly two million people die every year 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 of the 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 world's water was shrunk to the size of 1 gallon, then the total amount of fresh water would be about 1/3 cup, and the amount of readily usable fresh water would be 2 tablespoons.

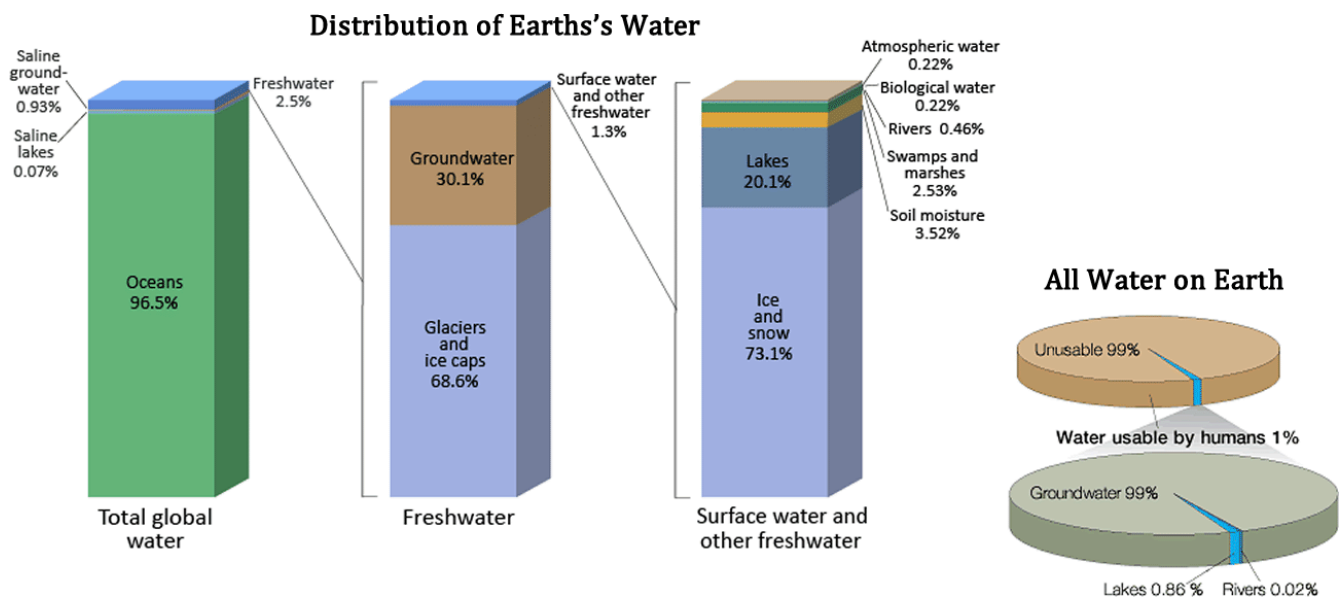


Figure 1: Earth's Water Reservoirs. Bar chart Distribution of Earth's water including total global water, fresh water, and surface water and other fresh water and Pie chart Water usable by humans and sources of usable water. Source: United States Geographical Survey Igor Skiklomanov's chapter "World 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** (that was covered in [Section 3.4](#)) shows the movement of water through different reservoirs, which include oceans, atmosphere, glaciers, groundwater, lakes, rivers, and biosphere (Figure 2). Remember that solar energy and gravity drive the motion of water in the water cycle.

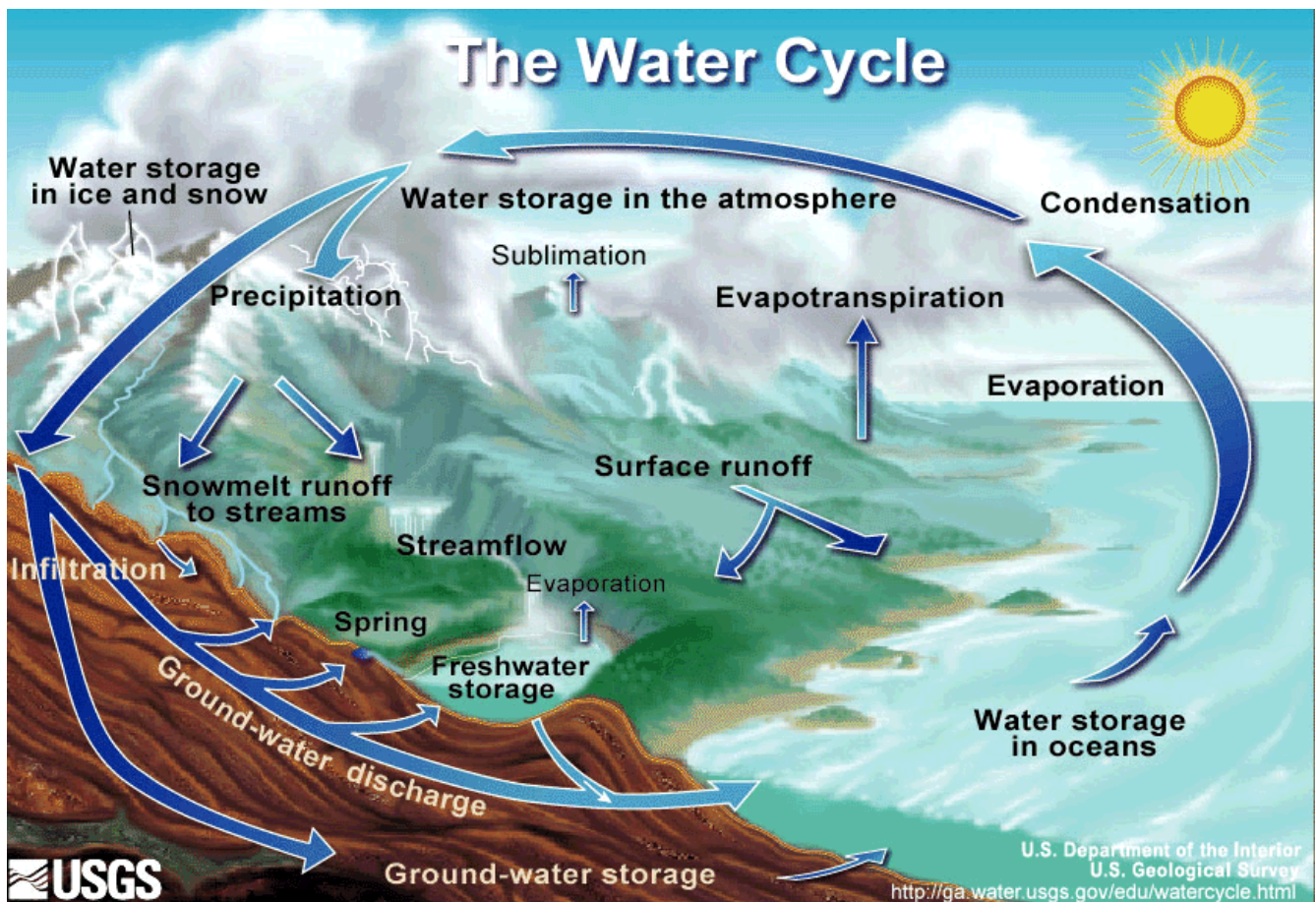


Figure 2: The Water Cycle; solar energy drives evaporation and gravity drives the movement of water across the surface of the earth (eventually reaching the ocean). Arrows depict movement of water to different reservoirs located above, at, and below Earth's surface. Source: United States Geological Survey

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 is a distillation process; as water vaporizes, it leaves the dissolved ions in the original liquid phase. This water regains small amounts of salinity when rainwater falls onto land; it dissolves minerals in rock and soil, which increases its salinity. Most lakes, rivers, and near-surface groundwater have a relatively low salinity and are called freshwater. The next several sections discuss important parts of the water cycle relating to fresh water reservoirs.

Primary Fresh Water Resources

Precipitation

Precipitation levels are unevenly distributed around the globe, affecting fresh water 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. The intense sunlight at the equator heats air, causing it to rise and cool, which decreases the ability of the air mass to hold water vapor. As a result, a band of land around the equator experiences frequent rainstorms. The air, now lower in water vapor,

is pushed north and south and cools in the upper atmosphere. Then, around 30 degrees north and south latitude, the air descends. However, in addition to having lost the water as it rose, the cool air warms as it descends, which increases its ability to hold water vapor. This creates conditions more favorable to evaporation than to precipitation. The result is the very dry conditions we see in deserts. Global precipitation and climate patterns are also affected by the size of continents, major ocean currents, and mountain ranges.

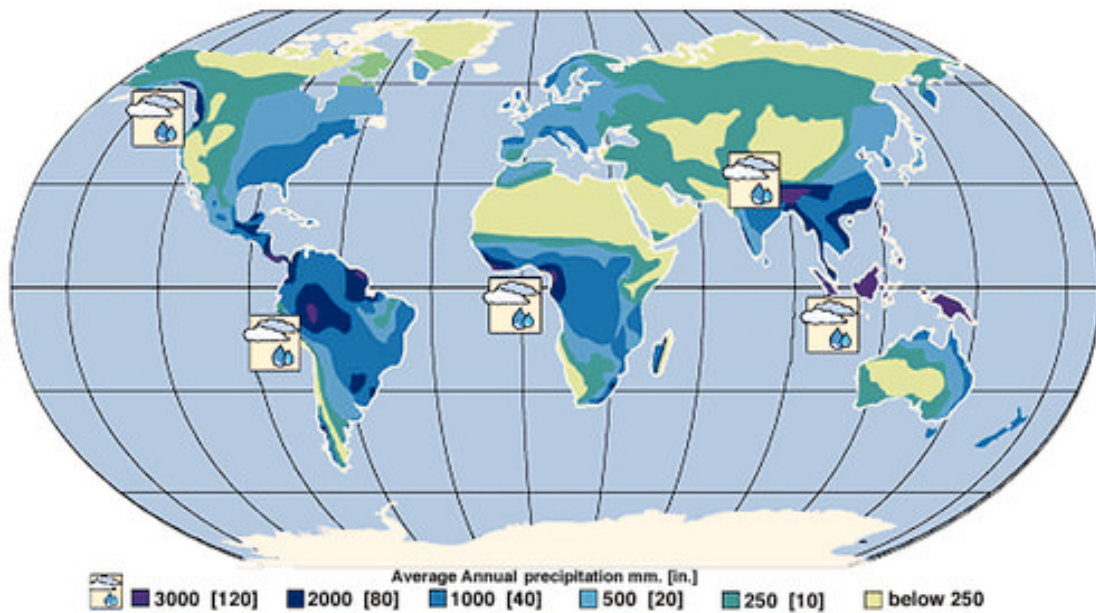


Figure 3: World Rainfall Map. The false-color map above shows the amount of rain that falls around the world. Areas of high rainfall include Central and South America, western Africa, and Southeast Asia. Since these areas receive so much rainfall, they are where most of the world's rainforests grow. 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: 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.

Flowing water from rain and melted snow on land enters river channels by surface runoff and groundwater seepage (Figure 4 and 5). Rivers are an important water resource for irrigation of cropland and drinking water for many cities around the world. Rivers that have had international disputes over water supply include the Colorado (Mexico, southwest U.S.), Nile (Egypt, Ethiopia, Sudan), Euphrates (Iraq, Syria, Turkey), Ganges (Bangladesh, India), and Jordan (Israel, Jordan, Syria).

River discharge describes the volume of water moving through a river channel over time (connect this idea to watersheds, discussed next). 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.



Figure 5: Groundwater Seepage. Groundwater seepage can be seen in Box Canyon in Idaho, where approximately 10 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 freshwater 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 are constantly filling in with sediment supplied by rivers.

Lakes form in a variety of 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 which had been 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 6). However, melt water from glaciers does provide a natural source of river water and groundwater, which can be a very important supply in local water cycles. 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, sea level has been rising in part due to melting glaciers. If Earth's climate continues to warm, the melting glaciers will cause an additional rise in sea level.

Groundwater Resources

The final source of freshwater is groundwater (Figure 7). Groundwater is a much larger reservoir of usable fresh water compared to surface waters, 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. **Groundwater** is defined as the water located in small spaces, called **pore space** (Figure 8), between mineral grains and fractures in subsurface earth materials (rock or sediment). Groundwater is divided into basins, called aquifers, that can act as independent waterbodies. Often, aquifers are made of porous rock that holds water, which can be drilled to provide water for agriculture and personal use (accessed via wells).



Figure 6: Mountain Glacier in Argentina. Glaciers are the largest reservoir of fresh water but they are not used much as a water resource directly by society because of their distance from most people. Source: Luca Galuzzi – www.galuzzi.it

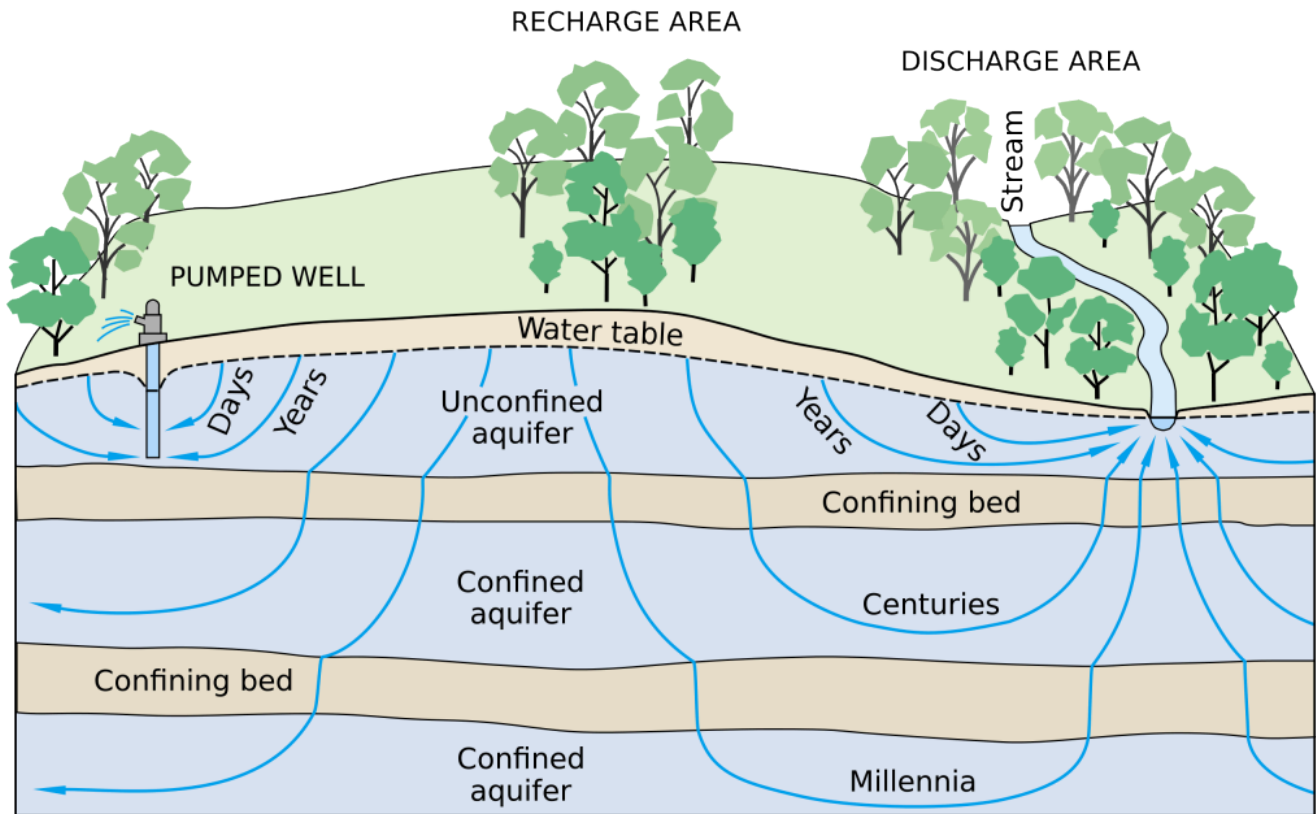
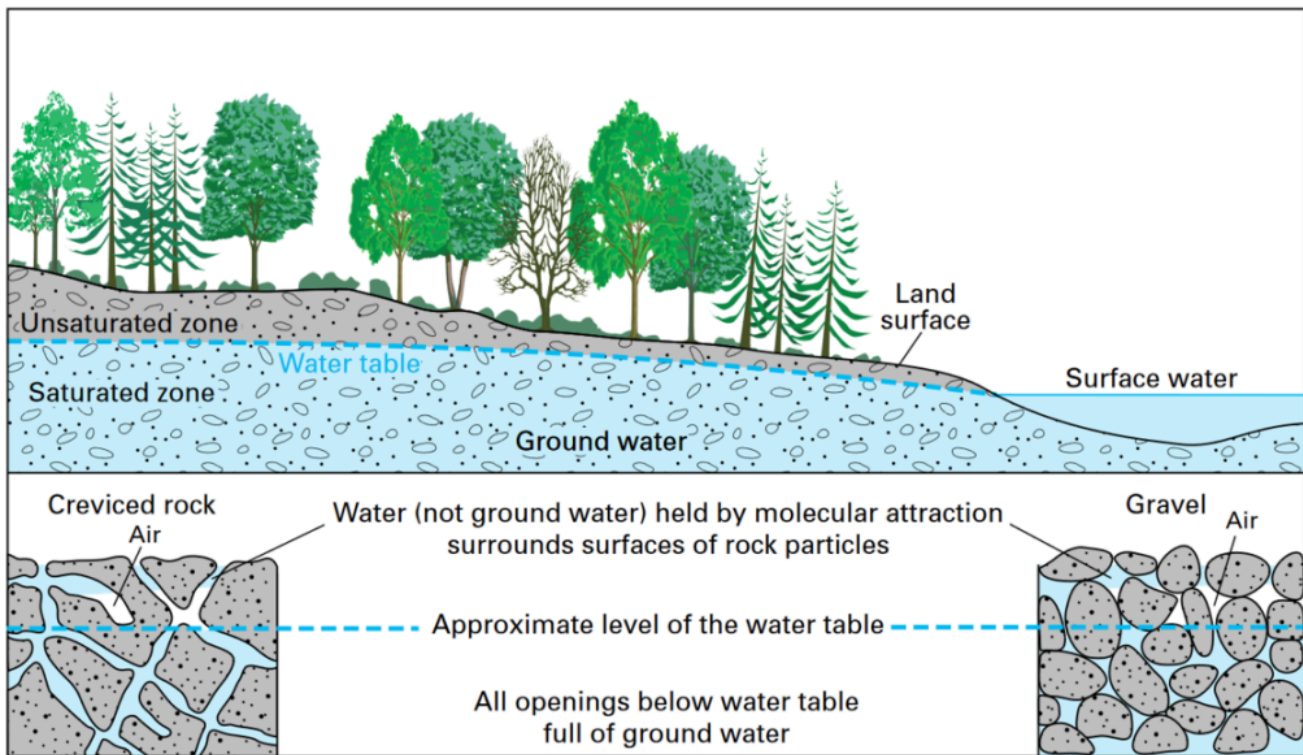


Figure 7: Schematic of an aquifer showing confined zones, groundwater travel times, a spring and a well. By T.C. Winter, J.W. Harvey, O.L. Franke, and W.M. Alley – Ground Water And Surface Water A Single Resource. U.S. Geological Survey Circular 1139, Figure 3., Public Domain, <https://commons.wikimedia.org/w/index.php?curid=25976976>

Most groundwater originates from rain or snowmelt, which infiltrates the ground and moves downward until it reaches the saturated zone (where groundwater completely fills pore spaces in earth materials). Other sources of groundwater 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.



How ground water occurs in rocks.

Figure 8: Groundwater is when the soil and pore space of rocks are full of water (not air). Credit: USGS. Public Domain.

Understanding Water Movement: Watersheds and the Water Table

Watersheds

The geographic area drained by a river and its tributaries is called a drainage basin or **watershed** (Figure 9). Imagine standing on the peak of a ridge; rain falling at that point could drain to either side of the high point. If the two sides of the high point end up in different bodies of water, that peak would be the boundary between the two watersheds. Essentially, a watershed is an area of land that drains all the streams and rainfall to a common outlet such as the outflow of a **reservoir**, mouth of a bay, or any point along a **stream** channel. Watersheds can be as small as a footprint or large enough to encompass all the land that drains water into rivers that drain into Chesapeake Bay, where it enters the Atlantic Ocean. For instance, the Mississippi River drainage basin includes approximately 40% of the U.S., and this large watershed is made of smaller drainage basins that can be analyzed as their own watershed. Both the Ohio River and Missouri River help to comprise the Mississippi watershed, and have their own bounded watershed within that larger watershed. The

most obvious usefulness of a watershed (to the average person) is that it defines which communities must work together to manage their freshwater resources. But the concept of a watershed, with a definitive land boundary that drains to a single point, is an enormously useful concept in ecology and environmental science; it allows scientists and agriculturalists to calculate and measure ecosystem processes which relate to the survival of our society and to managing food production.

The Water Table

The final piece of water movement that must be understood is the water table (Figure 10). The **water table** is the upper surface of the zone of saturation; the zone of saturation is where the pores and fractures of the ground are saturated with water. It can also be simply explained as the depth below which the ground is saturated. When precipitation enters the soil, free-flowing water will be pulled down by gravity until it reaches the water table (which may take a few days). Within an aquifer, the water table is rarely horizontal, but does reflect the surface relief. Where streams, rivers, lakes, and other surface waters are exposed, the surface of the water is essentially an extension of the water table.



Figure 9: Watershed map of North America showing 2-digit hydrologic units. Credit: Public Domain

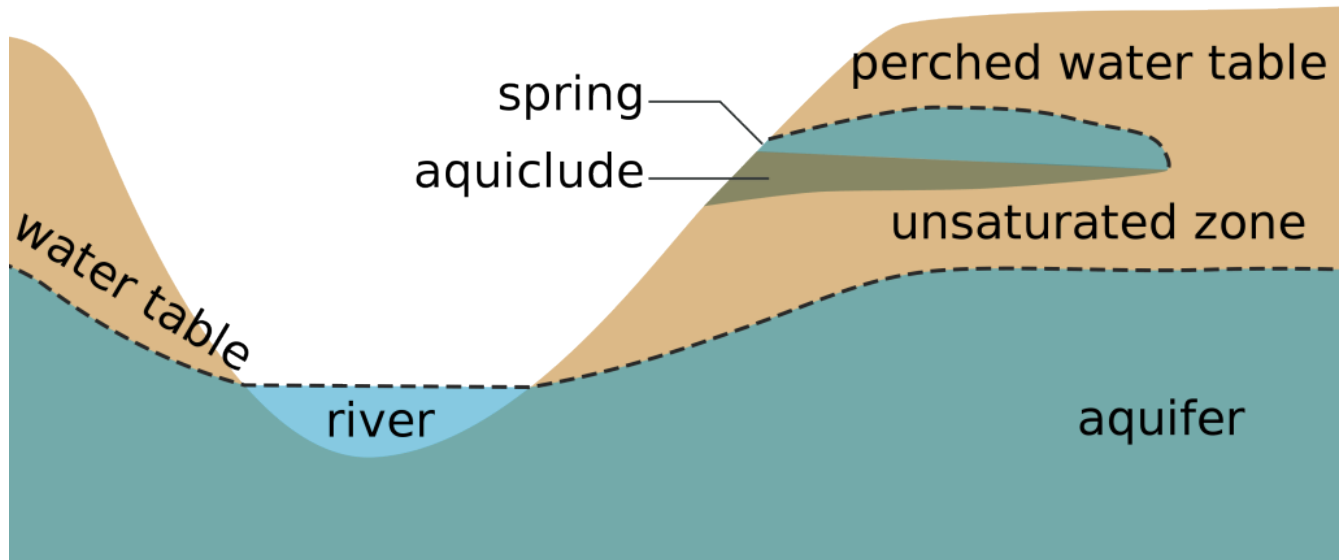


Figure 10: How the water table relates to the soil surface and rivers. By Jojko.sivekOriginal: Fiveless – File:WaterTable.gif and File:WTFfluctuations.gif, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=22391558>

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[Watersheds and Drainage Basins](#) by USGS; Public Domain. Modified by Joni Baumgarten.

7.2 Water Supply Problems and Solutions

Section Goals:

1. Understand water use throughout the world.
2. Understand the impact of groundwater drawdown on soil and land.
3. Consider sustainable ways to ensure fresh water availability to all people.

Water Use in the U.S. and World

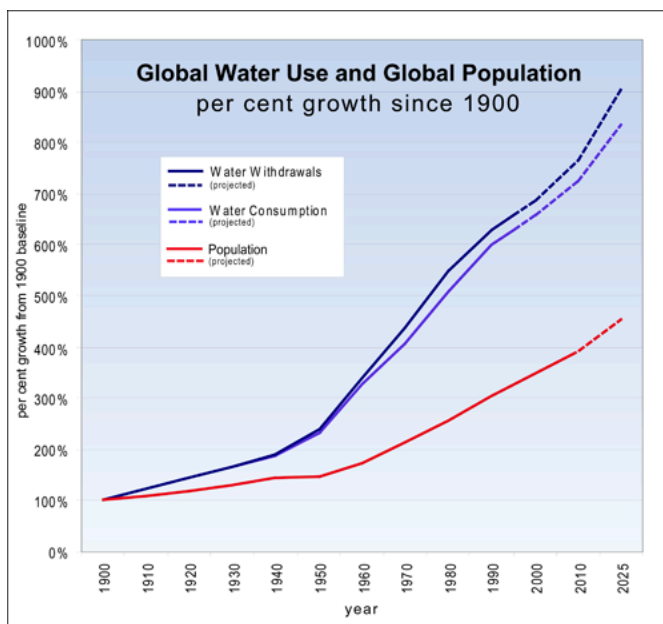


Figure 1: The rate of growth in freshwater withdrawal and consumption has been even more rapid than global population growth. Sources: Shikomanov 1999, US Census Bureau 2011. UNEP <https://na.unep.net/api/geas/articles/getArticleHtmlWithArticleIDScript.php?article_id=76>

population growth is due to improved standards of living without an offset by water conservation. Our society relies on water for agriculture and industrial production; therefore 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%).

Where has this “extra” water come from to meet the rising demand? Most often, from groundwater. Groundwater is calculated to be the most accessed source of freshwater around the world. Groundwater accounts for about half of the world’s drinking water, 40% of its irrigation water, and a third of water for industrial purposes.

People need water, oftentimes 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, but 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.

Global total water use is steadily increasing at a rate greater than world population growth; almost double the rate (Figure 1). During the 20th century global population tripled and water demand grew by a factor of six. The increase in global water demand beyond the rate of

Water Supply Problems: Resource Depletion

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 Yellow in China, run dry in some years. The case history of the Aral Sea discussed later in this chapter involves irreparable depletion of an inland sea. Glaciers are being depleted due to accelerated melting associated with global warming over the past century.

Of primary concern, though, is the depletion of groundwater. It may be hard to imagine water as a minable resource, but the fact is that groundwater aquifers have formed over geological timescales rather than human timescales. Groundwater flows, similar to surface water, but much more slowly. It can take years or decades for water to move through an aquifer. **Groundwater mining** is defined as a water resource depletion that occurs when withdraw rates are higher than the rate of recharge. Groundwater mining can be due to a large number of wells installed in the area. It causes the regional water table to drop significantly, which can force the drilling of deeper, more expensive wells. What occurs at a local scale highlights the issue: As groundwater is pumped from water wells, a localized drop in the water table around the well forms, called a **cone of depression** (Figure 2).

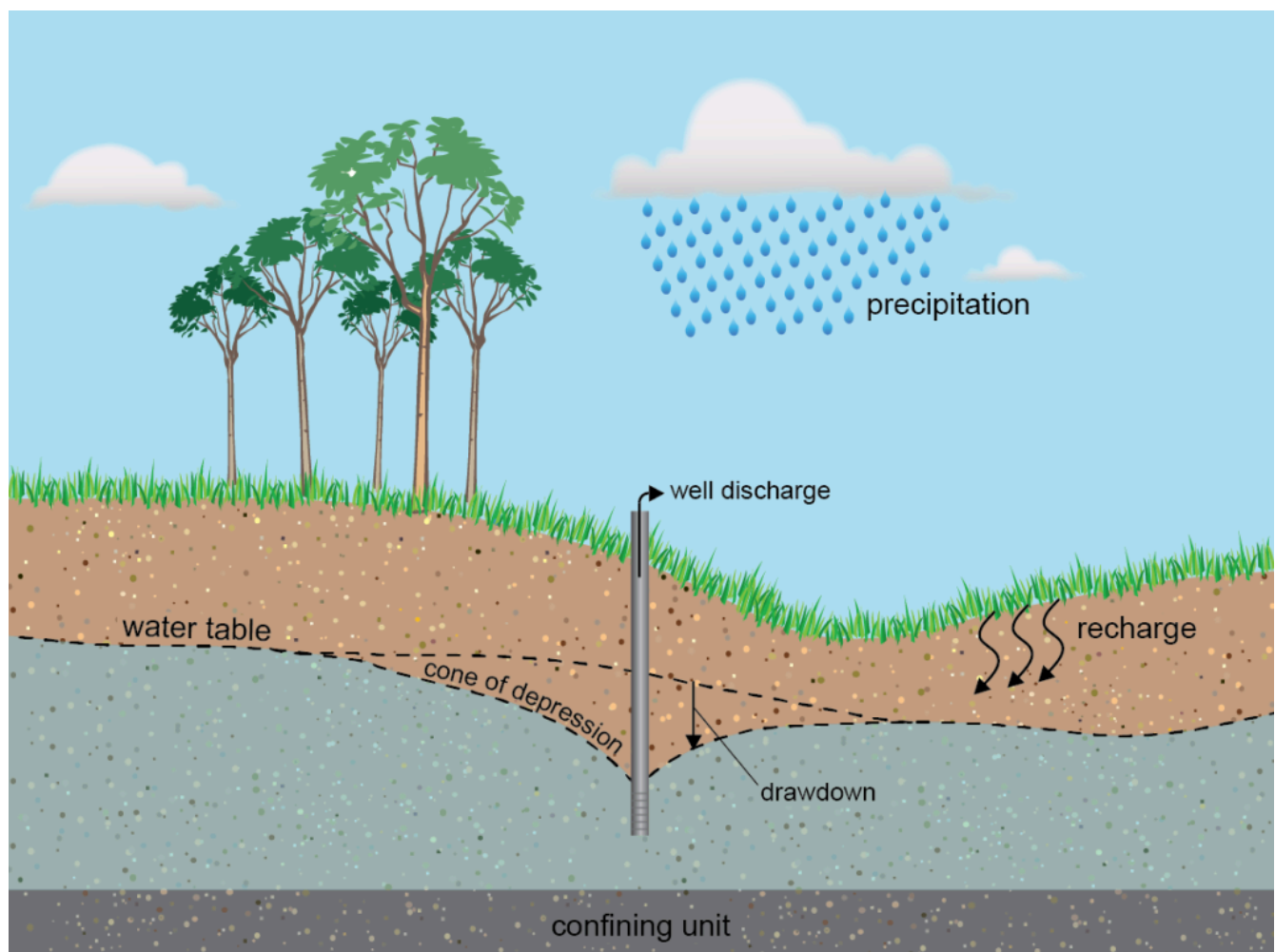


Figure 2: The removal of water from a well lowers the water table **in** the well, which then pulls the water table down in the immediate vicinity, forming a cone shape. Credit: USGS. Public Domain.

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. Subsidence occurs when too much water is pumped out from underground, deflating the space below the above-surface, and thus causing the ground to collapse. The result can look like craters on plots of land. This occurs because, in its natural equilibrium state, the hydraulic pressure of groundwater in the pore spaces of the aquifer supports some of the weight of the overlying sediments. When groundwater is removed from aquifers by excessive pumping, and the water is not replaced quickly enough, pore pressures drop in the aquifer, and compression of the mineral component of the aquifer will occur. In the middle United States, where groundwater has been heavily exploited (Figure 3), land subsidence has caused a drop in the land surface of two to ten feet (Figure 4).

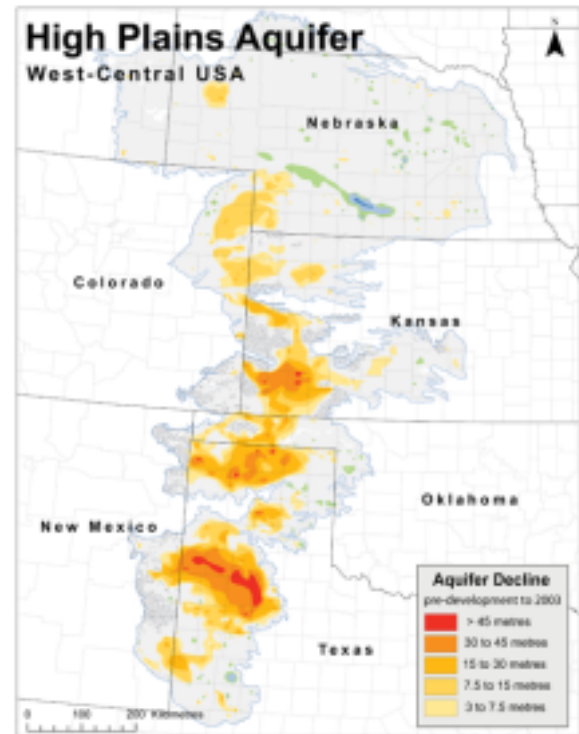


Figure 3: The High Plains Aquifer in the central United States has been heavily exploited for irrigation since the 1940s. Large parts of several counties in Texas have seen the water table decline by over 45 metres relative to pre-development levels. Source: McGuire 2004; Redrawn: UNEP GRID Sioux Falls



Figure 4: USGS scientist, John Ellis, showing how much the land has subsided in the Houston area since 1915.
 Credit: Public Domain.

The final water resource problem associated with groundwater mining is intrusion of saltwater or pollution into what was previously clean fresh water. Both issues are caused by a change in the direction of flow due to a cone of depression in an unconfined aquifer. Saltwater intrusion specifically occurs when aquifers near ocean coastlines are over-drawn. Saltwater enters freshwater zones because the freshwater water table drops below the saltwater table. In areas where pollution is a concern, over-drawn wells can reverse the flow of the local groundwater, causing pollution to flow toward the pumping well.

Water Supply Crisis

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

According to a 2006 report by the United Nations Development Programme, 700 million people (11% of the world's population) lived with water stress (Figure 5). 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 conflict to arise associated with water shortages and pollution. Historic 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).

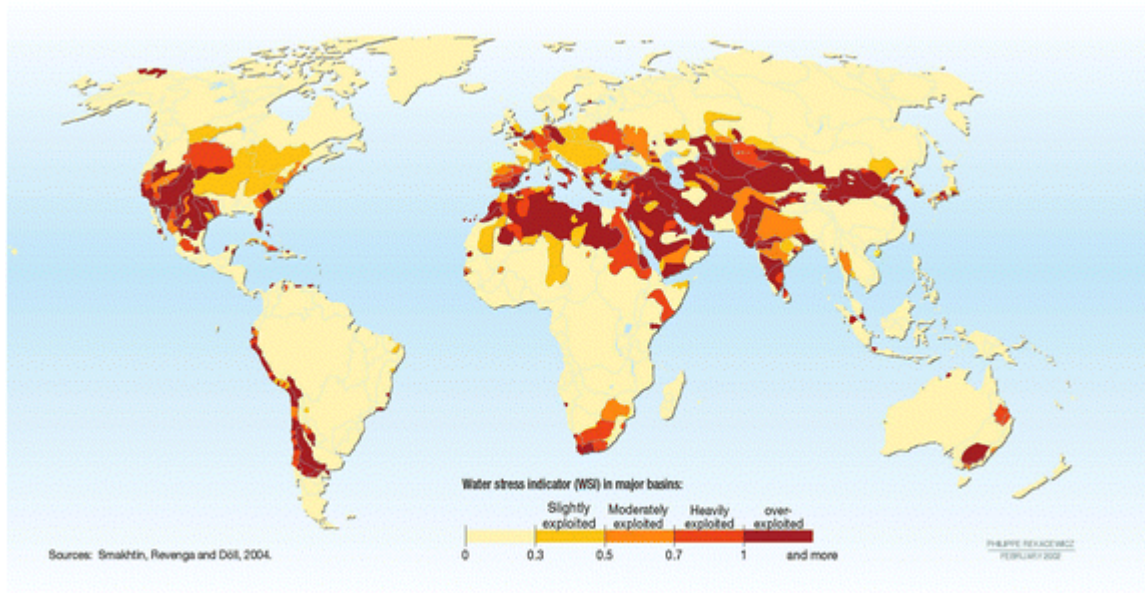


Figure 5: Credit: UNESCO World Water Assessment Programme. CC-BY-SA 3.0 IGO <https://creativecommons.org/licenses/by-sa/3.0/igo/>

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 (Figure 6). Some of the drawbacks are evaporative loss of water in arid climates, downstream river channel erosion, and impact on the ecosystem including a change upstream from a river to lake habitat, a change downstream to seasonal water temperature and flow, and interference with migration and spawning of fish.

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. 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 to disappear after their river flow was diverted to the Los Angeles aqueduct (Figure 7). 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. There are several ways to desalinate seawater including boiling, filtration, and electrodialysis. All of these procedures are moderately 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 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 require little irrigation in desert climates, turning off the water while you brush your teeth, and fixing leaky faucets.

Another important conservation technique is **efficient irrigation**, which is extremely important because irrigation accounts for a much larger water demand than 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,

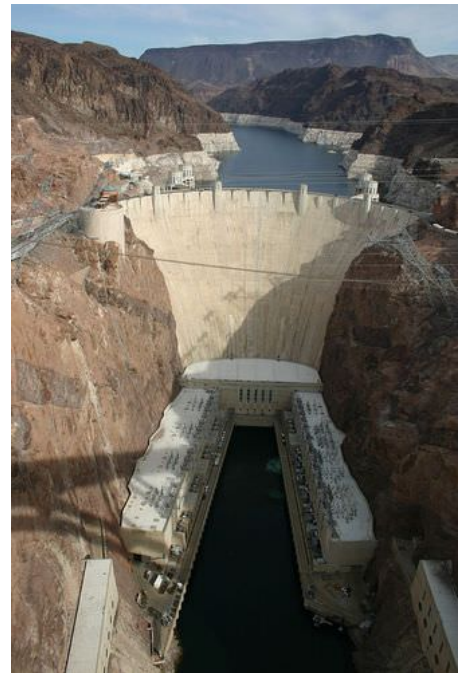


Figure 6: Hoover Dam, Nevada, U.S. Hoover Dam, Nevada, U.S.. Behind the dam is Lake Mead, the largest reservoir in U.S.. White band reflects the lowered water levels in the reservoir due to drought conditions from 2000 – 2010. Source: Cygnusloop99 at Wikimedia Commons



Figure 7: The California Aqueduct California Aqueduct in southern California, U.S. Source: David Jordan at en.wikipedia

and reusing treated wastewater from sewage treatment plants. Recycled wastewater has also been used to recharge aquifers.

Suggested Supplementary Reading:

Weiss, K.R. 2018. [Drying Lakes](#). *National Geographic*. March. p. 108-133.

This article documents how many lakes across the globe are drying up, the reasons why, and the effect on humans. Overuse and a warming climate threaten lakes that provide sustenance and jobs for humans, while also providing critical habitat for animals.

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7.3 Water Pollution

Section Goals:

1. Understand the risk of unsanitary water.
2. Describe the various pathways of water pollution.
3. Understand the common water pollutants.

Water Pollution as a Global Issue

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 in the world (or 13% of world population) did not have access to safe drinking water. At the same time, about 2.6 billion people (or 40% of world population) lived without improved sanitation, which is defined as having access to a public sewage system, septic tank, or even a simple pit latrine. Each year approximately 1.7 million people die 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% of them occur among children under the age of 5 (Figure 1). Globally, improving water safety, sanitation, and hygiene could prevent up to 9% of all disease and 6% of all deaths. Compounding the water crisis are issues of social justice; people in poverty more commonly lack clean water and sanitation compared to wealthy people in similar areas.

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, but most chemicals in use have poorly known long-term health effects. In the U.S. currently more than 40,000 water bodies fit the definition of “impaired” set by 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 issues such as air pollution, deforestation, species extinction, and global warming.

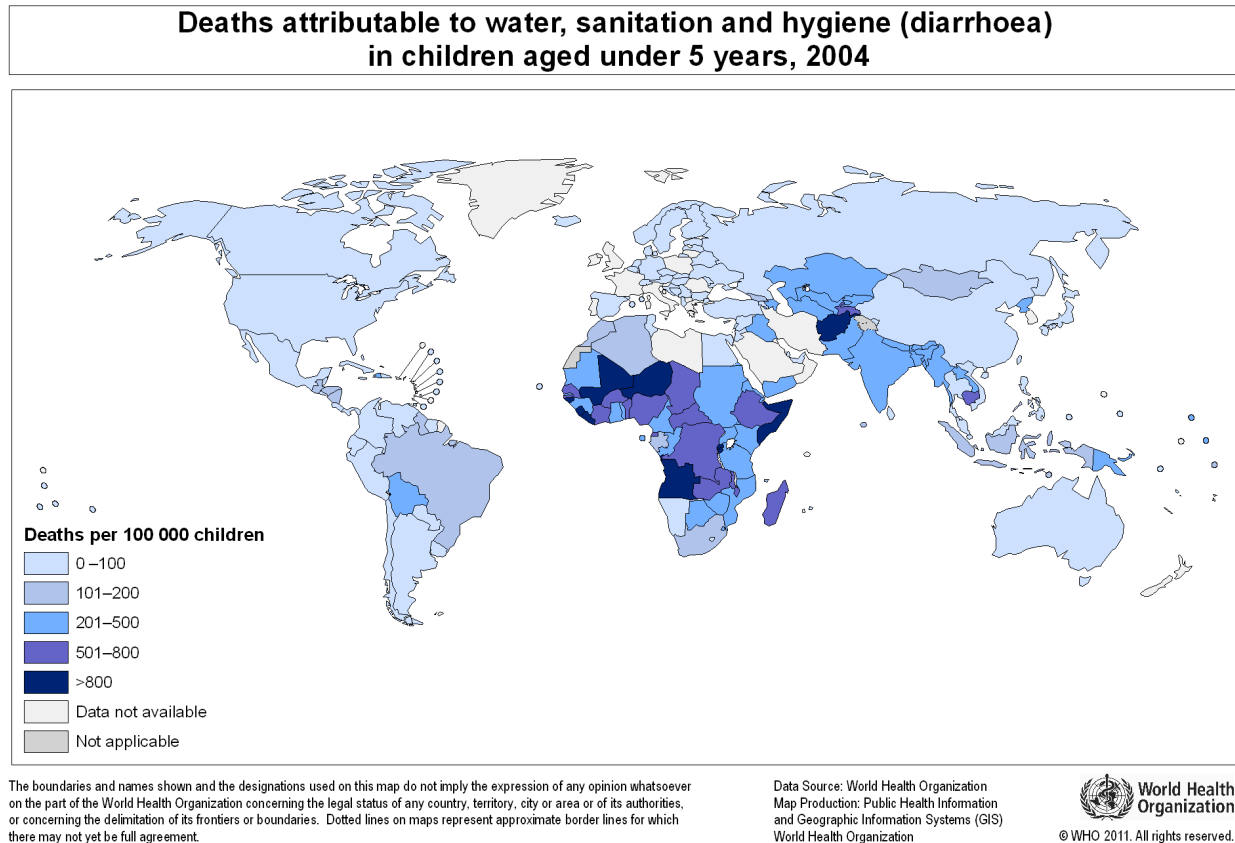


Figure 1: This work was created by the [World Health Organization](http://www.who.int).

Any natural water contains dissolved chemicals, some of which are important human nutrients while others can be harmful to 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 1 ppm to length units is 1 cm (0.4 in) in 10 km (6 miles) and converting 1 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 4 ppm, 120 ppm, and 35,000 ppm, respectively. Higher levels of TDS typically correlate with human-caused pollution.

Water Pollution Overview

Water pollution is the contamination of water by an excess amount of a substance that can cause harm to human beings and/or the ecosystem (see [Section 6.1](#)). The level of water pollution depends on the abundance of the pollutant, the ecological impact of the pollutant, and the use of the water. 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 carrying them progresses through stages of the water cycle (Figure 3). **Water residence time** (the average time that a water molecule spends in a water reservoir) affects pollution potential. Water in rivers has a relatively short residence time, so pollution will affect an area only briefly. However, given the interconnected water cycle, pollution in rivers will simply move to another reservoir, such as the ocean, where it can cause further problems. Typically, though, the ocean will disperse the pollutant enough that it becomes a chronic concern rather than an acute concern. Groundwater pollution is particularly problematic because the water is characterized by slow flow and longer residence time. 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 adsorbed onto sediment. Note that **adsorption** is the adhesion of atoms, ions or molecules from a gas, liquid or dissolved solid to a surface.



Figure 2: In this area, there is obvious water pollution in the form of floating debris; however, invisible water pollutants can be much more harmful than visible ones. Source: Stephen Codrington at Wikimedia Commons

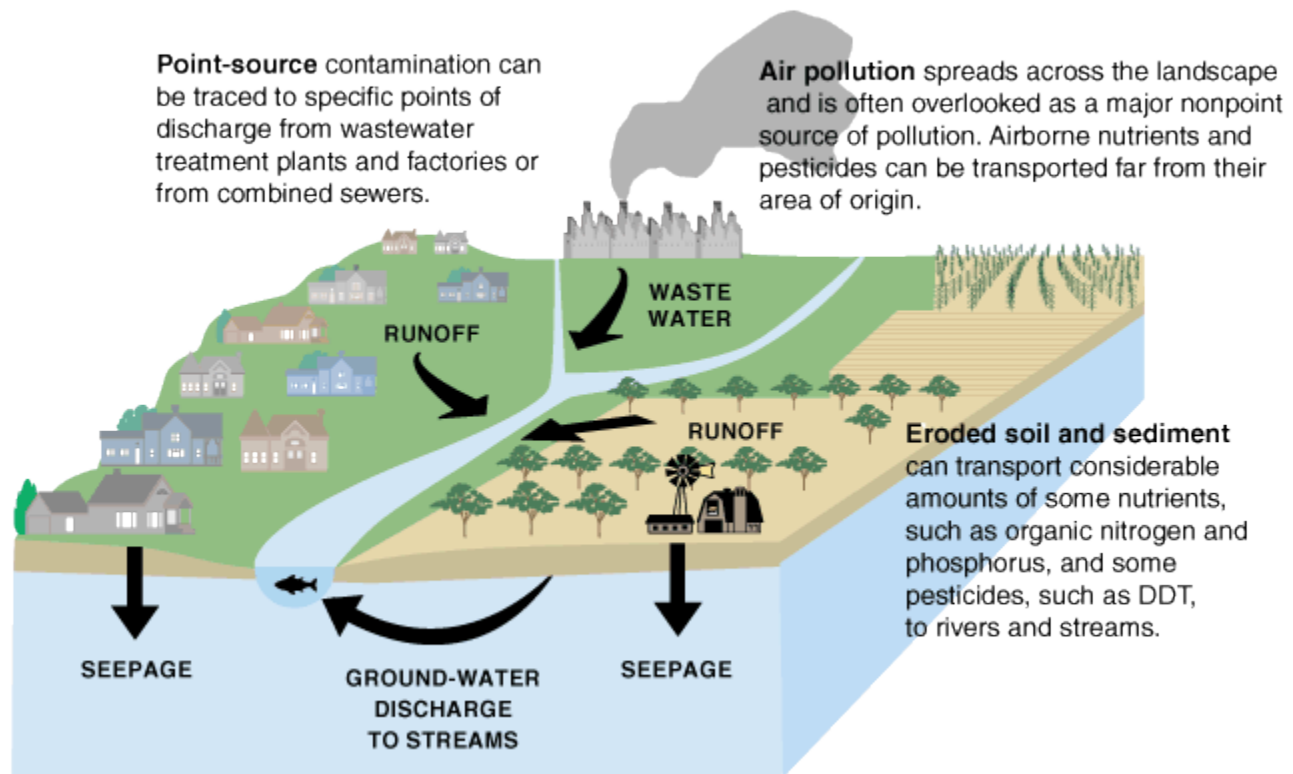


Figure 3: Figure names sources of some water pollutants and highlights the movement of pollutants into different water reservoirs of the water cycle through runoff, flowing surface water, and seepage into groundwater. Source: U.S. Geological Survey

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. Point sources also include pipes from factories and sewage treatment plants. Combined sewer systems that have a single set of underground pipes to collect both sewage and storm water runoff from streets for wastewater treatment can be major point sources of pollutants. During heavy rain, storm water runoff may exceed sewer capacity, causing it to back up and spilling untreated sewage directly into surface waters (Figure 5).



Figure 4: Large animal farms are often referred to as 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

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.

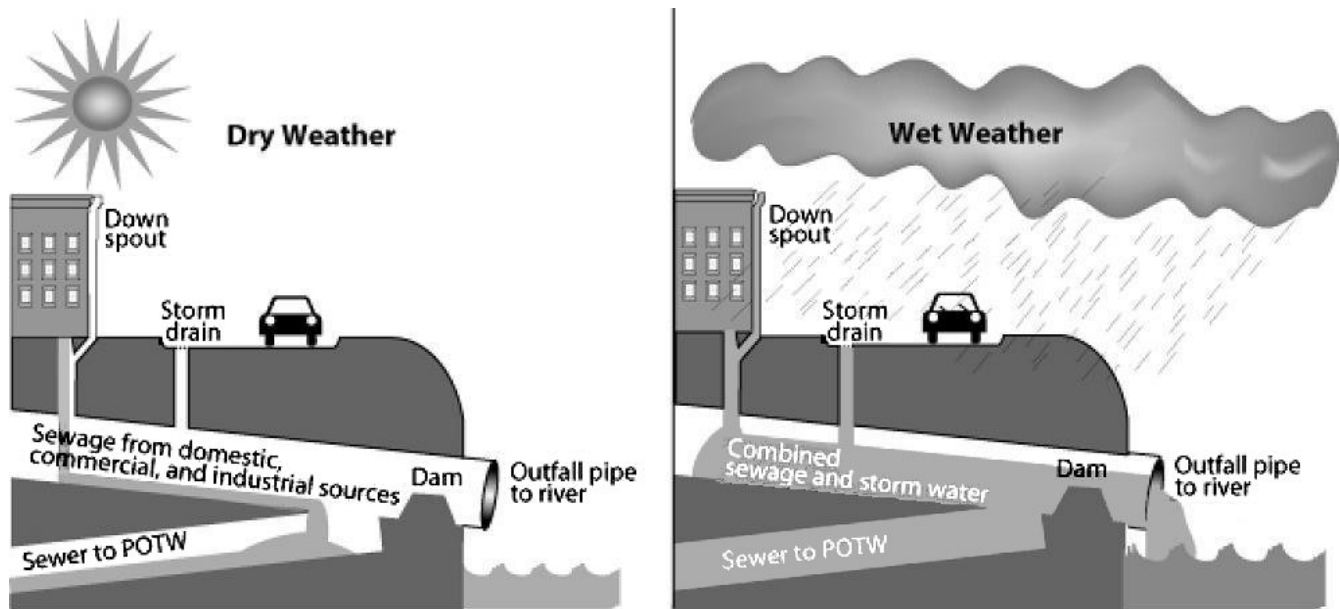
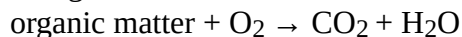


Figure 5: A combined sewer system is a possible major point source of water pollution during heavy rain due to overflow of untreated sewage. During dry weather (and small storms), all flows are handled by the publicly owned treatment works (POTW). During large storms, however, to prevent overflow at the treatment plant, 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 is needed by aquatic organisms for cellular respiration. Bacteria decompose dead organic matter and remove dissolved oxygen (O₂) according to the following reaction:



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 example unpolluted water body is a turbulent river that flows through a natural forest. Turbulence continually brings water in contact with the atmosphere, restoring the O₂ content. The dissolved oxygen content in such a river might range from 10 to 14 ppm O₂ and BOD is low, which then supports clean-water fish such as trout. An example polluted water body with high BOD might be a stagnant lake in an urban setting with nonpoint pollution from surface runoff. The combination of a high input of organic carbon and limited opportunities for water circulation and contact with the atmosphere means the dissolved O₂ content is typically ≤ 5 ppm O₂. Here, BOD is high and low-O₂-tolerant fish, such as carp and catfish, dominate.

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 and therefore restrict the total amount of plant growth. This explains why N and P are major ingredients in most fertilizer. 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. Thick mats of floating algae or rooted plants lead to a form of water pollution that damages 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, which can create very low O₂ concentrations in the water (< 2 ppm O₂), a condition called **hypoxia**. This results in a **dead zone** because it causes death from asphyxiation to organisms that are unable to leave that environment. An estimated 50% of lakes in North America, Europe, and Asia 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 a variety of 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 around the world are exposed to waterborne pathogen pollution daily and around 1.5 million children mainly in underdeveloped countries die every year 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 the 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 6) 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 6. Deepwater Horizon Explosion Boats fighting the fire from an explosion at the Deepwater Horizon drilling rig in 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 size of the spill but polluting the air. Then, bacteria begin to 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 different 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 a liquid insulator in electric transformers). **Persistent organic pollutants (POPs)** are long-lived in the environment, biomagnify 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 of arsenic-rich minerals and from human activities such as coal burning and smelting of metallic ores. The worst case of arsenic poisoning occurred in the densely populated impoverished country of Bangladesh, which had experienced 100,000s of 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 building millions of shallow water wells, which resulted in a dramatic drop in pathogenic diseases. Unfortunately, many of the wells produced water naturally rich in arsenic. Tragically, there are an estimated 77 million people (about half of the population) who 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 a variety of electrical products, such as dry cell batteries, fluorescent light bulbs, and switches, as well as in the manufacture of paint, paper, vinyl chloride, and fungicides. Mercury 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 enters the water supply naturally from weathering of mercury-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.

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 the dissolution of calcium and magnesium carbonate minerals in soil; it does not have negative health effects in people.

Groundwater pollution can occur from underground sources and all of the pollution sources that 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 5 km long contaminant plume. A major threat to groundwater quality is from underground fuel storage tanks. Fuel tanks commonly are 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. Currently there are around 600,000 underground fuel storage tanks in the U.S. and over 30% still do not comply with EPA regulations regarding either release prevention or leak detection.

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7.4 Water Treatment

Section Goals:

1. Describe the treatment of sewage.
2. Connect water quality in the United States to the Clean Water Act.

Quality of Water

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 in underdeveloped countries every year. The best strategy for addressing this problem is proper sewage (wastewater) treatment. Untreated sewage is not only a major cause of pathogenic diseases, but also 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 a variety of ways including landfill disposal, incineration, use as fertilizer, and anaerobic bacterial decomposition, which is done in the absence of 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 also use abandoned rock quarries to hold storm sewer overflow. After the rain stops, the stored water goes to the sewage treatment plant for processing.

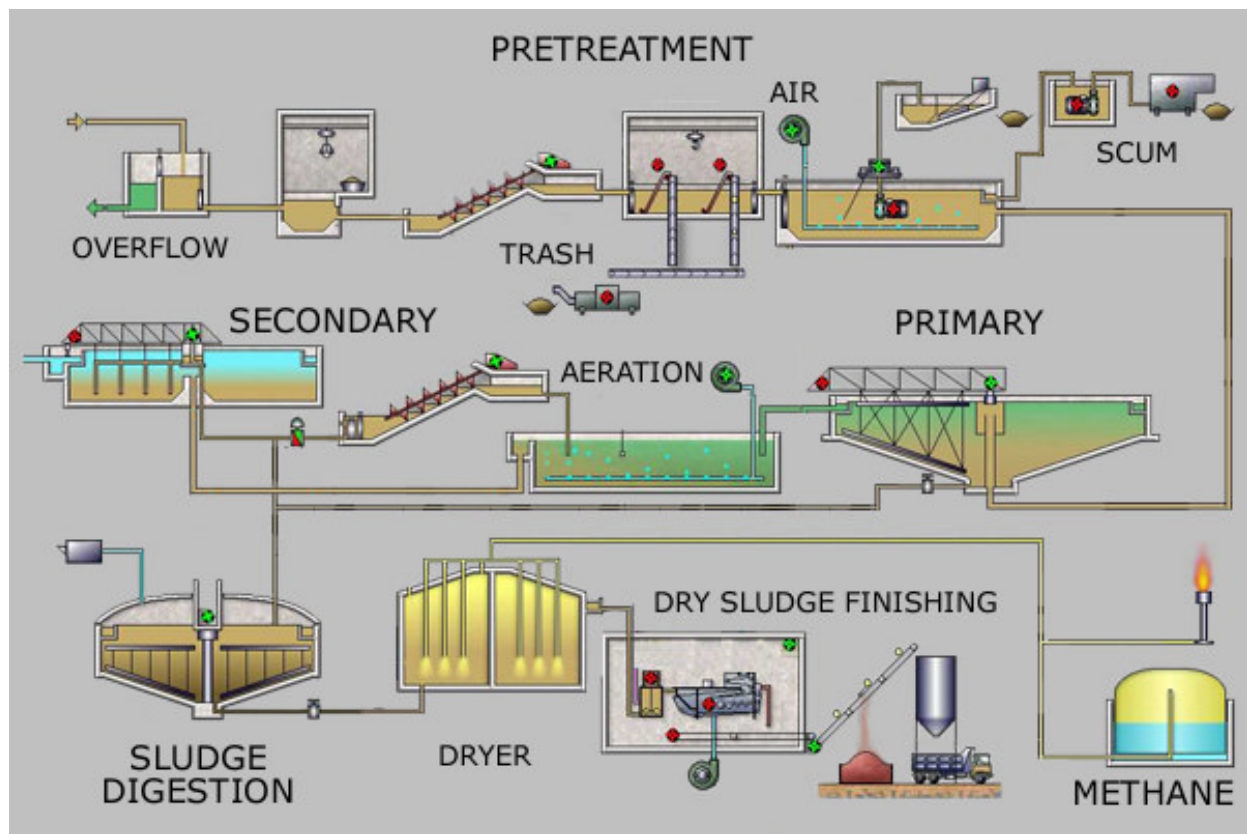


Figure 1: Figure shows the numerous processing steps at a conventional sewage treatment plant include pretreatment (screening and removal of sand and gravel), primary treatment (settling or floatation to remove organic solids, fat, and grease), and secondary treatment (aerobic bacterial decomposition of organic solids). The cleaner water then leaves the system. The sludge continues to be processed into a source of fuel (the methane can be used as an energy source). 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, which usually occurs when a system is established in the wrong type of soil 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, gains in work and school productivity, 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. Compared to tap water, it uses much more energy, 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!

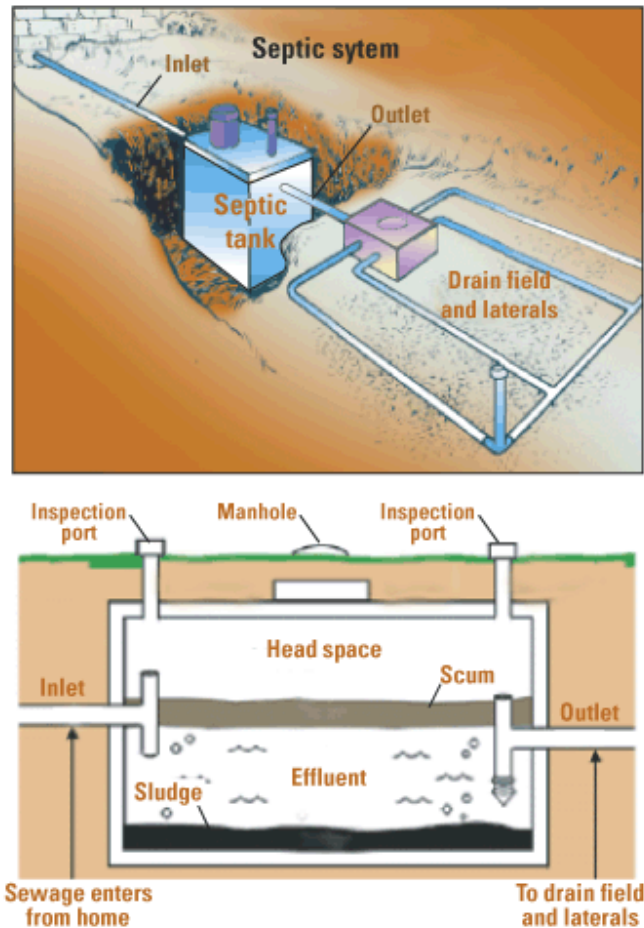


Figure 2: Septic System Septic tank system for sewage treatment. Source: United States Geological Survey

Clean Water Act in the United States



Figure 3. Cuyahoga River 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 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, which is 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. It became illegal to dump pollution into surface water 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 is not yet addressed sufficiently by federal law.

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7.5 Case Study: The Aral Sea - Going, Going, Gone

Section Goals:

1. Understand the factors that led to the drastic reduction in the Aral Sea.
2. Relate the Aral Sea case study to other areas of the world.

Aral Sea

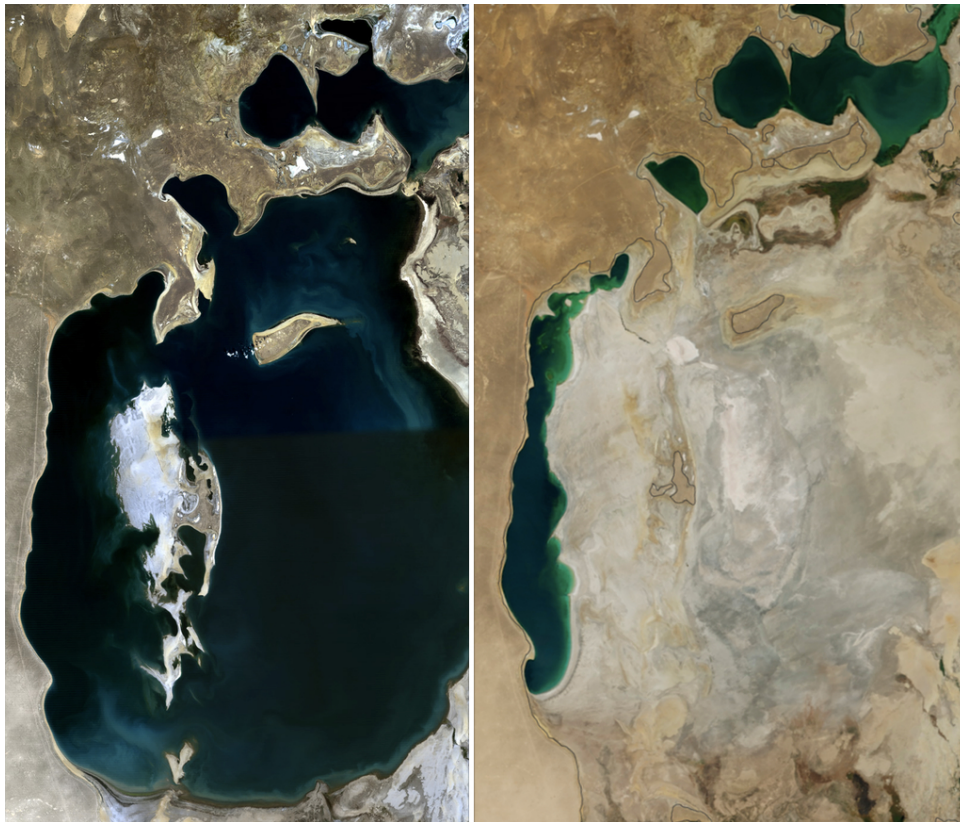


Figure 1: A comparison of the Aral Sea in 1989 (left) and 2014 (right). Credit: [This work](#) is in the [Public Domain, CC0](#)

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 in general. Summer temperatures can reach 60°C (140°F)! The water supply to the Aral Sea is mainly from two rivers, the Amu Darya and Syr Darya, which carry snow melt 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 essentially eliminated any river inflow to the Aral Sea and caused it to disappear almost completely (Figure 1).

In 1960, Aral Sea was the fourth largest inland water body; only the Caspian Sea, Lake Superior, and Lake Victoria were larger (Figure 2). Since then, it has progressively shrunk due to evaporation and lack of recharge by rivers. Before 1965, the Aral Sea received 2060 km³ 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 3 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 shing boats lie in the dried up lakebed of dust and salt. A frustrating part of the river diversion project is that many of the 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 a variety of respiratory illnesses including tuberculosis.



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



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 and it is caused entirely by humans (Figure 3). Lake Chad in Africa is another example of a massive lake that has nearly disappeared for the same reasons as the Aral Sea. 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 diversions of water include the Dead Sea in the Middle East, Lake Manchar in Pakistan, and Owens Lake and Mono Lake, both in California.

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7.6 Chapter Resources

Summary

Precipitation—a major control of fresh water availability—is unevenly distributed around the globe. More precipitation falls near the equator, and landmasses there are characterized by a tropical rainforest climate. Less precipitation tends to fall near 20°30' north and south latitude, where the world's largest deserts are located.

The water crisis refers to a global situation where people in many areas lack access to sufficient water 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 the contamination of water 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 in underdeveloped countries every year.

Resolution of the global water pollution crisis requires multiple approaches to improve the quality of fresh water. The best strategy for addressing this problem is proper sewage treatment. Untreated sewage is not only a major cause of pathogenic diseases, but also a major source of other pollutants, including oxygen-demanding waste, plant nutrients, and toxic heavy metals.

Review Questions

1. Approximately 97% of all water on Earth is found in what reservoir?
 - A. Oceans
 - B. Lakes
 - C. Streams
 - D. Groundwater
 - E. Glaciers and ice caps
2. The majority of freshwater, whether accessible to humans or not, is contained in what reservoir?
 - A. Ocean
 - B. Lakes
 - C. Streams
 - D. Groundwater
 - E. Glaciers and ice caps
3. You are studying a river and notice that it contains chemical waste. You have thoroughly searched the entire length of the stream and ruled out that the waste is directly entering the stream. Instead, the waste must be entering by one of its many tributary streams. Because these streams empty into the river you are studying, they must be within the same...

- A. Watershed
- B. Irrigation district
- C. Riparian area
- D. Aqueduct
- E. Water zone

4. Adding water to a recharge area would have what practical effect?

- A. Increased amount of groundwater
- B. A more pronounced cone of depression
- C. Depletion of an aquifer
- D. Less infiltration
- E. Greater precipitation

5. With removal of groundwater, which of the following may result?

- A. subsidence
- B. sinkholes
- C. cone of depression
- D. decreased water table
- E. All of the above.

6. For individuals living in areas where no freshwater is available, which one of the following would produce water that could be used for drinking?

- A. desalination
- B. groundwater mining
- C. sublimation
- D. transpiration
- E. saltation

7. Three carcinogens are equally harmful at equal concentrations. In a terrible industrial accident, 2 tons of each type of carcinogen were discharged into a river at the same time. The residence times of each pollutant is as follows: Chemical X = 2.8 days; Chemical Y = 3.5 days; Chemical Z = 17.2 hours. Which one possesses the greatest risk of exposure to the nearby community over the course of a week following the spill?

- A. Chemical X
- B. Chemical Y
- C. Chemical Z
- D. All chemicals provided equal likelihood of exposure

8. Fertilizers applied to residential lawns and gardens can end up in water bodies through the process of surface run-off or movement through ground water. This type of pollution would be considered...

- A. Point source
- B. Bioremediation
- C. Non-point source
- D. Throughput sourcing
- E. Tangential

9. Which one of the following would most directly prevent a dead zone from forming in a water body that is already experiencing eutrophication?

- A. Increase the O₂ concentration in the water
- B. Lower the nutrient levels
- C. Increase the amount of algae and phytoplankton
- D. Increase the amount of bacteria that decompose dead organic matter
- E. Make the water more hypoxic

10. If you analyzed waste water directly after primary treatment, what would you notice?

- A. Harmful bacteria and other biological agents have been killed or removed
- B. The water is potable
- C. Much of the dissolved solids have been removed
- D. Many suspended solids have been removed
- E. The water is mostly sludge

See Appendix for answers

Question Attributions

Theis, T. & Tomkin, J. (Eds.). (2015). *Sustainability: A comprehensive foundation*. Retrieved from <http://cnx.org/contents/1741effd-9cda-4b2b-a91e-003e6f587263@43.5>. Available under Creative Commons Attribution 4.0 International License. (CC BY 4.0). Modified from original.

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Chapter 8: Food & Hunger



Practices of composting, crop diversification, organic pesticide production, seed multiplication and agro-forestry allow farmers in Malawi 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
- Learn examples of genetically modified crops in order to understand the larger picture surrounding genetically modified organisms.

Chapter Outline

- 8.1 Food Security

- 8.2 Global Food Systems
- 8.3 Biotechnology and Genetic Engineering
- 8.4 Genetically Modified Crops
- 8.5 Chapter Resources

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8.1 Food Security

Section Goals:

1. Describe a comprehensive definition of food insecurity.
2. Connect the “Western Diet” with health outcomes.
3. Introduce basic nutrition facts.

Hunger Continues to Present a Challenge

Progress continues in the fight against hunger, yet an unacceptably large number of people lack the food they need for an active and healthy life. The latest available estimates indicate that about 795 million people in the world – 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 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, genders, ethnicities, religions, 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 and include things such as 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 have access to sufficient food of the right dietary mix (quality) at all times 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 not only of national production is important, but also of the country’s **access** to food from the global market, its foreign exchange earnings, and its 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 market place. 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), but 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: that is, 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 as a consequence of cyclical events, such as the dry season. When some lacks 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.

Challenges Beyond Basic Survival

The challenge of global food security is very complex. Because food is an inherent and interlinked part of human health, the global food systems impacts the lives of individuals in complex and unobvious ways.

Though many practitioners advocate that health is much more complex than just weight, the fact remains that a weight-based framework exists in the research and literature about global health. Because of the correlation of obesity with other health impacts, it will be discussed here. But, as with other parts of this textbook, please do not take this as a judgement or a blame on the individual; take the dominant narrative within the context of who or what that narrative benefits. The global food system has succeeded in producing enough quantity to overcome significant hunger challenges that have plagued our society in history, but it has come with a cost to individual health. And who benefits from individuals feeling that they are solely responsible for their own health, even when factors beyond their control regulate the global food system?

What is called an overweight/obesity problem initially emerged in industrial countries. For various reasons, this measure of human health now increasingly occurs in low- and middle-income countries, particularly in urban settings. In these areas, there is 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).

Obesity is correlated with a number of noncommunicable diseases, including diabetes, heart disease, and certain cancers. However, it also is correlated with better survival of individuals in extreme disasters and in populations of older adults. Additionally, though it is well understood that chronic stress can cause similar chronic health effects, and well proven that there is significant “fat stigma” in the world, especially in the United States, the data, doctors, researchers and policy makers have not been able to reduce their focus on weight and shift to reviewing markers of health instead. To focus on health indicators here, we can say that there is rise in diabetes, heart disease and certain cancers

which correlates with what is called a Western Diet: an increasing availability of processed, affordable, and effectively marketed food. The global food system is falling short by causing poor health outcomes even as the quantity and availability and reliability saves a large number from starvation.

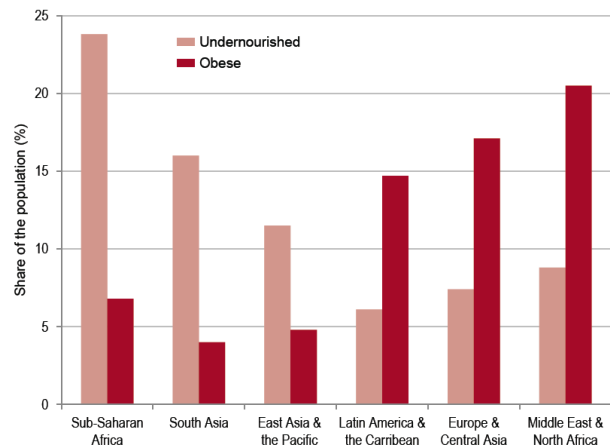


Figure 1: Obesity and undernourishment by region.

Nutrients, Energy, and Building Materials

A very brief introduction to nutrition is included here. The goal of its inclusion is to highlight that there are complexities in maintaining a functioning, healthy, human body. Ensuring that the global population has food security, as we just learned, means that the nutrition balance of individuals matters, not just the quantity of food. This understanding must be a part of any effort to change the global food system.

Nutrients are chemical elements or compounds that the body needs for normal functioning and good health. There are six main classes of nutrients: carbohydrates, proteins, lipids, water, vitamins, and minerals. The body needs these nutrients for three basic purposes: energy, building materials, and control of body processes.

A steady supply of energy is needed by cells for all body functions. Carbohydrates, proteins, and lipids provide this energy. Chemical bonds in molecules of these nutrients contain energy. When the bonds are broken during digestion to form simpler molecules, the energy is released. Energy is measured in units called kilocalories (kcal), commonly referred to as Calories.

Molecules that make up the body are continuously broken down or used up, so they must be replaced. Some nutrients, particularly proteins, provide the building materials for this purpose. Other nutrients—including proteins, vitamins, and minerals—are needed to regulate body processes. One way is by helping to form enzymes. Enzymes are compounds that control the rate of chemical reactions in the body.

Nutrients can be classified in two groups based on how much of them the body needs:

- **Macronutrients** are nutrients that the body needs in relatively large amounts. They include carbohydrates, proteins, lipids, and water.
- **Micronutrients** are nutrients the body needs in relatively small amounts. They include vitamins and minerals.

Finally, you may not think of water as a food, but it is a nutrient. Water is essential to life because it is the substance within which all the chemical reactions of life take place. An adult can survive only a few days without water.

Water is lost from the body in exhaled air, sweat, and urine. Dehydration occurs when a person does not take in enough water to replace the water that is lost. Symptoms of dehydration include headaches, low blood pressure, and dizziness. If dehydration continues, it can quickly lead to unconsciousness and even death. When you are very active, particularly in the heat, you can lose a great deal of water in sweat. To avoid dehydration, you should drink extra fluids before, during, and after exercise.

Taking in too much water—especially without consuming extra salts—can lead to a condition called hyponatremia. In this condition, the brain swells with water, causing symptoms such as nausea, vomiting, headache, and coma. Hyponatremia can be fatal, so it requires emergency medical care.

Suggested Supplementary Reading:

McMillan, T. 2018. [How China Plans to Feed 1.4 Billion Growing Appetites](#). *National Geographic*. February.

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8.2 Global Food Systems

Joni Baumgarten

Section Goals:

1. Consider how globalization of the food industry relates to people's local interaction with food.
2. Learn details about challenges to modern environments (cities) and modern farmers related to this process of globalization.
3. Relate global food systems and policies with the concept of a maximum sustainable yield.
4. Learn about the risk to ecosystems through a case study of cod fishing.

Globalization of Food

Many thousands of years ago, one of humanity's ancestors might have spied a sprout emerging from a refuse pile of pits, nuts, and seeds. Perhaps it was a lightbulb moment: "Hmm, I wonder if I could do that on purpose...." Or maybe it was somebody who dug up a plant and moved it closer to camp: "Genius! Now I don't have to walk so far!" Somehow, people discovered that they need not rely on the whims of nature to provide them with plants; rather, they could grow the plants they wanted in places more convenient to them. This basic manipulation of nature is called cultivation, and gather-hunters were experimenting with it for thousands of years before the development of farming.

Currently, most people, when they think about food, still consider it a local, individual choice based on personal preferences and economic possibilities. But food is a global commodity marketed by transnational corporations, health institutes, advertising campaigns, and subtle and not-so-subtle cultural messaging through global media such as movies, television, and online video. Most often, what people choose to eat is based on underlying structures that determine availability and cost. While there are now hothouse businesses growing year-round fruits and vegetables, affordability often prohibits everyone from having access to fresh, ripe foods. Instead, mainstream grocery stores most often stock foods imported across long distances. Most fruits and vegetables sold in the grocery store were harvested unripe (and often tasteless) so that they would last the days and weeks between harvesting and purchase.

Case Study of Agriculture

The Haudenosaunee people (also known as the Iroquois or Six Nations) of what is now the northern part of New York State practiced Three Sisters cultivation with maize, beans, and pumpkins, which

are a form of squash. Seeds from each of these crops were planted together in small mounds in an unplowed field. Each mound contained several maize seeds in the middle, with bean and pumpkin seeds placed around the perimeter. Note the difference from the row-based agriculture practiced on conventional American farms today. Each of the plants in the mound offers a benefit to the others. The vigorous pumpkin vines, with their large leaves, quickly form a canopy that shades out weeds, preserves moisture in the soil, and prevents erosion. The bean plants, with the help of bacteria, are able to fix nitrogen in the soil, making it available as a fertilizer to the plants growing around them. And the fast-growing maize plants, which require lots of nitrogen for healthy growth, provide trellises for the climbing beans.

Globalization

In her work on food and globalization, anthropologist and food studies specialist Lynne Phillips points out the “crooked pathways” (2006) that food takes to become a global commodity. Increasingly affected by transnational corporations, food today is marketed for endlessly higher profits. Food no longer goes simply from producer to consumer. There are many turns along the way.

Food globalization has numerous effects on our daily lives:

- The food chains from producers to consumers are increasingly fragile as a small number of transnational corporations provide the basic foods that we eat daily. Failures in this food chain might come from contamination during production or breaks in the supply chain due to climate crises, tariffs, or trade negotiations between countries. Our dependence on global food chains makes the food supply to our communities more vulnerable to disruption and scarcity.
- Our food cultures are less diverse and tend to revolve around a limited number of mass-produced meats or grains. With the loss of diversity, there is an accompanying loss not only of food knowledge but also of nutrition.
- As foods become more globalized, we are increasingly dependent on food additives to enhance the appearance and taste of foods and to ensure their preservation during the long journey from factory farm to table. We are also increasingly exposed to steroids, antibiotics, and other medicines in the meat we eat. This exposure poses health risks to large numbers of people.
- As plants and animals are subjected to ever more sophisticated forms of genetic engineering, there is an increasing monopoly on basic food items, allowing transnational companies to affect regulatory controls on food safety. As corporate laboratories develop patented seeds (such as the Monsanto Corporation’s genetically engineered corn) that are super-producers and able to withstand challenges such as harsh climate conditions and disease, growers become dependent on the seed sold by these corporations. No longer able to save seed from year to year, growers have little choice but to pay whatever price these corporations choose to charge for their genetic material.
- Factory farming of all types, but especially large-scale animal farms, are major contributors

to global warming. Not only do they produce large amounts of water and air pollution and contribute to worldwide deforestation, but as more and more forest is turned into pasture, the sheer number of livestock contributes significant levels of greenhouse gases that lead to global warming. Worldwide, livestock account for around 14.5 percent of global greenhouse gas emissions (Quinton 2019).

Food has long been an international commodity, even during the 17th and 18th centuries, when traders sought spice and trade routes connecting Europe and Asia. Today, however, food has become transnational, with production sometimes spanning many different countries and fresh and processed foods moving long distances from their original harvest or production. Because these migrating foods must be harvested early or packaged with preservatives that we may not know or even be able to pronounce, there has been a parallel development in local food movements, organic food movements, and farm-to-table establishments as people see the dangers of food globalization. In the very popular *The Omnivore's Dilemma: A Natural History of Four Meals* (2006), American author and food journalist Michael Pollan advocates that people should know the identity of the foods they eat and should make every effort to eat locally sourced products. Shortly after the book's publication, chef and author Jessica Prentice coined the term locavore to refer to those who eat locally and know the origins of their foods.

Urban Food: 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 makes provision for adequate land for food production in the city, a return to the community and to the allotment gardens of past days, where roof gardens become an urban market garden. It is essential that we bridge the urban-rural disconnect and move cities towards models that deal in natural eco-systems 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 re-using 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 terms of energy and water consumption and herds create methane and demand great quantities of electricity.

Contemporary Challenges of Farming Societies

Communities relying primarily on extensive horticulture or intensive agriculture are generally able to meet their own subsistence needs. However, with the development of cities into regional empires, many cultivators became incorporated into larger structures of trade and government. Under pressure from these structures, farmers past and present were and are obliged to sell their surplus for cash in order to pay taxes and purchase agricultural inputs such as seed and fertilizer. As cities and states grow, they exert pressure on cultivators to produce ever higher yields to support greater populations and more elaborate state projects. As cultivators become incorporated into demanding states, they become a class of peasants. A peasant is a farmer with a small plot of land incorporated into a larger regional economy. Nearly all contemporary cultivators are part of a peasant class in their nation-states (Sillitoe 2018).

Peasants are often marginalized and disadvantaged, reliant on economic and political structures they cannot control, and exploited by urban elites. Many farmers now make up a rural underclass.

Trade-offs: From Foragers to State Systems of Agriculture

As the world population continues to grow ([currently at around 7.9 billion people](#)), climate change accelerates, and food production becomes more and more concentrated in the hands of a few corporations, access to food will become increasingly critical to our survival. The story of progress embraced by Western society tells us that globalization and agricultural developments have stabilized and secured our food chains, but anthropological studies of foragers suggest otherwise.

Agricultural production is tied to access to arable land, clean water, stable climate, and a reliable workforce. Periodically, crops (and animals) fail due to disease, drought, and even disruption from warfare and extreme weather, leading to scarcity and famine in many parts of the world. In addition, as families and communities produce less and less of their own food and become more and more dependent on intermediaries to gain access to food, their vulnerabilities increase.

While there are many differences between state societies and foragers, there are valuable lessons we can learn from them. Foragers, facing the same unstable conditions that we all face worldwide, have a more varied and flexible diet and are able to adjust their needs seasonally based on local availability. They eat locally, and they adjust their needs to what is available.

Maximum Sustainable Yield

Some resources might be better managed if they are understood to be a global resource, such as fish caught in international waters. One way to conceptualize the management of fish populations is to think about how fish can be harvested without causing a collapse in the reproduction of the population; or being an example of the tragedy of the commons.

The useful concept of **maximum sustainable yield (MSY)** comes from population ecology and economics. It is theoretically the largest yield (or catch) that can be taken from a species' stock over an indefinite period. Fundamental to the notion of **sustainable harvest**, the concept of MSY aims to maintain the population size at the point of maximum growth rate by harvesting the individuals that would normally be added to the population, allowing the population to continue to be productive indefinitely. Under the assumption of logistic growth, resource limitation does not constrain individuals' reproductive rates when populations are small, but because there are few individuals, the overall yield is small. At intermediate population densities, individuals are able to breed to their maximum rate (Figure 1). At this point, there is a surplus of individuals that can be harvested because **growth** of the population is at its maximum point due to the large number of reproducing individuals.

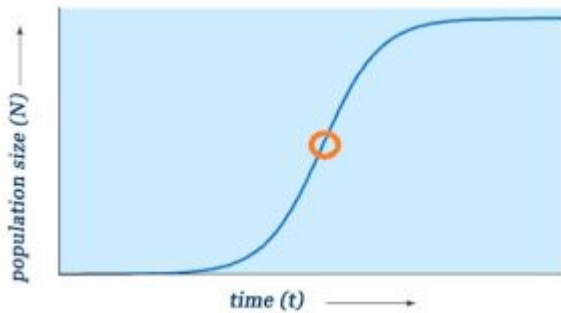


Figure 1: The logistic model for population growth has an inflection point (the orange circle) where the growth rate starts to decline. MSY would occur at this point. Credit: Graph is Public Domain, modified by Joni Baumgarten

However, the concept of maximum sustainable yield is not always easy to apply in practice. Estimation problems arise due to poor assumptions in some models and lack of reliability of the data. Biologists, for example, do not always have enough data to make a clear determination of the population's size and growth rate. Calculating the point at which a population begins to slow from competition is also very difficult. The concept of MSY also tends to treat all individuals in the population as identical, thereby ignoring all aspects of population structure such as size or age classes and their differential rates of growth, survival, and reproduction.

As a management goal, the static interpretation of MSY (i.e., MSY as a fixed catch that can be taken year after year) is generally not appropriate because it ignores the fact that fish populations undergo natural fluctuations (i.e., MSY treats the environment as unvarying) in abundance and will usually ultimately become severely depleted under a constant-catch strategy.

Case Study: Cod Fishery Collapse

The MSY approach has been widely criticized as ignoring several key factors involved in fisheries management and has led to the devastating collapse of many fisheries. One specific and devastating to the local economy is the cod fishing industry in Newfoundland.

Cod fishing in Newfoundland was carried out at a subsistence level for centuries, but large scale fishing began shortly after the European arrival in the North American continent in 1492, with the waters being found to be preternaturally plentiful, and ended after intense overfishing with the collapse of the fisheries in 1992 (Figure 2).

The challenge and what led to the eventual devastation to the cod populations were commercial fishing practices, estimated to have started with super-trawler vessels in 1951. The cod catch peaked in 1968 at 810,000 tons, approximately three times more than the maximum yearly catch achieved before the super-trawlers. Approximately eight million tons of cod were caught between 1647 and 1750, a period encompassing 25 to 40 cod generations. The factory trawlers took the same amount in 15 years.

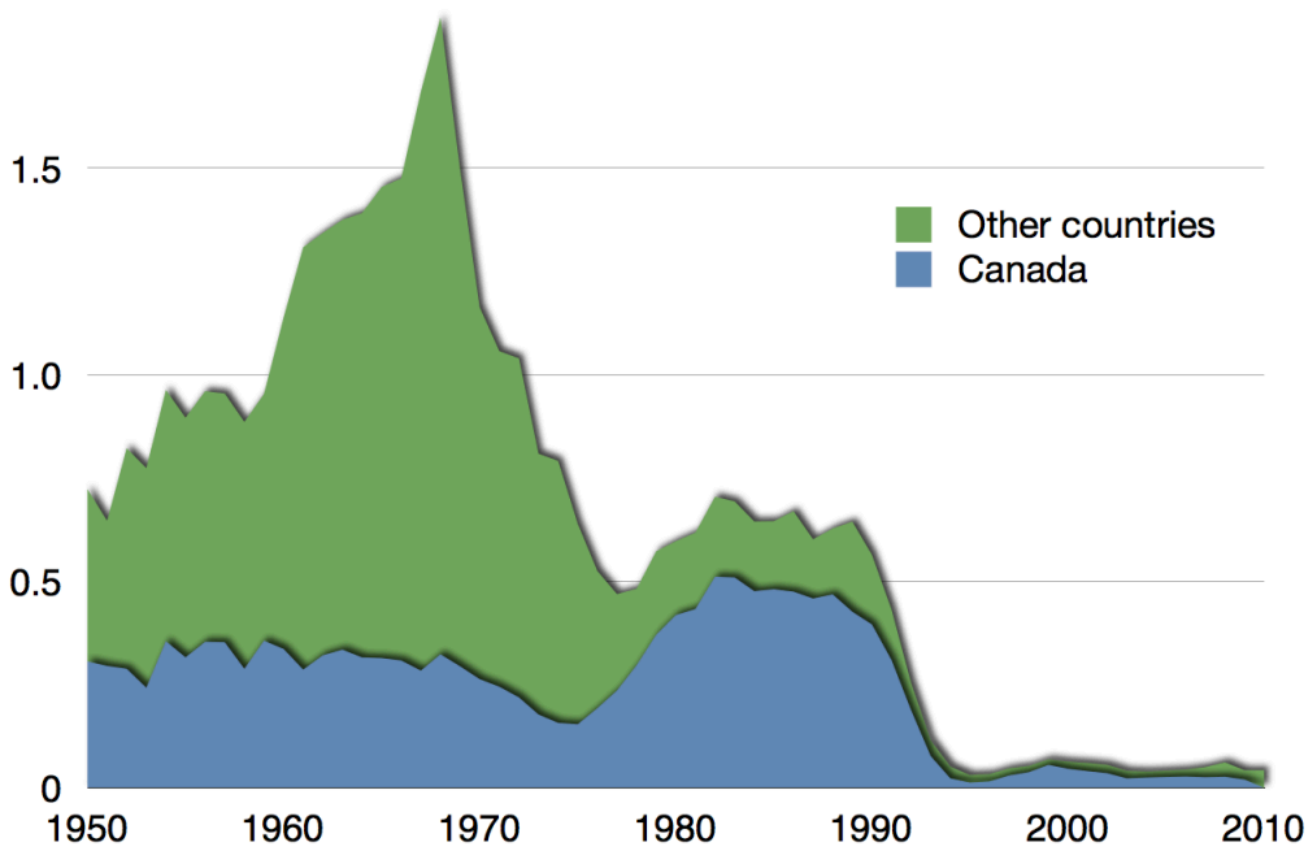


Figure 2: The sharp decline in cod catch after 1992. Credit: By Epipelagic – Own work, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=19281989>

The industry collapsed entirely in the early 1990s owing to overfishing and debatably, greed, lack of foresight and poor local administration. By 1993 six cod populations had collapsed, forcing a belated moratorium on fishing. Spawning biomass had decreased by at least 75% in all stocks, by 90% in three of the six stocks, and by 99% in the case of ‘northern’ cod, previously the largest cod fishery in the world. After a 10-year moratorium on fishing begun in 1992, the cod had still not returned.

The economic impact of the closure of the Atlantic cod fishery on Newfoundland has been compared to the effect of closing every manufacturing plant in Ontario. Cod fishing as a way of life came to an abrupt end for 19,000 workers after a 500-year history as a main industry.

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[History of Newfoundland and Labrador](#) by Wikipedia is licensed [CCA-SA 3.0](#). Modified by Joni Baumgarten. Accessed March 8, 2023.

8.3 Biotechnology and Genetic Engineering

Section Goals:

1. Define Genetic Engineering and Genetically Modified Organisms (GMOs).
2. Consider new technologies in the context of older plant breeding technologies.
3. Discuss the benefits and concerns of GMOs.

Genetic Engineering of Crops

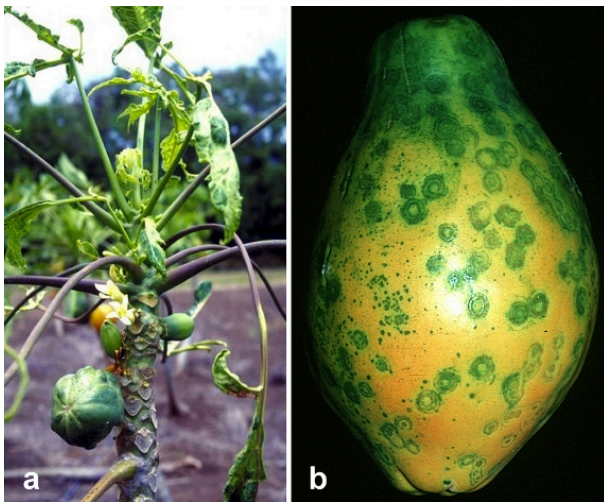


Figure 1: The symptoms of papaya ringspot virus are shown on the tree (a) and fruit (b). [“This work”](#) is in the [Public Domain, CC0](#).

In the early 1990s, an emerging disease was destroying Hawaii’s production of papaya and threatening to decimate the \$11 million industry (Figure 1). Fortunately, a man named Dennis Gonsalves, who was 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 seeds.

The development of a new strain of crop 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 name for the methods that scientists use to introduce new traits to an organism. This process results in **genetically modified organisms**, or **GMO**. For example, plants may be genetically engineered to produce characteristics to enhance the growth or nutritional profile of food crops. GMO 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 found in your local market would not occur naturally. In fact, they exist only because of human intervention that began thousands of years ago. Humans created the vast majority of crop species by 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 simple to perform, have the practical outcome of modifying an organism's genetic information, thus producing new traits.

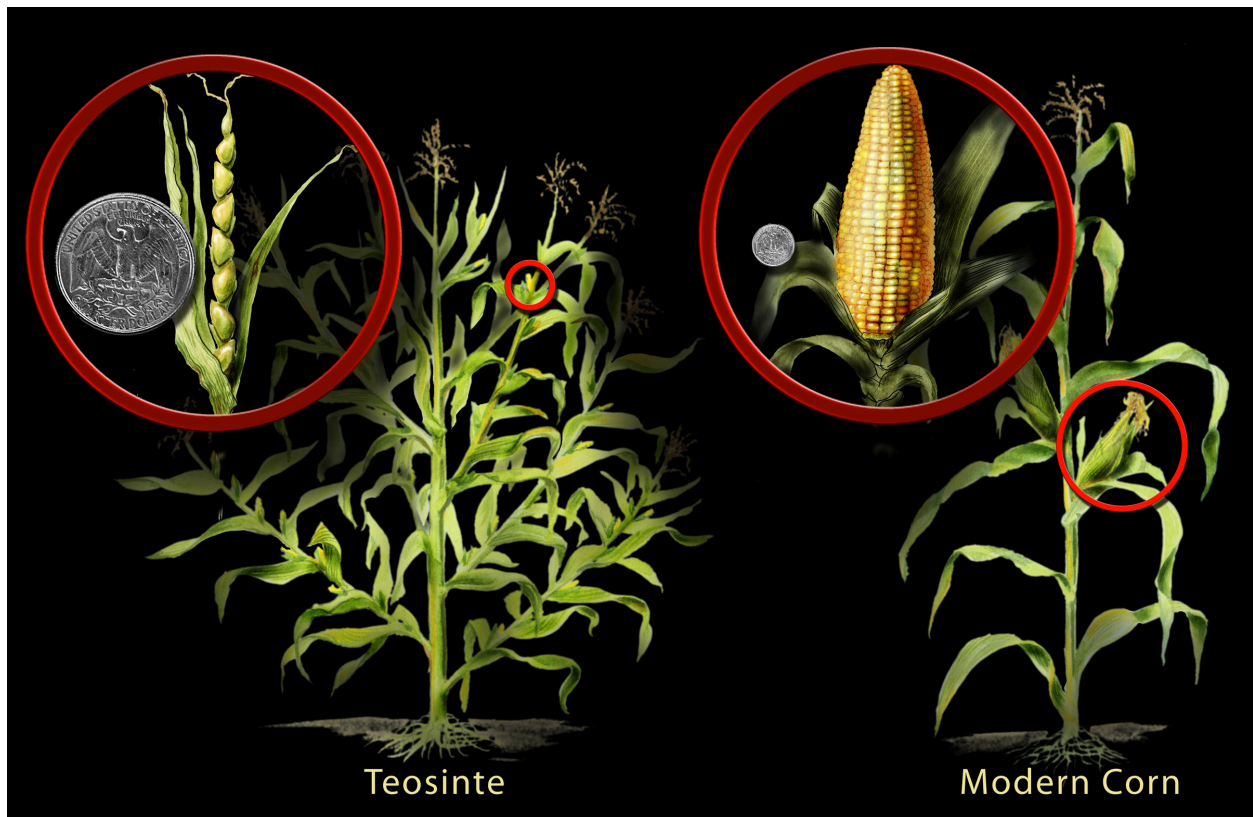


Figure 2: A wild grass called teosinte was genetically modified through selective breeding to produce what is now known as maize (corn). This process of transformation started thousands of years ago by indigenous people of what is now Mexico. [“This work”](#) by Nicolle Rager Fuller, National Science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

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 were able to transform the plant into what is now known as maize.

In doing so, they permanently (and unknowingly) altered its genetic instructions, allowing for new traits to emerge. Considering this history, we might ask the question: is there really such a thing as “non-GMO” maize?

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, the latter developed by humans 7,000 – 10,000 years ago in South America.

Traditional Breeding vs. Modern Genetic Engineering

To produce new traits in livestock, pets, crops, or other type of organism, 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 amongst the two techniques (Figure 3). Traditional breeding shuffles all of the genes between the two organisms being bred, which can number into the tens of thousands (maize, for example, has 32,000 genes). When mixing such a large number of genes, the results can be unpredictable. Modern genetic engineering is more precise in the sense that biologists can modify just 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 a process called **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.

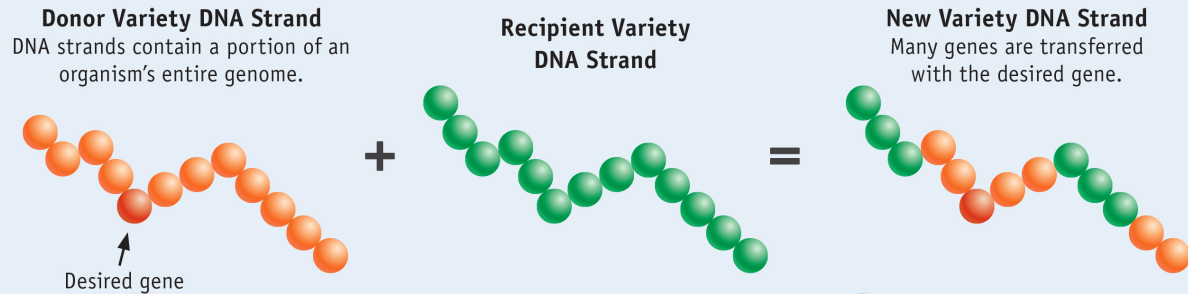


Figure 3: *Brassica oleracea* is a plant in the mustard family and is known as wild cabbage. From it were developed many familiar crops, such as cauliflower, broccoli, Brussel sprouts, and of course, cabbage. “[Brassica oleracea wild](#)” by [Kulac](#) is licensed under [CC BY-SA 4.0](#)

Methods of Plant Breeding

Traditional

The traditional plant breeding process introduces a number of genes into the plant. These genes may include the gene responsible for the desired characteristic, as well as genes responsible for unwanted characteristics.



Genetic Engineering

Genetic engineering enables the introduction into the plant of the specific gene or genes responsible for the characteristic(s) of interest. By narrowing the introduction to one or a few identified genes, scientists can introduce the desired characteristic without also introducing genes responsible for unwanted characteristics.

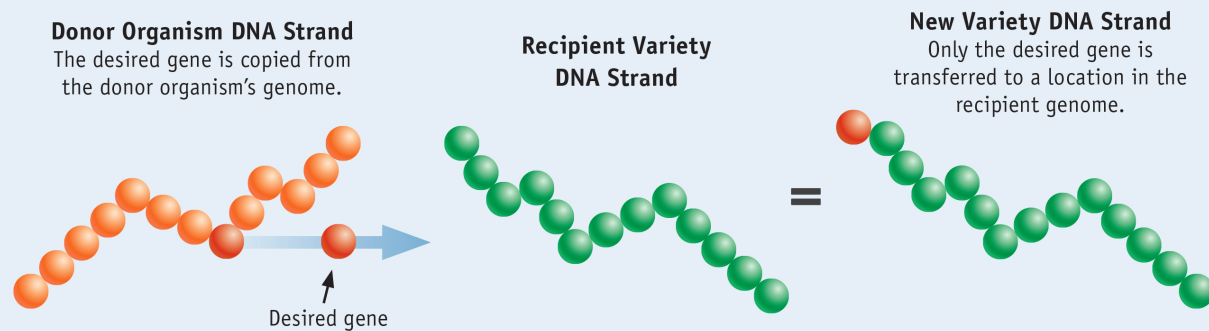


Figure 4: Both traditional breeding and modern genetic engineering produce genetic modifications. Genetic engineering allows for fewer and more precise genetic modifications. FDA graphic by Michael J. Ermarth (Methods of Plant Breeding) [CC0 Public Domain], via Wikimedia Commons.

Potential Benefits of Genetic Engineering

Enhanced nutrition

Advances in biotechnology may provide consumers with foods that are nutritionally-enriched (Figure 4), longer-lasting, or that contain lower levels of certain naturally occurring toxins present in some food plants. For example, developers are using biotechnology to try to reduce saturated fats in cooking oils, reduce allergens in foods, and increase disease-fighting nutrients in foods. Biotechnology may also be used to conserve natural resources, enable animals to more effectively use nutrients present in feed, 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 that can make production cheaper and more manageable. For example, some biotechnology crops can be engineered to tolerate specific herbicides, which make 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 to make both pest control and weed management safer and easier while safeguarding crops against disease. For example, genetically engineered insect-resistant cotton has allowed for a significant reduction in 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 that assess the risks and benefits of GE crops. 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 benefits and hazards to the environment.

In addition to environmental risks, some people are concerned about potential health risks of GE crops

because they feel that genetic modification alters the intrinsic properties, or essence, of an organism. 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 that summarized the 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, is shared in the various 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 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 could not be controlled by herbicide. Its rampant growth could then 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.

Consumers 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 firm in its opposition 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, which assures that they did not use any kind of 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 at this time, it is likely that the contamination has 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 may 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 used by farmers. Pollen from *Bt* corn can be harmful to 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 the validity of that initial monarch study was questioned by other scientists and this ultimately led 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 it was consequently removed from the market.

The GE Crop Report also mentioned a separate threat to monarch: 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 for 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 risks to human and animal health from the use of GMOs 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, in 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 evidences 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, for the safety of the environment and human health, both should be adequately studied.

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, which can lead 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 the concentration of seed-markets by a few companies, and the subsequent reduction of free market competition, may be affecting 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. Jim Myers, from Oregon State University notes that "In all but a few cases, all contemporary varieties developed by private breeders are [legally] protected, and most public varieties are protected as well."

Suggested Supplementary Reading

Achenbach, J. 2015. "Why Do Many Reasonable People Doubt Science?" *National Geographic Magazine*. <https://www.nationalgeographic.com/magazine/2015/03/science-doubters-climate-change-vaccinations-gmos/>

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

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8.4 Genetically Modified Crops

Section Goals:

1. Learn examples and relevant details about genetically modified crops.
2. Relate the examples to a larger understanding of the benefits and risks of GMOs.

Case Studies of GMO crops

The goal of this section is to talk about specific examples of GMO crops because the details matter. GMO crops are all different, and the trait that has been modified will result in different outcomes, especially if we are measuring the environmental impact.

Glyphosate Resistant Crops

Roundup Ready is the Monsanto trademark for its patented line of genetically modified crop seeds that are resistant to its glyphosate-based herbicide, Roundup.

Glyphosate kills plants by interfering with the synthesis of the essential amino acids phenylalanine, tyrosine and tryptophan. These amino acids are called “essential” because animals cannot make them; only plants and micro-organisms can make them, and animals obtain them by eating plants. Therefore, the fundamental way that glyphosate works means that the health risks to humans are low. The consensus among national pesticide regulatory agencies and scientific organizations is that labeled uses of glyphosate have demonstrated no evidence of human carcinogenicity, though that does not mean it is “safe”.

In 1996, genetically modified *Roundup Ready* soybeans resistant to Roundup became commercially available, followed by *Roundup Ready* corn in 1998. Current *Roundup Ready* crops include soy, maize (corn), canola, sugar beets, cotton, and alfalfa, with wheat still under development.

While the use of Roundup Ready crops has increased the usage of herbicides measured in pounds applied per acre, it has also changed the herbicide use profile away from atrazine, which is more easily leached into groundwater and drinking water sources.

Bt Cotton

Bt cotton is a genetically modified pest resistant plant cotton variety, which produce an insecticide to combat bollworm, the primary pest of cotton.

Strains of the bacterium *Bacillus thuringiensis* produce over 200 different Bt toxins, each harmful to different insects. Most notably, Bt toxins kill the larvae of moths and butterflies, beetles, cotton bollworms and flies but are harmless to other forms of life. The gene coding for Bt toxin has been inserted into cotton, allowing cotton to produce this natural insecticide in its tissues. In many regions, the main pests in commercial cotton are lepidopteran larvae, which are killed by the Bt protein when they

eat the Bt cotton plant. This eliminates the need to use large amounts of broad-spectrum insecticides to kill lepidopteran pests. A secondary benefit is to spare natural insect predators in the farm ecology and further contributes to non-insecticide pest management.

Bt cotton is ineffective against cotton pests in other insect families, such as plant bugs, stink bugs, and aphids; depending on circumstances it may be desirable to use insecticides in prevention. A 2006 study done by Cornell researchers, the Center for Chinese Agricultural Policy and the Chinese Academy of Science on Bt cotton farming in China found that after seven years these secondary pests that were normally controlled by pesticide had increased, necessitating the use of pesticides at similar levels to non-Bt cotton.

Golden Rice

Golden rice is a variety of rice (*Oryza sativa*) produced through genetic engineering to biosynthesize beta-carotene, a precursor of vitamin A, in the edible parts of the rice. It is intended to produce a fortified food to be grown and consumed in areas with a shortage of dietary vitamin A. Vitamin A deficiency causes a range of eye conditions; from night blindness to more severe clinical outcomes such as keratomalacia, corneal scars, and permanent blindness. It also increases risk of mortality from measles and diarrhea in children. In 2013, the prevalence of deficiency was the highest in sub-Saharan Africa (48%; 25–75), and South Asia (44%; 13–79).

Although golden rice has met significant opposition from environmental and anti-globalization activists, more than 100 Nobel laureates in 2016 encouraged use of genetically modified golden rice.

Bananas

Bananas are a unique fruit because the ones we eat are sterile fruits: no seeds are produced within the fruit. These plants must be reproduced vegetatively, which means that all banana plants from the same parent are clones. The risk of this is that any type of infection to which the parent is susceptible will also be equally impactful to the clones.

The current banana variety that is most commonly sold is the Cavendish. The Cavendish banana replaced the previously preferred Gros Michel variety because the Gros Michel was susceptible to a fungal pathogen; all Gros Michel bananas were effectively wiped out by the pathogen (called Tropical Race 1) by 1965. Unfortunately, in 1989 a similarly deadly fungus variety (Tropical Race 4) was discovered to kill Cavendish bananas. It is only a matter of time before the Cavendish variety is wiped out, as happened to the Gros Michel.

A number of genetic-engineering techniques and labs are working on modifying the Cavendish to resist TR4. Though there are successful results, the resistance of the world to accept and buy these GMOs is the limiting factor to potentially save the Cavendish banana.

Are All GMOs the Same?

The two most common GMOs are Bt-enhanced crops and glyphosate-resistant crops. These two types of GMOs have differing, contrasting results: to reduce the use of pesticides and to increase the use of herbicides. Though there are slightly oversimplified conclusions, it highlights that if a person was concerned about the amount of chemical applications in agricultural settings, they should avoid glyphosate-resistant crops but should choose to use Bt crops. Golden Rice and the modification of

Cavendish bananas similarly cannot be grouped together unambiguously. These examples highlight that knowledge of each type of GMO is necessary in order to evaluate the environmental risks and benefits. However, one thing is clear: all evidence shows that GMOs that have been approved are safe for human consumption. A similar conclusion can be made about the economic benefit to farmers. The adoption rate of many GMO crops is more positive than negative because the successful GMO crops outperform the non-GMO varieties. Though, as with all things, there are complexities and inequities by having specific GMO-varieties owned by a large company.

Are GE Crops the Solution We Need?

Significant resources, both financial and intellectual, 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 were threatened with eradication due to an 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 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. The vast majority of 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, but 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

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8.5 Chapter Resources

Summary

Progress continues in the fight against hunger, yet an unacceptably large number of people still lack the food they need for an active and healthy life. About 795 million people in the world still go to bed hungry every night, and an even greater number 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 the translation of 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.

Genetic engineering is the name for methods that scientists use to introduce new traits or characteristics to an organism. Advocates say that application of genetic engineering in agriculture has resulted in benefits to farmers, producers, and consumers. Critics advise that the risks for the introduction of a GMO into each new ecosystem need to be examined on a case-by-case basis, alongside appropriate risk management measures.

Review Questions

1. Which one of the following is not one of the four pillars of food security?
 - A. Availability
 - B. Access
 - C. Utilization
 - D. Transformation
 - E. Stability
2. Which one of the following statements is false regarding selective breeding?
 - A. It results in genetic changes in the offspring
 - B. It is anthropogenic
 - C. Is reliant upon modern, lab-based methods
 - D. It can produce new traits over time
 - E. It was responsible for creating many common crops, such as maize (corn)
3. The US National Academy of Sciences, Engineering, and Medicine, along with other organizations such as the American Medical Association, have determined that GE crops...
 - A. Are safe to consume
 - B. Likely pose a risk to human health
 - C. Pose a serious risk to human health
 - D. Should be banned

E. Have not been scientifically studied and therefore they cannot make any recommendations.

4. Which one of the following regions has obesity rates that are lower than rates of undernourishment?

- A. Middle East and North Africa
- B. Latin America and Caribbean
- C. Europe and Central Asia
- D. South Asia

5. Potatoes, tomatoes, and tobacco were developed by humans many thousands of years ago by the genetic modification of wild nightshade species. Specifically, these crops were developed using...

- A. Selective breeding
- B. Horizontal gene transfer
- C. Epigenetics
- D. Natural selection
- E. Anthropogenesis

See Appendix for answers

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Chapter 9: Conventional & Sustainable Agriculture



Women farmers planting 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

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9.1 Soil Profiles & Processes

Section Goals:

1. Understand the importance of soil as a resource.
2. Define the five soil forming factors.

What is Soil?

The word “**soil**” has been defined differently by different scientific disciplines. In agriculture and horticulture, 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 also 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 in which 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 as much as several hundred feet thick! Ancient soils, sometimes buried and preserved in the subsurface, are referred to as paleosols (Figure 2) and reflect past climatic and environmental conditions.

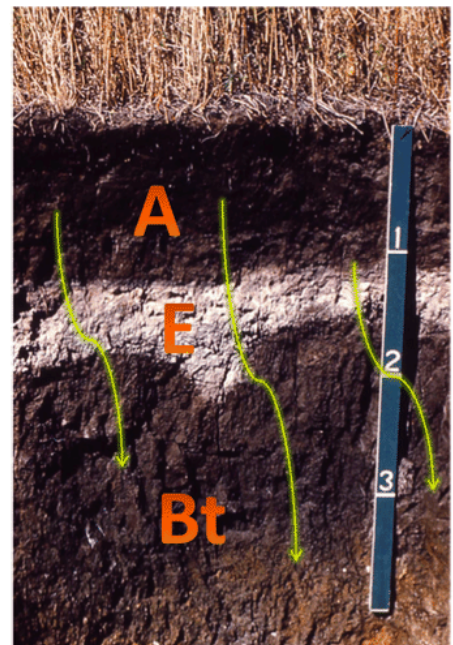


Figure 1: Soil Profile. Photograph shows a soil profile from South Dakota with A, E, and Bt horizons. The yellow arrows symbolize translocation of fine clays to the Bt horizon. The scale is in feet. Source: University of Idaho and modified by D. Grimley.

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 a critical component 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 soil. In the hydrologic cycle, soil helps to mediate the flow of precipitation from the surface into the groundwater. Microorganisms living in soil can also be important components of biogeochemical cycles through the action of 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, topography, parent material, and time. The combination of these five factors is unique to each location on the earth, and can vary over short distances. As soil is formed it often has distinct layers, which are formally described as **horizons**, the properties of which also reflect the five soil forming factors. 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 occur at an accelerated rate.

Organisms

Animals, plants, and microorganisms all have important roles in soil development processes, in providing a supply of organic matter, and/or in 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 soil and helps to recycle nutrients with uptake by roots in the subsurface. The type of plant life that occurs in a given area, such as types of trees or grasses, depends on the climate, along with parent material and soil type. With the annual dropping of leaves and needles, trees tend to add organic matter to soil surfaces, helping to create a thin, organic-rich A or O horizon over time. Grasses, on the other hand, have a 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.

Topography (and Drainage)

The local landscape can have a surprisingly strong effect on the soils that form on site. The local **topography** can have important microclimatic effects as well as affecting rates of soil erosion. In comparison 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 and are 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 sideslopes, are more brownish or reddish due to 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

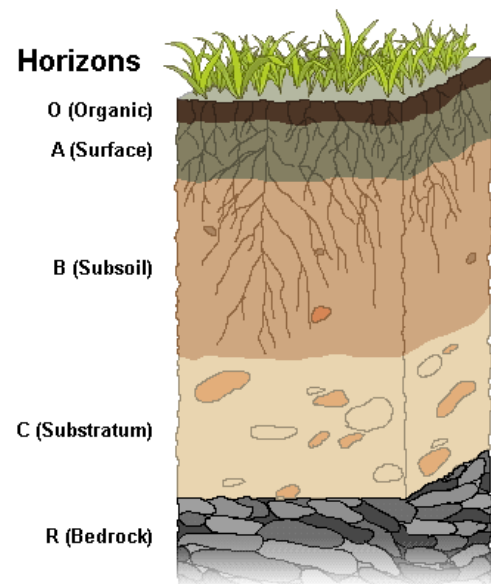


Figure 3: This images shows the different horizons, or layers, in soil. [This work](#) by Wilsonbiggs is licensed under [CC BY-SA 4.0](#)

from surrounding uplands, often resulting in overthickened 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 a 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 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. Parent materials that are highly weatherable (such as volcanic ash) will transform more quickly into highly developed soils, whereas parent materials that are quartz-rich, 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

In general, soil profiles tend to become thicker (deeper), more developed, and more altered over time. However, the rate of change is greater for soils in youthful stages of development. The degree of soil alteration and deepening slows with time and at some point, 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 as far as soil horizonation 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). Human activity has a huge impact on soil development and soil health.

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9.2 Soil-Plant Interactions

Section Goals:

1. Connect soil chemistry with plant health.
2. Understand how roots take up nutrients from the soil solution.

Soils support plant growth

Soil plays a key role in plant growth. Beneficial aspects to 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 are beneficial to plants, excessively high levels of trace metals (either naturally occurring or anthropogenically added) or applied herbicides can be toxic to some plants.

The mixture of water and dissolved or suspended materials that occupy the soil pore space is called the soil solution. Since soil water is never pure water, but contains hundreds of dissolved organic and mineral substances, it may be more accurately called the soil solution. Water is central to the dissolution, precipitation and leaching of minerals from the soil profile.

The ratio of solids/water/air in soil 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.

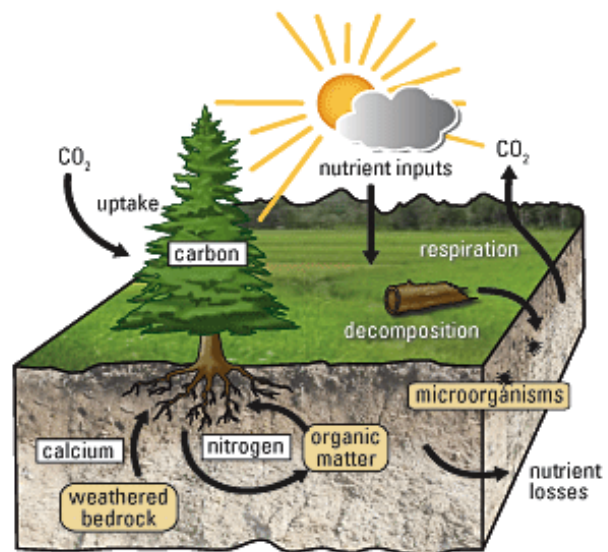


Figure 1: Soil-Plant Nutrient Cycle. This figure illustrates the uptake of nutrients by plants in the forest-soil ecosystem. Source: U.S. Geological Survey.

Nutrient Uptake by Plants

Several elements obtained from 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 from 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 by plant roots from the soil and are variously 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 that are needed only in small quantities, but can still be limiting to 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). There are some other elements that tend to aid plant growth but are not absolutely essential.

Micronutrients and macronutrients are desirable in particular concentrations and can be detrimental to plant growth when concentrations in 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 in solid mineral. Many nutrients move through the soil and into the root system as a result of concentration gradients, moving by diffusion from high to low concentrations. However, some nutrients are selectively absorbed by the root membranes, enabling concentrations to become higher inside the plant than in the soil.

Plant uptake of nutrients can only proceed when they are present in a plant-available form. In most situations, nutrients are absorbed in an ionic form from (or together with) soil water. Although minerals are the origin of most nutrients, and the bulk of most nutrient elements in the soil is held in crystalline form within primary and secondary minerals, they weather too slowly to support rapid plant growth. For example, the application of finely ground minerals, feldspar and apatite, to soil seldom provides the necessary amounts of potassium and phosphorus at a rate sufficient for good plant growth, as most of the nutrients remain bound in the crystals of those minerals.

Specific Nutrient-uptake Processes

Plants take up essential elements from the soil through their roots and from the air through their leaves. Nutrient uptake in the soil is achieved by cation exchange, wherein root hairs pump hydrogen ions (H^+) into the soil through proton pumps. These hydrogen ions displace cations attached to negatively charged soil particles so that the cations are available for uptake by the root. In the leaves, stomata open to take in carbon dioxide and expel oxygen. The carbon dioxide molecules are used as the carbon source in photosynthesis.

The root, especially the root hair, is the essential organ for the uptake of nutrients. The structure and architecture of the root can alter the rate of nutrient uptake. Nutrient ions are transported to the center of the root, the stele, in order for the nutrients to reach the conducting tissues, xylem and phloem. The Casparian strip, a cell wall outside the stele but in the root, prevents passive flow of water and nutrients, helping to regulate the uptake of nutrients and water. Xylem moves water and mineral ions in the plant and phloem accounts for organic molecule transportation. Water potential plays a key role in a plant's nutrient uptake. If the water potential is more negative in the plant than the surrounding soils, the nutrients will move from the region of higher solute concentration—in the soil—to the area of lower solute concentration – in the plant.

There are three fundamental ways plants uptake nutrients through the root:

1. Simple diffusion occurs when a nonpolar molecule, such as O_2 , CO_2 , and NH_3 follows a concentration gradient, moving passively through the cell lipid bilayer membrane without the use of transport proteins.
2. Facilitated diffusion is the rapid movement of solutes or ions following a concentration gradient, facilitated by transport proteins.
3. Active transport is the uptake by cells of ions or molecules against a concentration gradient; this requires an energy source, usually ATP, to power molecular pumps that move the ions or molecules through the membrane.

Nutrients can be moved in plants to where they are most needed. For example, a plant will try to supply more nutrients to its younger leaves than to its older ones. When nutrients are mobile in the plant, symptoms of any deficiency become apparent first on the older leaves. However, not all nutrients are equally mobile. Nitrogen, phosphorus, and potassium are mobile nutrients while the others have varying degrees of mobility. When a less-mobile nutrient is deficient, the younger leaves suffer because the nutrient does not move up to them but stays in the older leaves. This phenomenon is helpful in determining which nutrients a plant may be lacking.

Many plants engage in symbiosis with microorganisms. Two important types of these relationship are:

1. with bacteria such as rhizobia, that carry out biological nitrogen fixation, in which atmospheric nitrogen (N_2) is converted into ammonium (NH_4^+);
2. with mycorrhizal fungi, which through their association with the plant roots help to create a larger effective root surface area. Both of these mutualistic relationships enhance nutrient uptake.

The Earth's atmosphere contains over 78 percent nitrogen. Plants called legumes, including the agricultural crops alfalfa and soybeans, widely grown by farmers, harbor nitrogen-fixing bacteria that can convert atmospheric nitrogen into nitrogen the plant can use. Plants not classified as legumes such as wheat, corn and rice rely on nitrogen compounds present in the soil to support their growth. These can be supplied by mineralization of soil organic matter or added plant residues, nitrogen fixing bacteria, animal waste, through the breaking of triple bonded N_2 molecules by lightning strikes or through the application of fertilizers.

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9.3 Conventional Agriculture

Section Goals:

1. Define conventional agriculture.
2. Learn about the Green Revolution which allowed agricultural production to increase dramatically.
3. Review the concerns in industrial agriculture systems.

Conventional agriculture is Industrial agriculture

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 are the result of conventional agriculture rather than greater acreage under cultivation. U.S. consumers have come to expect abundant and inexpensive food.

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. Negative effects of current practices include the following:

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, and biological activity; and **salinization** (increased



Figure 1: Conventional agriculture is dependent 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](#).

salinity) of soils in highly-irrigated farming areas. Converting land to desert (**desertification**) can be caused by 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 that include 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 overuse of surface and ground water 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 stresses 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 levels of carbon dioxide 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 among the income of farmers and the escalating concentration of **agribusiness**—industries involved with manufacture, processing, and distribution of farm products—into fewer and fewer hands. Market competition is limited and farmers have little control over prices of their goods, and 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 so 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?

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, and large food imports and debt burden, make long-term food security especially urgent.

The Green Revolution

The **Green Revolution**, also known as the **Third Agricultural Revolution**, was a period of technology transfer initiatives that saw greatly increased crop yields and agricultural production. These changes in agriculture began in developed countries after World War II and spread globally till the late 1980s. In the late 1960s, farmers began incorporating new technologies such as high-yielding varieties of cereals, particularly dwarf wheat and rice, and the widespread use of chemical fertilizers (to produce their high yields, the new seeds require far more fertilizer than traditional varieties), pesticides, and controlled irrigation. Agriculture also saw the adoption of newer methods of cultivation, including mechanization. These changes were often implemented as a package of practices meant to replace traditional agricultural technology. These costlier technologies were often provided in conjunction with loans that were conditional on policy changes being made by the developing nations adopting them, such as privatizing fertilizer manufacture and distribution that was formerly done through public channels.

Both the Ford Foundation and the Rockefeller Foundation were heavily involved in its initial development in Mexico. One key leader was agricultural scientist Norman Borlaug, the “Father of the Green Revolution”, who received the Nobel Peace Prize in 1970. He is credited with saving over a billion people from starvation. Another important scientific figure was Yuan Longping, whose work on hybrid rice varieties is credited with saving at least as many lives. The basic approach was the development of high-yielding varieties of cereal grains, expansion of irrigation infrastructure, modernization of management techniques, distribution of hybridized seeds, synthetic fertilizers, and pesticides to farmers. As crops began to reach the maximum improvement possible through selective breeding, genetic modification technologies were developed to allow for continued efforts.

Studies show that the Green Revolution contributed to widespread reduction of poverty, averted hunger for millions, raised incomes, reduced greenhouse gas emissions, reduced land use for agriculture, and contributed to declines in infant mortality.

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9.4 Pests & Pesticides

Section Goals:

1. Connect agricultural practices with pests.
2. Define POPs (persistent organic pollutants) and the concern caused by their use in agricultural settings.

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 a highly subjective term. 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, the term pesticide also applies to herbicides, fungicides, and various 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 the damage it does to cotton plants. [This work](#) by Jimmy Smith is licensed under [CC BY-NC-ND 4.0](#).

Pest Control is a Common Tool

The management of pests is an essential part of agriculture, public health, and maintenance of 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, adaptable to all crops and situations. When first applied, pesticides can result in impressive production gains of crops. However, despite these initial gains, excessive use of pesticides can be ecologically unsound, leading to the destruction of natural enemies, the increase of pesticide resistance, and outbreaks

of secondary pests.

These consequences have often resulted in higher production costs as well as environmental and human health costs—side-effects which have been unevenly distributed. Despite the fact that the lion’s share of chemical pesticides are 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 exposure to pesticides has been associated with several chronic and acute health effects like non-Hodgkin's lymphoma, leukemia, as well as 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 the most important potato-growing area in Ecuador, where smallholder farmers dominate production. They use tremendous amounts of pesticides for the control of the Andean potato weevil and the late blight fungus. Virtually all farmers apply 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 by 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, that have been 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 a wide range of health effects in humans, wildlife and fish. They have been linked to effects on the nervous system, reproductive and developmental problems, suppression of the immune system, cancer, and endocrine disruption. The deliberate production and use of most POPs has been banned around the world, 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, bioaccumulative 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 on a daily basis 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 who are then eaten by larger fish. Because tissue concentrations can increase or biomagnify at each level of the food chain, 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 in addition to 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.

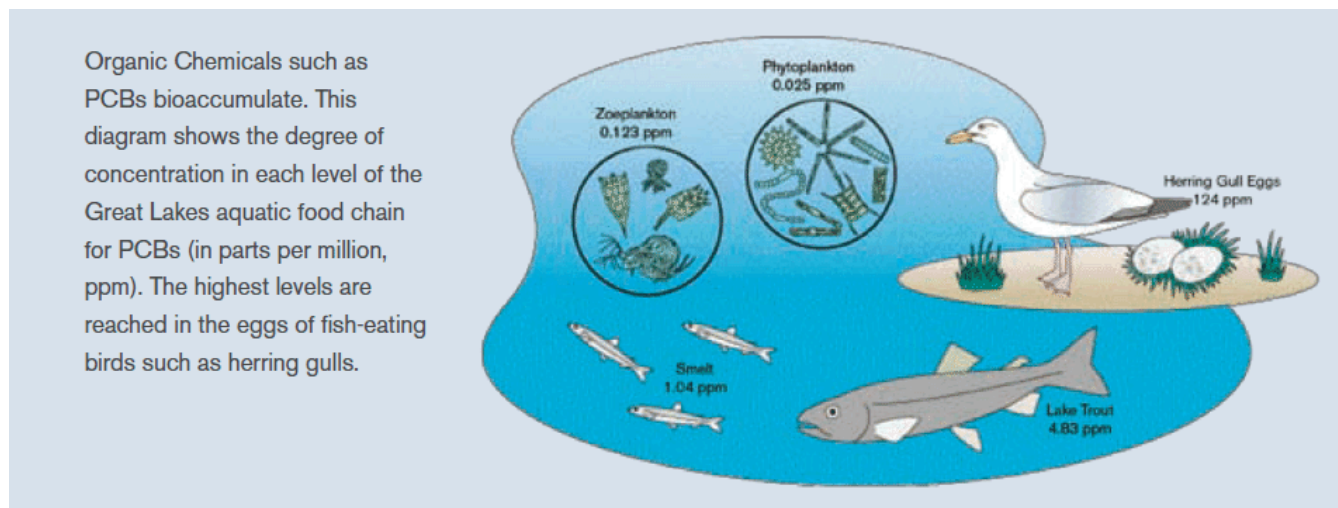


Figure 2. Bioaccumulation and biomagnification. U.S. EPA. *Great Lakes: The Great Lakes Atlas: Chapter Four the Great Lakes Today – Concerns*. January 2009

“Grasshopper Effect”

While generally banned or restricted, POPs make their way into and throughout the environment on a daily basis through a cycle of long-range air transport and deposition called the “**grasshopper effect**.” The “grasshopper” processes, illustrated in Figure 3, begin with the release of POPs into the environment. When POPs enter the atmosphere, they can be carried with wind currents, sometimes for long distances.

Through atmospheric processes, they are deposited onto land or into water ecosystems 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 highest concentrations in circumpolar countries. Through these processes, POPs can move thousands of kilometers from their original source of release in a cycle that may last decades.

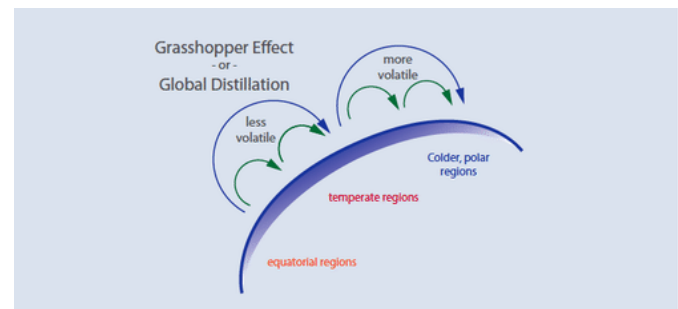


Figure 3. How POPs move throughout the environment. Source: Environment Canada. *The Science and the Environment Bulletin*. May/June 1998

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9.5 Sustainable Agriculture

Section Goals:

1. Define sustainable agriculture.
2. Define organic farming.
3. Review specific methods that are beneficial that could be integrated into general farming practices to lessen damage to the ecosystem.

Sustainable Agriculture

Sustainable agriculture was addressed by United States 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 the use of renewable resources and the conservation of soil and water to enhance environmental quality for future generations. Organic meat, poultry, eggs, and dairy products come from animals that are given no 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 soil health is therefore a more benign alternative to conventional, high-value horticulture. The organic food movement has been endorsed by the UN’s Food and Agricultural Organization, 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.

Though organic farming also can be beneficial on biodiversity and environmental protection at local

level, there are other drawbacks of converting industrial farms into organic farms. First and foremost, organic farming usually has lower yields compared to conventional farming. This is problematic to those concerned about global hunger. To get the same total yields using only organic farming methods, it is likely that additional agricultural land would be needed, which means that natural land will be converted into agricultural land. Land conversion would cause a loss of biodiversity and negative climate effects that would outweigh the local environmental gains achieved due to organic farming methods.

Certification of Organic Products

An additional challenge to the organic farming movement is the requirements put on the farmer. The certification process is an additional administrative burden that some farms cannot prioritize.

Organic certification is a certification process for producers of organic food and other organic agricultural products. In general, any business directly involved in food production can be certified, including seed suppliers, farmers, food processors, retailers and restaurants. A lesser known counterpart is certification for organic textiles (or organic clothing).

Requirements vary from country to country, and generally involve a set of production standards for growing, storage, processing, packaging and shipping that include:

- avoidance of synthetic chemical inputs (e.g. fertilizer, pesticides, antibiotics, food additives), irradiation, and the use of sewage sludge;
- avoidance of genetically modified seed;
- use of farmland that has been free from prohibited chemical inputs for a number of years (often, three or more);
- for livestock, adhering to specific requirements for feed, housing, and breeding;
- keeping detailed written production and sales records (audit trail);
- maintaining strict physical separation of organic products from non-certified products;
- undergoing periodic on-site inspections.

In some countries, certification is overseen by the government, and commercial use of the term *organic* is legally restricted. Certified organic producers are also subject to the same agricultural, food safety and other government regulations that apply to non-certified producers. Certified organic foods are not necessarily pesticide-free, as certain pesticides are allowed.

Ecologically Beneficial Practices

Some methods of farming that are associated with organic farming are used by farmers seeking to be more sustainable and ecologically beneficial, but may not be seeking to be certified as organic.

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 seeks 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, although this is often the case because pesticides are often over-used for a variety of 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 the use of one biological species to reduce populations of a different species. There has been a substantial increase in 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, use of the bacterium *Bacillus thuringiensis* to kill mosquito and moth larvae, and introduction of fungi, such as *Trichoderma*, to suppress fungal-caused plant diseases, leaf beetle (*Galerucella californiensis*) to suppress purple loosestrife, a noxious weed (Figure 1). In all of 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 a 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.

Reduced Tillage and No-Till

In modern agricultural practices, heavy machinery is used to prepare the seedbed for planting, to control weeds, and to harvest the crop. The use of heavy equipment has many advantages in saving time and labor, but can cause compaction of soil 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**. With proper planning, this can simultaneously limit compaction, protect soil organisms, reduce costs (if performed correctly), promote water infiltration, and help to prevent topsoil erosion (Figure 3).

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 composition. Another aspect of soil tillage is that it may lead to more rapid decomposition of organic matter due to greater soil aeration. Over large areas of farmland, 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 into the soil. Thus, no-till farming may be advantageous to sustainability issues on the local scale and the global scale. No-till systems of conservation farming have proved a major success in Latin America and are being used in South Asia and Africa.



Figure 3: Farmers should consider no-till farming as the most important tool to prevent loss of soil moisture.

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 in order to reduce their production risk through diversification or to manage scarce resources, such as labor, during planting and harvesting timing. This strategy reduces the 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 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 proved to be effective in controlling insect populations and insect resistance, protecting surroundings and lowering costs.

Soil Promoting Practices

Protecting the soil is a final method of farming that can be adopted for its own sake. **Soil health** is defined as the state of a soil meeting its range of ecosystem functions as appropriate to its environment. In more colloquial terms, the health of soil arises from favorable interactions of all soil components (living and non-living) that belong together, as in microbiota, plants and animals. It is possible that a soil can be healthy in terms of eco-system functioning but not necessarily serve crop production or human nutrition directly, hence the scientific debate on terms and measurements.

Soil health depends on soil biodiversity (with a robust soil biota), and it can be improved via soil management, especially by care to keep protective living covers on the soil and by natural (carbon-containing) soil amendments. Inorganic fertilizers do not necessarily damage soil health if 1) used at appropriate and not excessive rates and 2) if they bring about a general improvement of overall plant growth which contributes more carbon-containing residues to the soil.

The term soil health is used to describe the state of a soil in:

- Sustaining plant and animal productivity (agronomic focus);
- Enhancing biodiversity (ecological focus);
- Maintaining or enhancing water and air quality (environmental/climate focus);
- Supporting human health and habitation; and
- sequestering carbon

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.

Suggested Supplementary Reading

McMillan, T. 2018. “[Menu of the Future: Insects, Weeds, and Bleeding Veggie Burgers.](#)” *National Geographic*. November

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9.6 Chapter Resources

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 to 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. However, the methods of industrial farming that have achieved such high yields 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 and lost markets due to undesirable pesticide residue levels, as well as environmental and human health costs.

Alternative and sustainable practices in farming and land use include organic agriculture, integrated pest management and biological control.

Review Questions

1. Which of the following is not one of the five soil-forming factors?
 - A. Climate
 - B. Organisms
 - C. Relief
 - D. Transpiration rate
 - E. Time
2. You analyze a soil sample for a farmer that has been dealing with fertility issues on her land. You find that it is deficient in all of the soil-derived macronutrients. Which one of the following is macronutrient derived from the soil?
 - A. carbon
 - B. nitrogen
 - C. hydrogen
 - D. iron
 - E. oxygen
3. The farmer adjacent to your land plants a single crop (soybean) over their entire 100 hectare field. This practice is known as a...

- A. Monoculture
- B. Crop plot
- C. Agriplot
- D. Rotational farming
- E. Millibar

4. Salinization is bad for farmers because it results in...

- A. Pesticide resistance
- B. Increased salts in the soil
- C. Nutrient-poor soils
- D. Blight
- E. Desertification

5. Besides being long-lasting, persistent organic pollutants share which of the following characteristics:

- A. accumulate in higher trophic levels and are toxic
- B. accumulate in lower trophic levels and are toxic
- C. accumulate in higher trophic levels and are infectious biological agents
- D. accumulate in lower trophic levels and are infectious biological agents
- E. Are toxic and infectious

6. The grasshopper effect explains which one of the following phenomena?

- A. The mass migration patterns of insects that are similar to, and include, grasshoppers
- B. The lowering of nutrient capacity in soils due to the action of certain types of organisms
- C. The long-range movement of certain types of pollutants across different regions of the Earth
- D. The long-range atmospheric distribution of soil following tilling by farm equipment
- E. The spread of invasive species through international trade in potted plants

7. An important goal of integrated pest management is to reduce the amount of pests while also...

- A. Reducing the amount of genetically modified crops grown
- B. Reducing the amount of fertilizer used
- C. Introducing species that prey upon and destroy pest species
- D. Integrating market-based strategies for maximization of profits
- E. Reducing the amount of synthetic chemical pesticides used

8. Which one of the following describes the use of organisms to control pests?

- A. Bioremediation
- B. Intercropping
- C. Species niche partitioning
- D. Vector control
- E. Biological control

9. What practice allows farmers to improve soil fertility, diversify their crops, and reduce pesticide costs by naturally breaking the cycle of weeds, insects, and diseases?

- A. Monoculture
- B. Biological control

- C. Crop sharing
- D. Crop rotation
- E. Soil tilling

10. Which one of the following is more indicative of conventional agriculture, and not sustainable agriculture?

- A. Biological control
- B. Intercropping
- C. Monocultures
- D. Integrated pest management
- E. Minimal tillage

See Appendix for answers

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Chp 10: Air Pollution, Climate Change, & Ozone Depletion



Traffic congestion is a daily reality of 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 and Short-Lived Climate Pollutants
- 10.3 Acid Rain

- 10.4 Global Climate Change
- 10.5 Scientific Consensus: Global Climate Change is Real
- 10.6 Chapter Resources

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10.1 Atmospheric Pollution

Section Goals:

1. Define air pollution.
2. Correlate weather conditions with air quality.
3. Review concerning air pollutants.
4. Introduce the Clean Air Act of the United States.

Air Pollution

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 air pollution and indoor air pollution. **Outdoor air pollution** involves exposures that take place outside of the built environment. Examples include fine particles produced by the burning of coal, noxious gases such as sulfur dioxide, nitrogen oxides and carbon monoxide; ground-level ozone and tobacco smoke. **Indoor air pollution** involves exposures to particulates, carbon oxides, and other pollutants carried by indoor air or dust. 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** is used to describe 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 thought of as non-point sources, such as construction of housing developments, dry lake beds, and landfills.

A **mobile source** of air pollution refers to a source that is capable of moving under its own power. In general, mobile sources imply “on-road” transportation, which includes vehicles such as 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 the animal houses, manure storage areas, or from the 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”.

Air Quality is Influenced by Weather

Some types of pollution are worse in the summer heat, while others are worse in cold winter weather. The same atmospheric conditions that create weather — air pressure, temperature, and humidity — also affect air quality.

Because air is almost always on the move, air pollution is easily transported from one area to another. For example, studies in the 1980s found that sulfur dioxide from coal burning in the Ohio Valley was carried across large distances by the wind. This caused acid rain to fall on regions of the eastern US and Canada up to a thousand miles away. Acid rain causes “dead lakes,” where the acidic lake conditions prevent fish eggs from developing. Similar effects from coal burning have been found in Europe.

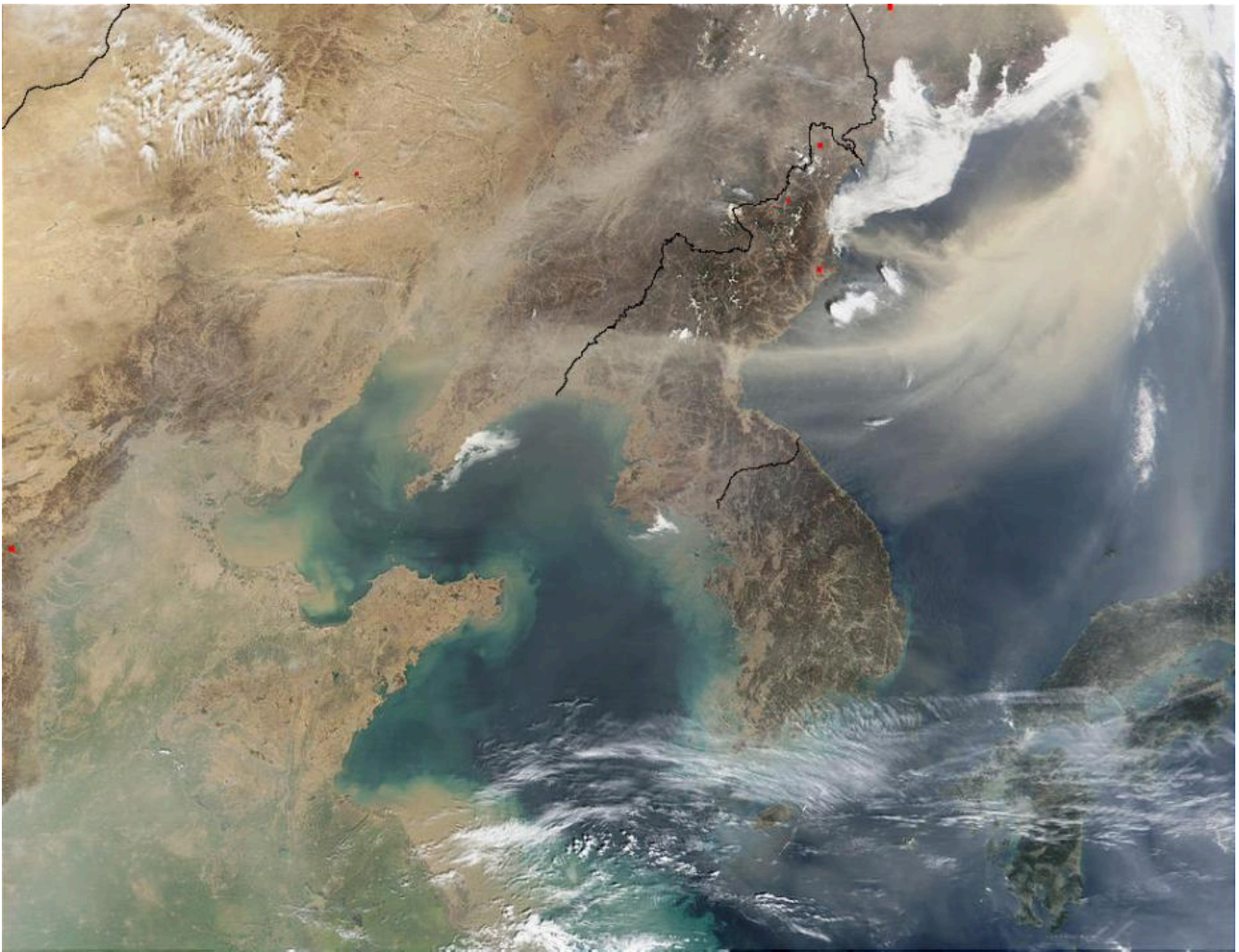


Figure 1: Yellow dust storm over Korea and the Sea of Japan (April 1, 2002)

NASA Goddard Space Flight Center

In Asia, powerful spring winds carry clouds of industrial pollutants from China across the Gobi Desert (Figure 1). As the contaminated winds cross the desert, they pick up particle pollution as well, causing massive yellow dust storms across the Korean Peninsula and parts of Japan. These yellow dust storms reduce visibility, damage plants and soils, and pose significant health risks to humans.

Low-pressure systems bring wet and windy conditions. A passing storm front can wash pollutants out of the atmosphere or transport them to a new area, producing clear skies. It is important to note, however, that the pollutants are not really gone — rather, they have been moved to a new location.

The opposite is true of high-pressure systems, which can create stagnant air. When the air stops moving, pollutants such as vehicle and factory exhaust concentrate over an area.

Cold Weather

When the weather is cold, exhaust from vehicles, chimneys, and smokestacks is more visible. Does this mean that there are more pollutants in the air, or just that the warm vapor exhaust is more visible? Typically, both are true. While industrial emissions remain mostly constant throughout the year,

particulate matter and carbon monoxide pollutants from wood burning increase during the cold winter months. Idling cars to defrost or keep them warm increases the amount of air pollution as well.

Typically, warm rising air near the ground lifts pollution away, but during the winter the layer of warm air acts like a lid, keeping cold air at the surface. This creates a thermal inversion, which forms when a layer of warm air above traps cool air and pollution close to the ground (Figure 2). Thermal inversions are more common above cities where cold, dense air gets trapped in mountain basins or valleys, such as Los Angeles, Denver, and Mexico City.

Hot Weather

Some pollution, such as ground-level ozone, is made more efficiently in sunny, hot weather. The reactions that create harmful ozone in our atmosphere require sunlight. In the summers and especially during extreme heat waves, ozone often reaches dangerous levels in cities or nearby rural areas.

Thankfully, humidity can help to decrease ozone pollution. Afternoon thunderstorm clouds block sunlight, causing ozone production to slow down for the day, while moisture from the storm destroys the ozone that has formed.

Heat waves often lead to poor air quality. The extreme heat and stagnant air during a heat wave increase the amount of ozone pollution and particulate pollution. Drought conditions can also occur during a heat wave, meaning that soils are very dry. During a drought, forest fires are more common. Fires add carbon monoxide and particle pollution to the atmosphere.

EPA">

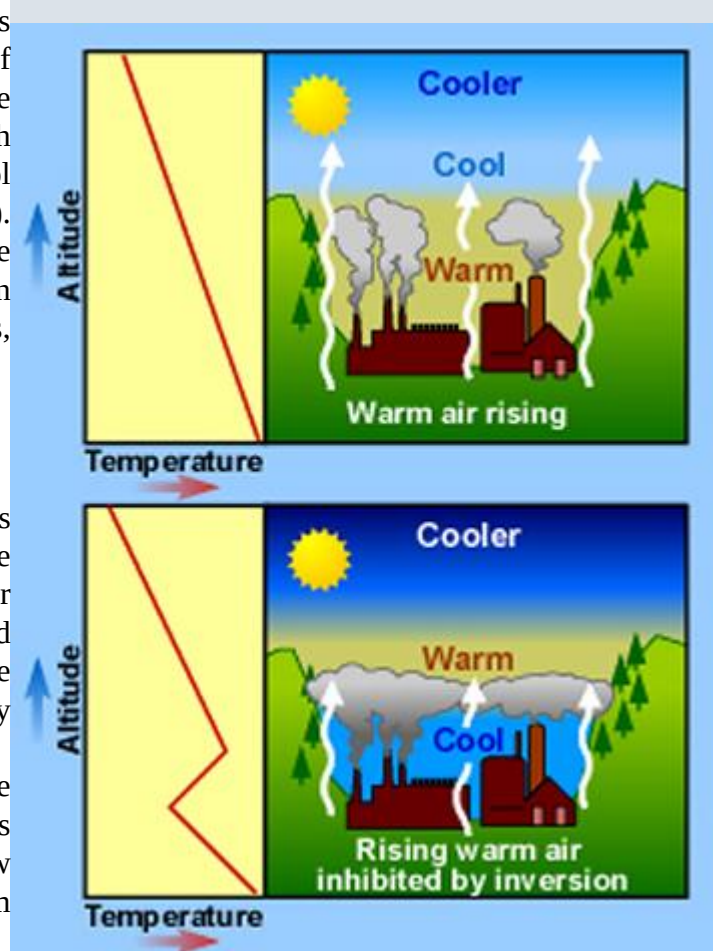


Figure 2: Rising, warm air often helps disperse pollution from near the surface (top), but in a temperature inversion the warm air cannot rise, trapping pollution at the surface (bottom). Credit: EPA

Six Common Air Pollutants

The most commonly found 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 considerations of human and environmental health.

Ground-level ozone is not emitted directly into the air, but is created by chemical reactions between oxides of nitrogen (NO_x) 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 NO_x and VOC. Breathing ozone can trigger a variety of health problems, particularly for children, the elderly, and people of all ages who have 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 is made up of a number of 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 for causing 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 (NO₂) is one of a group of highly reactive gasses known as "oxides of nitrogen," or nitrogen oxides (NO_x). Other nitrogen oxides include nitrous acid and nitric acid. EPA's National Ambient Air Quality Standard uses NO₂ as the indicator for the larger group of nitrogen oxides. NO₂ forms quickly from emissions from cars, trucks and 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 (SO₂) is one of a group of highly reactive gasses known as "oxides of sulfur." The largest sources of SO₂ emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO₂ emissions include industrial processes such as extracting metal from ore, and the burning of high sulfur containing fuels by locomotives, large ships, and non-road equipment. SO₂ is linked with a number of adverse effects on the respiratory system.

Lead is a metal found naturally in the environment as well as in manufactured products. The major sources of lead emissions have historically been from 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 levels of lead in air are usually found near lead smelters. The major sources of lead emissions to the air today are ore and metals processing and piston-engine aircraft operating on leaded aviation gasoline.

Indoor Air Pollution (Major concerns in developed countries)

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 of 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 in which building occupants have health

symptoms that are associated only with spending time in that building. Causes of sick building syndrome are believed to 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. Making sure that your building is well-ventilated and getting rid of pollutants can improve the quality of your indoor air.

Secondhand Smoke (Environmental Tobacco Smoke)

Secondhand smoke is the combination of smoke that comes 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 amount of 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 to not allow smoking indoors. Separating smokers from nonsmokers (like “no smoking” sections in restaurants), cleaning the air, and airing out buildings does not completely get rid of secondhand smoke.

Source: Smokefree.gov

The Clean Air Act in the United States

In 1970, fueled by persistent visible smog in many U.S. cities and industrial areas and an increase in health problems caused by air pollution, the Clean Air Act paved the way for numerous efforts to improve air quality in the United States. The Clean Air Act requires the Environmental Protection Agency (EPA) to set air quality standards for several hazardous air pollutants reported in the Air Quality Index (AQI), requires states to have a plan to address air pollution and emissions reduction, and also addresses problems such as acid rain, ozone holes, and greenhouse gas pollution which is causing the climate to warm.

Since the Clean Air Act was passed:

- The amounts of the six common pollutants in the atmosphere measured by the EPA (particulates, ozone, lead, carbon monoxide, nitrogen dioxide, and sulfur dioxide) are declining.
- The risks of premature death, low birth weight, and other health problems due to air pollution have decreased.
- Vehicle emissions have decreased, despite increases in the number of miles driven each year, due to stricter emissions standards and increased efficiency in vehicle engines.
- Emissions and toxic pollutants (such as mercury and benzenes) from factories and power plants have decreased, due to new technologies.

- There is less acid rain, due to decreased power plant emissions.
- The ozone hole continues to shrink as a result of banning the use of CFCs.
- Pollution-caused haze in cities and wilderness areas has decreased.

Source: EPA

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10.2 Ozone Depletion and Short-Lived Climate Pollutants

Section Goals:

1. Review ozone and its protective function in the stratosphere.
2. Connect depletion of protective ozone to CFCs.
3. Review other atmospheric pollutants that impact global climate and cause net warming.

The Ozone Layer

Ozone (O_3) is a gaseous molecule that occurs in different parts of the atmosphere (Figure 1). It is very reactive chemically 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](#)).

Ozone that occurs in the upper atmosphere is naturally occurring and beneficial to life due to its role in blocking harmful radiation from the sun. This type of ozone is called **stratospheric ozone**. Ozone in the stratosphere forms when the two oxygen atoms in an O_2 molecule are broken apart by the energy of sunlight. 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).

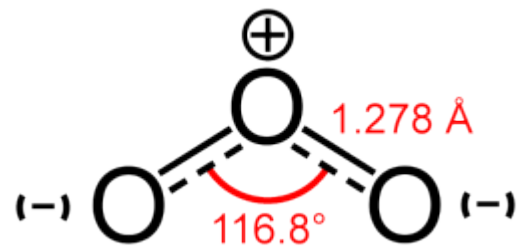


Figure 1: The ozone molecule is comprised of three oxygen atoms covalently bonded. This structure is less stable than oxygen gas (O_2). Credit: Public Domain

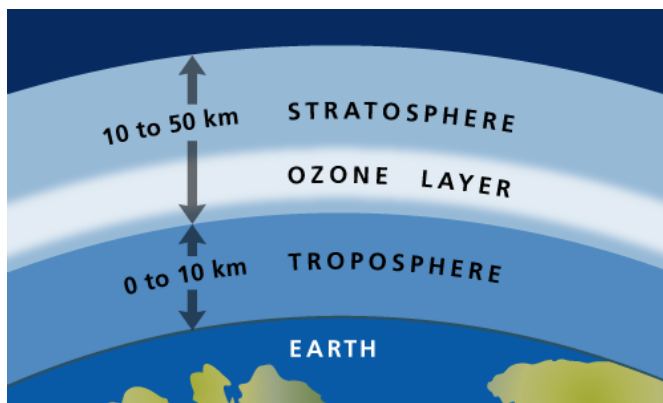


Figure 2: The ozone layer occurs in the region of the atmosphere called the stratosphere. [This Photo](#) by NC Climate Office is licensed under [CC BY-SA](#).

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 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, which can lead 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. CFCs were used by industry as refrigerants, degreasing solvents, and propellants. In the lower atmosphere, CFC molecules are extremely stable chemically and do not dissolve in rain, and thus can linger for long periods. After several years, ODS molecules eventually reach the ozone layer in the stratosphere, which starts at about 10 kilometers above the Earth's surface.

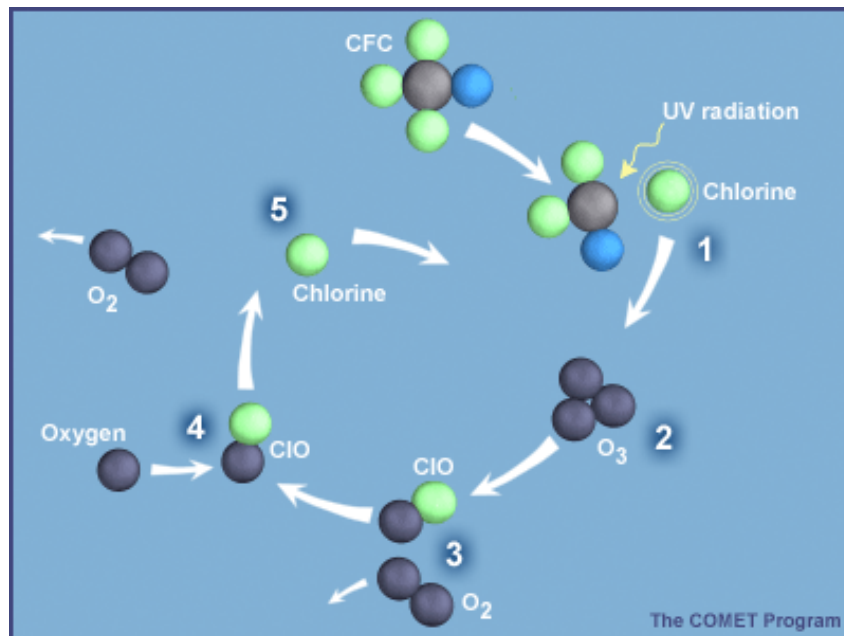


Figure 3: CFCs destroy ozone (O_3) when a chlorine atom breaks loose from the CFC and interacts with the oxygen atoms in the ozone molecule. [This Photo](#) by UCAR is licensed under [CC BY-SA-NC](#).

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), and this leads to a thinning of the ozone layer. This thinning represents a reduction in concentration of ozone molecules in a particular portion of the stratosphere. Areas where the ozone layer has thinned are commonly referred to as holes, although 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 all over the world. 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.

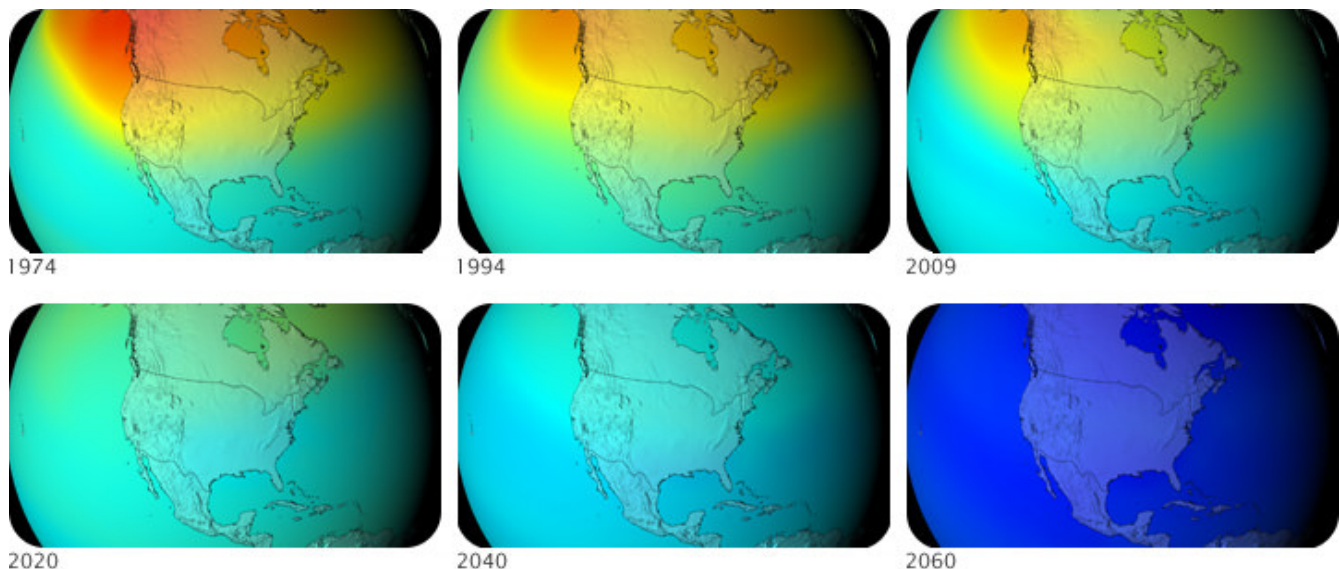


Figure 4: Ozone levels over North America decreased between 1974 and 2009. Models of the future predict what ozone levels would have been if CFCs were not being phased out. Warmer colors indicate more ozone.

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 emission of ODS like CFCs. The recovery process is slow, however, 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, it will take many more decades for the ozone layer to fully recover.

Constant vigilance and monitoring are needed, however, 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 as 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 all of the sun’s UV-C light and most of its UV-B light (Figure 5).

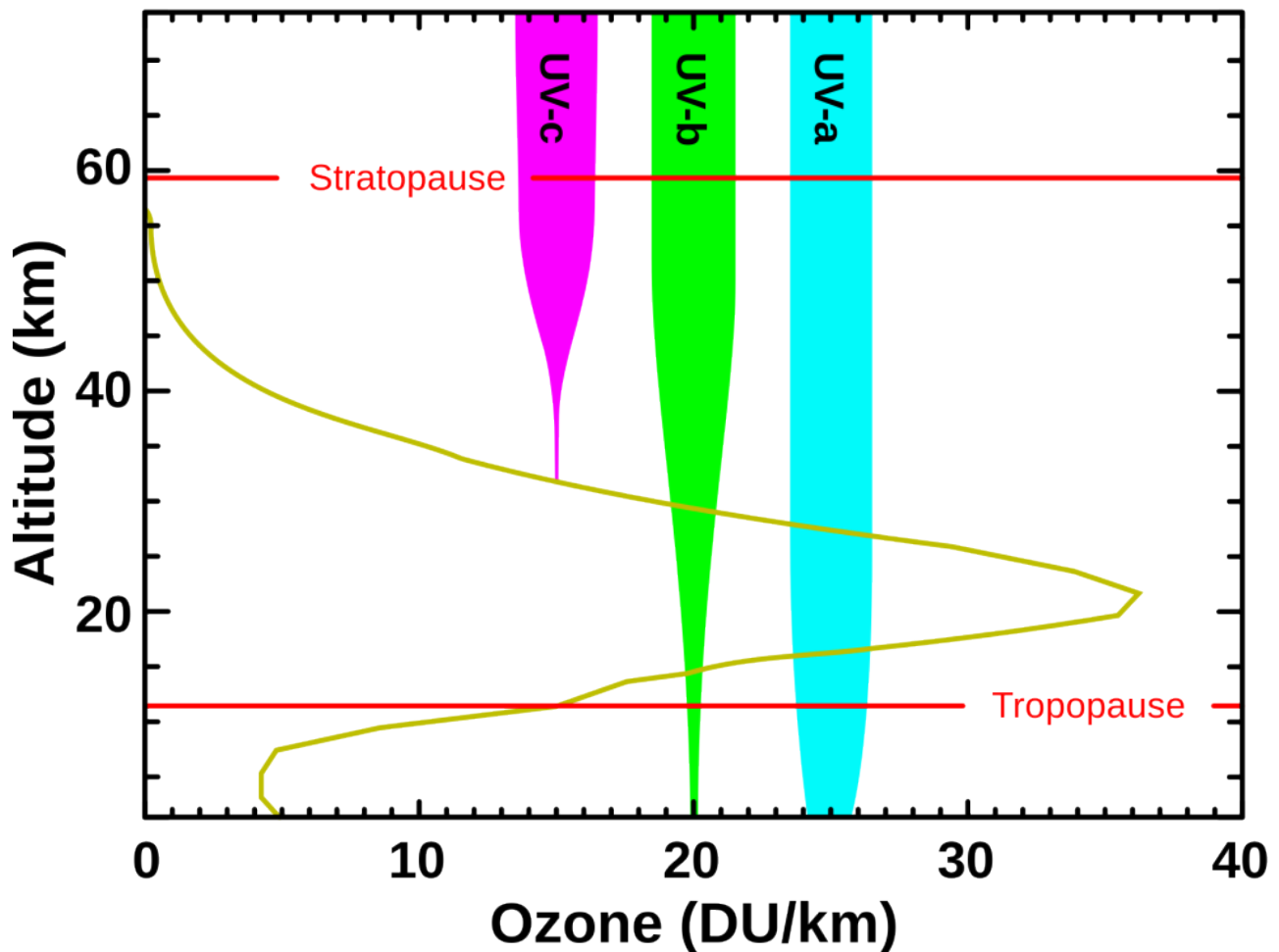


Figure 5: The ozone layer absorbs UV-B and UV-C light, protecting life on Earth from its harmful effects. [This Photo](#) by NASA is licensed under CCO Public Domain.

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 is harmful to cells because it can interact with biomolecules like DNA and damage it. This can lead to mutations and cell death. UV-B cannot penetrate multicellular organisms very far and thus tends to only 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 development of 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, it is important to protect your skin and eyes from the sun. Ozone layer depletion increases the amount of UV-B and the risk of health effects.

Short-Lived Climate Pollutants

Ozone also acts as a short-lived climate pollutant, which causes an increase in the greenhouse effect similar to CO₂, but which disperses quickly. **Short-lived climate pollutants (SLCPs)** are air pollutants that increase radiative forcing, contributing to a warming global climate, but which leave the atmosphere on a short timescale ranging from hours up to 15 years (Figure 6). Essentially, positive radiative forcing means Earth receives more incoming energy from sunlight than it radiates to space because SLCPs and CO₂ trap the heat energy reflected from the earth's surface, causing atmospheric warming. Additionally, SLCPs impact human health, as do all air pollutants ([Section 10.1](#)). SLCPs may cause millions of premature deaths every year. Compared to SLCPs, excess CO₂ remains in the atmosphere for 100 to 1,000 years.

Estimates for the relative responsibility of CO₂ and SLCPs to anthropogenically-induced warming are that CO₂ is responsible for about 60% and SLCPs are responsible for about 40% of the warming global climates. The SLCPs are specifically black carbon, tropospheric ozone, methane, and hydrofluorocarbons (HFCs). Fortunately, there are already some measures in place for regulating these atmospheric pollutants. The previously discussed Montreal Protocol can be applied to targeted reduction of hydrofluorocarbons (the Kigali Amendment to the Montreal Protocol).

Black Carbon: The main sources of black carbon are open burning of biomass, diesel engines, and the residential burning of solid fuels such as coal, wood, dung, and agricultural residues. Black carbon also harms human health; it is a primary component of fine particle air pollution (PM 2.5), which is a major health concern, and specifically can cause or contribute to asthma and other respiratory problems, low birth weights, heart attacks, and lung cancer. Though not all particulates released through combustion are dark or black color, with the lighter particles potentially leading to climatic cooling, there is evidence that the net effect is to increase climatic temperature. Any of these particulates released by combustion also increase the rate of melting of ice and snow, because deposition of particles, including dust, reduces the reflectivity (albedo) of snow and ice, allowing more solar radiation to be absorbed, causing faster melting.

Tropospheric ozone: Lower atmosphere (tropospheric) ozone is a major air and climate pollutant which causes warming and is harmful to human health and crop production. Breathing ozone is particularly dangerous to children, older adults and people with lung diseases, and can cause bronchitis, emphysema, asthma, and may permanently scar lung tissue. Its impacts on plant include not only lower crop yields but also a reduced ability to absorb CO₂.

Tropospheric ozone is not emitted directly but instead forms from reactions between precursor gases, both human-produced and natural. These precursor gases include carbon monoxide, oxides of nitrogen (NO_x), and volatile organic compounds (VOCs), which include methane. Globally increased methane emissions are responsible for approximately two thirds of the rise in tropospheric ozone. Reducing emissions of methane will lead to significant reductions in tropospheric ozone and its damaging effects.

Methane: Methane (CH₄) is released naturally from wetlands, but about 60% of current methane emissions are attributed to anthropogenic activity. An additional worry is that climate change could increase atmospheric methane levels by increasing methane production in natural ecosystems, forming a positive feedback. The main sources of anthropogenic methane emissions are oil and gas systems; agriculture, including enteric fermentation, manure management, and rice cultivations; landfills; wastewater treatment; and emissions from coal mines. Methane is the primary component of natural gas, with some emitted to the atmosphere during its production, processing, storage, transmission, and distribution.

Hydrofluorocarbons (HFCs): HFCs are factory-made chemicals used primarily in refrigeration and insulating foams. They have a warming effect hundreds to thousands of times more powerful than CO₂. The average lifetime of the mix of HFCs, weighted by usage, is 15 years. HFCs are the fastest growing greenhouse gases in many countries, including the U.S., where emissions grew nearly 9% between 2009 and 2010 compared to 3.6% for CO₂. Globally, HFC emissions are growing 10 to 15% per year and are expected to double by 2020. Fast action is needed to limit their growth.

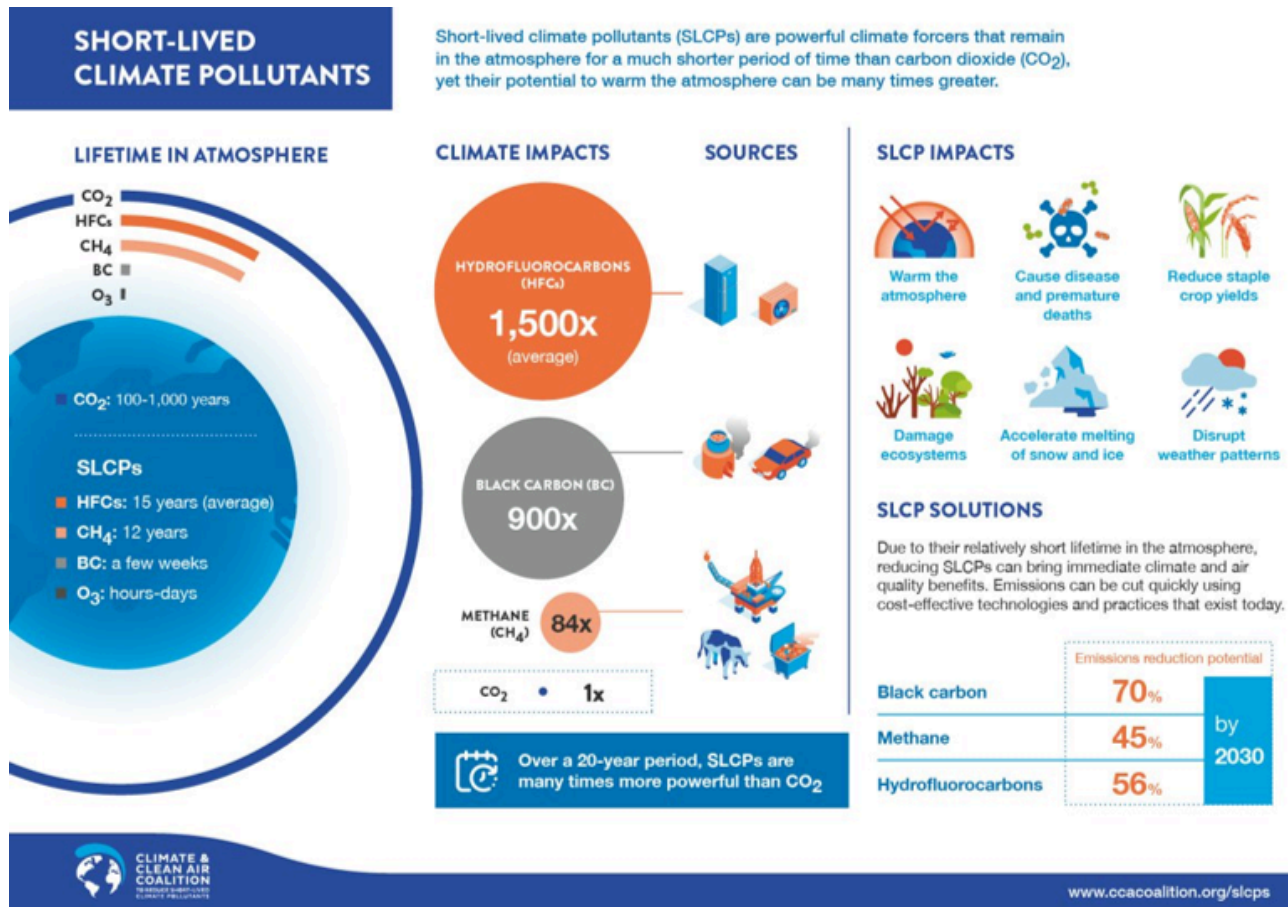


Figure 6: Though CO₂ is the longest lived and causes about 60% of anthropogenic climate warming, there are 4 other pollutants of concern that have a shorter lifetime in the atmosphere, but cause more warming when they are in the atmosphere. Credit: Climate and Clean Air Coalition www.ccacoalition.org/slcp; Licensed for non-commercial and educational use with attribution.

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10.3 Acid Rain

Section Goals:

1. Connect air pollution with acid rain.
2. Understand ecological and economic effects of acid rain.

Acid Rain

Acid–base reactions can have a strong environmental impact. For example, a dramatic increase in the acidity of rain and snow over the past 150 years is dissolving marble and limestone surfaces, accelerating the corrosion of metal objects, and decreasing the pH of natural waters. This environmental problem is called **acid rain** and has significant consequences for all living organisms. Acid rain is a term referring to a mixture of wet and dry deposition (deposited material) from the atmosphere containing higher than normal amounts of nitric and sulfuric acids. Recall that pH is a scale based on the quantity of H^+ ions present ([Section 2.1](#)). The lower a substance's pH, the more acidic it is. Pure water has a pH of 7.0.

To understand acid rain requires an understanding of acid–base reactions in aqueous solution. The term *acid rain* is actually somewhat misleading because even pure rainwater collected in areas remote from civilization is slightly acidic ($\text{pH} \approx 5.6$) due to dissolved carbon dioxide, which reacts with water to give carbonic acid, a weak acid.

The English chemist Robert Angus Smith is generally credited with coining the phrase *acid rain* in 1872 to describe the increased acidity of the rain in British industrial centers (such as Manchester), which was apparently caused by the unbridled excesses of the early Industrial Revolution, although the connection was not yet understood. At that time, there was no good way to measure hydrogen ion concentrations, so it is difficult to know the actual pH of the rain observed by Smith. Typical pH values for rain in the continental United States now range from 4 to 4.5, with values as low as 2.0 reported for areas such as Los Angeles. Recall that rain with a pH of 2 is comparable in acidity to lemon juice, and even “normal” rain is now as acidic as tomato juice or black coffee.

What is the source of the increased acidity in rain and snow? Chemical analysis shows the presence of large quantities of sulfate SO_4^{2-} and nitrate NO_3^- .

SO_4^{2-}

and nitrate NO_3^-

NO_3^-

ions, and a wide variety of evidence indicates that a significant fraction of these species come from nitrogen and sulfur oxides produced during the combustion of fossil fuels. The precursors, or chemical forerunners, of acid rain formation can also result from natural sources, such as volcanoes and decaying vegetation, but as just stated, the man-made sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) resulting from fossil fuel combustion are a growing contributor that

can be regulated and limited (Figure 1). 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 occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds.

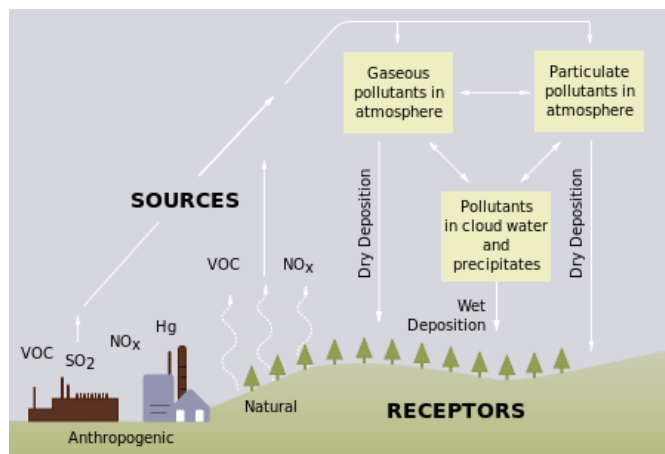


Figure 1: Processes involved in acid deposition. Credit: Public Domain.

Specifically, nitric acid is the ultimate result of the interaction of nitric oxide with rain. First, at the high temperatures found in both internal combustion engines and lightning discharges, molecular nitrogen and molecular oxygen react to give nitric oxide. Nitric oxide then reacts rapidly with excess oxygen to give nitrogen dioxide, the compound responsible for the brown color of smog. When nitrogen dioxide dissolves in water, it forms a 1:1 mixture of nitrous acid and nitric acid, and then molecular oxygen eventually oxidizes nitrous acid to nitric acid, thus nitric acid (HNO₃) is the ultimate end product of the reaction.

Large amounts of sulfur dioxide have always been released into the atmosphere by natural sources, such as volcanoes, forest fires, and the microbial decay of organic materials, but for most of Earth's recorded history the natural cycling of sulfur from the atmosphere into oceans and rocks kept the acidity of rain and snow in check. Unfortunately, the burning of fossil fuels seems to have tipped the balance. Many coals contain as much as 5%–6% pyrite FeS_2

by mass, and fuel oils typically contain at least 0.5% sulfur by mass. Since the mid-19th century, these fuels have been burned on a huge scale to supply the energy needs of our modern industrial society, releasing tens of millions of tons of additional SO_2

into the atmosphere annually. In addition, roasting sulfide ores to obtain metals such as zinc and copper produces large amounts of sulfur dioxide. Regardless of the source, the SO_2

dissolves in rainwater to give sulfurous acid, which is eventually oxidized by oxygen to sulfuric acid.

Concerns about the harmful effects of acid rain have led to strong pressure on industry to minimize the release of sulfur dioxide and nitric oxide. SO_2 NO

For example, coal-burning power plants now use sulfur dioxide SO_2

“scrubbers,” which trap sulfur dioxide by its reaction with lime SO_2 CaO

to produce calcium sulfite dihydrate (Figure 2). $\text{CaSO}_3 \cdot 2\text{H}_2\text{O}$

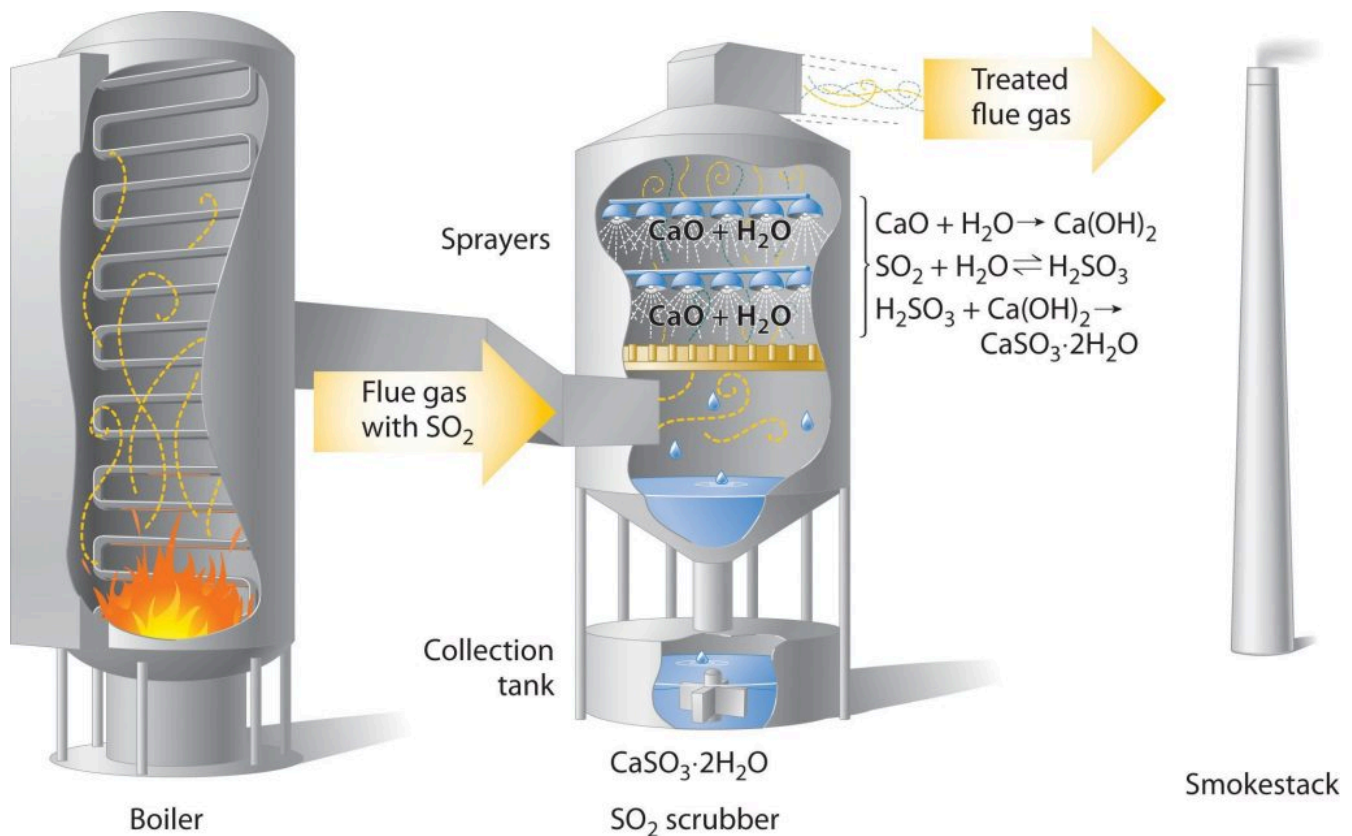


Figure 2: In coal-burning power plants, SO_2 can be removed ("scrubbed") from exhaust gases by its reaction with a lime (CaO) and water spray to produce calcium sulfite dihydrate ($\text{CaSO}_3 \cdot 2\text{H}_2\text{O}$). Removing SO_2 from the gases prevents its conversion to SO_3 and subsequent reaction with rainwater (acid rain). Scrubbing systems are now commonly used to minimize the environmental effects of large-scale fossil fuel combustion.

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. Prior to 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 the 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, which are located 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 itself and its surrounding soil cannot buffer the acid rain enough to neutralize it.

Biological fluids, such as blood, have a pH of 7–8. Organisms such as fish can maintain their internal

pH in water that has a pH in the range of 6.5–8.5. If the external pH is too low, however, many aquatic organisms can no longer maintain their internal pH, so they die. A pH of 4 or lower is fatal for virtually all fish, most invertebrate animals, and many microorganisms. As a result of acid rain, the pH of some lakes in Europe and the United States has dropped below 4. Recent surveys suggest that up to 6% of the lakes in the Adirondack Mountains of upstate New York and 4% of the lakes in Sweden and Norway are essentially dead and contain no fish. Neither location contains large concentrations of industry, but New York lies downwind of the industrial Midwest, and Scandinavia is downwind of the most industrialized regions of western Europe. Both regions appear to have borne the brunt of the pollution produced by their upwind neighbors. One possible way to counter the effects of acid rain in isolated lakes is by adding large quantities of finely ground limestone, which would neutralize the acidity.



Figure 3: A forest in the Czech Republic damaged by the toxicity of aluminum.

Acid rain also causes acidity in soils by releasing aluminum ions (Al^{3+}). Trees and many other plants are sensitive to the presence of aluminum and other metals in groundwater. Under normal circumstances, aluminum hydroxide, which is present in some soils, is insoluble. At lower pH values, however, it dissolves. The result is increased levels of Al^{3+} ions in groundwater. Because the Al^{3+} ion is toxic to plants, high concentrations can affect plant growth. Acid rain can also weaken the leaves and roots of plants so much that the plants are unable to withstand other stresses. The combination of the two effects can cause significant damage to established forests, such as the Black Forest in Germany and the forests of the

northeastern United States and Canada and other countries (Figure 4). Therefore, acid rain causes slower growth, injury, or death of forests.



Figure 4: A gargoyle that has been damaged by acid rain. Credit: Public Domain.

Another concern of acid rain is the corrosion to human-built structures and works of art. Acid rain and the dry deposition of acidic particles contribute to the corrosion of metals (such as bronze), the deterioration of paint, and dissolution of stone (such as marble and limestone). These effects significantly reduce the societal value of buildings, bridges, cars, and cultural objects (such as statues, monuments, and tombstones) (Figure 4).

Finally, there are other direct impacts to humans worth mentioning. The sulfates and nitrates that form in the atmosphere from sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions contribute to visibility impairment,

meaning we cannot see as far or as clearly through the air. The pollutants also damage human health ([Section 10.1](#)). As stated at the beginning of the section, 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.

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10.4 Global Climate Change

Section Goals:

1. Understand climate change.
2. Understand the benefits of the natural greenhouse effect.
3. Understand natural and human induced impacts on the global climate.

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 a wide range of 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 (GHG) concentrations. Recent changes in climate, however, cannot be explained by natural causes alone. Research indicates that natural causes are very unlikely to explain most observed warming, especially warming since the mid-20th century. Rather, it is extremely likely that human activities, especially our combustion of fossil fuels, explains most of that warming. The scientific consensus is clear: through alterations of the carbon cycle, humans are changing the global climate by increasing the effects of something known as the greenhouse effect.

The Greenhouse Effect Causes the Atmosphere to Retain Heat

Gardeners that live in moderate or cool environments use greenhouses because they trap heat and create an environment that is warmer 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 allow 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 with 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 much 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 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 with 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 that is radiated from the Earth towards 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 (H₂O), carbon dioxide (CO₂), and methane (CH₄). GHGs act like a blanket, making Earth significantly warmer than it would otherwise be. Scientists estimate that average temperature on Earth would be -18° 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.

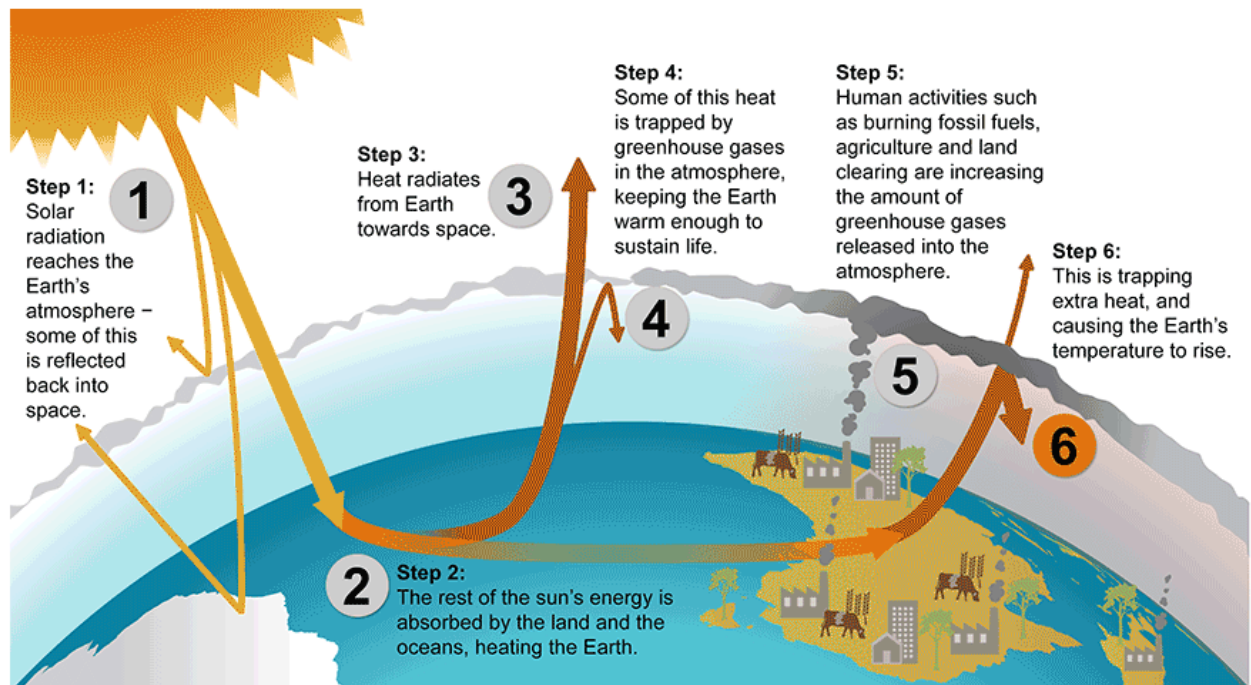


Figure 1: Enhanced Greenhouse Effect

The Main Greenhouse Gasses

The most important GHGs directly emitted by humans include CO₂ and methane. **Carbon dioxide** (CO₂) is the primary greenhouse gas that is contributing to recent global climate change. CO₂ 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 CO₂ to the atmosphere, causing its concentration in the atmosphere to rise.

Atmospheric CO₂ 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 (Figure 2). The current CO₂ 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 CO₂ into the atmosphere every year. While some volcanic eruptions released large quantities of CO₂ in the distant past, the U.S. Geological Survey (USGS) reports that human activities now emit more than 135 times as much CO₂ as volcanoes each year. This human-caused build-up of CO₂ in the atmosphere is like a tub filling with water, where more water flows from the faucet than the drain can take away.

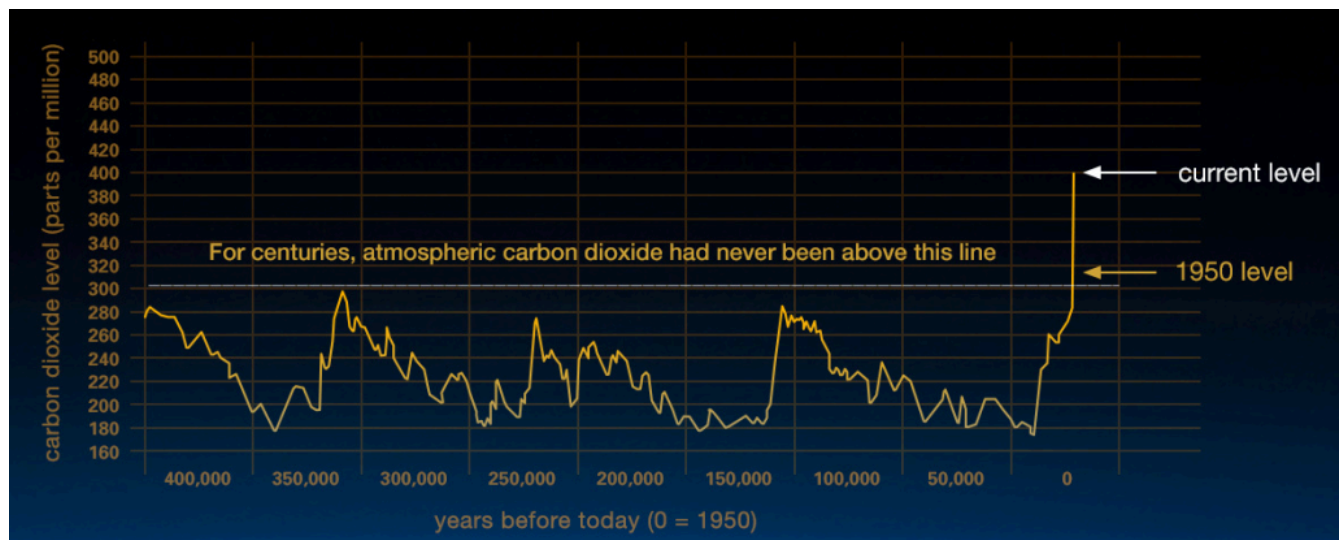


Figure 2: This graph, based on the comparison of atmospheric samples contained in ice cores and more recent direct measurements, provides evidence that atmospheric CO_2 has increased since the Industrial Revolution. (Credit: Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO_2 record.)

Methane (CH_4) is produced through both natural and human activities. For example, wetlands, agricultural activities, and fossil fuel extraction and transport all emit CH_4 . Methane is more abundant in Earth's atmosphere now than at any time 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

Water vapor is the most abundant greenhouse gas and also the most important in terms of its contribution to the natural greenhouse effect, despite having a short atmospheric lifetime. Some human activities can influence local water vapor levels. However, on a global scale, the concentration of water vapor is controlled by temperature, which influences overall rates of evaporation and precipitation. Therefore, the global concentration of water vapor is not substantially affected by direct human emissions.

Ground-level ozone (O_3), which also has a short atmospheric lifetime, 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 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 as well as 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 had a big impact on 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), as well as 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 the recent warming of Earth. Similarly, changes in the shape of Earth’s orbit as well as the tilt and position of Earth’s axis affect 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. The term **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 feedbacks 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 surface of the planet 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 for a much shorter time 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.

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10.5 Scientific Consensus: Global Climate Change is Real

Section Goals:

1. Review the results of the recent IPCC report.
2. Understand future predictions due to climate change.
3. Consider how climate change affects everyone and how you can take action.

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 charged with the task of evaluating and synthesizing the scientific evidence surrounding global climate change. The IPCC uses this information to evaluate current impacts and future risks, in addition to providing 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 from around the world 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 for 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), also agree that climate change is occurring and that humans are driving it. In 2010, the US National Research Council concluded that “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, both 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

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 continue to 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 fully respond to higher greenhouse gas concentrations. 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 the level of future greenhouse gas emissions, and the outcomes from various climate models.
- By 2100, global average temperature is expected to warm at least twice as much as it has 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 both rain and snowfall are likely to change. However, some of these changes are less certain than the changes associated with temperature. Projections show that future precipitation and storm changes will 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 is likely to 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 add significantly to global sea level rise. Glaciers are expected to continue to decrease in size. The rate of melting is expected to continue to increase, which will contribute to sea level rise.

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 around the world. For example, relative sea level rise depends on land elevation changes that occur as a result of subsidence (sinking) or uplift (rising), in addition to things such as 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 (CO₂) 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, which is 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 CO₂ 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 CO₂ concentrations double, coral calcification rates are projected to decline by more than 30%. If CO₂ 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. This spread has already been documented with dengue fever, a disease that affects hundreds of millions per year, according to the World Health Organization. Colder temperatures typically limit the distribution of certain species, such as the mosquitoes that transmit malaria, because freezing temperatures destroy their eggs.

Not only will the range of some disease-causing insects expand, the increasing temperatures will also accelerate their lifecycles, which allows 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 and transportation systems, the natural environment, and even our own health and safety.

Carbon dioxide can stay in the atmosphere for nearly a century, on average, 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 changes that are already underway, 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 on a local or state level 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). <http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf>

NASA. 2018. [Global Climate Change: Vital Signs of the Planet](https://climate.nasa.gov/). 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.

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10.6 Chapter Resources

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 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. The commonly found air pollutants, known as 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.

Acid rain is a term referring 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 (SO₂) and nitrogen oxides (NO_x) resulting from fossil fuel combustion. Acid rain causes acidification of lakes and streams, contributes to the damage of 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 that lead to negative health and environmental effects.

The historical record shows that the climate system varies naturally over a wide range of 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 very unlikely to explain most observed warming, especially warming 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 the burning of 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 level and increase the acidity of the oceans. These changes will impact our food supply, water resources, infrastructure, ecosystems, and even our own health.

Review Questions

1. Ground-level ozone...

- A. Protects us from radiation
- B. Is a primary pollutant
- C. Is a secondary pollutant

- D. Reduces visibility but is mostly harmless to human health
- E. Is emitted from motor vehicles

2. Secondary pollutants are pollutants...

- A. Emitted from non-point sources
- B. That are created from the reaction of primary pollutants and other chemicals
- C. That are less hazardous than primary pollutants
- D. That have reduced ability to stay aloft in the atmosphere
- E. Emitted by Class 2 polluters

3. Depletion of the stratospheric ozone layer occurs when molecules of ozone are destroyed by chemicals such as...

- A. CFC
- B. DDT
- C. O₃
- D. PCB
- E. CH₄

4. What is the function of the stratospheric ozone layer?

- A. Provides the biosphere with a source of elemental oxygen
- B. Protects against ultraviolet light
- C. Shields the Earth from high-energy cosmic rays
- D. Protects organisms from infrared radiation
- E. Creates UVB radiation for vitamin D synthesis

5. Anthropogenic causes of acid rain are primarily due to which one of the following?

- A. Destruction of the ozone layer
- B. Emissions of sulfur dioxide and nitrogen oxides from the combustion of fossil fuels
- C. Emissions of carbon dioxide from the combustion of fossil fuels
- D. Industrial emissions of acids
- E. Acids formed in the contrails of airplanes

6. The scientific consensus regarding global climate change is that these changes are...

- A. Caused by natural, Earth-based phenomena such as volcanoes
- B. Poorly understood and no scientific conclusions can be made at this time
- C. Primarily caused by human activities
- D. Caused by eccentricity in Earth's orbit and by changes in solar intensity
- E. No greater or different than changes seen in the medieval times

7. Greenhouse gases are known to raise air temperatures by...

- A. absorbing infrared radiation
- B. creating heat through chemical reactions with atmospheric pollutants
- C. absorbing incoming visible light from the sun
- D. trapping high energy molecules and atomic particles
- E. releasing heat stored in high-altitude catalytic cycles

8. Changes in reflectivity of visible light affect how much energy enters Earth's system. What term is used by scientists to describe the reflectivity of a surface?
- A. Contrastivity
 - B. Libido
 - C. Mirror-effect
 - D. Alluvium
 - E. Albedo
9. What is the primary cause of ocean acidification?
- A. Atmospheric CO₂ dissolving in ocean water
 - B. Increases in acid rain
 - C. Increased erosion of acid-containing rocks
 - D. Water draining into the ocean has a higher pH from industrial pollutants
 - E. All of the above
10. Which one of the following is not a predicted consequence of global climate change?
- A. Spread of diseases carried by insects, such as malaria
 - B. Rise in sea levels
 - C. Increases in the global average air and ocean temperatures
 - D. Intensity of precipitation events will likely increase on average.
 - E. All of the above

See Appendix for answers

Attribution

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Chapter 11: Conventional & 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

- 11.1 Challenges and Impacts of Energy Use
- 11.2 Non-Renewable Energy Sources
- 11.3 Renewable Energy Sources
- 11.4 Hydrogen and Electricity as Alternative Fuels

- 11.5 Electricity Grid and Sustainability Challenges
- 11.6 Chapter Resources

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11.1 Challenges and Impacts of Energy Use

Section Goals:

1. Review energy and its connection to human society.
2. Understand fossil fuels and some politics related to their extraction and use.

Our society runs on energy

Energy for lighting, heating and cooling our buildings, manufacturing products, and powering our transportation systems comes from a variety of natural sources. The earth's core provides geothermal energy. The gravitational pull of moon and sun create tides. The sun emits light (electromagnetic radiation), which creates 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, 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 and some environmental and health cost, and the distribution of energy 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 place of energy generation, and ends with the disposal of waste generated during use.

Extraction of fossil fuels can be used as a case study because its use has significant impacts on 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 of petroleum, gas and coal generates various types of emissions and wastes, as well as utilizes water resources. Production of energy 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 nuclear power plants are regulated by the Nuclear Regulatory Commission.

Geopolitical Challenges of Fossil Fuels

The use of 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 fossil fuel reserves of their own, they incur even more risk. The United States has become more and more dependent on foreign oil since 1970 when our own oil production peaked. The United States imported over half of the crude oil and refined petroleum products that we consumed during 2009. Just over half of these imports came from the Western Hemisphere (Figure 1).

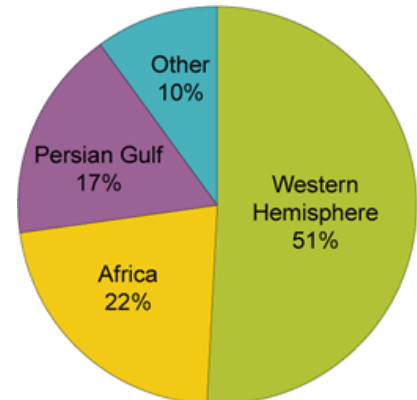


Figure 1: Sources of United States Net Petroleum Imports, 2009

Figure illustrates that the United States imported over half of the crude oil and refined petroleum products that it consumed during 2009. Source: U.S. Energy Information Administration, *Petroleum Supply Annual, 2009*, preliminary data.

The major holder of oil reserves is the **Organization of Petroleum Exporting Countries**, (OPEC) (Figure 2). 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. All of 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 have a large influence on how much of world demand is met by OPEC and non-OPEC supply. A recent example of this is the price increases that occurred during the year 2011 after multiple popular uprisings in Arab countries, including Libya.

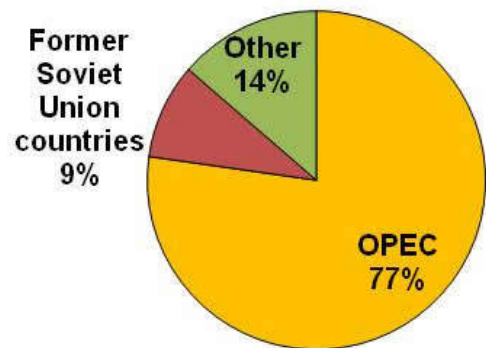


Figure 2: Proven Oil Reserves Holders Pie chart shows proven oil reserves holders.

Source: C. Klein-Banai using data from BP *Statistical Review of World Energy* (2010)

This pressure has lead the United States to developing 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 that has oil reserves. Oil wealth may be shared with the country's inhabitants or retained by the oil companies and dictatorships, such as in Nigeria prior to the 1990s.

The use of fossil fuels has an enormous impact on climate change by increasing the carbon dioxide in the atmosphere. Some fossil fuels have a lower climatic impact than others (Figure 3).

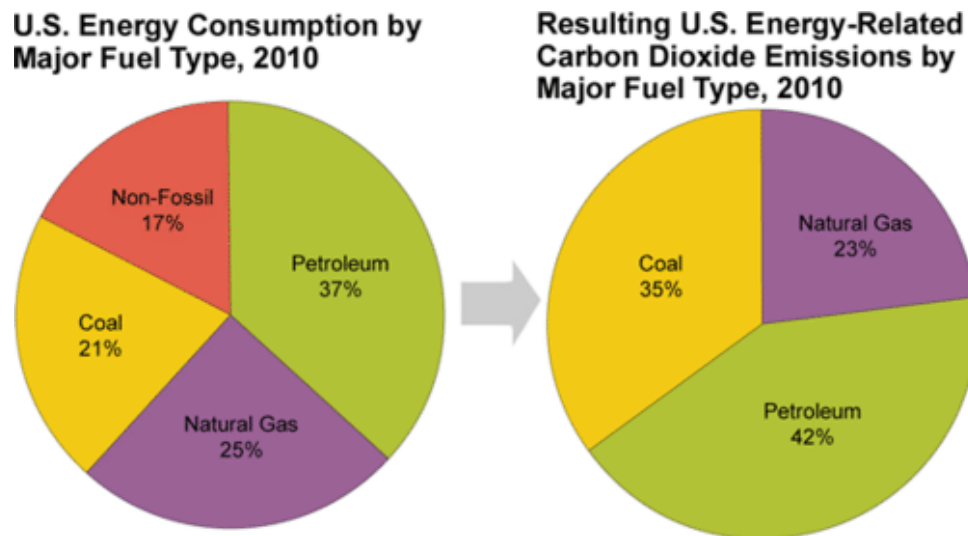


Figure 3: Fuel Type and Carbon Emissions The two charts show the relationship between fuel type and carbon emissions for U.S. energy consumption in 2010.

Source: U.S. Energy Information Administration

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11.2 Non-Renewable Energy Sources

Section Goals:

1. Review the types of fossil fuel.
2. Understand nuclear power.

Fossil Fuels

Fossil fuels comes from the organic matter of plants, algae, and cyanobacteria that was buried, heated, and compressed under high pressure over millions of years. The process transformed the biomass of those organisms into the three types of fossil fuels: oil, coal, and natural gas.

Petroleum (oil)

Thirty seven percent of the world's energy consumption and 43% of the United States energy consumption comes from oil. Scientists and policy-makers often discuss the question of 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 a lot of variables must be considered. Currently world reserves are 1.3 trillion barrels, or 45 years left at current level of production.

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 that is on land or ocean. Once 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 top sources of air pollution in the United States for volatile organic hydrocarbons and 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 (CO₂) is a greenhouse gas and a source of climate change.
- Sulfur dioxide (SO₂) causes acid rain, which damages plants and animals that live in water, and it 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 ozone at ground level, which is an irritant and causes damage to the lungs.
- 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.

There are other domestic sources of oil that are being considered as conventional resources and are being depleted. These include **tar sands** – deposits of moist sand and clay 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 the presence of hydrogen to extract liquid petroleum. However, the net energy values are low and they are expensive to extract and process. Both of these resources have severe environmental impacts due to strip mining, carbon dioxide, methane and other air pollutants similar to other 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 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 livelihood 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, providing fuel for 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 the price of oil in the last decade makes dependence on imported energy for transportation an economic as well as 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 a solid. Due to its relatively low cost and abundance, coal is used to generate 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 year (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.

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 have been linked to acid rain, smog, and health issues. Burning of coal emits higher amounts of carbon dioxide per unit of energy than the use of oil or natural gas. Coal accounted for 35% of the total United States emissions of carbon dioxide 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 in the vicinity of 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 and it has varied 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 less safety regulations, accidents occur more frequently. In May 2011, for example, three people died and 11 were trapped in a coalmine in Mexico for several days. There is also risk of getting **black lung disease** (pneumoconiosis). This is a disease of the lungs caused by the inhalation of coal dust over a long period of 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 gets increasingly worse.



Figure 1. Historic U.S. Coal Production Graph shows U.S. Coal Production from 1950-2010.

Source: U.S. Energy Information Administration



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, has particularly detrimental effects on 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 habitat.

Natural Gas

Natural gas meets 20% of world energy needs and 25% of 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 anaerobic decay of organic matter by bacteria, 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, and 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 to be 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 it has become more economical to extract the gas from shale. 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).

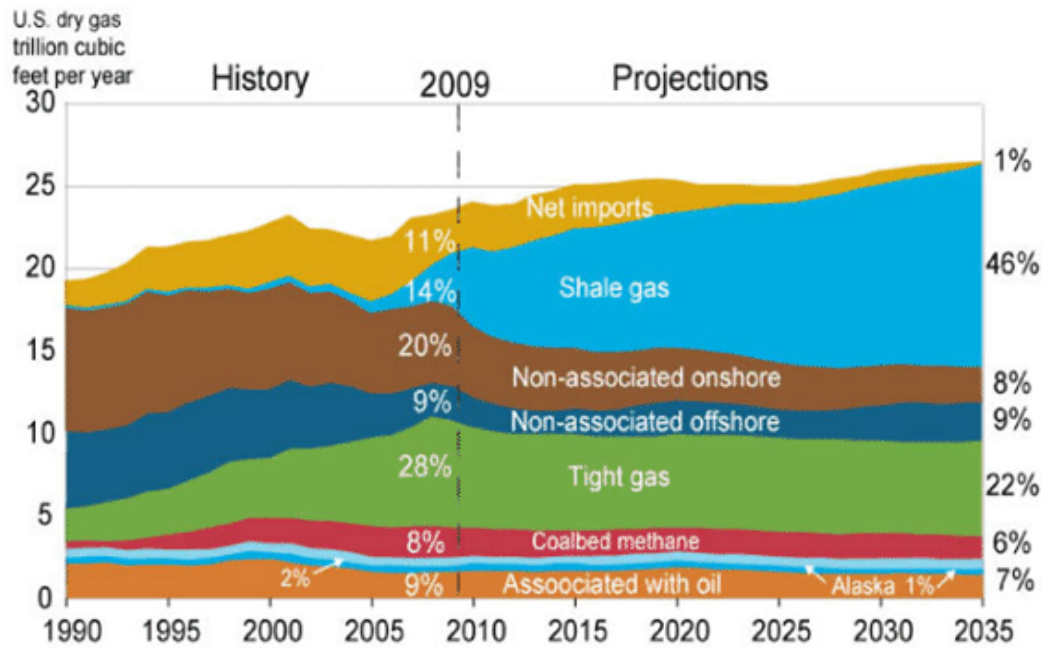


Figure 3. U.S. Natural Gas Supply, 1990-2035 Graph shows U.S. historic and projected natural gas production from various sources. Source: U.S. Energy Information Administration

Natural gas is a preferred fossil fuel when considering its environmental impacts. Specifically, when burned, much less carbon dioxide (CO₂), nitrogen oxides, and sulfur dioxide are omitted than 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. Extraction of shale gas 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 the flow of gas 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 the availability of water for other uses in some regions and this 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).

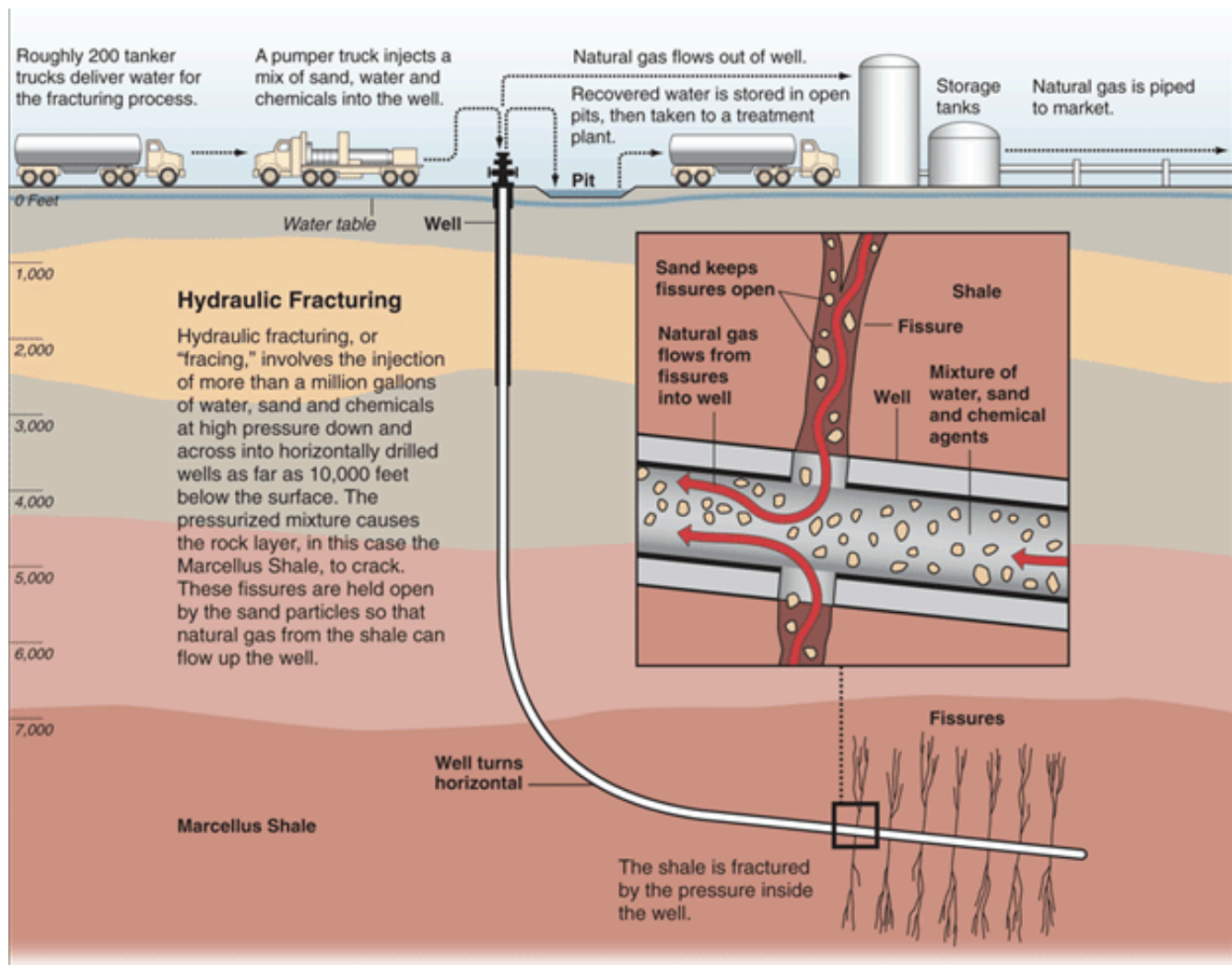


Figure 4. Graphic illustrates the process of hydraulic fracturing. Source: Al Granberg, ProPublica.

The raw gas from a well may contain many other compounds besides the methane that is being sought, including hydrogen sulfide, a very toxic gas. Natural gas with high concentrations of hydrogen sulfide is usually flared which produces CO₂, 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

At present the fossil fuels used for electricity generation in the US 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 significantly greater contributor to global warming and climate change.

The Future of Natural Gas and Coal

The future development of coal and natural gas depend on the degree of public and regulatory concern for carbon emissions, and the relative price and supply of the two fuels. Supplies of coal 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 retirement of coal and 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 has increased 48% annually in the years 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.

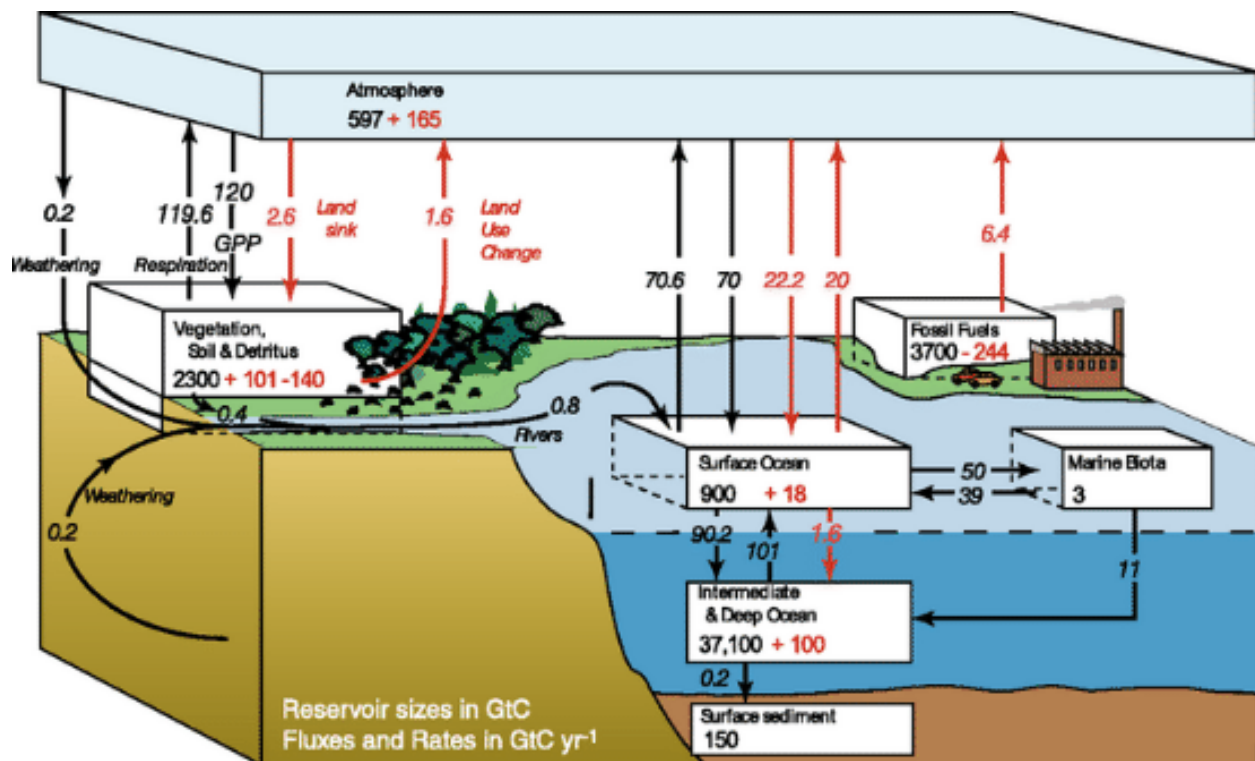


Figure 5. Global Carbon Cycle, 1990s The global carbon cycle for the 1990s, showing the main annual fluxes in GtC yr⁻¹: pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red. Source: Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment 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, therefore, are often considered an **alternative fuel** (fuels other than fossil fuels). Currently, world production of electricity 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 the wastes including uranium mill tailings, spent (used) reactor fuel, and other radioactive wastes. These materials have long radioactive half-lives and thus remain a threat to human health for thousands of years. The **half life** of a radioactive element is the time it takes for 50% of the material to radioactively decay. 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.

There are many other regulatory precautions governing permitting, construction, operation, and decommissioning of nuclear power plants due to risks from an uncontrolled nuclear reaction. The potential for contamination of air, water and food is high should an uncontrolled reaction occur. Even when planning for worst-case scenarios, there are always risks of unexpected events. 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.

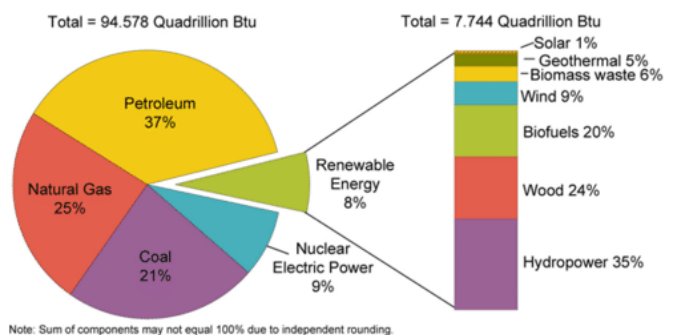


Figure 7. U.S. Energy Consumption by Energy Source, 2009 Renewable energy makes up 8% of U.S. energy consumption. Source: U.S. Energy Information Administration

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 could be diverted by terrorists or others to destroy cities and poison the environment, and iii) threatens the natural and built environment through accidental leaks of long-lived radiation. Thoughtful scientists, policy makers, 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 permanently change the dynamics of the earth. 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 on the negative side for the risk of nuclear proliferation.

Nuclear electricity came on 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 production of electricity. 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 Chernobyl 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 Chernobyl, reminds us that safety and public confidence are especially important in nuclear energy; without them expansion of nuclear energy will not happen.

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11.3 Renewable Energy Sources

Section Goals:

1. Review types of renewable energy source.
2. Understand the potential expansion of use for these energy sources.

Hydropower

Hydropower (hydroelectric) relies on water to spin turbines and create electricity. It is considered a clean and renewable source of energy because it does not directly produce pollutants and because the source of power is regenerated. Hydropower provides 35% of the United States' renewable energy consumption.

Hydropower dams and the reservoirs they create can have environmental impacts. For example, 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 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.

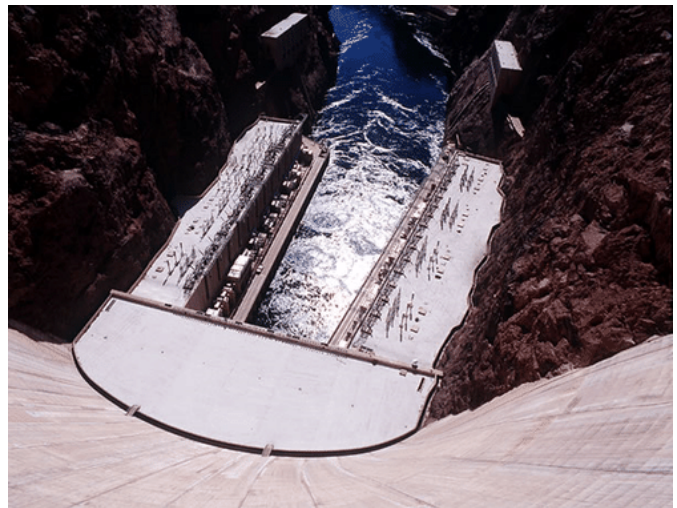


Figure 1. Hoover Power Plant View of Hoover Power Plant on the Colorado River as seen from above. Source: U.S. Department of the Interior

Small hydropower systems

Large-scale dam hydropower projects are often criticized for their impacts on wildlife habitat, fish migration, and 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.

Small hydropower projects offer emissions-free power solutions for many remote communities throughout the world, such as those in Nepal, India, China, and Peru, as well as for highly industrialized countries like the United States. **Small hydropower systems** are those that 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 microhydropower systems. In fact, a 10 kW system generally can provide enough power for a large home, a small resort, or a hobby farm.

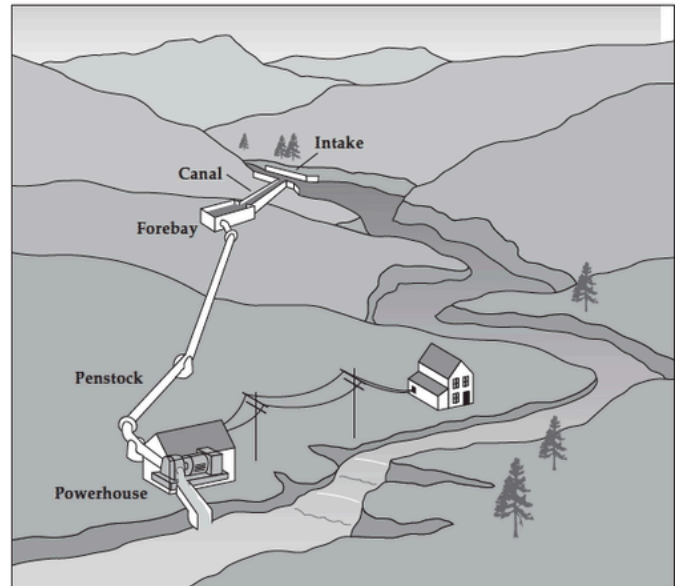


Figure 2. Microhydropower system. Although there are several ways to harness the moving water to produce energy, run-of-the-river systems, which do not require large storage reservoirs, are often used for microhydro, and sometimes for small-scale hydro, projects. For run-of-the-river hydro projects, 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.

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: disposal of waste and production of energy from a renewable resource. Many of the 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 anti-pollution devices to be installed. Also, while incinerating at high temperature many of the toxic chemicals may break down into less harmful compounds. The ash from these plants may contain high concentrations of various metals

that were present in the original waste. If ash is clean enough it can be “recycled” as an MSW landfill cover or to build roads, cement block and artificial reefs

Biofuel



Figure 3. Woodchips Photograph shows a pile of woodchips, which are 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 to a lesser extent, algae. 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. The use of biomass can help mitigate climate change because when burned it adds no new carbon to the atmosphere. Thinking back to the carbon cycle (chapter 3), you will recall that photosynthesis removes CO_2 through the process of carbon fixation. When biomass is burnt, CO_2 is

created, but this 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 in order 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 habitat.

Burning Wood

Using wood, and charcoal made from wood, for heating and cooking can replace fossil fuels and may result in lower 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. For home heating, it is most efficient and least polluting when using a modern wood stove or fireplace insert that are 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-1980's 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 sort of man-made “biogenic” gas as discussed above. Methane is formed as a result of 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 CO₂ emissions. The only environmental impacts are from the construction of the plant itself, 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 and 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 less sulfur oxides, particulate matter, carbon monoxide, and unburned and other hydrocarbons, but it 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 the energy of light into electrical energy and has minimal impact on the environment, 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 the 8% of the total electricity generation that was from renewable sources. The manufacturing of **photovoltaic** (PV) cells 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 and particularly in deserts where those fragile ecosystems could be damaged if care is not taken. 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.

Wind

Wind energy is a renewable energy source that is clean and has very few environmental challenges. Wind turbines are becoming a more prominent sight across the United States, even in regions that are considered to have less wind potential. Wind turbines (often called windmills) do not release emissions that pollute the air or water (with rare exceptions), and they 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 4. Rooftop Solar Installations Rooftop solar installation on Douglas Hall at the University of Illinois at Chicago has no effect on land resources, while producing electricity with zero emissions. Source: Office of Sustainability, UIC



Figure 5. Twin Groves Wind Farm, Illinois Wind power is becoming a more popular source of energy 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 mountain top 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. There are aesthetic concerns to some people 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 and it 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 10 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 away from oil and gas to plentiful domestic coal for electricity production and the imposition of fuel economy standards for vehicles to reduce consumption of oil 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 security, 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 production of electricity 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 the formation of high- and low-pressure areas in the atmosphere that make wind. The sun also generates the heat required for 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, for 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. The time scale for fossil fuel regeneration, however, is too long to consider them renewable in human terms.

Geothermal energy originates from heat rising to the surface from earth's molten iron core created during the formation and compression of the early earth as well as from heat produced continuously by 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 rotation of the earth. These three sources – sunlight, the heat trapped in earth's core and continuously generated in its crust, and gravitational force of the moon and sun 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. Wind and solar electricity, despite their large capacity and significant recent growth, 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 surface of the earth 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 that remain 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 thought to be relatively evenly distributed, is concentrated in deserts where cloud cover is rare. 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.

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11.4 Hydrogen and Electricity as Alternative Fuels

Section Goals:

1. Understand the particular challenge of changing the mode of powering vehicles.
2. Describe alternates to gas: hydrogen, electricity, hybrids.

Introduction

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 market for transportation is growing rapidly. China has an emerging middle class that is 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, 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 with internal combustion engines.

Hydrogen as an Alternative Fuel

The traditional synergy of oil with automobiles may now be showing 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 is beginning to diversify 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 Helmholtz, 2010, Crabtree, Dresselhaus, & Buchanan, 2004). One advantage of hydrogen is efficiency, up to 50 percent or greater for fuel cells, 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 from 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 below](#). Many scientists and automobile companies are exploring hydrogen as a long-term alternative to oil.

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 batteries for vehicles 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 a matter of 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 their 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 ~ 20 kWh/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 that of the gasoline car. If electricity is generated by combined cycle natural gas turbines 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 Table below.

The Hybrid Solution

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 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, 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 simply 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.

From a sustainability perspective, the comparison of gasoline, electric, hybrid and plug-in hybrid cars is interesting. Hybrid cars take all their energy from gasoline and represent the least difference from gasoline cars. Their supplementary electric drive systems reduce gasoline usage by 30-40 percent, thus promoting 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 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. In terms of 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, but 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.

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11.5 Electricity Grid and Sustainability Challenges

Section Goals:

1. Learn about electricity and the electricity grid of the United States.
2. Discuss the challenges to the current grid and how to integrate renewable energy sources into the electricity grid.

Electricity

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 carrier of energy. 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 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 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. It is the post-production versatility, cleanliness, and efficiency of electricity that make it a prime energy carrier for the future. Electricity generation, based on relatively plentiful domestic coal and gas, 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 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 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 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, the operational state of the delivery system, and implements demand response measures adjusting 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 selling 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 most urgent challenges facing the grid. 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. 30 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 to accommodate the variability of wind and solar electricity. Without significant storage capacity, the grid must precisely balance generation to demand in real time. At present, 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 insure 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 at the 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 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 is limited. The situation is much like 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 indirect. To use renewable electricity resources effectively, we must create a kind of interstate highway system for electricity.

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11.6 Chapter Resources

Summary

We derive our energy from a multitude of resources that have varying environmental challenges related to air and water pollution, land use, carbon dioxide emissions, resource extraction and supply, as well as 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 users of primary energy and producers of carbon emissions in the United States. Transportation is almost completely dependent on oil and internal combustion engines for its energy. The concentration of oil in a few regions of the world 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 up to hundreds of thousands of years. Reprocessing spent fuel offers the advantages of higher energy efficiency and reduced spent fuel storage requirements with the disadvantage of higher risk of weapons proliferation through 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.

Review Questions

1. Which one of the following is not a renewable source of energy?
 - A. Nuclear
 - B. Wind
 - C. Solar
 - D. Hydropower
 - E. Geothermal
2. Coal, oil, and natural gas are created _____ and contain the remains of_____.

- A. over millions of years; algae and plants
 - B. over millions of years; dinosaurs and other animals
 - C. over hundreds of years; algae and plants
 - D. over hundreds of years; dinosaurs and other animals
 - E. instantaneously; comet fragments
3. Which one of the following is a consortium of oil-producing countries that hold a significant portion of the world's oil reserves (and thus influence global oil prices)?
- A. UAE
 - B. OPEC
 - C. UN
 - D. CITES
 - E. UNESCO
4. About 44% of the electricity in the US is produced from _____. It produces about twice as much CO₂ as an equivalent amount of _____.
- A. Burning natural gas; coal
 - B. Hydropower; solar
 - C. Natural gas; Geothermal
 - D. Hydropower; geothermal
 - E. Burning coal; natural gas
5. Which one of the following is not true regarding nuclear power?
- A. Energy is captured from the radioactive decay of elements
 - B. Nuclear power is considered an alternative fuel
 - C. Radioactive wastes must be stored 2-5 years before disposal
 - D. No CO₂ is directly produced in nuclear power plants
 - E. Nuclear power is used to produce electricity
6. Which one of the following directly produces CO₂ but is considered carbon neutral?
- A. Wind
 - B. Biodiesel
 - C. Oil
 - D. Coal
 - E. Hydropower
7. The original source of energy that powers both wind energy and hydropower is...
- A. Precipitation
 - B. Rotation of the Earth
 - C. The sun
 - D. Gravity
 - E. Radioactive decay within the Earth's mantle
8. Burning sawdust that is leftover from lumber production and using it to generate electricity would be an example of which one of the following?
- A. Municipal solid waste

- B. Biofuel
- C. Biogas
- D. Bioethanol
- E. Biofission

9. In the process of fracking, how is gas and oil extracted?

- A. Layers of earth are stripped away from the surface, exposing the fossil fuels
- B. Mining tunnels are created and the fossil fuels are extracted by teams working below ground
- C. Ocean sediments are mined and the fossil fuels are chemically extracted
- D. High-pressure fluids are injected underground to force out the fossil fuels
- E. Offshore drilling pads tap into pre-existing cracks in the Earth's crust

10. What fundamental similarity is shared between the following energy sources: biogas and municipal solid waste?

- A. Both burn waste to generate CO₂, which itself is burned to create electricity
- B. Both chemically transform waste into oil
- C. Both trap the heat generated from decaying waste and use it to generate energy
- D. Both rely on the generation and combustion of methane
- E. Both produce no CO₂

See Appendix for answers

Attributions

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Afterword

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Appendix

Answer Key for End-of-Chapter Review Questions

Chapter 1

#1. **A** #2. **D** #3. **E** #4. **B** #5. **A** #6. **C** #7. **C** #8. **A** #9. **B** #10. **B**

Chapter 2

#1. **B** #2. **B** #3. **C** #4. **B** #5. **C** #6. **D** #7. **A** #8. **D** #9. **A** #10. **B**

Chapter 3

#1. **C** #2. **A** #3. **A** #4. **D** #5. **C** #6. **A** #7. **D** #8. **A** #9. **E** #10. **A**

Chapter 4

#1. **D** #2. **B** #3. **A** #4. **A** #5. **B** #6. **A** #7. **B** #8. **B** #9. **C** #10. **A**

Chapter 5

#1. **E** #2. **D** #3. **C** #4. **D** #5. **E** #6. **B** #7. **B** #8. **C** #9. **B** #10. **A**

Chapter 6

#1. **C** #2. **C** #3. **B** #4. **B** #5. **D** #6. **A** #7. **A** #8. **E** #9. **C** #10. **D**

Chapter 7

#1. **A** #2. **E** #3. **A** #4. **A** #5. **E** #6. **A** #7. **B** #8. **C** #9. **A** #10. **D**

Chapter 8

#1. **D** #2. **C** #3. **A** #4. **D** #5. **A**

Chapter 9

#1. **D** #2. **B** #3. **A** #4. **B** #5. **A** #6. **C** #7. **E** #8. **E** #9. **D** #10. **E**

Chapter 10

#1. **C** #2. **B** #3. **A** #4. **B** #5. **B** #6. **C** #7. **A** #8. **E** #9. **A** #10. **E**

Chapter 11

#1. **A** #2. **A** #3. **B** #4. **E** #5. **C** #6. **B** #7. **C** #8. **B** #9. **D** #10. **D**

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About the Author

Joni Baumgarten

Dr. Joni Baumgarten received her PhD in Ecology and Evolution from Rutgers, The State University of New Jersey. Her BA in Environmental Science was received from Barnard College, Columbia University.

Following the model of [Dr. Max Liboiron](#) in their introduction to “Pollution is Colonialism”, Dr. Baumgarten would like to give some context that played into the writing of this textbook. Dr. Baumgarten grew up in Philadelphia, and still lives there currently. Her extended families were farming families in Wisconsin and in Pennsylvania. Therefore, she has what might be a unique perspective of empathy for the challenging issues in both rural and urban settings. Additionally, as a soil scientist, Dr. Baumgarten studies detailed ecological communities where our understanding is limited and there are more questions than there are answers. Given all this, Dr. Baumgarten hopes that reading this textbook will help people feel grounded with a better understanding of science when they are confronted with the challenges of climate change.