ENVIRONMENTAL SCIENCE (WCTC)



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806-191 Environmental Science

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1: INTRODUCTION

The objective of this unit is to introduce you the book's topics as well as the rigors and structure of science. Science and mathematics are not just for scientists. A base understanding of these subjects is crucial in our very complex modern world. Without a solid understanding of how science and mathematics play a role in our everyday lives, we cannot respond appropriately in everyday situations, know how to vote on scientific laws, or hold public representatives responsible for their decisions on scientific policy.

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1.1: What is Environmental Science?

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1.1: What is Environmental Science?

What is 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.

Environmental Science is Interdisciplinary

Environmental science includes disciplines in the physical sciences (like geology, soil science, physical geography, chemistry, and atmospheric sciences), life sciences (like ecology, conservation biology, restoration biology, and population biology), social sciences (like human geography, economics, law, political science, and anthropology), and humanities (philosophy, ethics). As such, environmental scientists are a diverse bunch. However, they all come together for the focus of studying and identifying past, current, and future environmental issues while also exploring solutions to the environmental issues and also considering practical needs.

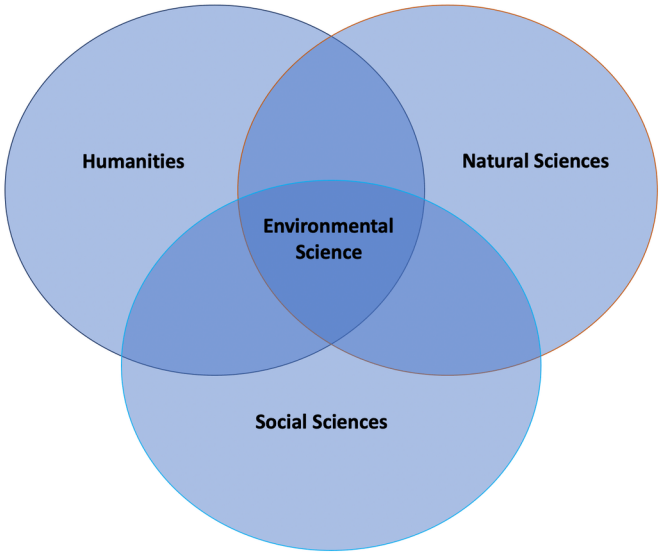


Figure 1.1.a: Venn diagram illustrating how environmental science is interdisciplinary between humanities, natural sciences (which includes physical and life sciences) and social sciences. Image by Rachel Schleiger (CC-BY-NC(opens in new window)).

Why Study Environmental Science?

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.

From global climate change to habitat loss driven by human population growth and development, Earth is becoming a different planet—right before our eyes. The global scale and rate of environmental change are beyond anything in recorded human history. Our challenge is to 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.

The Tragedy of the Commons

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

Hardin went on to apply the situation to modern commons: overgrazing of public lands, overuse of public forests and parks, depletion of fish populations in the ocean, use of rivers as a common dumping ground for sewage, and releasing air pollutants.

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.

Some Indicators of Global Environmental Stress

- **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. CO_2 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.

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1.2: Themes and Concepts of Biology

Alot of what this course will focus on has a foundation in **Biology,** which is the scientific study of life. What exactly is life? This may sound like a silly question with an obvious answer, but it is not easy to define life. For example, a branch of biology called virology studies viruses, which exhibit some of the characteristics of living entities but lack others. It turns out that although viruses can attack living organisms, cause diseases, and even reproduce, they do not meet the criteria that biologists use to define life.

From its earliest beginnings, biology has wrestled with four questions: What are the shared properties that make something “alive”? How do those various living things function? When faced with the remarkable diversity of life, how do we organize the different kinds of organisms so that we can better understand them? And, finally—what biologists ultimately seek to understand—how did this diversity arise and how is it continuing? As new organisms are discovered every day, biologists continue to seek answers to these and other questions.

Properties of Life

All groups of living organisms share several key characteristics or functions: order, sensitivity or response to stimuli, reproduction, adaptation, growth and development, regulation, homeostasis, and energy processing. When viewed together, these eight characteristics serve to define life.

Order

Organisms are highly organized structures that consist of one or more cells. Even very simple, single-celled organisms are remarkably complex. Inside each cell, atoms make up molecules. These in turn make up cell components or organelles. Multicellular organisms, which may consist of millions of individual cells, have an advantage over single-celled organisms in that their cells can be specialized to perform specific functions, and even sacrificed in certain situations for the good of the organism as a whole. How these specialized cells come together to form organs such as the heart, lung, or skin in organisms like the toad shown in Figure 1.2.1 will be discussed later.



Figure 1.2.1: A toad represents a highly organized structure consisting of cells, tissues, organs, and organ systems. (credit: "Ivengo(RUS)"/Wikimedia Commons)

Sensitivity or Response to Stimuli

Organisms respond to diverse stimuli. For example, plants can bend toward a source of light or respond to touch (Figure 1.2.2). Even tiny bacteria can move toward or away from chemicals (a process called chemotaxis) or light (phototaxis). Movement toward

a stimulus is considered a positive response, while movement away from a stimulus is considered a negative response.



Figure 1.2.2: The leaves of this sensitive plant (Mimosa pudica) will instantly droop and fold when touched. After a few minutes, the plant returns to its normal state. (credit: Alex Lomas)

CONCEPT IN ACTION

Watch this video to see how the sensitive plant responds to a touch stimulus.

Reproduction

Single-celled organisms reproduce by first duplicating their DNA, which is the genetic material, and then dividing it equally as the cell prepares to divide to form two new cells. Many multicellular organisms (those made up of more than one cell) produce specialized reproductive cells that will form new individuals. When reproduction occurs, DNA containing genes is passed along to an organism's offspring. These genes are the reason that the offspring will belong to the same species and will have characteristics similar to the parent, such as fur color and blood type.

Adaptation

All living organisms exhibit a "fit" to their environment. Biologists refer to this fit as adaptation and it is a consequence of evolution by natural selection, which operates in every lineage of reproducing organisms. Examples of adaptations are diverse and unique, from heat-resistant Archaea that live in boiling hot springs to the tongue length of a nectar-feeding moth that matches the size of the flower from which it feeds. All adaptations enhance the reproductive potential of the individual exhibiting them, including their ability to survive to reproduce. Adaptations are not constant. As an environment changes, natural selection causes the characteristics of the individuals in a population to track those changes.

Growth and Development

Organisms grow and develop according to specific instructions coded for by their genes. These genes provide instructions that will direct cellular growth and development, ensuring that a species' young (Figure 1.2.3) will grow up to exhibit many of the same characteristics as its parents.



Figure 1.2.3: Although no two look alike, these kittens have inherited genes from both parents and share many of the same characteristics. (credit: Pieter & Renée Lanser)

Regulation

Even the smallest organisms are complex and require multiple regulatory mechanisms to coordinate internal functions, such as the transport of nutrients, response to stimuli, and coping with environmental stresses. For example, organ systems such as the digestive or circulatory systems perform specific functions like carrying oxygen throughout the body, removing wastes, delivering nutrients to every cell, and cooling the body.

Homeostasis

To function properly, cells require appropriate conditions such as proper temperature, pH, and concentrations of diverse chemicals. These conditions may, however, change from one moment to the next. Organisms are able to maintain internal conditions within a narrow range almost constantly, despite environmental changes, through a process called **homeostasis** or "steady state"—the ability of an organism to maintain constant internal conditions. For example, many organisms regulate their body temperature in a process known as **thermoregulation**. Organisms that live in cold climates, such as the polar bear (Figure 1.2.4), have body structures that help them withstand low temperatures and conserve body heat. In hot climates, organisms have methods (such as perspiration in humans or panting in dogs) that help them to shed excess body heat.



Figure 1.2.4: Polar bears and other mammals living in ice-covered regions maintain their body temperature by generating heat and reducing heat loss through thick fur and a dense layer of fat under their skin. (credit: "longhorndave"/Flickr)

Energy Processing

All organisms (such as the California condor shown in Figure 1.2.5) use a source of energy for their metabolic activities. Some organisms capture energy from the Sun and convert it into chemical energy in food; others use chemical energy from molecules they take in.



Figure 1.2.5: A lot of energy is required for a California condor to fly. Chemical energy derived from food is used to power flight. California condors are an endangered species; scientists have strived to place a wing tag on each bird to help them identify and locate each individual bird. (credit: Pacific Southwest Region U.S. Fish and Wildlife)

Levels of Organization of Living Things

Living things are highly organized and structured, following a hierarchy on a scale from small to large. The atom is the smallest and most fundamental unit of matter. It consists of a nucleus surrounded by electrons. Atoms form molecules. A molecule is a chemical structure consisting of at least two atoms held together by a chemical bond. Many molecules that are biologically important are macromolecules, large molecules that are typically formed by combining smaller units called monomers. An

example of a macromolecule is deoxyribonucleic acid (DNA) (Figure 1.2.6), which contains the instructions for the functioning of the organism that contains it.

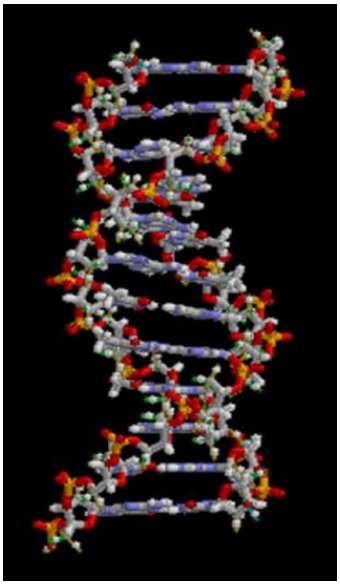


Figure 1.2.6: A molecule, like this large DNA molecule, is composed of atoms. (credit: "Brian0918"/Wikimedia Commons)

CONCEPT IN ACTION

This link takes you to an animation of a DNA molecule.

Some cells contain aggregates of macromolecules surrounded by membranes; these are called **organelles**. Organelles are small structures that exist within cells and perform specialized functions. All living things are made of **cells**; the cell itself is the smallest fundamental unit of structure and function in living organisms. (This requirement is why viruses are not considered living: they are not made of cells. To make new viruses, they have to invade and hijack a living cell; only then can they obtain the materials they need to reproduce.) Some organisms consist of a single cell and others are multicellular. Cells are classified as prokaryotic or eukaryotic. Prokaryotes are single-celled organisms that lack organelles surrounded by a membrane and do not have nuclei surrounded by nuclear membranes; in contrast, the cells of eukaryotes do have membrane-bound organelles and nuclei.

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. Single-celled prokaryotes and single-celled eukaryotes are also considered organisms and are typically referred to as microbes or microorganisms.

ART CONNECTION

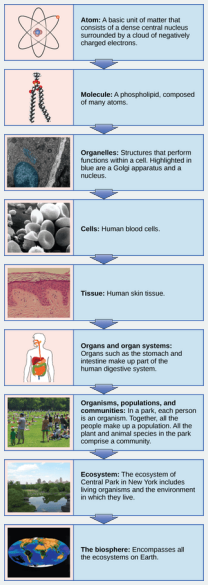


Figure 1.2.7: From an atom to the entire Earth, biology examines all aspects of life. (credit "molecule": modification of work by Jane Whitney; credit "organelles": modification of work by Louisa Howard; credit "cells": modification of work by Bruce Wetzel, Harry Schaefer, National Cancer Institute; credit "tissue": modification of work by "Kilbad"/Wikimedia Commons; credit "organs": modification of work by Mariana Ruiz Villareal, Joaquim Alves Gaspar; credit "organisms": modification of work by Peter Dutton; credit "ecosystem": modification of work by "gigi4791"/Flickr; credit "biosphere": modification of work by NASA)

Which of the following statements is false?

A. Tissues exist within organs which exist within organ systems.
B. Communities exist within populations which exist within ecosystems.
C. Organelles exist within cells which exist within tissues.
D. Communities exist within ecosystems which exist in the biosphere.

Answer available at the end of this section.

All the individuals of a species living within a specific area are collectively called a **population**. For example, a forest may include many white pine trees. All of these pine trees represent the population of white pine trees in this forest. Different populations may live in the same specific area. For example, the forest with the pine trees includes populations of flowering plants and also insects and microbial populations. A **community** is the set of populations inhabiting a particular 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 (Figure 1.2.7), 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 Diversity of Life

The science of biology is very broad in scope because there is a tremendous diversity of life on Earth. The source of this diversity is **evolution**, wherein a population's genetic composition changes over successive generations. Evolutionary biologists study the evolution of living things in everything from the microscopic world to ecosystems.

In the 18th century, a scientist named Carl Linnaeus first proposed organizing the known species of organisms into a hierarchical taxonomy. In this system, species that are most similar to each other are put together within a grouping known as a **genus**. Furthermore, similar genera (the plural of genus) are put together within a **family**. This grouping continues until all organisms are collected together into groups at the highest level. **The current taxonomic system now has eight levels in its hierarchy, from lowest to highest, they are: species, genus, family, order, class, phylum, kingdom, domain.** Thus species are grouped within genera, genera are grouped within families, families are grouped within orders, and so on (Figure 1.2.8).

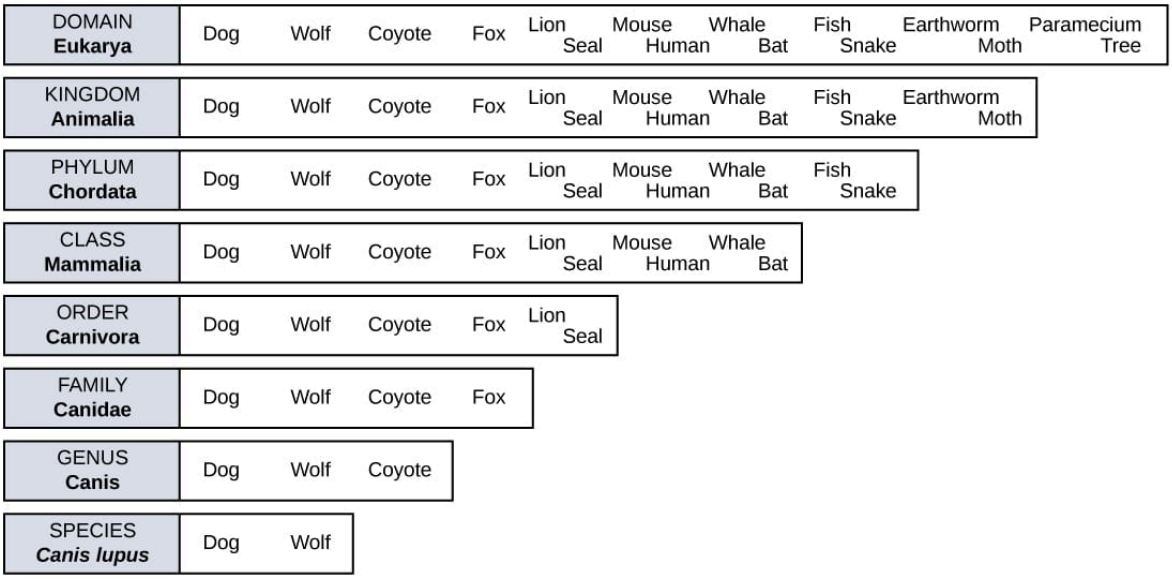


Figure 1.2.8: This diagram shows the levels of taxonomic hierarchy for a dog, from the broadest category—domain—to the most specific—species.

The highest level, **domain**, is a relatively new addition to the system since the 1990s. Scientists now recognize three domains of life, the Eukarya, the Archaea, and the Bacteria. The domain **Eukarya** contains organisms that have cells with nuclei. It includes the kingdoms of fungi, plants, animals, and several kingdoms of protists. The **Archaea**, are single-celled organisms without nuclei and include many extremophiles that live in harsh environments like hot springs. The Bacteria are another quite different group of single-celled organisms without nuclei (Figure 1.2.9). Both the Archaea and the Bacteria are prokaryotes, an informal name for cells without nuclei. The recognition in the 1990s that certain "bacteria," now known as the Archaea, were as different genetically and biochemically from other bacterial cells as they were from eukaryotes, motivated the recommendation to divide life into three domains. This dramatic change in our knowledge of the tree of life demonstrates that classifications are not permanent and will change when new information becomes available.

In addition to the hierarchical taxonomic system, Linnaeus was the first to name organisms using two unique names, now called the **binomial nomenclature system**. Before Linnaeus, the use of common names to refer to organisms caused confusion because there were regional differences in these common names. Binomial names consist of the genus name (which is capitalized) and the species name (all lower-case). Both names are set in italics when they are printed. Every species is given a unique binomial which is recognized the world over, so that a scientist in any location can know which organism is being referred to. For example, the North American blue jay is known uniquely as *Cyanocitta cristata*. Our own species is *Homo sapiens*.



Figure 1.2.9: These images represent different domains. The scanning electron micrograph shows (a) bacterial cells belong to the domain Bacteria, while the (b) extremophiles, seen all together as colored mats in this hot spring, belong to domain Archaea. Both the (c) sunflower and (d) lion are part of domain Eukarya. (credit a: modification of work by Rocky Mountain Laboratories, NIAID, NIH; credit b: modification of work by Steve Jurvetson; credit c: modification of work by Michael Arrighi; credit d: modification of work by Frank Vassen)

EVOLUTION IN ACTION: Carl Woese and the Phylogenetic Tree

The evolutionary relationships of various life forms on Earth can be summarized in a phylogenetic tree. A **phylogenetic tree** is a diagram showing the evolutionary relationships among biological species based on similarities and differences in genetic or physical traits or both. A phylogenetic tree is composed of branch points, or **nodes**, and **branches**. The internal nodes represent ancestors and are points in evolution when, based on scientific evidence, an ancestor is thought to have diverged to form two new species. The **length of each branch** can be considered as estimates of relative time.

In the past, biologists grouped living organisms into five kingdoms: animals, plants, fungi, protists, and bacteria. The pioneering work of American microbiologist Carl Woese in the early 1970s has shown, however, that life on Earth has evolved along three lineages, now called domains—Bacteria, Archaea, and Eukarya. Woese proposed the domain as a new taxonomic level and Archaea as a new domain, to reflect the new phylogenetic tree (Figure 1.2.10). Many organisms belonging to the Archaea domain live under extreme conditions and are called extremophiles. To construct his tree, Woese used genetic relationships rather than similarities based on morphology (shape). Various genes were used in phylogenetic studies. Woese's tree was constructed from comparative sequencing of the genes that are universally distributed, found in some slightly altered form in every organism, conserved (meaning that these genes have remained only slightly changed throughout evolution), and of an appropriate length.

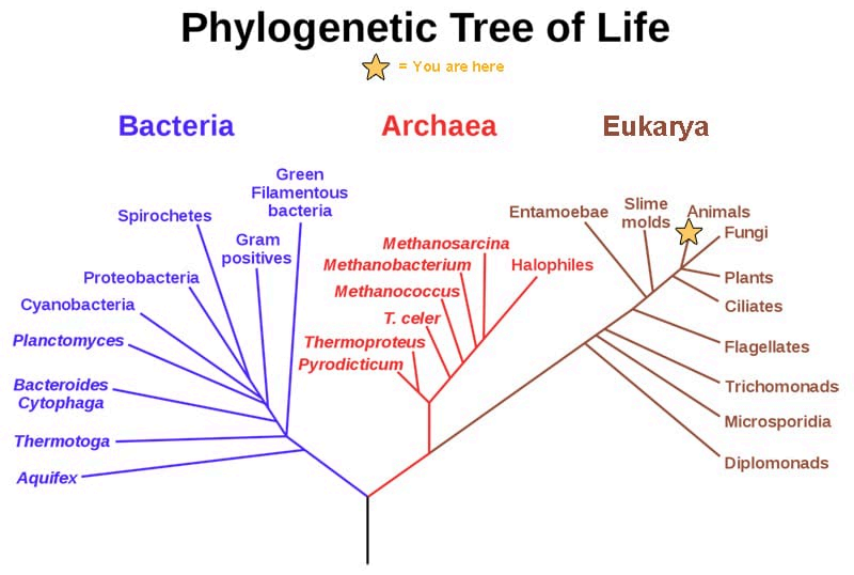


Figure 1.2.10: This phylogenetic tree was constructed by microbiologist Carl Woese using genetic relationships. The tree shows the separation of living organisms into three domains: Bacteria, Archaea, and Eukarya. Bacteria and Archaea are organisms without a nucleus or other organelles surrounded by a membrane and, therefore, are prokaryotes. (credit: modification of work by Eric Gaba)

Branches of Biological Study

The scope of biology is broad and therefore contains many branches and sub disciplines. Biologists may pursue one of those sub disciplines and work in a more focused field. For instance, molecular biology studies biological processes at the molecular level, including interactions among molecules such as DNA, RNA, and proteins, as well as the way they are regulated. Microbiology is the study of the structure and function of microorganisms. It is quite a broad branch itself, and depending on the subject of study, there are also microbial physiologists, ecologists, and geneticists, among others.

Another field of biological study, neurobiology, studies the biology of the nervous system, and although it is considered a branch of biology, it is also recognized as an interdisciplinary field of study known as neuroscience. Because of its interdisciplinary nature, this sub discipline studies different functions of the nervous system using molecular, cellular, developmental, medical, and computational approaches.



Figure 1.2.11: Researchers work on excavating dinosaur fossils at a site in Castellón, Spain. (credit: Mario Modesto)

Paleontology, another branch of biology, uses fossils to study life's history (Figure 1.2.11). **Zoology** and **botany** are the study of animals and plants, respectively. Biologists can also specialize as biotechnologists, ecologists, or physiologists, to name just a few areas. Biotechnologists apply the knowledge of biology to create useful products. Ecologists study the interactions of organisms in their environments. Physiologists study the workings of cells, tissues and organs. This is just a small sample of the many fields that biologists can pursue. From our own bodies to the world we live in, discoveries in biology can affect us in very direct and important ways. We depend on these discoveries for our health, our food sources, and the benefits provided by our ecosystem. Because of this, knowledge of biology can benefit us in making decisions in our day-to-day lives.

The development of technology in the twentieth century that continues today, particularly the technology to describe and manipulate the genetic material, DNA, has transformed biology. This transformation will allow biologists to continue to understand the history of life in greater detail, how the human body works, our human origins, and how humans can survive as a species on this planet despite the stresses caused by our increasing numbers. Biologists continue to decipher huge mysteries about life suggesting that we have only begun to understand life on the planet, its history, and our relationship to it. For this and other reasons, the knowledge of biology gained through this textbook and other printed and electronic media should be a benefit in whichever field you enter.

CAREERS IN ACTION: Forensic Scientist

Forensic science is the application of science to answer questions related to the law. Biologists as well as chemists and biochemists can be forensic scientists. Forensic scientists provide scientific evidence for use in courts, and their job involves examining trace material associated with crimes. Interest in forensic science has increased in the last few years, possibly because of popular television shows that feature forensic scientists on the job. Also, the development of molecular techniques and the establishment of DNA databases have updated the types of work that forensic scientists can do. Their job activities

are primarily related to crimes against people such as murder, rape, and assault. Their work involves analyzing samples such as hair, blood, and other body fluids and also processing DNA (Figure 1.2.12) found in many different environments and materials. Forensic scientists also analyze other biological evidence left at crime scenes, such as insect parts or pollen grains. Students who want to pursue careers in forensic science will most likely be required to take chemistry and biology courses as well as some intensive math courses.



Figure 1.2.12: This forensic scientist works in a DNA extraction room at the U.S. Army Criminal Investigation Laboratory. (credit: U.S. Army CID Command Public Affairs)

Summary

Biology is the science of life. All living organisms share several key properties such as order, sensitivity or response to stimuli, reproduction, adaptation, growth and development, regulation, homeostasis, and energy processing. Living things are highly organized following a hierarchy that includes atoms, molecules, organelles, cells, tissues, organs, and organ systems. Organisms, in turn, are grouped as populations, communities, ecosystems, and the biosphere. Evolution is the source of the tremendous biological diversity on Earth today. A diagram called a phylogenetic tree can be used to show evolutionary relationships among organisms. Biology is very broad and includes many branches and sub disciplines. Examples include molecular biology, microbiology, neurobiology, zoology, and botany, among others.

Contributors and Attributions

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Answers

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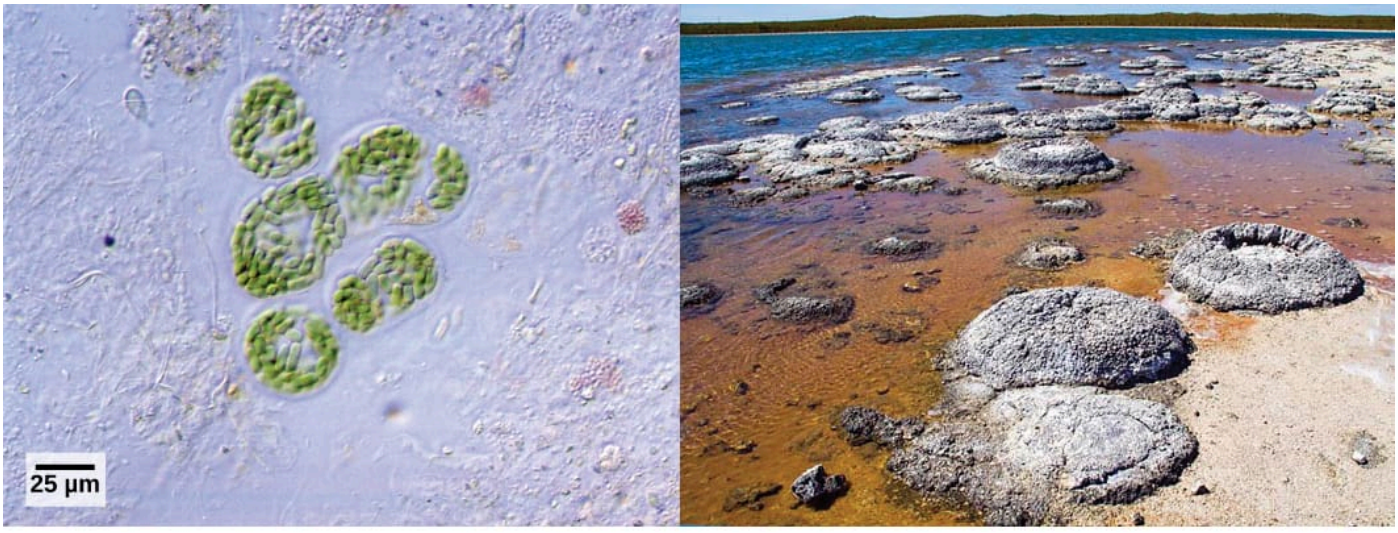
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1.3: The Process of Science

Like geology, physics, and chemistry, biology is a science that gathers knowledge about the natural world. Specifically, biology is the study of life. The discoveries of biology are made by a community of researchers who work individually and together using agreed-on methods. In this sense, biology, like all sciences is a social enterprise like politics or the arts.



(a) (b)

Figure 1.3.1: Formerly called blue-green algae, the (a) 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)

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. Like politics, science has considerable practical implications and some science is dedicated to practical applications, such as the prevention of disease (Figure 1.3.2). Other science proceeds largely motivated by curiosity. Whatever its goal, there is no doubt that science, including biology, has transformed human existence and will continue to do so.

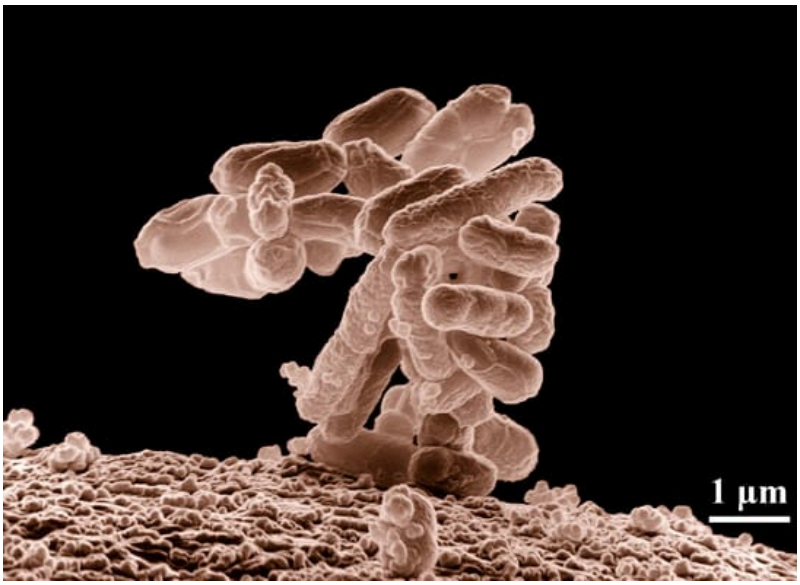


Figure 1.3.2: Biologists may choose to study *Escherichia coli* (*E. coli*), a bacterium that is a normal resident of our digestive tracts but which is also sometimes responsible for disease outbreaks. In this micrograph, the bacterium is visualized using a scanning electron microscope and digital colorization. (credit: Eric Erbe; digital colorization by Christopher Pooley, USDA-ARS)

The Nature of Science

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 knowledge about the natural world.

Science is a very specific way of learning, or knowing, about the world. The history of the past 500 years demonstrates that science is a very powerful way of knowing about the world; it is largely responsible for the technological revolutions that have taken place during this time. There are however, areas of knowledge and human experience that the methods of science cannot be applied to. These include such things as answering purely moral questions, aesthetic questions, or what can be generally categorized as spiritual questions. Science has 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 a suggested explanation for an observation, phenomenon, or event, and which can be tested. Hypotheses, or tentative explanations, are generally produced within the context of a scientific theory. A **scientific theory** is a generally accepted, thoroughly tested and confirmed explanation for a set of observations or phenomena. Scientific theory is the foundation of scientific knowledge. Many scientific disciplines further contain **scientific laws** which describe how elements of nature will behave under certain specific conditions. Theories and laws serve different purposes. Scientific Laws describe what happens in nature under specific conditions, and are often expressed in mathematical equations. Scientific theories explain why or how those phenomena occur., and are well-substantiated frameworks that tie facts, observations, and multiple laws together.

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, biology, computer sciences, geology, logic, physics, chemistry, and mathematics (Figure 1.3.3). However, those fields of science related to the physical world and its phenomena and processes are considered **natural sciences**. Thus, a museum of natural sciences might contain any of the items listed above.

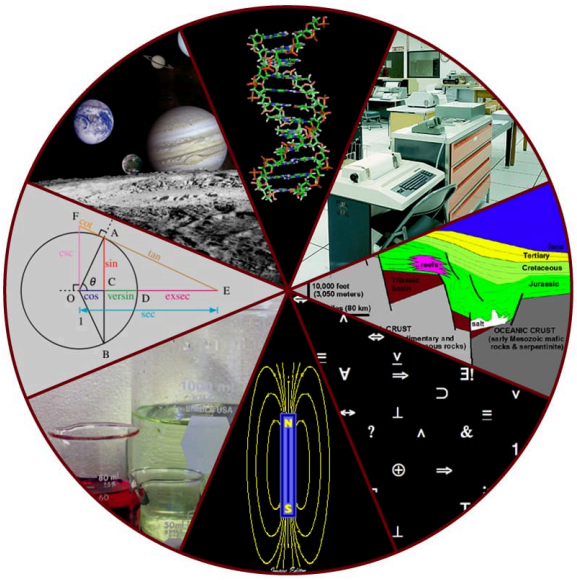


Figure 1.3.3: Some fields of science include astronomy, biology, computer science, geology, logic, physics, chemistry, and mathematics. (credit: "Image Editor"/Flickr)

There is no complete agreement when it comes to defining what the natural sciences include. For some experts, the natural sciences are astronomy, biology, chemistry, earth science, and physics. Other scholars choose to divide natural sciences into life sciences, which study living things and include biology, and physical sciences, which study nonliving matter and include astronomy, physics, and chemistry. Some disciplines such as biophysics and biochemistry build on two sciences and are interdisciplinary.

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.

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) (Figure 1.3.4), 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 1.3.4: Sir Francis Bacon is credited with being the first to document the scientific method.

The scientific process typically starts with an observation (often a problem to be solved) that leads to a question. Let's think about a simple problem that starts with an observation and apply the scientific method to solve the problem. 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. A **variable** is any part of the experiment that can vary or change during the experiment. A **control** is a part of the experiment that does not change. Look for the variables and controls in the example that follows. As a simple example, an experiment might be conducted to test the hypothesis that phosphate limits 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 salt that is known not to be used by algae. The variable here is the phosphate (or lack of phosphate), the experimental or treatment cases are the ponds with added phosphate and the control

ponds are those with something inert added, such as the salt. Just adding something is also a control against the possibility that adding extra matter to the pond has an effect. If the treated ponds show lesser growth of algae, then we have found support for our 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 1.3.5). Using the scientific method, the hypotheses that are inconsistent with experimental data are rejected.

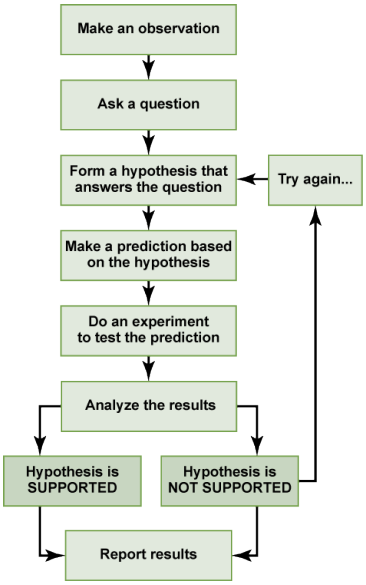


Figure 1.3.5: The scientific method is a series of defined steps that include experiments and careful observation. If a hypothesis is not supported by data, a new hypothesis can be proposed.

Example 1.3.1

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.

Solution

The hypothesis is #3 (there is something wrong with the electrical outlet), and the prediction is #4 (if something is wrong with the outlet, then the coffeemaker also won't work when plugged into the outlet). The original hypothesis is not supported, as the coffee maker works when plugged into the outlet. Alternative hypotheses may include (1) the toaster might be broken or (2) the toaster wasn't turned on.

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

The scientific community has been debating for the last few decades about the value of different types of 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** or "technology," aims to use science to solve real-world problems, making it possible, for example, to improve a 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 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. 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 DNA subunits 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 1.3.6) 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 genetically related diseases.

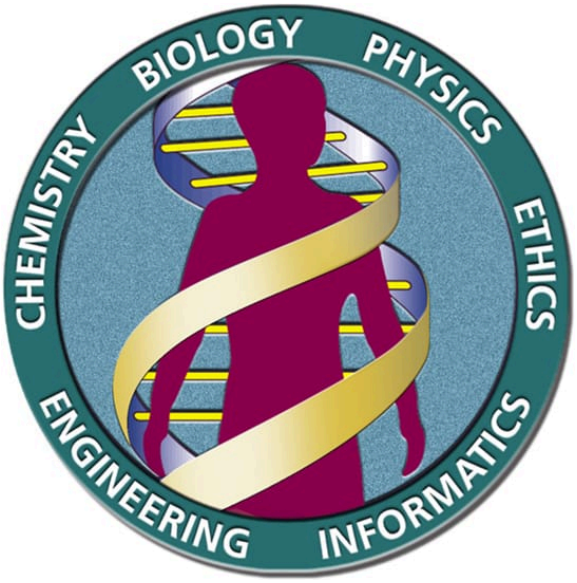


Figure 1.3.6: The Human Genome Project was a 13-year collaborative effort among researchers working in several different fields of science. The project was completed in 2003. (credit: the U.S. Department of Energy Genome Programs)

While research efforts in both basic science and applied science are usually carefully planned, it is important to note that some discoveries are made by serendipity, that is, by means of a fortunate accident or a lucky surprise. Penicillin was discovered when biologist Alexander Fleming accidentally left a petri dish of *Staphylococcus* bacteria open. An unwanted mold grew, killing the bacteria. The mold turned out to be *Penicillium*, and a new antibiotic was discovered. Even in the highly organized world of

science, luck—when combined with an observant, curious mind—can lead to unexpected breakthroughs.

Reporting Scientific Work

Whether scientific research is basic science or applied science, scientists must share their findings for other researchers to expand and build upon their discoveries. Communication and collaboration within and between sub disciplines of science are key to the advancement of knowledge in science. 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, and thorough. Grant proposals, which are requests for research funding, are also subject to peer review. 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.

There are many journals and the popular press that do not use a peer-review system. A large number of online open-access journals, journals with articles available without cost, are now available many of which use rigorous peer-review systems, but some of which do not. Results of any studies published in these forums without peer review are not reliable and should not form the basis for other scientific work. In one exception, journals may allow a researcher to cite a personal communication from another researcher about unpublished results with the cited author's permission.

Summary

Biology is the science that studies living organisms and their interactions with one another and their environments. 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.

Contributors and Attributions

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1.4: Introduction to Biology (Exercises)

1.1: Themes and Concepts of Biology

Multiple Choice

The smallest unit of biological structure that meets the functional requirements of “living” is the _____.

A. organ
B. organelle
C. cell
D. macromolecule

Answer

C

Which of the following sequences represents the hierarchy of biological organization from the most complex to the least complex level?

A. organelle, tissue, biosphere, ecosystem, population
B. organ, organism, tissue, organelle, molecule
C. organism, community, biosphere, molecule, tissue, organ
D. biosphere, ecosystem, community, population, organism

Answer

D

Free Response

Using examples, explain how biology can be studied from a microscopic approach to a global approach.

Answer

Researchers can approach biology from the smallest to the largest, and everything in between. For instance, an ecologist may study a population of individuals, the population’s community, the community’s ecosystem, and the ecosystem’s part in the biosphere. When studying an individual organism, a biologist could examine the cell and its organelles, the tissues that the cells make up, the organs and their respective organ systems, and the sum total—the organism itself.

1.2: The Process of Science

Multiple Choice

A suggested and testable explanation for an event is called a _____.

A. hypothesis
B. variable
C. theory
D. control

Answer

A

The type of logical thinking that uses related observations to arrive at a general conclusion is called _____.

A. deductive reasoning
B. the scientific method
C. hypothesis-based science
D. inductive reasoning

Answer

D

Free Response

Give an example of how applied science has had a direct effect on your daily life.

Answer

Answers will vary. One example of how applied science has had a direct effect on daily life is the presence of vaccines. Vaccines to prevent diseases such polio, measles, tetanus, and even the influenza affect daily life by contributing to individual and societal health.

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2: CHEMISTRY OF LIFE

2.1: The Building Blocks of Molecules
2.2: Water
2.3: Biological Molecules
2.4: Chemistry of Life (Exercises)

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2.1: The Building Blocks of Molecules

At its most fundamental level, life is made up of matter. Matter occupies space and has mass. All **matter** is composed of elements, substances that cannot be broken down or transformed chemically into other substances. Each **element** is made of atoms, each with a constant number of protons and unique properties. A total of 118 elements have been defined; however, only 92 occur naturally, and fewer than 30 are found in living cells. The remaining 26 elements are unstable and, therefore, do not exist for very long or are theoretical and have yet to be detected.

Each element is designated by its chemical symbol (such as H, N, O, C, and Na), and possesses unique properties. These unique properties allow elements to combine and to bond with each other in specific ways.

Atoms

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 can interact to form cells that combine to form tissues, which make up organs. These combinations continue until entire multicellular organisms are formed.

All atoms contain protons, electrons, and neutrons (Figure 2.1.1). 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.

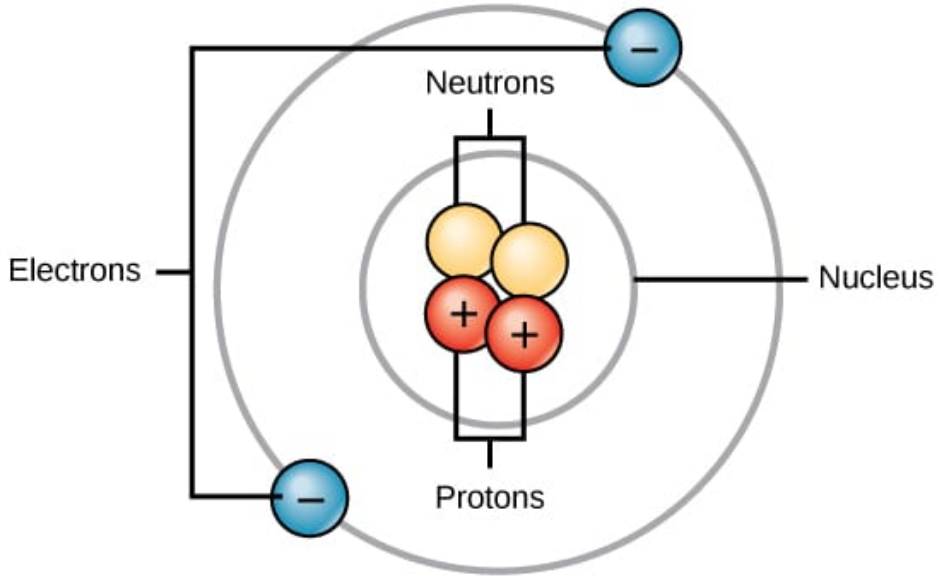


Figure 2.1.1: Atoms are made up of protons and neutrons located within the nucleus, and electrons surrounding the nucleus.

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.

Because protons and neutrons each have a mass of 1, the mass of an atom (**atomic mass**) is equal to the number of protons and neutrons of that atom. The number of electrons does not factor into the overall mass, because their mass is so small.

As stated earlier, each element has its own unique properties. Each 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. The mass number, or atomic mass, 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.

These numbers provide information about the elements and how they will react when combined. Different elements have different melting and boiling points, and are in different states (liquid, solid, or gas) at room temperature. They also combine in different ways. Some form specific types of bonds, whereas others do not. How they combine is based on the number of electrons present. Because of these characteristics, the elements are arranged into the **periodic table of elements**, a chart of the elements that includes the atomic number and relative atomic mass of each element. The periodic table also provides key information about the properties of elements (Figure 2.1.2)—often indicated by color-coding. The arrangement of the table also shows how the electrons in each element are organized and provides important details about how atoms will react with each other to form molecules.

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.

ART CONNECTION

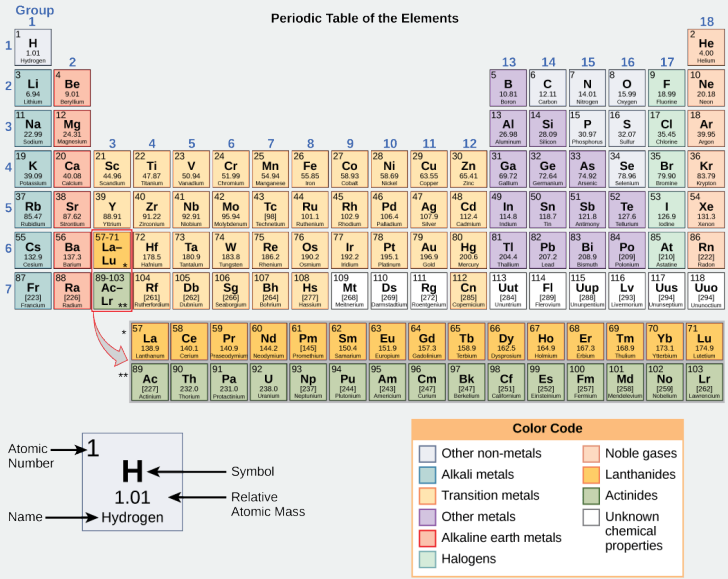


Figure 2.1.2: Arranged in columns and rows based on the characteristics of the elements, the periodic table provides key information about the elements and how they might interact with each other to form molecules. Most periodic tables provide a key or legend to the information they contain.

How many neutrons do (K) potassium-39 and potassium-40 have, respectively?

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 ^{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 2.1.3). 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 2.1.3: 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)

CONCEPT IN ACTION

To learn more about atoms and isotopes, and how you can tell one isotope from another, visit this site and run the simulation.

Chemical Bonds

How elements interact with one another depends on how their electrons are arranged and how many openings for electrons exist at the outermost region where electrons are present in an atom. Electrons exist at energy levels that form shells around the nucleus. The closest shell can hold up to two electrons. The closest shell to the nucleus is always filled first, before any other shell can be filled. Hydrogen has one electron; therefore, it has only one spot occupied within the lowest shell. Helium has two electrons; therefore, it can completely fill the lowest shell with its two electrons. If you look at the periodic table, you will see that hydrogen and helium are the only two elements in the first row. This is because they only have electrons in their first shell. Hydrogen and helium are the only two elements that have the lowest shell and no other shells.

The second and third energy levels can hold up to eight electrons. The eight electrons are arranged in four pairs and one position in each pair is filled with an electron before any pairs are completed.

Looking at the periodic table again (Figure 2.1.2), you will notice that there are seven rows. These rows correspond to the number of shells that the elements within that row have. The elements within a particular row have increasing numbers of electrons as the columns proceed from left to right. Although each element has the same number of shells, not all of the shells are completely filled with electrons. If you look at the second row of the periodic table, you will find lithium (Li), beryllium (Be), boron (B), carbon (C), nitrogen (N), oxygen (O), fluorine (F), and neon (Ne). These all have electrons that occupy only the first and second shells. Lithium has only one electron in its outermost shell, beryllium has two electrons, boron has three, and so on, until the entire shell is filled with eight electrons, as is the case with neon.

Not all elements have enough electrons to fill their outermost shells, but an atom is at its most stable when all of the electron

positions in the outermost shell are filled. Because of these vacancies in the outermost shells, we see the formation of chemical bonds, or interactions between two or more of the same or different elements that result in the formation of molecules. To achieve greater stability, atoms will tend to completely fill their outer shells and will bond with other elements to accomplish this goal by sharing electrons, accepting electrons from another atom, or donating electrons to another atom. Because the outermost shells of the elements with low atomic numbers (up to calcium, with atomic number 20) can hold eight electrons, this is referred to as the octet rule. An element can donate, accept, or share electrons with other elements to fill its outer shell and satisfy the octet rule.

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. Positive ions are formed by losing electrons and are called cations. Negative ions are formed by gaining electrons and are called anions.

For example, sodium only has one electron in its outermost shell. It takes less energy for sodium to donate that one electron than it does to accept seven more electrons to fill the outer shell. If sodium loses an electron, it now has 11 protons and only 10 electrons, leaving it with an overall charge of +1. It is now called a sodium ion.

The chlorine atom has seven electrons in its outer shell. Again, it is more energy-efficient for chlorine to gain one electron than to lose seven. Therefore, it tends to gain an electron to create an ion with 17 protons and 18 electrons, giving it a net negative (–1) charge. It is now called a chloride ion. This movement of electrons from one element to another is referred to as electron transfer. As Figure 2.1.4 illustrates, a sodium atom (Na) only has one electron in its outermost shell, whereas a chlorine atom (Cl) has seven electrons in its outermost shell. A sodium atom will donate its one electron to empty its shell, and a chlorine atom will accept that electron to fill its shell, becoming chloride. Both ions now satisfy the octet rule and have complete outermost shells. Because the number of electrons is no longer equal to the number of protons, each is now an ion and has a +1 (sodium) or –1 (chloride) charge.

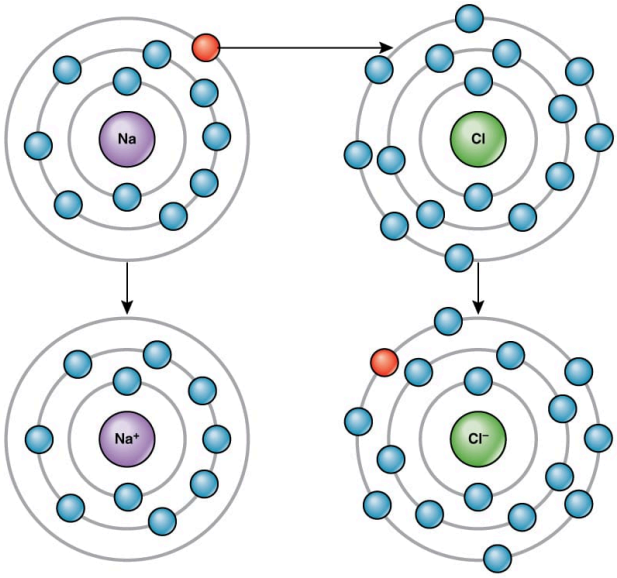


Figure 2.1.4: Elements tend to fill their outermost shells with electrons. To do this, they can either donate or accept electrons from other elements.

Ionic Bonds

There are four types of bonds or interactions: ionic, covalent, hydrogen bonds, and van der Waals interactions. Ionic and covalent bonds are strong interactions that require a larger energy input to break apart. When an element donates an electron from its outer shell, as in the sodium atom example above, a positive ion is formed. The element accepting the electron is now negatively charged. Because positive and negative charges attract, these ions stay together and form an ionic bond, or a bond between ions. The elements bond together with the electron from one element staying predominantly with the other element. When Na^+ and Cl^- ions combine to produce NaCl, an electron from a sodium atom stays with the other seven from the chlorine atom, and the sodium and chloride ions attract each other in a lattice of ions with a net zero charge.

Covalent Bonds

Another type of strong chemical bond between two or more atoms is a covalent bond. These bonds form when an electron is shared between two elements and are the strongest and most common form of chemical bond in living organisms. Covalent bonds form between the elements that make up the biological molecules in our cells. Unlike ionic bonds, covalent bonds do not dissociate in water.

The hydrogen and oxygen atoms that combine to form water molecules are bound together by covalent bonds. The electron from the hydrogen atom divides its time between the outer shell of the hydrogen atom and the incomplete outer shell of the oxygen atom. To completely fill the outer shell of an oxygen atom, two electrons from two hydrogen atoms are needed, hence the subscript "2" in H_2O. The electrons are shared between the atoms, dividing their time between them to "fill" the outer shell of each. This sharing is a lower energy state for all of the atoms involved than if they existed without their outer shells filled.

There are two types of covalent bonds: polar and nonpolar. **Nonpolar covalent bonds** form between two atoms of the same element or between different elements that share the electrons equally. For example, an oxygen atom can bond with another oxygen atom to fill their outer shells. This association is nonpolar because the electrons will be equally distributed between each oxygen atom. Two covalent bonds form between the two oxygen atoms because oxygen requires two shared electrons to fill its outermost shell. Nitrogen atoms will form three covalent bonds (also called triple covalent) between two atoms of nitrogen because each nitrogen atom needs three electrons to fill its outermost shell. Another example of a nonpolar covalent bond is found in the methane (CH_4) molecule. The carbon atom has four electrons in its outermost shell and needs four more to fill it. It gets these four from four hydrogen atoms, each atom providing one. These elements all share the electrons equally, creating four nonpolar covalent bonds (Figure 2.1.5).

In a **polar covalent bond**, the electrons shared by the atoms spend more time closer to one nucleus than to the other nucleus. Because of the unequal distribution of electrons between the different nuclei, a slightly positive (δ+) or slightly negative (δ–) charge develops. The covalent bonds between hydrogen and oxygen atoms in water are polar covalent bonds. The shared electrons spend more time near the oxygen nucleus, giving it a small negative charge, than they spend near the hydrogen nuclei, giving these molecules a small positive charge.

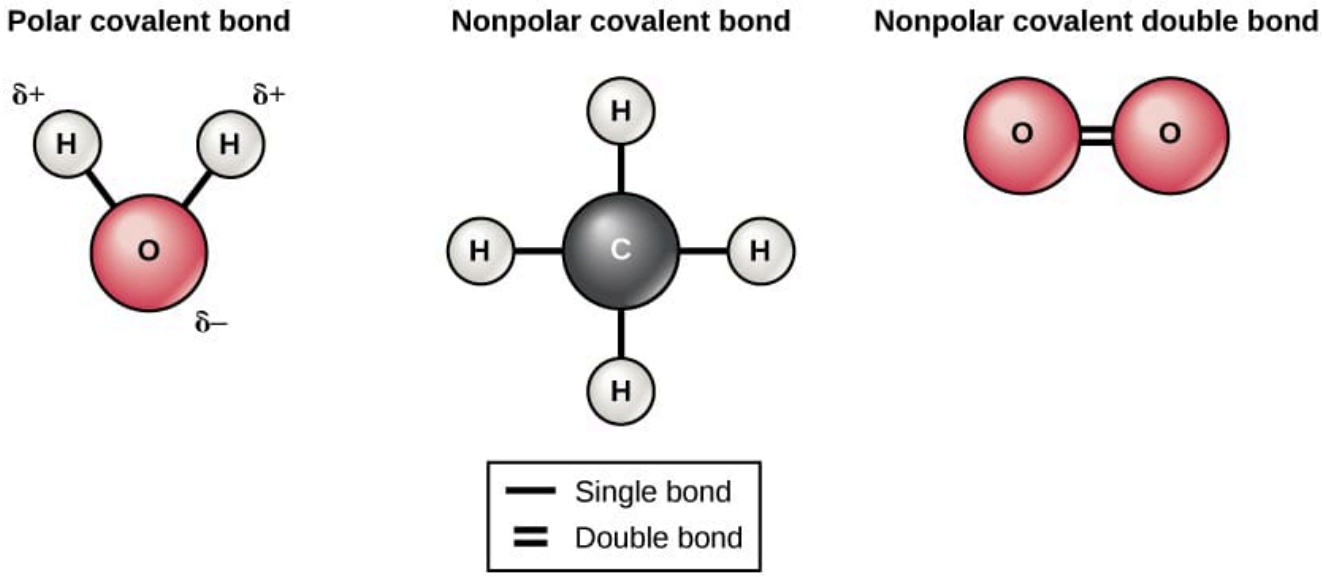


Figure 2.1.5: The water molecule (left) depicts a polar bond with a slightly positive charge on the hydrogen atoms and a slightly negative charge on the oxygen. Examples of nonpolar bonds include methane (middle) and oxygen (right).

Hydrogen Bonds

Ionic and covalent bonds are strong bonds that require considerable energy to break. However, not all bonds between elements are ionic or covalent bonds. Weaker bonds can also form. These are attractions that occur between positive and negative charges that do not require much energy to break. Two weak bonds that occur frequently are hydrogen bonds and **van der Waals interactions**. These bonds give rise to the unique properties of water and the unique structures of DNA and proteins.

When polar covalent bonds containing a hydrogen atom form, the hydrogen atom in that bond has a slightly positive charge. This is because the shared electron is pulled more strongly toward the other element and away from the hydrogen nucleus. Because the hydrogen atom is slightly positive (δ+), it will be attracted to neighboring negative partial charges (δ–). When this happens, a weak interaction occurs between the δ+ charge of the hydrogen atom of one molecule and the δ– charge of the other molecule. This interaction is called a **hydrogen bond**. This type of bond is common; for example, the liquid nature of water is caused by the hydrogen bonds between water molecules (Figure 2.1.6). 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.

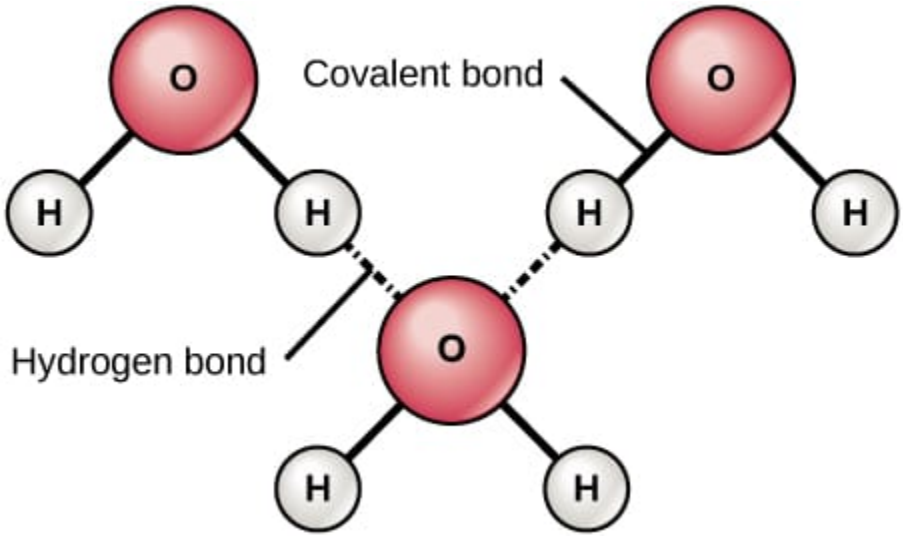


Figure 2.1.6: Hydrogen bonds form between slightly positive (δ+) and slightly negative (δ–) charges of polar covalent molecules, such as water.

Hydrogen bonds can form between different molecules and they do not always have to include a water molecule. Hydrogen atoms in polar bonds within any molecule can form bonds with other adjacent molecules. For example, hydrogen bonds hold together two long strands of DNA to give the DNA molecule its characteristic double-stranded structure. Hydrogen bonds are also responsible for some of the three-dimensional structure of proteins.

van der Waals Interactions

Like hydrogen bonds, van der Waals interactions are weak attractions or interactions between molecules. They occur between polar, covalently bound, atoms in different molecules. Some of these weak attractions are caused by temporary partial charges formed when electrons move around a nucleus. These weak interactions between molecules are important in biological systems.

Summary

Matter is anything that occupies space and has mass. It is made up of atoms of different elements. All of the 92 elements that occur naturally have unique qualities that allow them to combine in various ways to create compounds or molecules. Atoms, which consist of protons, neutrons, and electrons, are the smallest units of an element that retain all of the properties of that element. Electrons can be donated or shared between atoms to create bonds, including ionic, covalent, and hydrogen bonds, as well as van der Waals interactions.

Connections

Figure 2.1.2: How many neutrons do (K) potassium-39 and potassium-40 have, respectively?

Answer

Potassium-39 has twenty neutrons. Potassium-40 has twenty one neutrons.

Contributors and Attributions

- Samantha Fowler (Clayton State University), Rebecca Roush (Sandhills Community College), James Wise (Hampton University). Original content by OpenStax (CC BY 4.0; Access for free at https://cnx.org/contents/b3c1e1d2-83...4-e119a8aafbdd).

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2.2: Water

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.

Water Is Polar

The hydrogen and oxygen atoms within water molecules form polar covalent bonds. The shared electrons spend more time associated with the oxygen atom than 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 repel each other and form the unique shape seen in Figure 2.1.6. Each water molecule attracts other water molecules because of the positive and negative charges in the different parts of the molecule. Water also attracts other polar molecules (such as sugars), forming hydrogen bonds. When a substance readily forms hydrogen bonds with water, it can dissolve in water and is referred to as **hydrophilic** (“water-loving”). Hydrogen bonds are not readily formed with nonpolar substances like oils and fats (Figure 2.2.1). These nonpolar compounds are **hydrophobic** (“water-fearing”) and will not dissolve in water.



Figure 2.2.1: As this macroscopic image of oil and water show, oil is a nonpolar compound and, hence, will not dissolve in water. Oil and water do not mix. (credit: Gautam Dogra)

Water Stabilizes Temperature

The hydrogen bonds in water give it a **high specific heat capacity,** allowing it to absorb and release heat energy more slowly than many other substances. Temperature is a measure of the motion (**kinetic energy**) of molecules. As the motion increases, energy is higher and thus temperature is higher. Water absorbs a great deal of energy before its temperature rises. Increased energy disrupts the hydrogen bonds between water molecules. Because these bonds can be created and disrupted rapidly, water absorbs an increase in energy and temperature changes only minimally. This means that water moderates temperature changes within organisms and in their environments. As energy input continues, the balance between hydrogen-bond formation and destruction swings toward the destruction side. More bonds are broken than are formed. Because of this, water has a high **heat of vaporization**, the amount of energy required to convert a liquid substance into a gas. This process results in the release of individual water molecules at the surface of the liquid (such as a body of water, the leaves of a plant, or the skin of an organism) in a process called **evaporation**. Evaporation of sweat, which is 90 percent water, allows for cooling of an organism, because breaking hydrogen bonds requires an input of energy and takes heat away from the body.

Conversely, as molecular motion decreases and temperatures drop, less energy is present to break the hydrogen bonds between water molecules. These bonds remain intact and begin to form a rigid, lattice-like structure (e.g., ice) (Figure 2.2.2a). When frozen, ice is less dense than liquid water (the molecules are farther apart). This means that ice floats on the surface of a body of water (Figure 2.2.2**b**). In lakes, ponds, and oceans, ice will form on the surface of the water, creating an insulating barrier to protect the animal and plant life beneath from freezing in the water. If this did not happen, plants and animals living in water would freeze in a block of ice and could not move freely, making life in cold temperatures difficult or impossible.

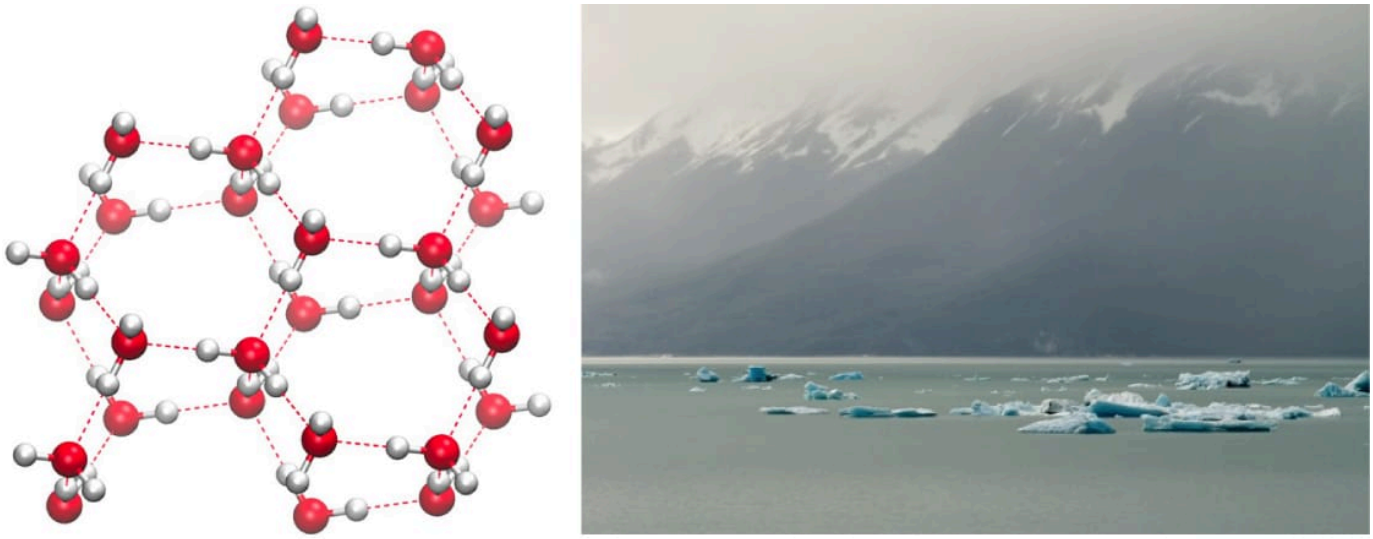


Figure 2.2.2: (a) The lattice structure of ice makes it less dense than the freely flowing molecules of liquid water. Ice's lower density enables it to (b) float on water. (credit a: modification of work by Jane Whitney; credit b: modification of work by Carlos Ponte)

CONCEPTS IN ACTION

This link takes you to a 3-D animation of the structure of an ice lattice. (credit: image created by Jane Whitney using Visual Molecular Dynamics (VMD) software [1])

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 **solvent** — a substance capable of dissolving another substance. The charged particles will form hydrogen bonds with a surrounding layer of water molecules. This is referred to as a **sphere of hydration** and serves to keep the particles separated or dispersed in the water. In the case of table salt (NaCl) mixed in water (Figure 2.2.3), the sodium and chloride ions separate, or dissociate, in the water, and spheres of hydration are formed around the ions. A positively charged sodium ion is surrounded by the partially negative charges of oxygen atoms in water molecules. A negatively charged chloride ion is surrounded by the partially positive charges of hydrogen atoms in water molecules. These spheres of hydration are also referred to as **hydration shells**. The polarity of the water molecule makes it an effective solvent and is important in its many roles

in living systems.

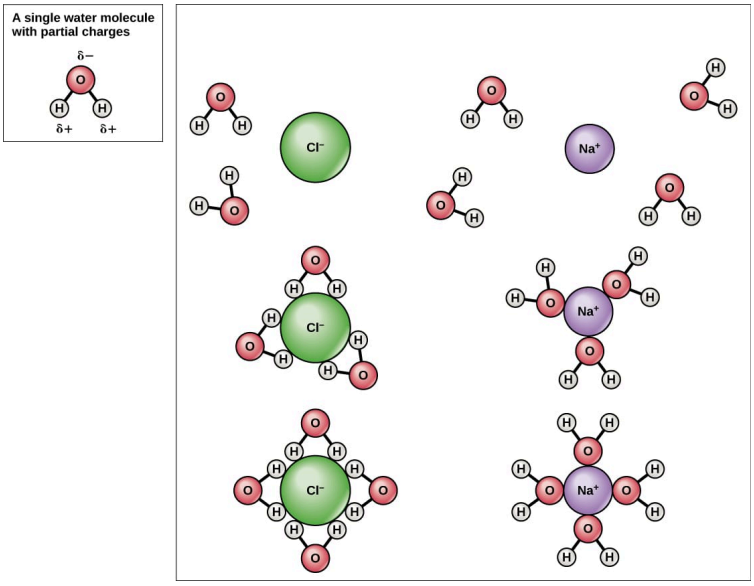


Figure 2.2.3: When table salt (NaCl) is mixed in water, spheres of hydration form around the ions.

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, although there is no more room in the glass. Cohesion gives rise to **surface tension**, the capacity of a substance to withstand rupture when placed under tension or stress. 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. Cohesion and surface tension keep the water molecules intact and the item floating on the top. 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 (Figure 2.2.4).

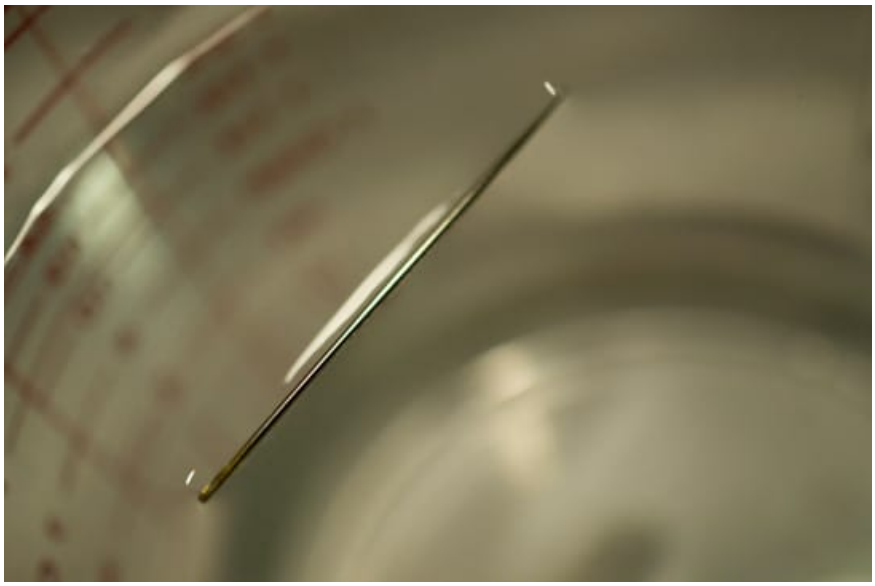


Figure 2.2.4: The weight of a needle on top of water pulls the surface tension downward; at the same time, the surface tension of the water is pulling it up, suspending the needle on the surface of the water and keeping it from sinking. Notice the indentation in the water around the needle. (credit: Cory Zanker)

These cohesive forces are also related to the water's property of **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.

CONCEPT IN ACTION

To learn more about water, visit the U.S. Geological Survey Water Science for Schools: All About Water! website.

Buffers, pH, Acids, and Bases

The **pH** of a solution is a measure of its acidity or alkalinity. You have probably used litmus paper, paper that has been treated with a natural water-soluble dye so it can be used as a pH indicator, to test how much acid or base (alkalinity) exists in a solution. You might have even used some to make sure the water in an outdoor swimming pool is properly treated. In both cases, this pH test measures the amount of hydrogen ions that exists in a given solution. High concentrations of hydrogen ions yield a low pH, whereas low levels of hydrogen ions result in a high pH. The overall concentration of hydrogen ions is inversely related to its pH and can be measured on the pH scale (Figure 2.2.5). Therefore, the more hydrogen ions present, the lower the pH; conversely, the fewer hydrogen ions, the higher the pH.

The pH scale ranges from 0 to 14. A change of one unit on the pH scale represents a change in the concentration of hydrogen ions by a factor of 10, a change in two units represents a change in the concentration of hydrogen ions by a factor of 100. Thus, small changes in pH represent large changes in the concentrations of hydrogen ions. Pure water is neutral. It is neither acidic nor basic, and has a pH of 7.0. Anything below 7.0 (ranging from 0.0 to 6.9) is acidic, and anything above 7.0 (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 to 2). Orange juice is mildly acidic (pH = approximately 3.5), whereas baking soda is basic (pH = 9.0).

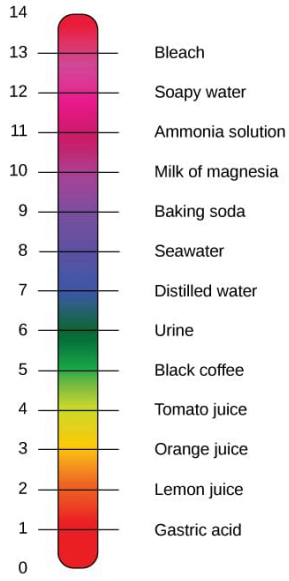


Figure 2.2.5: The pH scale measures the amount of hydrogen ions (H^+) in a substance. (credit: modification of work by Edward Stevens)

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.

Most cells in our bodies operate within a very narrow window of the pH scale, typically ranging only from 7.2 to 7.6. If the pH of the body is outside of this range, the respiratory system malfunctions, as do other organs in the body. Cells no longer function properly, and proteins will break down. Deviation outside of the pH range can induce coma or even cause death.

So 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 rapidly dissociate into bicarbonate and H^+ ions. The H^+ ions can combine with the OH^- ions, limiting 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.

Summary

Water has many properties that are critical to maintaining life. It is polar, allowing for the formation of hydrogen bonds, which allow ions and other polar molecules to dissolve in water. Therefore, water is an excellent solvent. The hydrogen bonds between water molecules give water the ability to hold heat better than many other substances. As the temperature rises, the hydrogen bonds between water continually break and reform, allowing for the overall temperature to remain stable, although increased energy is added to the system. Water's cohesive forces allow for the property of surface tension. All of these unique properties of water are important in the chemistry of living organisms.

The pH of a solution is a measure of the concentration of hydrogen ions in the solution. A solution with a high number of hydrogen ions is acidic and has a low pH value. A solution with a high number of hydroxide ions is basic and has a high pH value. The pH scale ranges from 0 to 14, with a pH of 7 being neutral. Buffers are solutions that moderate pH changes when an acid or base is added to the buffer system. Buffers are important in biological systems because of their ability to maintain constant pH conditions.

Footnotes

1. 1 Humphrey, W., Dalke, A. and Schulten, K., "VMD—Visual Molecular Dynamics", *J. Molec. Graphics*, 1996, vol. 14, pp. 33-38

Contributors and Attributions

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2.3: Biological Molecules

The large molecules necessary for life that are built from smaller organic molecules are called **biological macromolecules**. There are four major classes of biological macromolecules (carbohydrates, lipids, proteins, and nucleic acids), and each is an important component of the cell and performs a wide array of functions. Combined, these molecules make up the majority of a cell's mass. Biological macromolecules are organic, meaning that they contain carbon (with some exceptions, like carbon dioxide). In addition, they may contain hydrogen, oxygen, nitrogen, phosphorus, sulfur, and additional minor elements.

Carbon

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, if not most, 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 Bonding

Carbon contains four electrons in its outer shell. Therefore, it can form four covalent bonds with other atoms or molecules. The simplest organic carbon molecule is methane (CH_4), in which four hydrogen atoms bind to a carbon atom (Figure $2.3.1$).

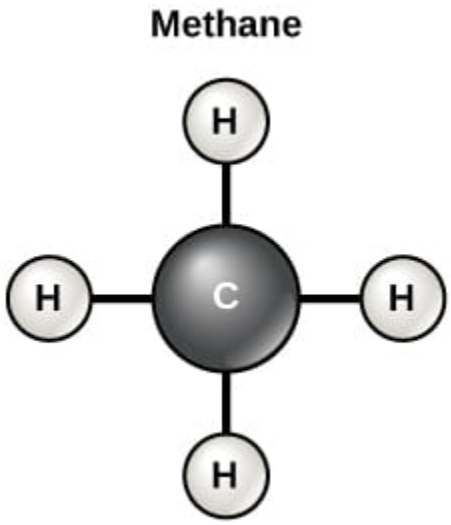


Figure $2.3.1$: Carbon can form four covalent bonds to create an organic molecule. The simplest carbon molecule is methane (CH_4), depicted here.

However, structures that are more complex are made using carbon. Any of the hydrogen atoms can be replaced with another carbon atom covalently bonded to the first carbon atom. In this way, long and branching chains of carbon compounds can be made (Figure $2.3.2$**a**). The carbon atoms may bond with atoms of other elements, such as nitrogen, oxygen, and phosphorus (Figure $2.3.2$**b**). The molecules may also form rings, which themselves can link with other rings (Figure $2.3.2$**c**). This diversity of molecular forms accounts for the diversity of functions of the biological macromolecules and is based to a large degree on the ability of carbon to form multiple bonds with itself and other atoms.

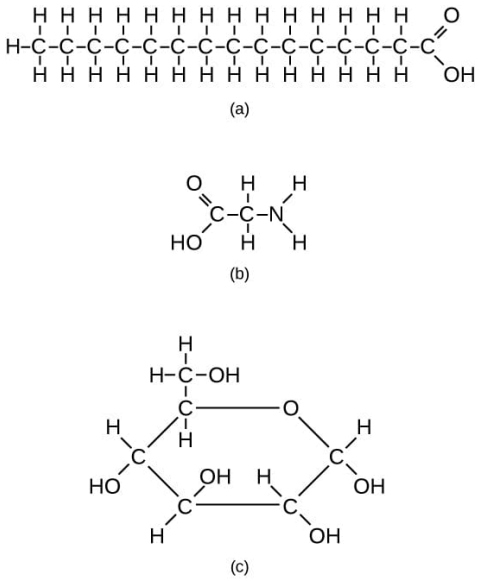


Figure 2.3.2: These examples show three molecules (found in living organisms) that contain carbon atoms bonded in various ways to other carbon atoms and the atoms of other elements. (a) This molecule of stearic acid has a long chain of carbon atoms. (b) Glycine, a component of proteins, contains carbon, nitrogen, oxygen, and hydrogen atoms. (c) Glucose, a sugar, has a ring of carbon atoms and one oxygen atom.

Carbohydrates

Carbohydrates are macromolecules with which most consumers are somewhat familiar. To lose weight, some individuals adhere to "low-carb" diets. Athletes, in contrast, often "carb-load" before important competitions to ensure that they have sufficient energy to compete at a high level. Carbohydrates are, in fact, an essential part of our diet; grains, fruits, and vegetables are all natural sources of carbohydrates. Carbohydrates provide energy to the body, particularly through glucose, a simple sugar. Carbohydrates also have other important functions in humans, animals, and plants.

Carbohydrates can be represented by the formula $\mathbf{(CH_2O)_{\mathit{n}}}$, where *n* is the number of carbon atoms in the molecule. In other words, the ratio of carbon to hydrogen to oxygen is 1:2:1 in carbohydrate molecules. Carbohydrates are classified into three subtypes: monosaccharides, disaccharides, and polysaccharides.

Monosaccharides (mono- = "one"; sacchar- = "sweet") are simple sugars, the most common of which is glucose. In monosaccharides, the number of carbon atoms usually ranges from three to six. Most monosaccharide names end with the suffix -ose. Depending on the number of carbon atoms in the sugar, they may be known as trioses (three carbon atoms), pentoses (five carbon atoms), and hexoses (six carbon atoms).

Monosaccharides may exist as a linear chain or as ring-shaped molecules; in aqueous solutions, they are usually found in the ring form.

The chemical formula for glucose is $C_6H_{12}O_6$. In most living species, glucose is an important source of energy. During cellular respiration, energy is released from glucose, and that energy is used to help make adenosine triphosphate (ATP). Plants synthesize glucose using carbon dioxide and water by the process of photosynthesis, and the glucose, in turn, is used for the energy requirements of the plant. The excess synthesized glucose is often stored as starch that is broken down by other organisms that feed on plants.

Galactose (part of lactose, or milk sugar) and **fructose** (found in fruit) are other common monosaccharides. Although glucose, galactose, and fructose all have the same chemical formula ($C_6H_{12}O_6$), they differ structurally and chemically (and are known as isomers) because of differing arrangements of atoms in the carbon chain (Figure 2.3.3).

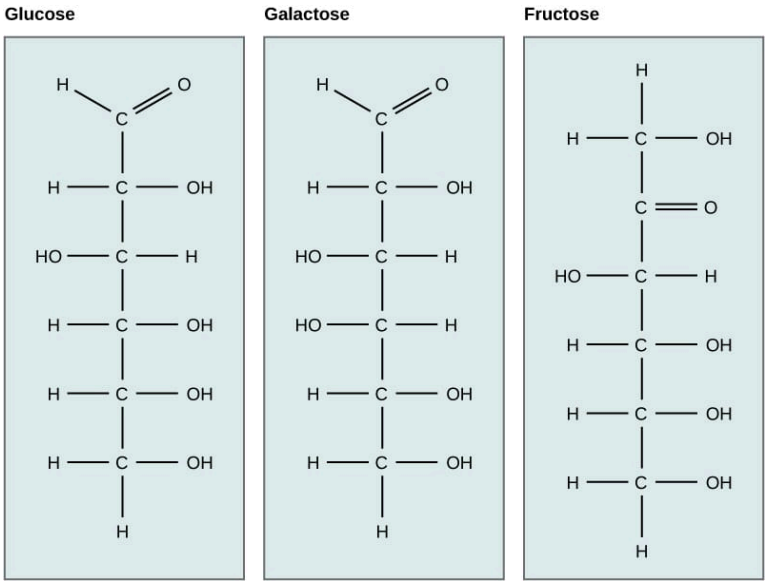


Figure 2.3.3: Glucose, galactose, and fructose are isomeric monosaccharides, meaning that they have the same chemical formula but slightly different structures.

Disaccharides (di- = "two") form when two monosaccharides undergo a dehydration reaction (a reaction in which the removal of a water molecule occurs). During this process, the hydroxyl group (–OH) of one monosaccharide combines with a hydrogen atom of another monosaccharide, releasing a molecule of water (H_2O) and forming a covalent bond between atoms in the two sugar molecules.

Common disaccharides include **lactose**, **maltose**, and **sucrose**. Lactose is a disaccharide consisting of the monomers glucose and galactose. **Monomers** are single molecules that can chemically bond with other identical or similar molecules to form a larger chain - a polymer. **Polymers** are A large molecule made up of many repeating monomer units bonded together in a long chain. Lactose is found naturally in milk. Maltose, or malt sugar, is a disaccharide formed from a dehydration reaction between two glucose molecules. The most common disaccharide is sucrose, or table sugar, which is composed of the monomers glucose and fructose.

A long chain of monosaccharides linked by covalent bonds is known as a **polysaccharide** (poly- = "many"). The chain may be branched or unbranched, and it may contain different types of monosaccharides. Polysaccharides may be very large molecules. Starch, glycogen, cellulose, and chitin are examples of polysaccharides.

Starch is the stored form of sugars in plants and is made up of amylose and amylopectin (both polymers of glucose). Plants are able to synthesize glucose, and the excess glucose is stored as starch in different plant parts, including roots and seeds. The starch that is consumed by animals is broken down into smaller molecules, such as glucose. The cells can then absorb the glucose.

Glycogen is the storage form of glucose in humans and other vertebrates, and is made up of monomers of glucose. Glycogen is the animal equivalent of starch and is a highly branched molecule usually stored in liver and muscle cells. Whenever glucose levels decrease, glycogen is broken down to release glucose.

Cellulose is one of the most abundant natural biopolymers. The cell walls of plants are mostly made of cellulose, which provides structural support to the cell. Wood and paper are mostly cellulosic in nature. Cellulose is made up of glucose monomers that are linked by bonds between particular carbon atoms in the glucose molecule.

Every other glucose monomer in cellulose is flipped over and packed tightly as extended long chains. This gives cellulose its rigidity and high tensile strength—which is so important to plant cells. Cellulose passing through our digestive system is called dietary fiber. While the glucose-glucose bonds in cellulose cannot be broken down by human digestive enzymes, herbivores such as cows, buffalos, and horses are able to digest grass that is rich in cellulose and use it as a food source. The animals themselves are not breaking the cellulose down, but instead it is the microbes that live in their digestive tracts. In these animals, certain species of bacteria reside in the rumen (part of the digestive system of herbivores) and secrete the enzyme cellulase. The appendix also contains bacteria that break down cellulose, giving it an important role in the digestive systems of ruminants. Cellulase enzymes can break down cellulose into glucose monomers that can be used as an energy source by the animal.

Carbohydrates serve other functions in different animals. Arthropods, such as insects, spiders, and crabs, have an outer skeleton, called the exoskeleton, which protects their internal body parts. This exoskeleton is made of the biological macromolecule chitin, which is a nitrogenous carbohydrate. It is made of repeating units of a modified sugar containing nitrogen.

Thus, through differences in molecular structure, carbohydrates are able to serve the very different functions of energy storage (starch and glycogen) and structural support and protection (cellulose and chitin) (Figure 2.3.4).

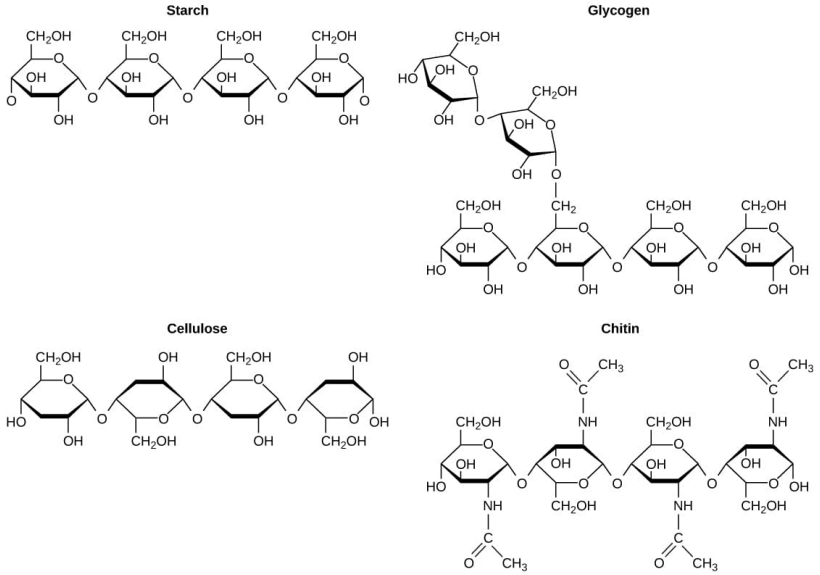


Figure 2.3.4: Although their structures and functions differ, all polysaccharide carbohydrates are made up of monosaccharides and have the chemical formula $(CH_2O)n$.

CAREERS IN ACTION: Registered Dietitian

Obesity is a worldwide health concern, and many diseases, such as diabetes and heart disease, are becoming more prevalent because of obesity. This is one of the reasons why registered dietitians are increasingly sought after for advice. Registered dietitians help plan food and nutrition programs for individuals in various settings. They often work with patients in health-care facilities, designing nutrition plans to prevent and treat diseases. For example, dietitians may teach a patient with diabetes how to manage blood-sugar levels by eating the correct types and amounts of carbohydrates. Dietitians may also work in nursing homes, schools, and private practices.

To become a registered dietitian, one needs to earn at least a bachelor's degree in dietetics, nutrition, food technology, or a related field. In addition, registered dietitians must complete a supervised internship program and pass a national exam. Those who pursue careers in dietetics take courses in nutrition, chemistry, biochemistry, biology, microbiology, and human physiology. Dietitians must become experts in the chemistry and functions of food (proteins, carbohydrates, and fats).

Lipids

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 nonpolar molecules. This is because they are hydrocarbons that include only nonpolar carbon-carbon or carbon-hydrogen 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 (Figure 2.3.5). 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 the plasma membrane. Lipids include fats, oils, waxes, phospholipids, and steroids.



Figure 2.3.5: Hydrophobic lipids in the fur of aquatic mammals, such as this river otter, protect them from the elements. (credit: Ken Bosma)

A fat molecule, such as a **triglyceride**, consists of two main components—glycerol and fatty acids. **Glycerol** is an organic compound with three carbon atoms, five hydrogen atoms, and three hydroxyl (–OH) groups. **Fatty acids** have a long chain of hydrocarbons to which an acidic carboxyl group is attached, hence the name "fatty acid." The number of carbons in the fatty acid may range from 4 to 36; most common are those containing 12–18 carbons. In a fat molecule, a fatty acid is attached to each of the three oxygen atoms in the –OH groups of the glycerol molecule with a covalent bond (Figure 2.3.6).

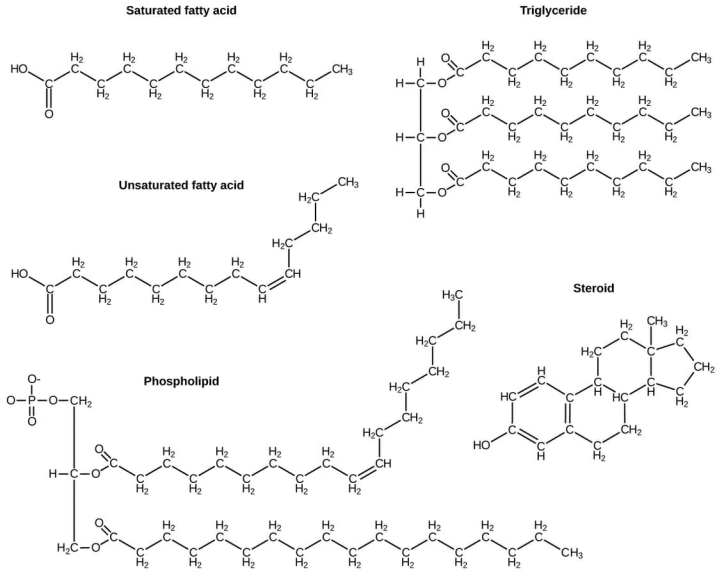


Figure 2.3.6: Lipids include fats, such as triglycerides, which are made up of fatty acids and glycerol, phospholipids, and steroids.

During this covalent bond formation, three water molecules are released. The three fatty acids in the fat may be similar or dissimilar. These fats are also called triglycerides because they have three fatty acids. Some fatty acids have common names that specify their origin. For example, palmitic acid, a saturated fatty acid, is derived from the palm tree. Arachidic acid is derived from *Arachis hypogaea*, the scientific name for peanuts.

Fatty acids may be **saturated** or **unsaturated**. In a fatty acid chain, if there are only single bonds between neighboring carbons in the hydrocarbon chain, the fatty acid is saturated. Saturated fatty acids are saturated with hydrogen; in other words, the number of hydrogen atoms attached to the carbon skeleton is maximized.

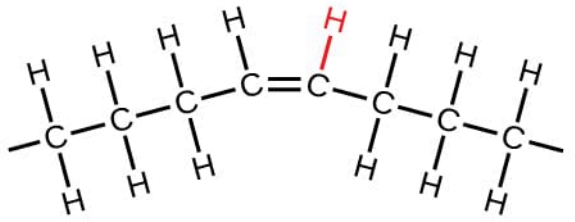
When the hydrocarbon chain contains a double bond, the fatty acid is an unsaturated fatty acid.

Most unsaturated fats are liquid at room temperature and are called **oils**. If there is one double bond in the molecule, then it is known as a **monounsaturated fat** (e.g., olive oil), and if there is more than one double bond, then it is known as a **polyunsaturated fat** (e.g., canola oil).

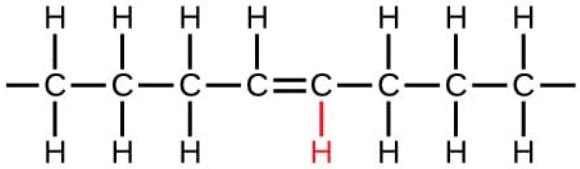
Saturated fats tend to get packed tightly and are solid at room temperature. Animal fats with stearic acid and palmitic acid contained in meat, and the fat with butyric acid contained in butter, are examples of saturated fats. Mammals store fats in specialized cells called adipocytes, where globules of fat occupy most of the cell. In plants, fat or oil is stored in seeds and is used as a source of energy during embryonic development.

Unsaturated fats or **oils** are usually of plant origin and contain unsaturated fatty acids. The double bond causes a bend or a "kink" that prevents the fatty acids from packing tightly, keeping them liquid at room temperature. Olive oil, corn oil, canola oil, and cod liver oil are examples of unsaturated fats. Unsaturated fats help to improve blood cholesterol levels, whereas saturated fats contribute to plaque formation in the arteries, which increases the risk of a heart attack.

In the food industry, oils are artificially hydrogenated to make them semi-solid, leading to less spoilage and increased shelf life. Simply speaking, hydrogen gas is bubbled through oils to solidify them. During this hydrogenation process, double bonds of the *cis*-conformation in the hydrocarbon chain may be converted to double bonds in the *trans*-conformation. This forms a *trans*-fat from a *cis*-fat. The orientation of the double bonds affects the chemical properties of the fat (Figure 2.3.7).



***cis*-fat molecule**



***trans*-fat molecule**

Figure 2.3.7: During the hydrogenation process, the orientation around the double bonds is changed, making a trans-fat from a cis-fat. This changes the chemical properties of the molecule.

Margarine, some types of **peanut butter**, and shortening are examples of artificially hydrogenated *trans*-fats. Recent studies have shown that an increase in *trans*-fats in the human diet may lead to an increase in levels of low-density lipoprotein (LDL), or "bad" cholesterol, which, in turn, may lead to plaque deposition in the arteries, resulting in heart disease. Many fast food restaurants have recently eliminated the use of *trans*-fats, and U.S. food labels are now required to list their *trans*-fat content.

Essential fatty acids are fatty acids that are required but not synthesized by the human body. Consequently, they must be supplemented through the diet. Omega-3 fatty acids fall into this category and are one of only two known essential fatty acids for humans (the other being omega-6 fatty acids). They are a type of polyunsaturated fat and are called omega-3 fatty acids because the third carbon from the end of the fatty acid participates in a double bond.

Salmon, trout, and tuna are good sources of omega-3 fatty acids. Omega-3 fatty acids are important in brain function and normal growth and development. They may also prevent heart disease and reduce the risk of cancer.

Like carbohydrates, fats have received a lot of bad publicity. It is true that eating an excess of fried foods and other "fatty" foods leads to weight gain. However, fats do have important functions. Fats serve as long-term energy storage. They also provide insulation for the body. Therefore, "healthy" unsaturated fats in moderate amounts should be consumed on a regular basis.

Phospholipids are the major constituent of the plasma membrane. Like fats, they are composed of fatty acid chains attached to

a glycerol or similar backbone. Instead of three fatty acids attached, however, there are two fatty acids and the third carbon of the glycerol backbone is bound to a phosphate group. The phosphate group is modified by the addition of an alcohol.

A phospholipid has both hydrophobic and hydrophilic regions. The fatty acid chains are hydrophobic and exclude themselves from water, whereas the phosphate is hydrophilic and interacts with water.

Cells are surrounded by a membrane, which has a bilayer of phospholipids. The fatty acids of phospholipids face inside, away from water, whereas the phosphate group can face either the outside environment or the inside of the cell, which are both aqueous.

Steroids and Waxes

Unlike the phospholipids and fats discussed earlier, steroids have a ring structure. Although they do not resemble other lipids, they are grouped with them because they are also hydrophobic. All steroids have four, linked carbon rings and several of them, like cholesterol, have a short tail.

Cholesterol is a steroid. Cholesterol is mainly synthesized in the liver and is the precursor of many steroid hormones, such as testosterone and estradiol. It is also the precursor of vitamins E and K. Cholesterol is the precursor of bile salts, which help in the breakdown of fats and their subsequent absorption by cells. Although cholesterol is often spoken of in negative terms, it is necessary for the proper functioning of the body. It is a key component of the plasma membranes of animal cells.

Waxes are made up of a hydrocarbon chain with an alcohol (–OH) group and a fatty acid. Examples of animal waxes include beeswax and lanolin. Plants also have waxes, such as the coating on their leaves, that helps prevent them from drying out.

Proteins

Proteins are one of the most abundant organic molecules in living systems and have the most diverse range of functions of all macromolecules. Proteins may be structural, regulatory, contractile, or protective; they may serve in transport, storage, or membranes; or they may be toxins or enzymes. Each cell in a living system may contain thousands of different proteins, each with a unique function. Their structures, like their functions, vary greatly. They are all, however, polymers of amino acids, arranged in a linear sequence.

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. For example, proteins can function as enzymes or hormones. Enzymes, which are produced by living cells, are catalysts in biochemical reactions (like digestion) and are usually proteins. 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. An example of an enzyme is salivary amylase, which breaks down amylose, a component of starch.

Hormones are chemical signaling molecules, usually proteins or steroids, secreted by an endocrine gland or group of endocrine cells that act to control or regulate specific physiological processes, including growth, development, metabolism, and reproduction. For example, insulin is a protein hormone that maintains blood glucose levels.

Proteins have different shapes and molecular weights; some proteins are globular in shape whereas others are fibrous in nature. For example, hemoglobin is a globular protein, but collagen, found in our skin, is a fibrous protein. Protein shape is critical to its function. Changes in temperature, pH, and exposure to chemicals may lead to permanent changes in the shape of the protein, leading to a loss of function or denaturation (to be discussed in more detail later). All proteins are made up of different arrangements of the same 20 kinds of amino acids.

Amino acids are the monomers that make up proteins. Each amino acid has the same fundamental structure, which consists of a central carbon atom bonded to an amino group ($-NH_2$), a carboxyl group (–COOH), and a hydrogen atom. Every amino acid also has another variable atom or group of atoms bonded to the central carbon atom known as the **R group**. The R group is the only difference in structure between the 20 amino acids; otherwise, the amino acids are identical (Figure 2.3.8).

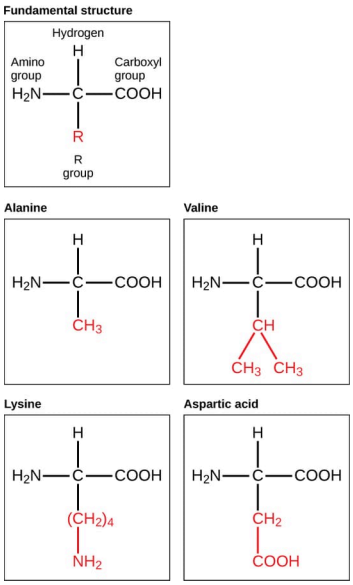


Figure 2.3.8: Amino acids are made up of a central carbon bonded to an amino group ($–NH_2$), a carboxyl group (–COOH), and a hydrogen atom. The central carbon's fourth bond varies among the different amino acids, as seen in these examples of alanine, valine, lysine, and aspartic acid.

The chemical nature of the R group determines the chemical nature of the amino acid within its protein (that is, whether it is acidic, basic, polar, or nonpolar).

The sequence and number of amino acids ultimately determine a protein's shape, size, and function. Each amino acid is attached to another amino acid by a covalent bond, known as a peptide bond, which is formed by a dehydration reaction. The carboxyl group of one amino acid and the amino group of a second amino acid combine, releasing a water molecule. The resulting bond is the peptide bond.

The products formed by such a linkage are called polypeptides. While the terms polypeptide and protein are sometimes used interchangeably, a polypeptide is technically a polymer of amino acids, whereas the term protein is used for a polypeptide or polypeptides that have combined together, have a distinct shape, and have a unique function.

EVOLUTION IN ACTION: The Evolutionary Significance of Cytochrome c

Cytochrome c is an important component of the molecular machinery that harvests energy from glucose. Because this protein's role in producing cellular energy is crucial, it has changed very little over millions of years. Protein sequencing has shown that there is a considerable amount of sequence similarity among cytochrome c molecules of different species; evolutionary relationships can be assessed by measuring the similarities or differences among various species' protein sequences.

For example, scientists have determined that human cytochrome c contains 104 amino acids. For each cytochrome c molecule that has been sequenced to date from different organisms, 37 of these amino acids appear in the same position in each cytochrome c. This indicates that all of these organisms are descended from a common ancestor. On comparing the human and chimpanzee protein sequences, no sequence difference was found. When human and rhesus monkey sequences were compared, a single difference was found in one amino acid. In contrast, human-to-yeast comparisons show a difference in 44 amino acids, suggesting that humans and chimpanzees have a more recent common ancestor than humans and the rhesus monkey, or humans and yeast.

Protein Structure

As discussed earlier, the shape of a protein is critical to its function. To understand how the protein gets its final shape or conformation, we need to understand the four levels of protein structure: primary, secondary, tertiary, and quaternary (Figure 2.3.9).

The unique sequence and number of amino acids in a polypeptide chain is its **primary structure**. The unique sequence for every protein is ultimately determined by the gene that encodes the protein. Any change in the gene sequence may lead to a different amino acid being added to the polypeptide chain, causing a change in protein structure and function. In sickle cell anemia, the hemoglobin β chain has a single amino acid substitution, causing a change in both the structure and function of the protein. What is most remarkable to consider is that a hemoglobin molecule is made up of two alpha chains and two beta chains that each consist of about 150 amino acids. The molecule, therefore, has about 600 amino acids. The structural difference between a normal hemoglobin molecule and a sickle cell molecule—that dramatically decreases life expectancy in the affected individuals—is a single amino acid of the 600.

Because of this change of one amino acid in the chain, the normally biconcave, or disc-shaped, red blood cells assume a crescent or "sickle" shape, which clogs arteries. This can lead to a myriad of serious health problems, such as breathlessness, dizziness, headaches, and abdominal pain for those who have this disease.

Folding patterns resulting from interactions between the non-R group portions of amino acids give rise to the **secondary structure** of the protein. The most common are the alpha (α)-helix and beta (β)-pleated sheet structures. Both structures are held in shape by hydrogen bonds. In the alpha helix, the bonds form between every fourth amino acid and cause a twist in the amino acid chain.

In the β-pleated sheet, the "pleats" are formed by hydrogen bonding between atoms on the backbone of the polypeptide chain. The R groups are attached to the carbons, and extend above and below the folds of the pleat. The pleated segments align parallel to each other, and hydrogen bonds form between the same pairs of atoms on each of the aligned amino acids. The α-helix and β-pleated sheet structures are found in many globular and fibrous proteins.

The unique three-dimensional structure of a polypeptide is known as its **tertiary structure**. This structure is caused by chemical interactions between various amino acids and regions of the polypeptide. Primarily, the interactions among R groups create the complex three-dimensional tertiary structure of a protein. There may be ionic bonds formed between R groups on different amino acids, or hydrogen bonding beyond that involved in the secondary structure. When protein folding takes place, the hydrophobic R groups of nonpolar amino acids lay in the interior of the protein, whereas the hydrophilic R groups lay on the outside. The former types of interactions are also known as hydrophobic interactions.

In nature, some proteins are formed from several polypeptides, also known as subunits, and the interaction of these subunits forms the **quaternary structure**. Weak interactions between the subunits help to stabilize the overall structure. For example, hemoglobin is a combination of four polypeptide subunits.

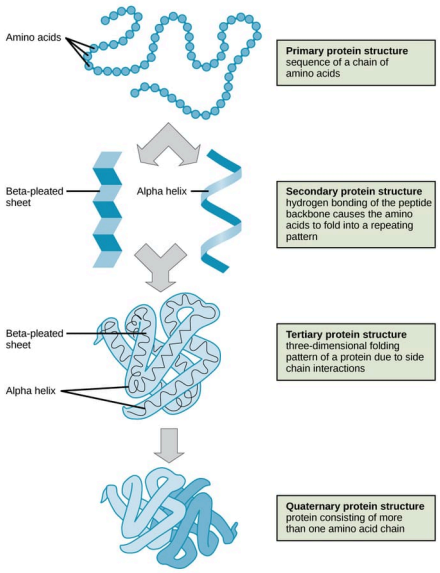


Figure 2.3.9: The four levels of protein structure can be observed in these illustrations. (credit: modification of work by National Human Genome Research Institute)

Each protein has its own unique sequence and shape held together by chemical interactions. If the protein is subject to changes in temperature, pH, or exposure to chemicals, the protein structure may change, losing its shape in what is known as denaturation as discussed earlier. Denaturation is often reversible because the primary structure is preserved if the denaturing agent is

removed, allowing the protein to resume its function. Sometimes denaturation is irreversible, leading to a loss of function. One example of protein denaturation can be seen when an egg is fried or boiled. The albumin protein in the liquid egg white is denatured when placed in a hot pan, changing from a clear substance to an opaque white substance. Not all proteins are denatured at high temperatures; for instance, bacteria that survive in hot springs have proteins that are adapted to function at those temperature.

Nucleic Acids

Nucleic acids are key macromolecules in the continuity of life. They carry the genetic blueprint of a cell and carry instructions for the functioning of the cell.

The two main types of nucleic acids are **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**. DNA is the genetic material found in all living 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 monomers 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 group (Figure 2.3.10). Each nitrogenous base in a nucleotide is attached to a sugar molecule, which is attached to a phosphate group.

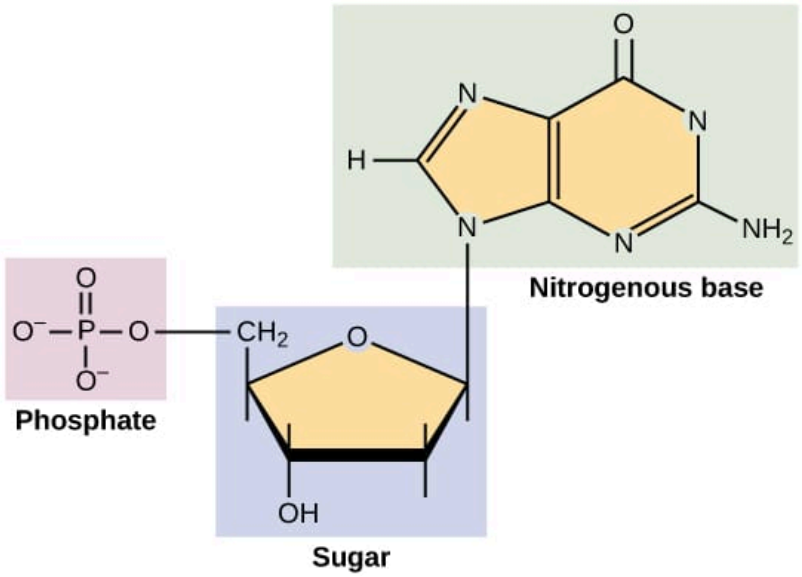


Figure 2.3.10: A nucleotide is made up of three components: a nitrogenous base, a pentose sugar, and a phosphate group.

DNA Double-Helical Structure

DNA has a double-helical structure (Figure 2.3.11). It is composed of two strands, or polymers, of nucleotides. The strands are formed with bonds between phosphate and sugar groups of adjacent nucleotides. The strands are bonded to each other at their bases with hydrogen bonds, and the strands coil about each other along their length, hence the “double helix” description, which means a double spiral.

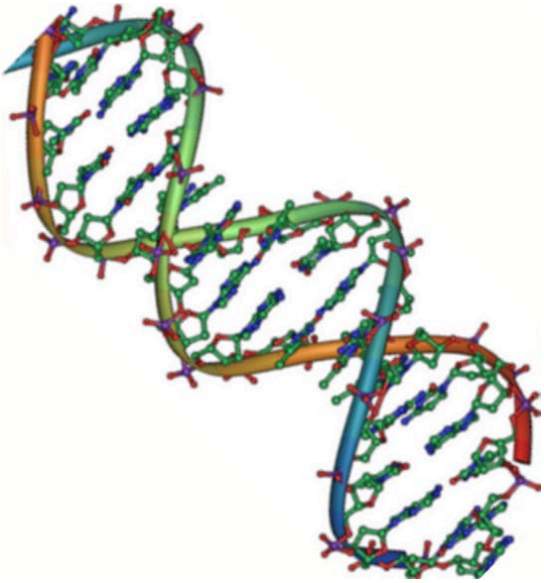


Figure 2.3.11: The double-helix model shows DNA as two parallel strands of intertwining molecules. (credit: Jerome Walker, Dennis Myts)

The alternating sugar and phosphate groups lie on the outside of each strand, forming the backbone of the DNA. The nitrogenous bases are stacked in the interior, like the steps of a staircase, and these bases pair; the pairs are bound to each other by hydrogen bonds. The bases pair in such a way that the distance between the backbones of the two strands is the same all along the molecule.

Summary

Living things are carbon-based because carbon plays such a prominent role in the chemistry of living things. The four covalent bonding positions of the carbon atom can give rise to a wide diversity of compounds with many functions, accounting for the importance of carbon in living things. Carbohydrates are a group of macromolecules that are a vital energy source for the cell, provide structural support to many organisms, and can be found on the surface of the cell as receptors or for cell recognition. Carbohydrates are classified as monosaccharides, disaccharides, and polysaccharides, depending on the number of monomers in the molecule.

Lipids are a class of macromolecules that are nonpolar and hydrophobic in nature. Major types include fats and oils, waxes, phospholipids, and steroids. Fats and oils are a stored form of energy and can include triglycerides. Fats and oils are usually made up of fatty acids and glycerol.

Proteins are a class of macromolecules that can perform a diverse range of functions for the cell. They help in metabolism by providing structural support and by acting as enzymes, carriers or as hormones. The building blocks of proteins are amino acids. Proteins are organized at four levels: primary, secondary, tertiary, and quaternary. Protein shape and function are intricately linked; any change in shape caused by changes in temperature, pH, or chemical exposure may lead to protein denaturation and a loss of function.

Nucleic acids are molecules made up of repeating units of nucleotides that direct cellular activities such as cell division and protein synthesis. Each nucleotide is made up of a pentose sugar, a nitrogenous base, and a phosphate group. There are two types of nucleic acids: DNA and RNA.

Contributors and Attributions

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2.4: Chemistry of Life (Exercises)

2.1: The Building Blocks of Molecules

At its most fundamental level, life is made up of matter. Matter 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. Each element is designated by its chemical symbol and possesses unique properties. These unique properties allow elements to combine and to bond with each other in specific ways.

Multiple Choice

Magnesium has an atomic number of 12. Which of the following statements is true of a neutral magnesium atom?

A. It has 12 protons, 12 electrons, and 12 neutrons.
B. It has 12 protons, 12 electrons, and six neutrons.
C. It has six protons, six electrons, and no neutrons.
D. It has six protons, six electrons, and six neutrons.

Answer

A

Which type of bond represents a weak chemical bond?

A. hydrogen bond
B. ionic bond
C. covalent bond
D. polar covalent bond

Answer

A

An isotope of sodium (Na) has a mass number of 22. How many neutrons does it have?

A. 11
B. 12
C. 22
D. 44

Answer

A

Free Response

Why are hydrogen bonds and van der Waals interactions necessary for cells?

Answer

Hydrogen bonds and van der Waals interactions form weak associations between different molecules. They provide the structure and shape necessary for proteins and DNA within cells so that they function properly. Hydrogen bonds also give water its unique properties, which are necessary for life.

2.2: Water

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.

Multiple Choice

Which of the following statements is not true?

A. Water is polar.
B. Water stabilizes temperature.
C. Water is essential for life.
D. Water is the most abundant atom in Earth's atmosphere.

Answer

D

Using a pH meter, you find the pH of an unknown solution to be 8.0. How would you describe this solution?

A. weakly acidic
B. strongly acidic
C. weakly basic
D. strongly basic

Answer

C

The pH of lemon juice is about 2.0, whereas tomato juice's pH is about 4.0. Approximately how much of an increase in hydrogen ion concentration is there between tomato juice and lemon juice?

A. 2 times
B. 10 times
C. 100 times
D. 1000 times

Answer

C

Free Response

Why can some insects walk on water?

Answer

Some insects can walk on water, although they are heavier (denser) than water, because of the surface tension of water. Surface tension results from cohesion, or the attraction between water molecules at the surface of the body of water [the liquid-air (gas) interface].

Explain why water is an excellent solvent.

Answer

Water molecules are polar, meaning they have separated partial positive and negative charges. Because of these

charges, water molecules are able to surround charged particles created when a substance dissociates. The surrounding layer of water molecules stabilizes the ion and keeps differently charged ions from reassociating, so the substance stays dissolved.

2.3: Biological Molecules

There are four major classes of biological macromolecules (carbohydrates, lipids, proteins, and nucleic acids), and each is an important component of the cell and performs a wide array of functions. Combined, these molecules make up the majority of a cell's mass. Biological macromolecules are organic, meaning that they contain carbon (with some exceptions, like carbon dioxide).

Multiple Choice

An example of a monosaccharide is _____.

A. fructose
B. glucose
C. galactose
D. all of the above

Answer

D

Cellulose and starch are examples of _____.

A. monosaccharides
B. disaccharides
C. lipids
D. polysaccharides

Answer

D

Phospholipids are important components of _____.

A. the plasma membrane of cells
B. the ring structure of steroids
C. the waxy covering on leaves
D. the double bond in hydrocarbon chains

Answer

A

The monomers that make up proteins are called _____.

A. nucleotides
B. disaccharides
C. amino acids
D. chaperones

Answer

C

Free Response

Explain at least three functions that lipids serve in plants and/or animals.

Answer

Fat serves as a valuable way for animals to store energy. It can also provide insulation. Phospholipids and steroids are important components of cell membranes.

Explain what happens if even one amino acid is substituted for another in a polypeptide chain. Provide a specific example.

Answer

A change in gene sequence can lead to a different amino acid being added to a polypeptide chain instead of the normal one. This causes a change in protein structure and function. For example, in sickle cell anemia, the hemoglobin β chain has a single amino acid substitution. Because of this change, the disc-shaped red blood cells assume a crescent shape, which can result in serious health problems.

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3: ECOLOGY AND THE BIOSPHERE

Humans are a part of the ecological landscape, and human health is one important part of human interaction with our physical and living environment.

3.1: Introduction

3.2: The Scope of Ecology

3.3: Biogeography

3.4: Terrestrial Biomes

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3.1: Introduction



3.1.1 The (a) deer tick carries the bacterium that produces Lyme disease in humans, often evident in (b) a symptomatic bull's eye rash. The (c) white-footed mouse is one well-known host to deer ticks carrying the Lyme disease bacterium. (credit a: modification of work by Scott Bauer, USDA ARS; credit b: modification of work by James Gathany, CDC; credit c: modification of work by Rob Ireton)

Why study ecology? Perhaps you are interested in learning about the natural world and how living things have adapted to the physical conditions of their environment. Or, perhaps you're a future physician seeking to understand the connection between your patients' health and their environment.

Humans are a part of the ecological landscape, and human health is one important part of human interaction with our physical and living environment. Lyme disease, for instance, serves as one modern-day example of the connection between our health and the natural world (3.1.1). **Lyme disease** is caused by a bacterial infection from *Lyme borreliosis*. It can be transmitted to humans when they are bitten by the deer tick (*Ixodes scapularis* in the eastern U.S., and *Ixodes pacificus* along the Pacific coast). Deer ticks are the primary **vectors** (a vector is an organism that transmits a pathogen) for this disease. However, not all ticks carry the pathogen, and not all deer ticks carry the bacteria that will cause Lyme disease in humans. Also, the ticks *I. scapularis* and *I. pacificus* can have other hosts besides deer. It turns out that the **probability of infection** depends on the type of host upon which the tick develops: a higher proportion of ticks that live on white-footed mice carry the bacterium than do ticks that live on deer. Knowledge about the environments and population densities in which the host species is abundant would help a physician or an epidemiologist better understand how Lyme disease is transmitted and how its incidence could be reduced.

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3.2: The Scope of Ecology

Ecology is the study of the interactions of living organisms with their environment. One core goal of ecology is to understand the distribution and abundance of living things in the physical environment. Attainment of this goal requires the integration of scientific disciplines inside and outside of biology, such as mathematics, statistics, biochemistry, molecular biology, physiology, evolution, biodiversity, geology, and climatology.

Levels of Ecological Study

When a discipline such as biology is studied, it is often helpful to subdivide it into smaller, related areas. For instance, cell biologists interested in cell signaling need to understand the chemistry of the signal molecules (which are usually proteins) as well as the result of cell signaling. Ecologists interested in the factors that influence the survival of an endangered species might use mathematical models to predict how current conservation efforts affect endangered organisms.

To produce a sound set of management options, a conservation biologist needs to collect accurate data, including current population size, factors affecting reproduction (like physiology and behavior), habitat requirements (such as plants and soils), and potential human influences on the endangered population and its habitat (which might be derived through studies in sociology and urban ecology). Within the discipline of ecology, researchers work at four general levels, which sometimes overlap. These levels are organism, population, community, and ecosystem (Figure 3.2.1).

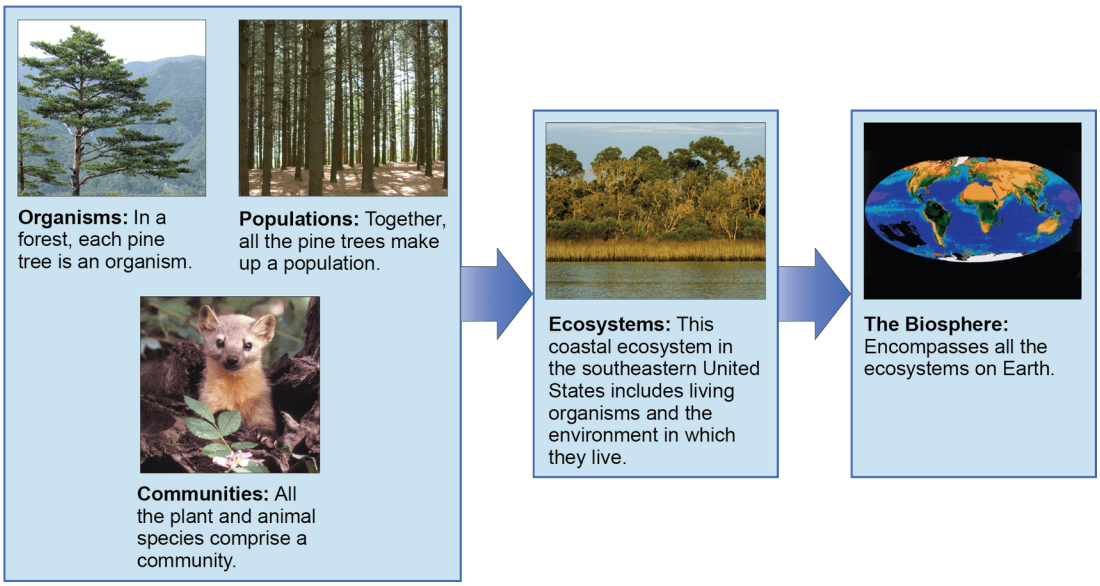


Figure 3.2.1 Ecologists study within several biological levels of organization. (credit “organisms”: modification of work by yeowatzup”/Flickr; credit “populations”: modification of work by "Crystl"/Flickr; credit “communities”: modification of work by US Fish and Wildlife Service; credit “ecosystems”: modification of work by Tom Carlisle, US Fish and Wildlife Service Headquarters; credit “biosphere”: NASA)

Organismal Ecology

Researchers studying ecology at the organismal level are interested in the adaptations that enable individuals to live in specific habitats. These adaptations can be morphological, physiological, and behavioral. For instance, the Karner blue butterfly (*Lycaeides melissa samuelis*) (Figure 3.2.2) is considered a specialist because the females only lay eggs on one type of plant, wild lupine (*Lupinus perennis*). This specific requirement and adaptation means that the Karner blue butterfly is completely dependent on the presence of wild lupine plants for its survival.



Figure 3.2.2: The Karner blue butterfly (*Lycaeides melissa samuelis*) is a rare butterfly that lives only in open areas with few trees or shrubs, such as pine barrens and oak savannas. It can only lay its eggs on lupine plants. (credit: modification of work by J & K Hollingsworth, USFWS)

After hatching, the (first instar) caterpillars emerge and spend four to six weeks feeding solely on wild lupine (Figure 3.2.3). The caterpillars pupate as a chrysalis to undergo the final stage of metamorphosis and emerge as butterflies after about four weeks. The adult butterflies feed on the nectar of flowers of wild lupine and other plant species, such as milkweeds. Generally there are two broods of the Karner blue each year.

A researcher interested in studying Karner blue butterflies at the organismal level might, in addition to asking questions about egg laying requirements, ask questions about the butterflies' preferred thoracic flight temperature (a physiological question), or the behavior of the caterpillars when they are at different larval stages (a behavioral question).



Figure 3.2.3: The wild lupine (*Lupinus perennis*) is the only known host plant for the Karner blue butterfly.

Population Ecology

A **population** is a group of interbreeding organisms that are members of the same species living in the same area at the same time. (Organisms that are all members of the same species are called **conspecifics**.) A population is identified, in part, by where it lives, and its area of population may have natural or artificial boundaries. Natural boundaries might be rivers, mountains, or deserts, while artificial boundaries may be mowed grass, manmade structures, or roads. The study of **population ecology** focuses

on the number of individuals in an area and how and why population size changes over time.

For example, population ecologists are particularly interested in counting the Karner blue butterfly because it is classified as a federally endangered species. However, the distribution and density of this species is highly influenced by the distribution and abundance of wild lupine, and the biophysical environment around it. Researchers might ask questions about the factors leading to the decline of wild lupine and how these affect Karner blue butterflies. For example, ecologists know that wild lupine thrives in open areas where trees and shrubs are largely absent. In natural settings, intermittent wildfires regularly remove trees and shrubs, helping to maintain the open areas that wild lupine requires. Mathematical models can be used to understand how wildfire suppression by humans has led to the decline of this important plant for the Karner blue butterfly.

Community Ecology

A biological **community** consists of the different species within an area, typically a three-dimensional space, and the interactions within and among these species. Community ecologists are interested in the processes driving these interactions and their consequences. Questions about *conspecific* interactions often focus on competition among members of the same species for a limited resource. Ecologists also study interactions between various species; members of different species are called **heterospecifics**. Examples of heterospecific interactions include predation, parasitism, herbivory, competition, and pollination. These interactions can have regulating effects on population sizes and can impact ecological and evolutionary processes affecting diversity.

For example, Karner blue butterfly larvae form mutualistic relationships with ants (especially *Formica* spp). Mutualism is a form of long-term relationship that has coevolved between two species and from which each species benefits. For mutualism to exist between individual organisms, each species must receive *some* benefit from the other as a consequence of the relationship. Researchers have shown that there is an increase in survival when ants protect Karner blue butterfly larvae (caterpillars) from predaceous insects and spiders, an act known as “tending.” This might be because the larvae spend less time in each life stage when tended by ants, which provides an advantage for the larvae. Meanwhile, to attract the ants, the Karner blue butterfly larvae secrete ant-like pheromones and a carbohydrate-rich substance that is an important energy source for the ants. Both the Karner blue larvae and the ants benefit from their interaction, although the species of attendant ants may be partially opportunistic and vary over the range of the butterfly.

Ecosystem Ecology

Ecosystem ecology is an extension of organismal, population, and community ecology. An **ecosystem** is a community of living organisms and their abiotic (non-living) environment. Some of the abiotic components include air, water, and soil. Life in an ecosystem often involves competition for limited resources, which occurs both within a single species and between different species. Organisms compete for food, water, sunlight, space, and mineral nutrients. These resources provide the energy for metabolic processes and the matter to make up organisms’ physical structures. Other critical factors influencing community dynamics are the components of its physical environment: a habitat’s climate (seasons, sunlight, and rainfall), elevation, and geology. These can all be important environmental variables that determine which organisms can exist within a particular area.

Ecosystem biologists ask questions about how nutrients and energy are stored and how they move among organisms and through the surrounding atmosphere, soil, and water. For example, the Karner blue butterflies and the wild lupine live in an oak-pine barren habitat. This habitat is characterized by natural disturbance and nutrient-poor soils that are low in nitrogen. The availability of nutrients is an important factor in the distribution of the plants that live in this habitat. Researchers interested in ecosystem ecology could ask questions about the importance of limited resources and the movement of resources, such as nutrients, though the biotic and abiotic portions of the ecosystem.

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 3.2.1).



Figure 3.2.1**:** 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)

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, yet the deep ocean water is known for large numbers of plankton and krill (small crustaceans) that support it. These two environments are especially important to aerobic respirators worldwide, as the phytoplankton perform 40 percent of all photosynthesis on Earth. Although not as diverse as the other two, deep ocean bottom ecosystems contain a wide variety of marine organisms. Such ecosystems exist even at depths where light is unable to penetrate through the water.

Terrestrial ecosystems, also known for their diversity, are grouped into large categories called biomes. A **biome** is a large-scale community of organisms, primarily defined on land by the dominant plant types that exist in geographic regions of the planet with similar climatic conditions. Examples of biomes include tropical rainforests, savannas, deserts, grasslands, temperate forests, and tundras. Grouping these ecosystems into just a few biome categories obscures the great diversity of the individual ecosystems within them. For example, the saguaro cacti (*Carnegiea gigantean*) and other plant life in the Sonoran Desert, in the United States, are relatively diverse compared with the desolate rocky desert of Boa Vista, an island off the coast of Western Africa (Figure 3.2.2).



(a) (b)

Figure 3.2.2**:** 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)

Ecosystems and Disturbance

Ecosystems are complex with many interacting parts. They are routinely exposed to various disturbances: changes in the environment that affect their compositions, such as yearly variations in rainfall and temperature. Many disturbances are a result of natural processes. For example, when lightning causes a forest fire and destroys part of a forest ecosystem, the ground is eventually populated with grasses, followed by bushes and shrubs, and later mature trees: thus, the forest is restored to its former state. This process is so universal that ecologists have given it a name — **succession**. The impact of environmental disturbances caused by human activities is now as significant as the changes wrought by natural processes. Human agricultural practices, air pollution, acid rain, global deforestation, overfishing, oil spills, and illegal dumping on land and into the ocean all have impacts on ecosystems.

Equilibrium is a dynamic state of an ecosystem in which, despite changes in species numbers and occurrence, biodiversity remains somewhat constant. In ecology, two parameters are used to measure changes in ecosystems: resistance and resilience. The ability of an ecosystem to remain at equilibrium in spite of disturbances is called **resistance**. The speed at which an ecosystem recovers equilibrium after being disturbed is called **resilience**. Ecosystem resistance and resilience are especially important when considering human impact. The nature of an ecosystem may change to such a degree that it can lose its resilience entirely. This process can lead to the complete destruction or irreversible altering of the ecosystem.

Contributors and Attributions

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Career Connection

A career in ecology contributes to many facets of human society. Understanding ecological issues can help society meet the basic human needs of food, shelter, and health care. Ecologists can conduct their research in the laboratory and outside in natural environments (Figure 3.2.4). These natural environments can be as close to home as the stream running through your campus or as far away as the hydrothermal vents at the bottom of the Pacific Ocean. Ecologists manage natural resources such as white-tailed deer populations (*Odocoileus virginianus*) for hunting or aspen (*Populus* spp.) timber stands for paper production. Ecologists also work as educators who teach children and adults at various institutions including universities, high schools, museums, and nature centers. Ecologists may also work in advisory positions assisting local, state, and federal

policymakers to develop laws that are ecologically sound, or they may develop those policies and legislation themselves. To become an ecologist requires at least an undergraduate degree, usually in a natural science. The undergraduate degree is often followed by specialized training or an advanced degree, depending on the area of ecology selected. Ecologists should also have a broad background in the physical sciences, as well as a solid foundation in mathematics and statistics.



Figure 3.2.4 This landscape ecologist is releasing a black-footed ferret into its native habitat as part of a study. (credit: USFWS Mountain Prairie Region, NPS)

Link to Learning

Link to Learning

Visit this site(opens in new window) to see Stephen Wing, a marine ecologist from the University of Otago, discuss the role of an ecologist and the types of issues ecologists explore.

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3.3: Biogeography

The **biosphere** is the global ecological system that consists of **biotic** (living) and **abiotic** (non-living) things and their interactions. The biosphere extends into the atmosphere (several kilometers above Earth) and into the depths of the oceans. Despite its apparent vastness to an individual human, the biosphere occupies only thin sliver of Earth, and only a minute space of the known universe. Many abiotic forces influence where life can exist and the types of organisms found in different parts of the biosphere. The abiotic factors influence the distribution of biomes: large areas of land with similar climate, flora, and fauna.

Biogeography

Biogeography is the study of the geographic distribution of living things and the abiotic factors that affect their distribution. Abiotic factors such as temperature and rainfall vary based mainly on latitude and elevation. As these abiotic factors change, the composition of plant and animal communities also changes. For example, if you were to begin a journey at the equator and walk north, you would notice gradual changes in plant communities. At the beginning of your journey, you would see tropical wet forests with broad-leaved evergreen trees, which are characteristic of plant communities found near the equator. As you continued to travel north, you would see these broad-leaved evergreen plants eventually give rise to seasonally dry forests with scattered trees. You would also begin to notice changes in temperature and moisture. At about 30 degrees north, these forests would give way to deserts, which are characterized by low precipitation and high **insolation** (the amount of solar radiation that reaches a specific area of Earth's surface over a set period of time).

Moving farther north, you would see that deserts are replaced by grasslands or prairies. Eventually, grasslands are replaced by deciduous temperate forests. These deciduous forests give way to the boreal forests and taiga found in the subarctic, the area south of the Arctic Circle. Finally, you would reach the Arctic tundra, which is found at the most northern latitudes. This trek north reveals gradual changes in both climate and the types of organisms that have adapted to environmental factors associated with ecosystems found at different latitudes. However, different ecosystems exist at the same latitude due in part to abiotic factors such as jet streams, the Gulf Stream, and ocean currents. If you were to hike up a mountain, the changes you would see in the vegetation would parallel in many ways those as you move to higher latitudes.

Ecologists who study biogeography examine patterns of **species distribution.** No species exists everywhere; for example, the Venus flytrap (*Dionaea muscipula*) is endemic to a small area in North and South Carolina. An endemic species is one which is naturally found only in a specific geographic area that is usually restricted in size. Other species are generalists: species which live in a wide variety of geographic areas; the raccoon (*Procyon* spp) for example, is native to most of North and Central America.

Species distribution patterns are based on biotic and abiotic factors and their influences during the very long periods of time required for species evolution; therefore, early studies of biogeography were closely linked to the emergence of evolutionary thinking in the eighteenth century. Some of the most distinctive assemblages of plants and animals occur in regions that have been physically separated for millions of years by geographic barriers. Biologists estimate that Australia, for example, has between 600,000 and 700,000 species of plants and animals. Approximately 3/4 of living plant and mammal species are endemic species found solely in Australia (Figure 3.3.1).



(a) (b)

Figure

:

Australia is home to many endemic species. The (a) wallaby (*Wallabia bicolor*), a medium-sized member of the kangaroo family, is a pouched mammal, or marsupial. The (b) echidna (*Tachyglossus aculeatus*) is an egg-laying mammal. (credit a: modification of work by Derrick Coetzee; credit b: modification of work by Allan Whittome)

Sometimes ecologists discover unique patterns of species distribution by determining where species are not found. Despite being tropical, Hawaii, for example, has no native land species of reptiles or amphibians, only a few native species of butterflies, and only one native terrestrial mammal, the hoary bat. Most of New Guinea, as another example, lacks placental mammals.

Like animals, plants can be **endemic** or **generalists**: endemic plants are found only on specific regions of the Earth, while generalists are found on many regions. Isolated land masses—such as Australia, Hawaii, and Madagascar—often have large numbers of endemic plant species. Some of these plants are endangered due to human activity. The forest gardenia (*Gardenia brighamii*), for instance, is endemic to Hawaii; only an estimated 15–20 trees are thought to exist (Figure 3.3.2).



Figure

:

Listed as federally endangered, the forest gardenia is a small tree with distinctive flowers. It is found only in five of the Hawaiian Islands in small populations consisting of a few individual specimens. (credit: Forest & Kim Starr)

Energy Sources

Energy from the sun is captured by green plants, algae, cyanobacteria, and photosynthetic protists. These organisms convert solar energy into the chemical energy needed by all living things. Light availability can be an important force directly affecting the evolution of adaptations in photosynthesizers. For instance, plants in the understory of a temperate forest are shaded when the trees above them in the canopy completely leaf out in the late spring. Not surprisingly, understory plants have adaptations to successfully capture available light that passes through the canopy. One such adaptation is the rapid growth of spring ephemeral plants such as the spring beauty (*Claytonia virginica*) (Figure 3.3.3). These spring flowers achieve much of their growth and finish their life cycle (reproduce) early in the season before the trees in the canopy develop leaves.



Figure 3.3.3: The spring beauty is an ephemeral spring plant that flowers early in the spring to avoid competing with larger forest trees for sunlight. (credit: John Beetham)

In aquatic ecosystems, the availability of light may be limited because sunlight is absorbed by water, plants, suspended particles, and resident microorganisms. Toward the bottom of a lake, pond, or ocean, there is a zone that light cannot reach (because most wavelengths except for the shortest blues are absorbed by the water column). Photosynthesis cannot take place there and, as a result, a number of adaptations have evolved that enable living things to survive without light. For instance, aquatic plants have photosynthetic tissue near the surface of the water. You can think of the broad, floating leaves of a water lily—water lilies cannot survive without light. In environments such as hydrothermal vents, some bacteria extract energy from inorganic chemicals because there is no light for photosynthesis.

The availability of nutrients in aquatic systems such as oceans is also an important aspect of energy or photosynthesis. Many organisms sink to the bottom of the ocean when they die in the open water; when this occurs, the energy found in that living organism is sequestered for some time unless ocean upwelling occurs. **Ocean upwelling** is the rising of deep ocean waters that occurs when prevailing winds blow along surface waters near a coastline (Figure 3.3.4). As the wind pushes ocean waters offshore, water from the bottom of the ocean moves up to replace this water. As a result, the nutrients once contained in dead organisms become available for reuse by other living organisms.

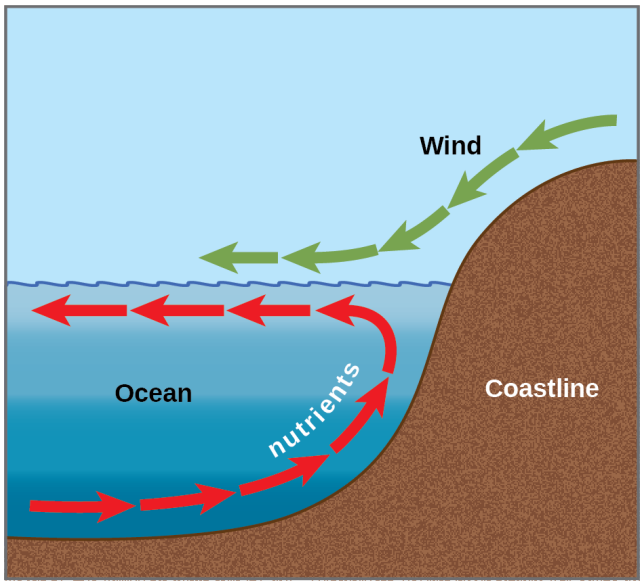


Figure 3.3.4: Ocean upwelling is an important process that recycles nutrients and energy in the ocean. As wind (green arrows) pushes offshore, it causes water from the ocean bottom (red arrows) to move to the surface, bringing up nutrients from the ocean depths. (credit: OpenStax; licensed under CC BY 4.0)

In freshwater systems, such as lakes, the recycling of nutrients occurs in response to air temperature and wind changes. The nutrients at the bottom of lakes are recycled twice each year: in the spring and fall turnover. The **spring-and-fall turnover** are seasonal processes that recycle nutrients and oxygen from the bottom of a freshwater lake to the top of the lake (Figure 3.3.5). These turnovers are caused by the formation of a **thermocline**: layers of water with temperatures that are significantly different from those above and below it.

In wintertime, the surface of lakes found in many northern regions is frozen. However, the water under the ice is slightly warmer, and the water at the bottom of the lake is warmer yet at 4 °C to 5 °C (39.2 °F to 41 °F). Water is densest at about 4 °C; therefore, the deepest water is also the densest. The deepest water is oxygen-poor because the decomposition of organic material at the bottom of the lake uses up available oxygen that cannot be replaced by means of oxygen diffusion into the surface of the water, due to the surface ice layer.

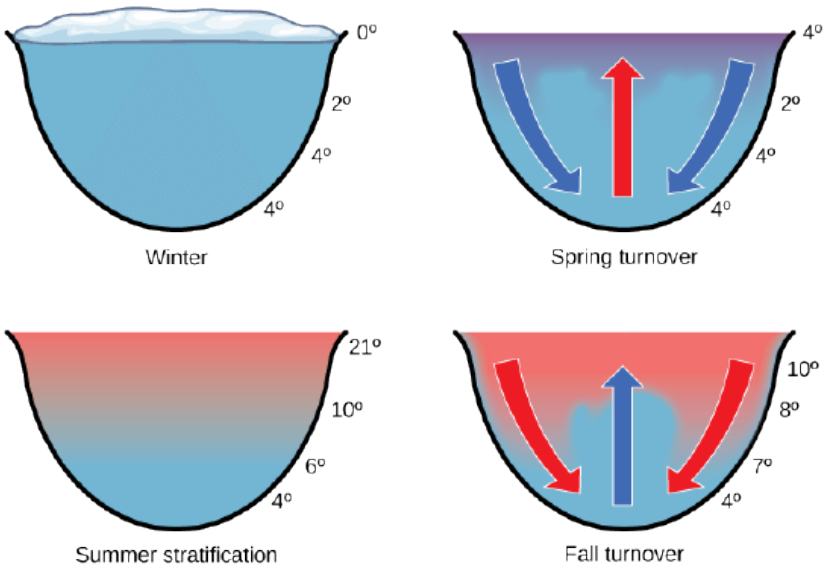


Figure 3.3.5: The spring and fall turnovers are important processes in freshwater lakes that act to move the nutrients and oxygen at the bottom of deep lakes to the top. Turnover occurs because water has a maximum density at 4 °C. Surface water temperature changes as the seasons progress, and denser water sinks. (Credit: OpenStax; licensed under CC BY 4.0)

How might turnover in tropical lakes differ from turnover in lakes that exist in temperate regions? Think of the variation, or lack

of variation, in seasonal temperature change.

In springtime, air temperatures increase and surface ice melts. When the temperature of the surface water begins to approach 4 °C, the water becomes heavier and sinks to the bottom. The water at the bottom of the lake is then displaced by the heavier and denser surface water and, thus, rises to the top. As that water rises to the top, the sediments and nutrients from the lake bottom are brought along with it. This is called the **spring turnover**. During the summer months, the lake water stratifies, or forms layers, with the warmest water at the lake surface.

As air temperatures drop in the fall, the temperature of the lake water cools to 4 °C; therefore, this causes **fall turnover** as the heavy cold water sinks and displaces the water at the bottom. The oxygen-rich water at the surface of the lake then moves to the bottom of the lake, while the nutrients at the bottom of the lake rise to the surface (Figure 3.3.5). During the winter, the oxygen at the bottom of the lake is used by decomposers and other organisms requiring oxygen, such as fish. It is important to note, however, that the relative transparency of ice also allows the penetration of the shorter wavelengths of visible light so that photosynthesis, especially by algae can continue.

Temperature

Temperature affects the physiology of organisms as well as the density and state of water. Temperature exerts an important influence on living things because few living things can survive at temperatures below 0 °C (32 °F) due to metabolic constraints. It is also rare for living things to survive at temperatures exceeding 45 °C (113 °F); this is a reflection of evolutionary response to typical temperatures near the Earth's surface. Enzymes are most efficient within a narrow and specific range of temperatures; enzyme degradation can occur at higher temperatures. Therefore, organisms either must maintain an internal temperature or they must inhabit an environment that will keep the body within a temperature range that supports metabolism. Some animals have adapted to enable their bodies to survive significant temperature fluctuations, such as seen in hibernation or reptilian torpor. Similarly, some Archaea bacteria have evolved to tolerate extremely hot temperatures such as those found in the geysers within Yellowstone National Park. Such bacteria are examples of **extremophiles:** organisms that thrive in extreme environments.

The temperature (of both water and air) can limit the distribution of living things. Animals faced with temperature fluctuations may respond with adaptations, such as migration, in order to survive. Migration, the regular movement from one place to another, is an adaptation found in many animals, including many that inhabit seasonally cold climates. Migration solves problems related to temperature, locating food, and finding a mate. For example, the Arctic Tern (*Sterna paradisaea*) makes a 40,000 km (24,000 mi) round-trip flight each year between its feeding grounds in the southern hemisphere and its breeding grounds in the Arctic Ocean. Monarch butterflies (*Danaus plexippus*) live in the eastern and western United States in the warmer months, where they build up enormous populations, and migrate to areas around Michoacan, Mexico as well as areas along the Pacific Coast, and the southern United States in the wintertime. Some species of mammals also make migratory forays. Reindeer (*Rangifer tarandus*) travel about 5,000 km (3,100 mi) each year to find food. Amphibians and reptiles are more limited in their distribution because they generally lack migratory ability. Not all animals that could migrate do so: migration carries risk and comes at a high-energy cost.

Some animals **hibernate** or **estivate** to survive hostile temperatures. Hibernation enables animals to survive cold conditions, and estivation allows animals to survive the hostile conditions of a hot, dry climate. Animals that hibernate or estivate enter a state known as **torpor**: a condition in which their metabolic rate is significantly lowered. This enables the animal to wait until its environment better supports its survival. Some amphibians, such as the wood frog (*Rana sylvatica*), have an antifreeze-like chemical in their cells, which retains the cells' integrity and prevents them from freezing and bursting.

Water

Water is required by all living things because it is critical for cellular processes. Since terrestrial organisms lose water to the environment, they have evolved many adaptations to retain water.

- Plants have a number of interesting features on their leaves, such as leaf hairs and a waxy cuticle, that serve to decrease the rate of water loss via transpiration and convection.
- Freshwater organisms are surrounded by water and are constantly in danger of having water rush into their cells because of osmosis. Many adaptations of organisms living in freshwater environments have evolved to ensure that solute concentrations in their bodies remain within appropriate levels. One such adaptation is the excretion of dilute urine.
- Marine organisms are surrounded by water with a higher solute concentration than the organism and, thus, are in danger of losing water to the environment because of osmosis. These organisms have morphological and physiological adaptations to retain water and release solutes into the environment. For example, Marine iguanas (*Amblyrhynchus cristatus*), sneeze out

water vapor that is high in salt in order to maintain solute concentrations within an acceptable range while swimming in the ocean and eating marine plants.

Inorganic Nutrients and Soil

Inorganic nutrients, such as nitrogen and phosphorus, are important in determining the distribution and the abundance of living things. Plants obtain these inorganic nutrients from the soil when water moves into the plant through the roots. Therefore, soil structure (particle size of soil components), soil pH, and soil nutrient content together all play an important role in the distribution of plants. Animals obtain inorganic nutrients from the food they consume. Therefore, animal distributions are related to the distribution of what they eat. In some cases, animals will follow their food resource as it moves through the environment.

Other Aquatic Factors

Some abiotic factors, such as oxygen, are important in aquatic ecosystems as well as terrestrial environments. Terrestrial animals obtain oxygen from the air they breathe. Oxygen availability can be an issue for organisms living at very high elevations, however, where there are fewer molecules of oxygen in the air. In aquatic systems, the concentration of dissolved oxygen is related to water temperature and the speed at which the water moves. Cold water has more dissolved oxygen than warmer water. In addition, salinity, currents, and tidal changes can be important abiotic factors in aquatic ecosystems.

Other Terrestrial Factors

Wind can be an important abiotic factor because it influences the rate of evaporation, transpiration, and convective heat loss from the surface of all organisms. The physical force of wind is also important because it can move soil, water, or other abiotic factors, as well as an ecosystem's organisms.

Fire is another terrestrial factor that can be an important agent of disturbance in terrestrial ecosystems. Some organisms are adapted to fire and, thus, require the high heat associated with fire to complete a part of their life cycle. For example, the jack pine (*Pinus banksiana*) requires heat from fire for its seed cones to open (Figure 3.3.6). Through the burning of pine needles, fire adds nitrogen to the soil and limits competition by destroying undergrowth.



Figure 3.3.6: The mature cones of the jack pine *(Pinus banksiana)* open only when exposed to high temperatures, such as during a forest fire. A fire is likely to kill most vegetation, so a seedling that germinates after a fire is more likely to receive ample sunlight than one that germinates under normal conditions. (credit: USDA)

Abiotic Factors Influencing Plant Growth

Temperature and moisture are important influences on plant production (primary productivity) and the amount of organic matter

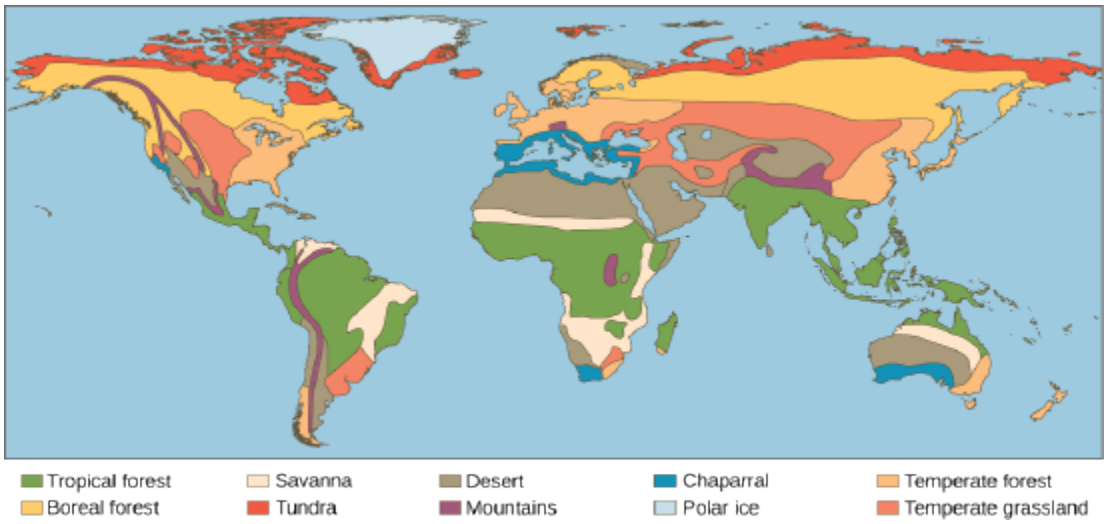
available as food (net primary productivity). Net primary productivity is an estimation of all of the organic matter available as food; it is calculated as the total amount of carbon fixed per year minus the amount that is oxidized during cellular respiration. In terrestrial environments, net primary productivity is estimated by measuring the above-ground biomass per unit area, which is the total mass of living plants, excluding roots (whose mass is very difficult to measure). This means that a large percentage of plant biomass which exists underground is not included in this measurement. Net primary productivity is an important variable when considering differences in biomes. Very productive biomes have a high level of aboveground biomass.

Annual biomass production is directly related to the abiotic components of the environment. Environments with the greatest amount of biomass produce conditions in which photosynthesis, plant growth, and the resulting net primary productivity are optimized. The climate of these areas is warm and wet. Photosynthesis can proceed at a high rate, enzymes can work most efficiently, and stomata can remain open without the risk of excessive transpiration; together, these factors lead to the maximal amount of carbon dioxide (CO_2) moving into the plant, resulting in high biomass production. The above-ground biomass produces several important resources for other living things, including habitat and food. Conversely, dry and cold environments have lower photosynthetic rates and therefore less biomass. The animal communities living there will also be affected by the decrease in available food.

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3.4: Terrestrial Biomes

Earth's surface is made up of large, distinct geographical regions call **biomes**, that are characterized by their specific climates, and plant and animal life. The Earth's biomes are categorized into two major groups: terrestrial and aquatic. **Terrestrial biome**s are based on land, while **aquatic biomes** include both ocean and freshwater biomes. The eight major terrestrial biomes on Earth are each distinguished by characteristic temperatures and amount of precipitation. Comparing the annual totals of precipitation and fluctuations in precipitation from one biome to another provides clues as to the importance of abiotic factors in the distribution of biomes. Temperature variation on a daily and seasonal basis is also important for predicting the geographic distribution of the biome and the vegetation type in the biome. The distribution of these biomes shows that the same biome can occur in geographically distinct areas with similar climates (Figure 3.4.1).



Figure

:

Each of the world's major biomes is distinguished by characteristic temperatures and amounts of precipitation. Polar ice and mountains are also shown. (Credit: OpenStax; licensed under CC BY 4.0)

Tropical Wet Forest

Tropical wet forests are also referred to as tropical rainforests. This biome is found in equatorial regions (Figure 44.12). The vegetation is characterized by plants with broad leaves that fall and are replaced throughout the year. Unlike the trees of deciduous forests, the trees in this biome do not have a seasonal loss of leaves associated with variations in temperature and sunlight; these forests are "evergreen" year-round.

The temperature and sunlight profiles of tropical wet forests are very stable in comparison to that of other terrestrial biomes, with the temperatures ranging from 20 °C to 34 °C (68 °F to 93 °F). When one compares the annual temperature variation of tropical wet forests with that of other forest biomes, the lack of seasonal temperature variation in the tropical wet forest becomes apparent. This lack of seasonality leads to year-round plant growth, rather than the seasonal (spring, summer, and fall) growth seen in other more temperate biomes. In contrast to other ecosystems, tropical ecosystems do not have long days and short days during the yearly cycle. Instead, a constant daily amount of sunlight (11–12 hrs per day) provides more solar radiation, thereby, a longer period of time for plant growth.

The annual rainfall in tropical wet forests ranges from 125 cm to 660 cm (50–200 in) with some monthly variation. While sunlight and temperature remain fairly consistent, annual rainfall is highly variable. Tropical wet forests typically 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 wet forest still exceeds the *annual* rainfall of some other biomes, such as deserts.

Tropical wet forests have high net primary productivity because the annual temperatures and precipitation values in these areas

are ideal for plant growth. Therefore, the extensive biomass present in the tropical wet forest leads to plant communities with very high species diversities (Figure 3.4.2). Tropical wet forests have more species of trees than any other biome; on average between 100 and 300 species of trees are present in a single hectare (2.5 acres) of South American Amazonian rain forest. One way to visualize this is to compare the distinctive horizontal layers within the tropical wet forest biome. 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, fungi, animals, and other organisms within the tropical wet forests.

For example, epiphytes are plants that grow on other plants, which typically are not harmed. Epiphytes are found throughout tropical wet forest biomes. 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 and have adapted to this arboreal lifestyle.



Figure 3.4.2: Tropical wet forests, such as these forests along the Madre de Dios river, Peru, near the Amazon River, have high species diversity. (credit: Roosevelt Garcia)

Savannas

Savannas are grasslands with scattered trees, and they are located in Africa, South America, and northern Australia (Figure 44.12). Savannas are usually hot, tropical areas with temperatures averaging from 24 °C to 29 °C (75 °F to 84 °F) and an annual rainfall of 10–40 cm (3.9–15.7 in). Savannas have an extensive dry season; for this reason, forest trees do not grow as well as they do in the tropical wet forest (or other forest biomes). As a result, within the grasses and *forbs* (herbaceous flowering plants) that dominate the savanna, there are relatively few trees (Figure 3.4.3). Since 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 3.4.3: Savannas, like this one in Taita Hills Wildlife Sanctuary in Kenya, are dominated by grasses. (credit: Christopher T. Cooper)

Subtropical Deserts

Subtropical deserts exist between 15° and 30° north and south latitude and are centered on the Tropics of Cancer and Capricorn (Figure 44.12). This biome is very dry; in some years, evaporation exceeds precipitation. Subtropical hot deserts can have daytime soil surface temperatures above 60 °C (140 °F) and nighttime temperatures approaching 0 °C (32 °F). This is largely due to the lack of atmospheric water. In cold deserts, temperatures can be as high as 25 °C and can drop below -30 °C (-22 °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. 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 vegetation and low animal diversity of this biome is closely related to low and unpredictable precipitation. 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, and then die. Many other plants in these areas are characterized by having a number of adaptations that conserve water, such as deep roots, reduced foliage, and water-storing stems (Figure 3.4.4). Seed plants in the desert produce seeds that can be in dormancy for extended periods between rains. Adaptations in desert animals include nocturnal behavior and burrowing.



Figure 3.4.4: To reduce water loss, many desert plants have tiny leaves or no leaves at all. The leaves of ocotillo (*Fouquieria splendens*), shown here in the Sonora Desert near Gila Bend, Arizona, appear only after rainfall, and then are shed. (Credit: OpenStax; licensed under CC BY 4.0)

Chaparral

The chaparral is also called the scrub forest and is found in California, along the Mediterranean Sea, and along the southern coast of Australia (Figure 44.12). 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, shown in Figure 3.4.5, is dominated by shrubs adapted to periodic fires, with some plants producing seeds that only germinate after a hot fire. The ashes left behind after a fire are rich in nutrients like nitrogen that fertilize the soil and promote plant regrowth.



Figure 3.4.5: The chaparral is dominated by shrubs. (credit: Miguel Vieira)

Temperate Grasslands

Temperate grasslands are found throughout central North America, where they are also known as *prairies*; they are also in Eurasia, where they are known as *steppes* (Figure 44.12). 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 and when ample water is available, which occurs in the spring, summer, and fall. During much of the winter, temperatures are low, and water, which is stored in the form of ice, is not available for plant growth.

Annual precipitation ranges from 25 cm to 75 cm (9.8–29.5 in). Because of relatively lower annual precipitation in temperate grasslands, there are few trees except for those found growing along rivers or streams. The dominant vegetation tends to consist of grasses dense enough to sustain populations of grazing animals Figure 3.4.6. 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.



Figure 3.4.6: The American bison (*Bison bison*), more commonly called the buffalo, is a grazing mammal that once populated American prairies in huge numbers. (credit: Jack Dykinga, USDA Agricultural Research Service)

Fires, mainly caused by lightning, are a *natural disturbance* in temperate grasslands. When fire is suppressed in temperate grasslands, the vegetation eventually converts to scrub and sometimes dense forests with drought-tolerant tree species. 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

Temperate forests are the most common biome in eastern North America, Western Europe, Eastern Asia, Chile, and New Zealand (Figure 3.4.7). 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 periodically during cold winters. 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).

Because of the moderate annual rainfall and temperatures, deciduous trees are the dominant plant in this biome (Figure 44.18). Deciduous trees lose their leaves each fall and remain leafless in the winter. Thus, no photosynthesis occurs in the deciduous trees during the dormant winter period. Each spring, new leaves appear as the temperature increases. Because of the dormant period, the net primary productivity of temperate forests is less than that of tropical wet forests. In addition, temperate forests show less diversity of tree species than tropical wet forest biomes.



Figure 3.4.7: Deciduous trees are the dominant plant in the temperate forest. (credit: Oliver Herold)

The trees of the temperate forests leaf out and shade much of the ground; however, this biome is more open than tropical wet forests because most trees in the temperate forests do not grow as tall as the trees in tropical wet forests. The soils of the temperate forests are rich in inorganic and organic nutrients. This is due to the thick layer of leaf litter on forest floors, which does not develop in tropical rainforests. 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 (such as the pill bug or roly-poly, *Armadillidium vulgare*) and their predators, such as the red-backed salamander (*Plethodon cinereus*).

Boreal Forests

The boreal forest, also known as taiga or coniferous forest, is found south of the Arctic Circle and across most of Canada, Alaska, Russia, and northern Europe (Figure 44.12). 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. Little evaporation occurs because of the cold temperatures.

The long and cold winters in the boreal forest have led to the predominance of cold-tolerant cone-bearing (coniferous) 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. This benefits evergreen trees, which 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 may have a competitive advantage over the broad-leafed deciduous trees.

The net primary productivity of boreal forests is lower than that of temperate forests and tropical wet forests. The above-ground biomass of boreal forests is high because these slow-growing tree species are long-lived and accumulate a large standing biomass over time. Plant species diversity is less than that seen in temperate forests and tropical wet forests. Boreal forests lack the pronounced elements of the layered forest structure seen in tropical wet forests. The structure of a boreal forest is often only a tree layer and a ground layer (Figure 3.4.8. When conifer needles are dropped, they decompose more slowly than broad leaves; therefore, fewer nutrients are returned to the soil to fuel plant growth.



Figure 3.4.8: The boreal forest (taiga) has low lying plants and conifer trees. (credit: L.B. Brubaker)

Arctic Tundra

The Arctic tundra lies north of the subarctic boreal forest and is located throughout the Arctic regions of the northern hemisphere (Figure 44.12). The average winter temperature is –34 °C (–29.2 °F) and the average summer temperature is from 3 °C to 12 °C (37 °F–52 °F). Plants in the arctic tundra have a very short growing season of approximately 10–12 weeks.

However, during this time, there are almost 24 hours of daylight and plant growth is rapid. The annual precipitation of the Arctic tundra is very low with little annual variation in precipitation. And, as in the boreal forests, there is little evaporation due to the cold temperatures.

Plants in the Arctic tundra are generally low to the ground (Figure 3.4.9). 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 deep into the soil and slows the decay of organic matter, which inhibits the release of nutrients from organic matter. During the growing season, the ground of the Arctic tundra can be completely covered with plants or lichens.



Figure 3.4.9: Low-growing plants such as shrub willow dominate the tundra landscape, shown here in the Arctic National Wildlife Refuge. (credit: USFWS Arctic National Wildlife Refuge)

Link to Learning

Link to Learning

Watch this *Assignment Discovery: Biomes* video(opens in new window) for an overview of biomes. To explore further, select one of the biomes on the extended playlist: desert, savanna, temperate forest, temperate grassland, tropic, tundra.

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4: ENVIRONMENTAL SYSTEMS

4.1: Energy Enters Ecosystems Through Photosynthesis
4.2: Energy Flow through Ecosystems
4.3: Biogeochemical Cycles

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4.1: Energy Enters Ecosystems Through Photosynthesis

Cells run on the chemical energy found mainly in carbohydrate molecules, and the majority of these molecules are produced by one process: photosynthesis. Through photosynthesis, certain organisms convert solar energy (sunlight) into chemical energy, which is then used to build carbohydrate molecules. The energy stored in the bonds to hold these molecules together is released when an organism breaks down food. Cells then use this energy to perform work, such as movement. The energy 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.

Solar Dependence and Food Production



Figure 4.1.1. (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 4.1.1). 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.



Figure 4.1.2. 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)

Heterotrophs are organisms incapable of photosynthesis that must therefore 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 4.1.2). Using this reasoning, all food eaten by humans can be traced back to autotrophs that carry out photosynthesis.

Summary of Photosynthesis

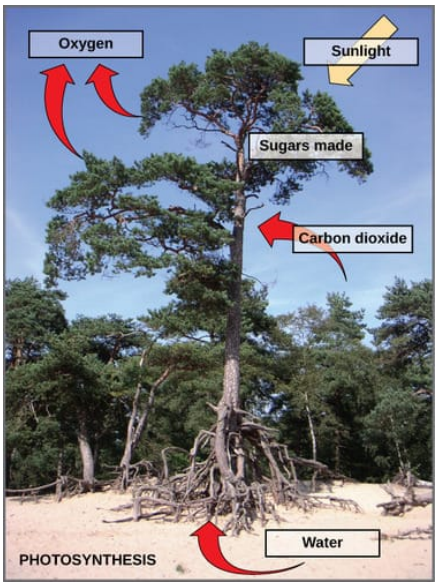


Figure 4.1.3. Photosynthesis uses solar energy, carbon dioxide, and water to release oxygen and to produce energy-storing sugar molecules.

Photosynthesis requires sunlight, carbon dioxide, and water as starting reactants (Figure 4.1.3). 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 4.1.4 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.

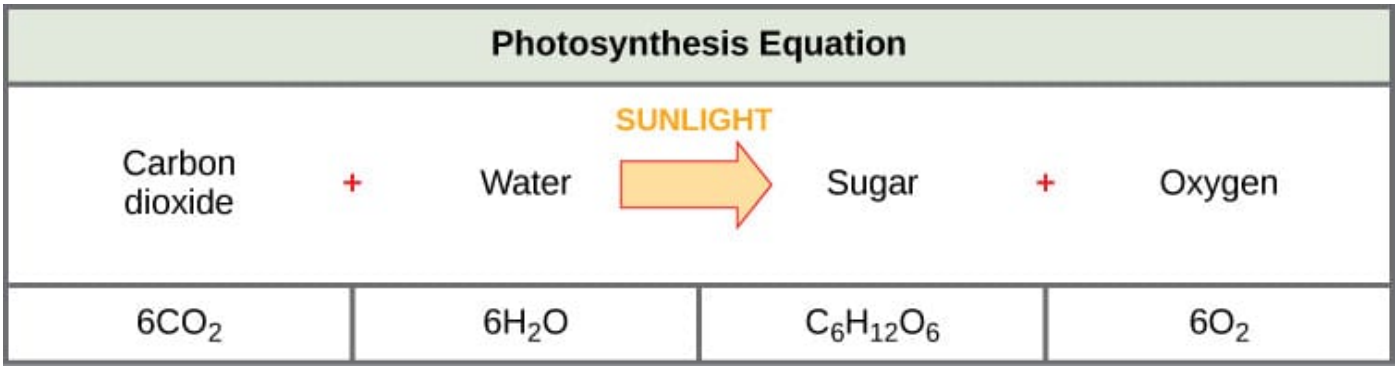


Figure 4.1.4. This equation means that six molecules of carbon dioxide (CO2) combine with six molecules of water (H2O) in the presence of sunlight. This produces one molecule of glucose ($C_6H_{12}O_6$) and six molecules of oxygen (O2).

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 O_2, which is important for two reasons. The molecular oxygen in Earth's atmosphere was created by photosynthetic organisms; without photosynthesis there would be no O_2 to support cellular respiration needed by single-celled and 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% O_2. Also, this O_2 is vital for the creation of the ozone layer, which protects life from harmful ultraviolet radiation emitted by the sun. Ozone (O_3) is created from the breakdown and reassembly of O_2.
2. It provides energy for nearly all ecosystems. By transforming light energy into chemical energy, photosynthesis provides the energy used by organisms, whether those organisms are plants, grasshoppers, wolves, or fungi. The only exceptions are found in very rare and isolated ecosystems, such as near deep sea hydrothermal vents where organisms get energy that originally came from minerals, not the sun.
3. It provides the carbon needed for organic molecules. Organisms are primarily made of two things: water and organic molecules, the latter being carbon based. Through the process of **carbon fixation,** photosynthesis takes carbon from CO_2 and converts it into sugars (which are organic). Carbon in these sugars can be re-purposed to create the other types of organic molecules that organisms need, such as lipids, proteins, and nucleic acids. For example, the carbon used to make your DNA was once CO_2 used by photosynthetic organisms. All of these organisms and activities make up what is called a **food web** - a complex, overlapping network of multiple food chains that encompass the feeding relationships and energy transfer within an ecosystem.

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4.2: Energy Flow through Ecosystems

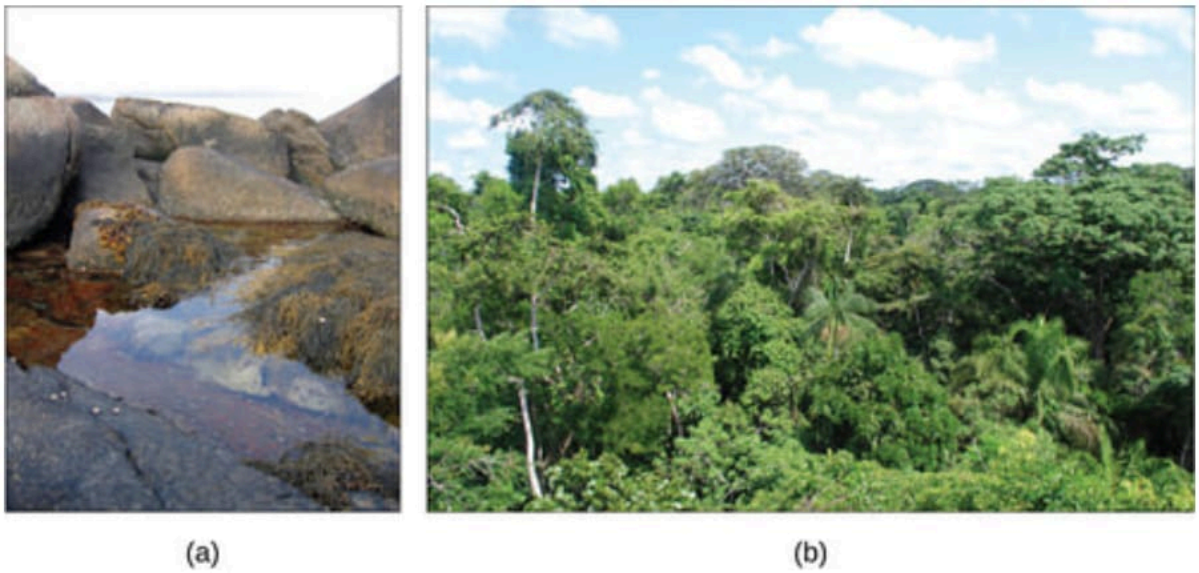


Figure 4.2.1. A (a) tidal pool ecosystem in Matinicus Island, Maine, is a small ecosystem, while the (b) Amazon rainforest in Brazil is a large ecosystem. (credit a: modification of work by Jim Kuhn; credit b: modification of work by Ivan Mlinaric)

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 4.2.1).

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 tundras. Grouping these ecosystems into just a few biome categories obscures the great diversity of the individual ecosystems within them. For example, the saguaro cacti (*Carnegiea gigantean*) and other plant life in the Sonoran Desert, in the United States, are relatively diverse compared with the desolate rocky desert of Boa Vista, an island off the coast of Western Africa (Figure 4.2.2).

Food Chains and Food Webs



Figure 4.2.2. 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)

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

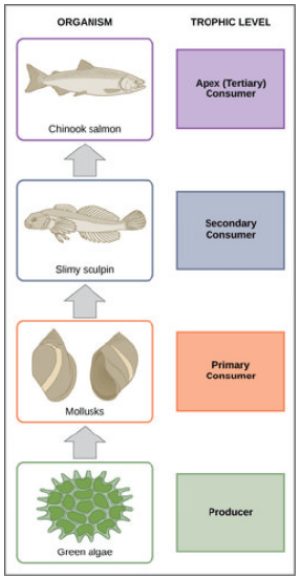


Figure 4.2.3. These are the trophic levels of a food chain in Lake Ontario at the United States–Canada border. Energy and nutrients flow from photosynthetic green algae at the base to the top of the food chain: the Chinook salmon. (credit: modification of work by National Oceanic and Atmospheric Administration/NOAA)

In many ecosystems, the base, or foundation, of the food chain consists of photosynthetic organisms (plants or phytoplankton), which are called **producers**. The organisms that consume the producers are herbivores called **primary consumers**. **Secondary consumers** are usually carnivores that eat the primary consumers. **Tertiary consumers** are carnivores that eat other carnivores. Higher-level consumers feed on the next lower trophic levels, and so on, up to the organisms at the top of the food chain. In the Lake Ontario food chain, shown in Figure 4.2.3, 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 4.2.4 below). Thus, after a limited number of trophic energy transfers, the amount of energy remaining in the food chain may not be great enough to support viable populations at higher trophic levels.

There is a one problem when using food chains to describe most ecosystems. Even when all organisms are grouped into appropriate trophic levels, some of these organisms can feed at more than one trophic level. In addition, species feed on and are eaten by more than one species. In other words, the linear model of ecosystems, the food chain, is a hypothetical and overly simplistic representation of ecosystem structure. A holistic model—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 4.2.5 below).

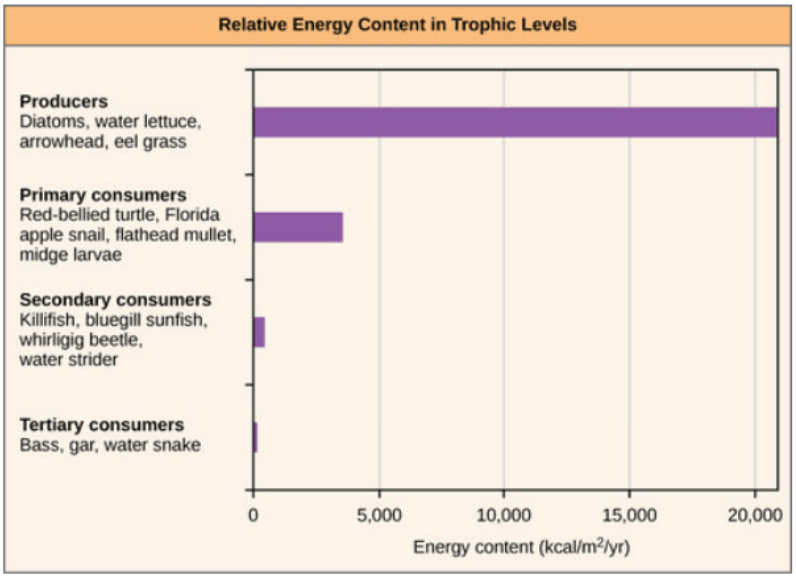


Figure 4.2.4. The relative energy in trophic levels in a Silver Springs, Florida, ecosystem is shown. Each trophic level has less energy available, and usually, but not always, supports a smaller mass of organisms at the next level.

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

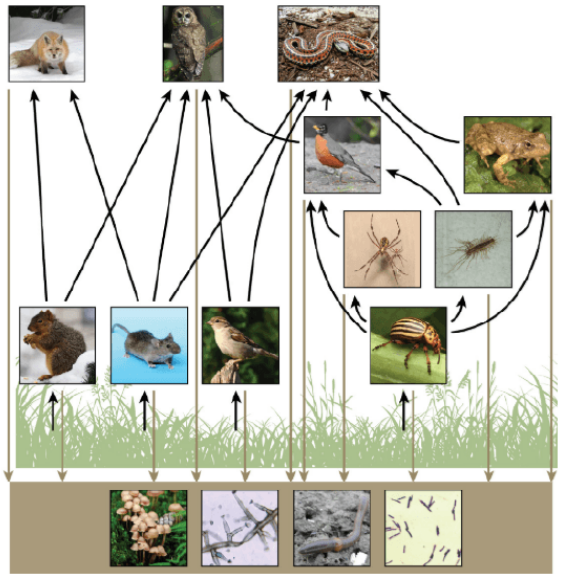


Figure 4.2.5. This food web shows the interactions between organisms across trophic levels. Arrows point from an organism that is consumed to the organism that consumes it. All the producers and consumers eventually become nourishment for the decomposers (fungi, mold, earthworms, and bacteria in the soil). (credit "fox": modification of work by Kevin Bacher, NPS; credit "owl": modification of work by John and Karen Hollingsworth, USFWS; credit "snake": modification of work by Steve Jurvetson; credit "robin": modification of work by Alan Vernon; credit "frog": modification of work by Alessandro Catenazzi; credit "spider": modification of work by "Sanba38"/Wikimedia Commons; credit "centipede": modification of work by "Bauerph"/Wikimedia Commons; credit "squirrel": modification of work by Dawn Huczek; credit "mouse": modification of work by NIGMS, NIH; credit "sparrow": modification of work by David Friel; credit "beetle": modification of work by Scott Bauer, USDA Agricultural Research Service; credit "mushrooms": modification of work by Chris Wee; credit "mold": modification of work by Dr. Lucille Georg, CDC; credit "earthworm": modification of work by Rob Hille; credit "bacteria": modification of work by Don Stalons, CDC)

How Organisms Acquire Energy in a Food Web

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

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.

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 (GPP)**. 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 (NPP)** is the energy that remains in the producers after accounting for these organisms' metabolism and heat loss. The net productivity is then available to the primary consumers at the next trophic level.

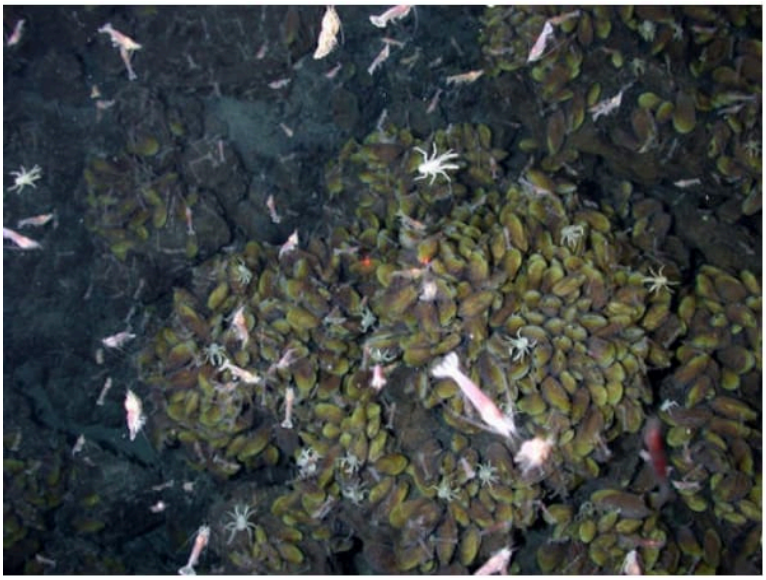


Figure 4.2.6. Swimming shrimp, a few squat lobsters, and hundreds of vent mussels are seen at a hydrothermal vent at the bottom of the ocean. As no sunlight penetrates to this depth, the ecosystem is supported by chemoautotrophic bacteria and organic material that sinks from the ocean's surface. This 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.

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 4.2.6). 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.

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.

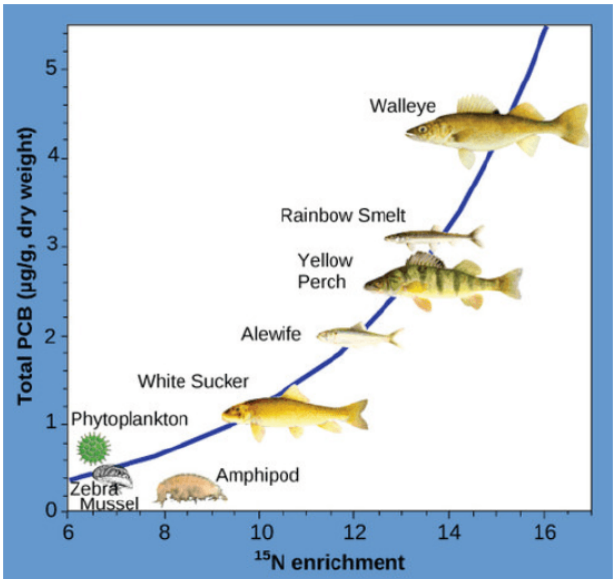


Figure 4.2.7. This chart shows the PCB concentrations found at the various trophic levels in the Saginaw Bay ecosystem of Lake Huron. Notice that the fish in the higher trophic levels accumulate more PCBs than those in lower trophic levels. (credit: Patricia Van Hoof, NOAA)

Another substances 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 4.2.7 below), PCB concentrations increased from the producers of the ecosystem (phytoplankton) through the different trophic levels of fish species. The apex consumer, the walleye, has more than four times the amount of PCBs compared to phytoplankton. Also, research found that birds that eat these fish may have PCB levels 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.

Suggested Supplementary Reading

Canales, M. et al. 2018. 6 Things that Make Like on Earth Possible [Infographic]. *National Geographic*. March.

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4.3: Biogeochemical Cycles

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

The six aforementioned elements 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, whereas nitrogen is an important component of nucleic acids and proteins. Phosphorus is used to make nucleic acids and the phospholipids that comprise biological membranes. Lastly, sulfur is critical to the three-dimensional shape of proteins.

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

The Water Cycle

The **hydrosphere** is the area of Earth where water movement and storage occurs: as liquid water on the surface (rivers, lakes, oceans) and beneath the surface (groundwater) or ice, (polar ice caps and glaciers), and as water vapor in the atmosphere.The human body is about 60 percent water and human cells are more than 70 percent water. Of the stores of water on Earth, 97.5 percent is salt water (see Figure $4.3.1$ below). Of the remaining water, more than 99 percent is groundwater or ice. Thus, less than one percent of freshwater is present in lakes and rivers. Many organisms 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.

The various processes that occur during the cycling of water are illustrated in Figure $4.3.2$ below. The processes include the following:

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

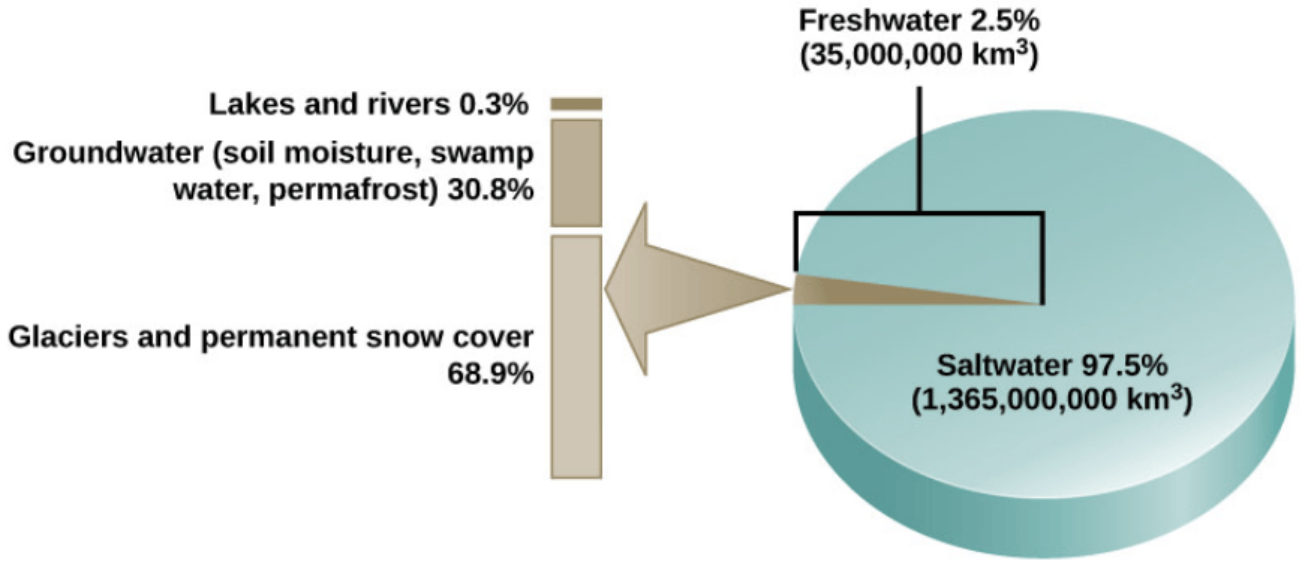


Figure 4.3.1. Only 2.5 percent of water on Earth is fresh water, and less than 1 percent of fresh water is easily accessible to living things.

The **water cycle** is driven by the Sun's energy as it warms the oceans and other surface waters. This leads to **evaporation** (liquid water to water vapor) of liquid surface water and **sublimation** (ice to water vapor) of frozen water, thus moving large amounts of water into the atmosphere as water vapor. Over time, this water vapor condenses into clouds as liquid or frozen droplets 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. Most groundwater reservoirs, or **aquifers**, are the source of drinking or irrigation water drawn up through wells. In many cases these aquifers are being depleted faster than they are being replenished by water percolating down from above.

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 these cycles are described.

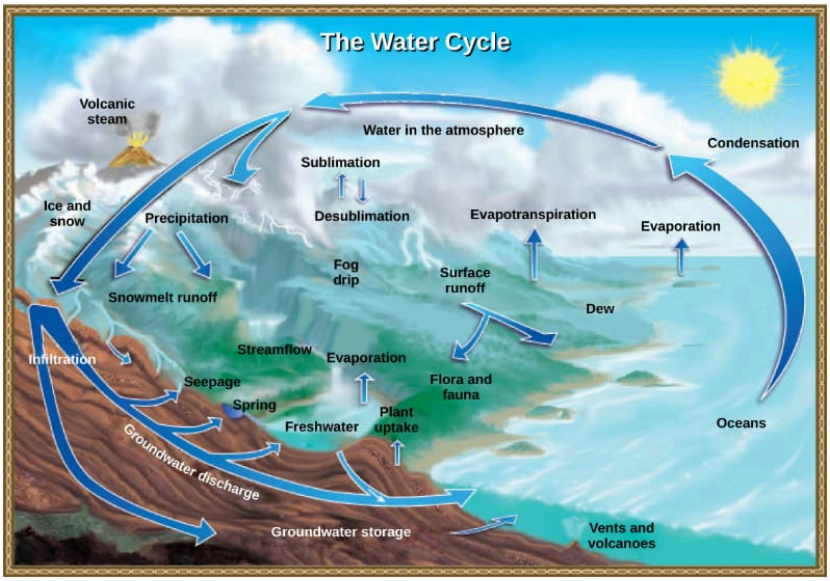


Figure 4.3.2. Water from the land and oceans enters the atmosphere by evaporation or sublimation, where it condenses into clouds and falls as rain or snow. Precipitated water may enter freshwater bodies or infiltrate the soil. The cycle is complete when surface or groundwater reenters the ocean. (credit: 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, and many of these compounds from dead plants and algae have fossilized over millions of years and are known as **fossil fuels**. Since the 1800s, the use of fossil fuels has accelerated. Since the beginning of the Industrial Revolution the demand for Earth's limited fossil fuel supplies has risen, causing the amount of carbon dioxide in our atmosphere to 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 4.3.3 below.

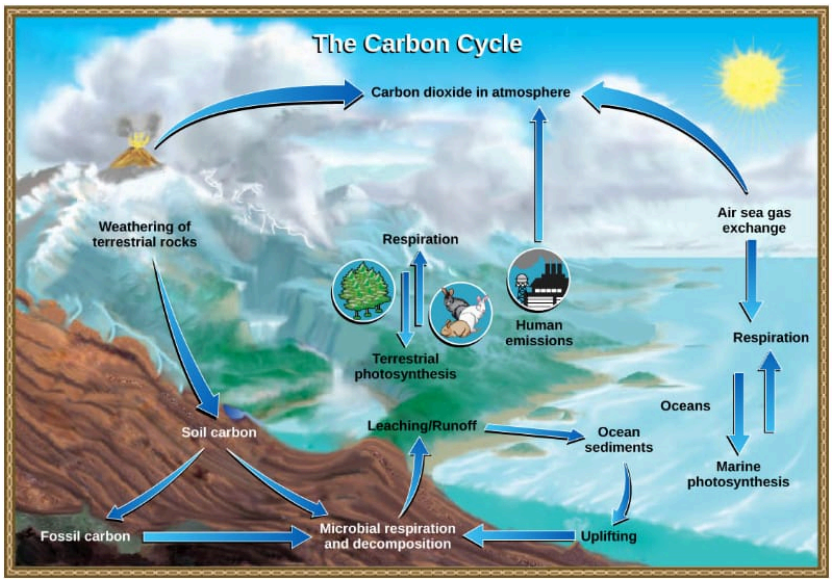


Figure 4.3.3. Carbon dioxide gas exists in the atmosphere and is dissolved in water. Photosynthesis converts carbon dioxide gas to organic carbon, and respiration cycles the organic carbon back into carbon dioxide gas. Long-term storage of organic carbon occurs when matter from living organisms is buried 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, even among different ecosystems. 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. These chemical bonds store this energy for later use in the process of respiration. Most terrestrial autotrophs obtain their carbon dioxide directly from the atmosphere, while marine autotrophs acquire it in the dissolved form (bicarbonate, HCO_3^-).

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

The Biogeochemical Carbon Cycle

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

As stated, the atmosphere is a major 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 is from land (including land beneath the surface of the ocean) by the eruption of volcanoes and other geothermal systems. Carbon sediments from the ocean floor are taken deep within Earth by the process of **subduction**: the movement of one tectonic plate beneath another. Carbon is released as carbon dioxide when a volcano erupts or from volcanic hydrothermal vents.

The Nitrogen Cycle

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

Organic nitrogen is especially important to the study of ecosystem dynamics because many ecosystem processes, such as primary production, are limited by the available supply of nitrogen. As shown in Figure 4.3.4 below, the nitrogen that enters living systems is eventually converted from organic nitrogen back into nitrogen gas by bacteria (Figure 4.3.4). The process of **denitrification** is when bacteria convert the nitrates into nitrogen gas, thus allowing it to re-enter the atmosphere.

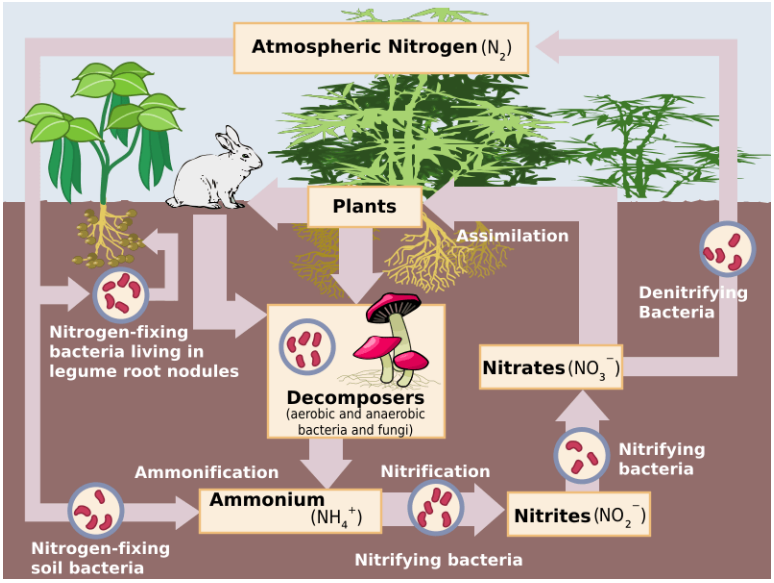


Figure 4.3.4. Nitrogen enters the living world from the atmosphere via nitrogen-fixing bacteria. This nitrogen and nitrogenous waste from animals is then processed back into gaseous nitrogen by soil bacteria, which also supply terrestrial food webs with the organic nitrogen they need. (credit: *"Nitrogen cycle" by Johann Dréo & Raeky is licensed under CC BY-SA 3.0*)

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

In marine ecosystems, nitrogen compounds created by bacteria, or through decomposition, collects in ocean floor sediments. It can then be moved to land in geologic time by uplift of Earth's crust and thereby incorporated into terrestrial rock. Although the

movement of nitrogen from rock directly into living systems has been traditionally seen as insignificant compared with nitrogen fixed 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.

The Phosphorus Cycle

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

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

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

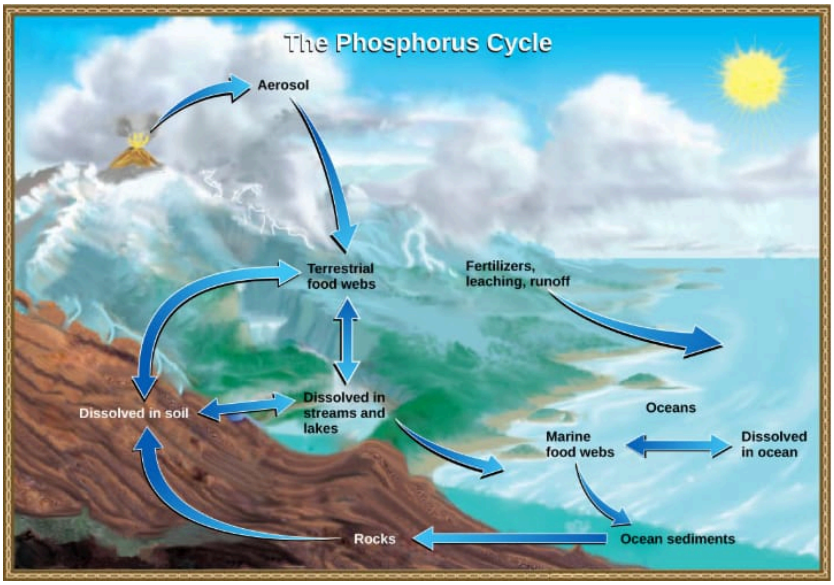


Figure 4.3.5. In nature, phosphorus exists as the phosphate ion (PO43-). Weathering of rocks and volcanic activity releases phosphate into the soil, water, and air, where it becomes available to terrestrial food webs. Phosphate enters the oceans in surface runoff, groundwater flow, and river flow. Phosphate 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 (see Figure 4.3.6 below).

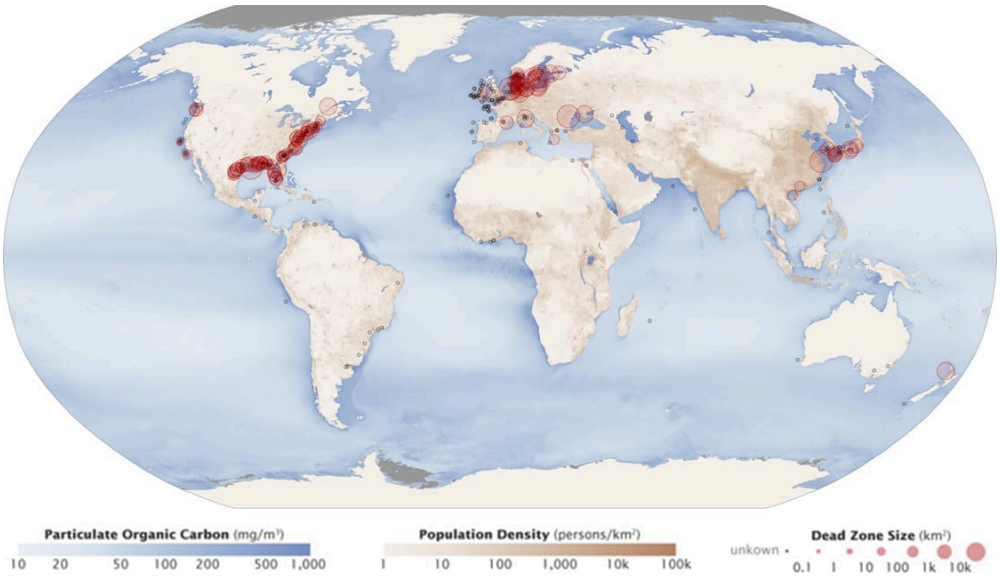


Figure 4.3.6. Dead zones occur when phosphorus and nitrogen from fertilizers cause excessive growth of microorganisms, which depletes oxygen and kills fauna. Worldwide, large dead zones are found in coastal areas of high population density. (credit: NASA Earth Observatory)

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 4.3.7 below, sulfur cycles between the oceans, land, and atmosphere. Atmospheric sulfur is found in the form of sulfur dioxide (SO_2), which enters the atmosphere in three ways: first, from the decomposition of organic molecules; second, from volcanic activity and geothermal vents; and, third, from the burning of fossil fuels by humans.

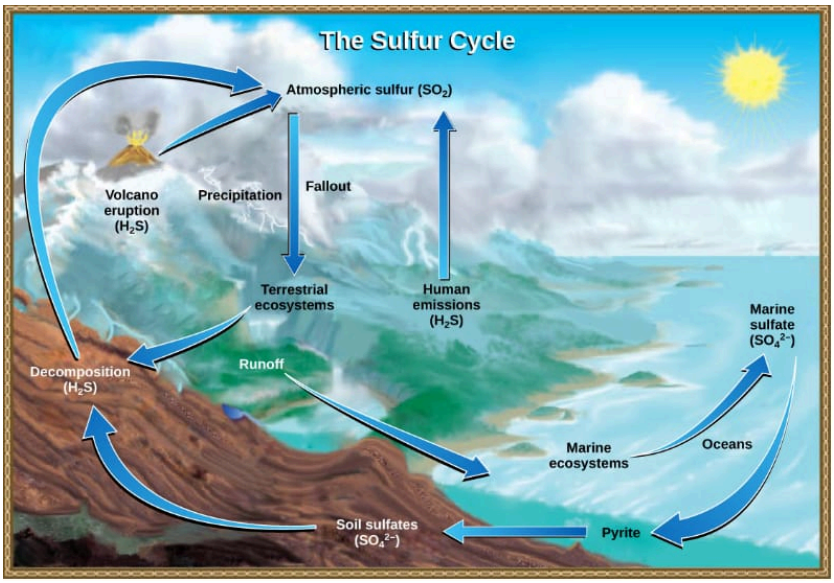


Figure 4.3.7. Sulfur dioxide from the atmosphere becomes available to terrestrial and marine ecosystems when it is dissolved in precipitation as weak sulfuric acid or when it falls directly to Earth as fallout. Weathering of rocks also makes sulfates available to terrestrial ecosystems. Decomposition 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. [Website] <https://serc.carleton.edu/microbelif...one/index.html>

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5: POPULATION AND COMMUNITY ECOLOGY

5.1: Population Demographics and Dynamics
5.2: Population Growth and Regulation
5.3: The Human Population
5.4: Community Ecology
5.5: Population and Community Ecology (Exercises)

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5.1: Population Demographics and Dynamics

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 statistical study of populations is called demography: a set of mathematical tools designed to describe populations and investigate how they change. Many of these tools were actually designed to study human populations. For example, life tables, which detail the life expectancy of individuals within a population, were initially developed by life insurance companies to set insurance rates. In fact, while the term “demographics” is sometimes assumed to mean a study of human populations, all living populations can be studied using this approach.

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 5.1.1).

ART CONNECTION

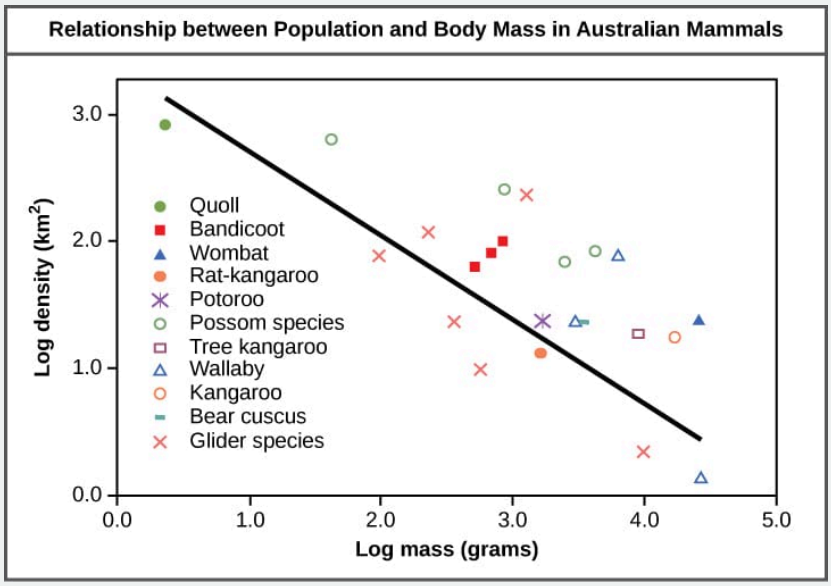


Figure 5.1.1: Australian mammals show a typical inverse relationship between population density and body size.

As this graph shows, population density typically decreases with increasing body size. Why do you think this is the case?

Estimating Population Size

The most accurate way to determine population size is to count all 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 wood, plastic, or metal square 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. This counting method will provide an estimate of both population size and density. The number and size of quadrat samples depends on the type of organisms and the nature of their distribution.

For smaller mobile organisms, such as mammals, a technique called mark and recapture is often used. This method involves marking a sample of captured animals in some way and releasing them back into the environment to mix with the rest of the population; then, 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:

$$\frac{\text{number marked first catch} \times \text{total number second catch}}{\text{number marked second catch}} = N$$

Using our example, the population size would be 400.

$$\frac{80 \times 100}{20} = 400$$

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 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 5.1.2). 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.

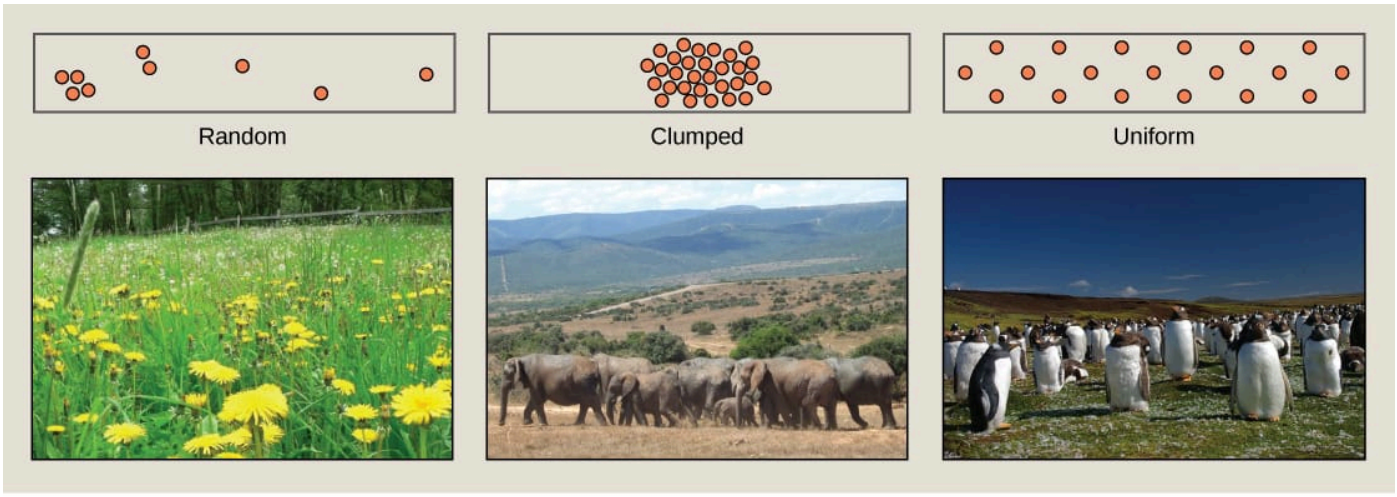


Figure 5.1.2**:** Species may have a random, clumped, or uniform distribution. Plants such as (a) dandelions with wind-dispersed seeds tend to be randomly distributed. Animals such as (b) elephants that travel in groups exhibit a clumped distribution. Territorial birds such as (c) penguins tend to have 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)

Demography

While population size and density describe a population at one particular point in time, scientists must use demography to study the dynamics of a population. Demography is the statistical study of population changes over time: birth rates, death rates, and life expectancies. These population characteristics are often displayed in a life table.

Life Tables

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 5.1.1 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). The mortality rate (per 1000) shown in column D is based on the number of individuals dying during the age interval (column B), divided by the number of individuals surviving at the beginning of the interval (Column C) multiplied by 1000.

$$\text{mortality rate} = \frac{\text{number of individuals dying}}{\text{number of individuals surviving}} \times 1000$$

For example, between ages three and four, 12 individuals die out of the 776 that were remaining from the original 1000 sheep. This number is then multiplied by 1000 to give the mortality rate per thousand.

$$\text{mortality rate} = \frac{12}{776} \times 1000 \approx 15.5$$

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.

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.

Table 5.1.1: Life Table of Dall Mountain Sheep[1]

A	B	C	D	E
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

Survivorship Curves

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 5.1.3). 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.

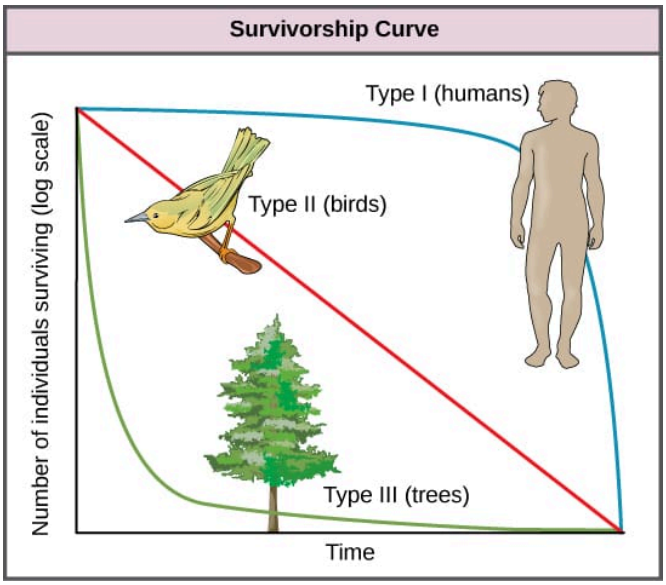


Figure 5.1.3**:** Survivorship curves show the distribution of individuals in a population according to age. Humans and most mammals have a Type I survivorship curve, because death primarily occurs in the older years. Birds have a Type II survivorship curve, as death at any age is equally probable. Trees 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.

Section Summary

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.

Art Connections

Figure 5.1.1: As this graph shows, population density typically decreases with increasing body size. Why do you think this is the case?

Answer

Smaller animals require less food and others resources, so the environment can support more of them per unit area.

Footnotes

1. 1 Data Adapted from Edward S. Deevey, Jr., "Life Tables for Natural Populations of Animals," *The Quarterly Review of Biology* 22, no. 4 (December 1947): 283-314.

Glossary

demography
the statistical study of changes in populations over time

life table
a table showing the life expectancy of a population member based on its age

mark and recapture
a method used to determine population size in mobile organisms

mortality rate
: the proportion of population surviving to the beginning of an age interval that dies during that age interval

population density
: the number of population members divided by the area being measured

population size
: the number of individuals in a population

quadrat
: a square within which a count of individuals is made that is combined with other such counts to determine population size and density in slow moving or stationary organisms

species distribution pattern
: the distribution of individuals within a habitat at a given point in time

survivorship curve
: a graph of the number of surviving population members versus the relative age of the member

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5.2: Population Growth and Regulation

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

Population Growth

The two simplest models of population growth use deterministic equations (equations that do not account for random events) to describe the rate of change in the size of a population over time. The first of these models, exponential growth, describes theoretical 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.

The best example of exponential growth in organisms is seen in bacteria. Bacteria are prokaryotes that reproduce largely by binary fission. This division takes about an hour for many bacterial 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 $5.2.1$**a**).

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. The growth rate of a population is largely determined by subtracting the death rate, *D*, (number organisms that die during an interval) from the birth rate, *B*, (number organisms that are born during an interval). The growth rate can be expressed in a simple equation that combines the birth and death rates into a single factor: *r*. This is shown in the following formula:

$$\text{Population growth} = rN$$

The value of *r* can be positive, meaning the population is increasing in size (the rate of change is positive); or negative, meaning the population is decreasing in size; or zero, in which case the population size is unchanging, a condition known as zero population growth.

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.

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 5.2.1**b**). This population size, which is determined by the maximum population size that a particular environment can sustain, is called the carrying capacity, or *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.

The formula used to calculate logistic growth adds the carrying capacity as a moderating force in the growth rate. The expression "*K* – *N*" is equal to the number of individuals that may be added to a population at a given time, and "*K* – *N*" divided by "*K*" is the fraction of the carrying capacity available for further growth. Thus, the exponential growth model is restricted by this factor to generate the logistic growth equation:

$$\text{Population growth} = rN\left[\frac{K-N}{K}\right]$$

Notice that when *N* is almost zero the quantity in brackets is almost equal to 1 (or *K*/*K*) and growth is close to exponential. When the population size is equal to the carrying capacity, or *N* = *K*, the quantity in brackets is equal to zero and growth is equal to zero. A graph of this equation (logistic growth) yields the S-shaped curve (Figure 5.2.1**b**). 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.

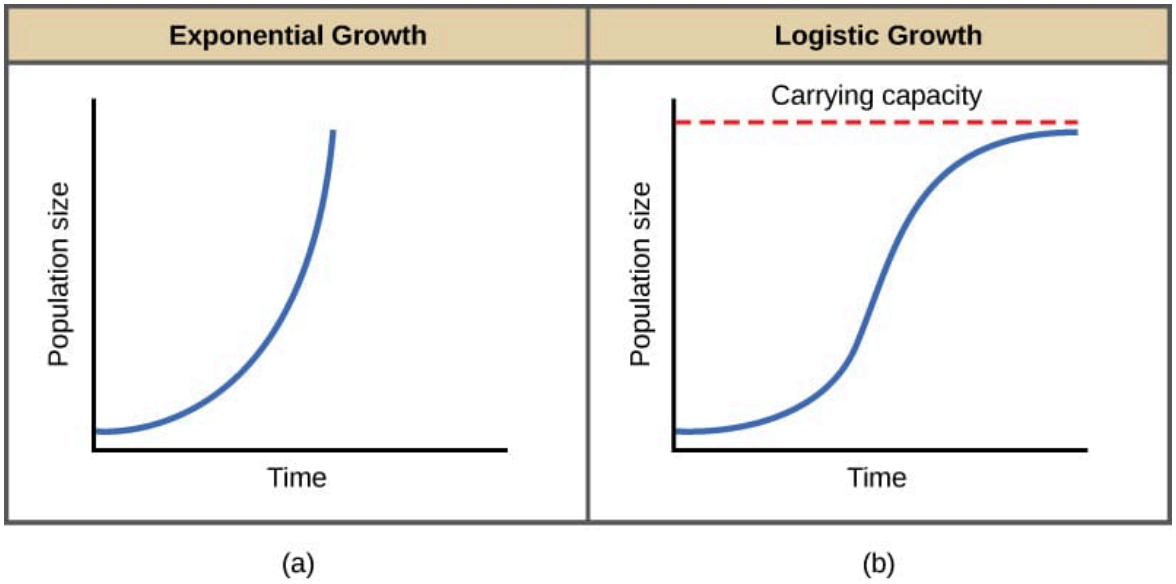


Figure 5.2.1**:** When resources are unlimited, populations exhibit (a) exponential growth, shown in a J-shaped curve. When resources are limited, populations exhibit (b) logistic growth. In logistic growth, population expansion decreases as resources become scarce, and it levels off when the carrying capacity of the environment is reached. The logistic growth curve is S-shaped.

Role of Intraspecific Competition

The logistic model assumes that every individual within a population will have equal access to resources and, thus, an equal chance for survival. For plants, the amount of water, sunlight, nutrients, and space to grow are the important resources, whereas in animals, important resources include food, water, shelter, nesting space, and mates.

In the real world, phenotypic variation among individuals within a population means that some individuals will be better adapted to their environment than others. The resulting competition for resources among population members of the same species is termed intraspecific competition. Intraspecific competition may not affect populations that are well below their carrying capacity, as resources are plentiful and all individuals can obtain what they need. However, as population size increases, this competition intensifies. In addition, the accumulation of waste products can reduce carrying capacity in an environment.

Examples of Logistic Growth

Yeast, a microscopic fungus used to make bread and alcoholic beverages, exhibits the classical S-shaped curve when grown in a test tube (Figure 5.2.2**a**). 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 5.2.2**b**). 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.

ART CONNECTION

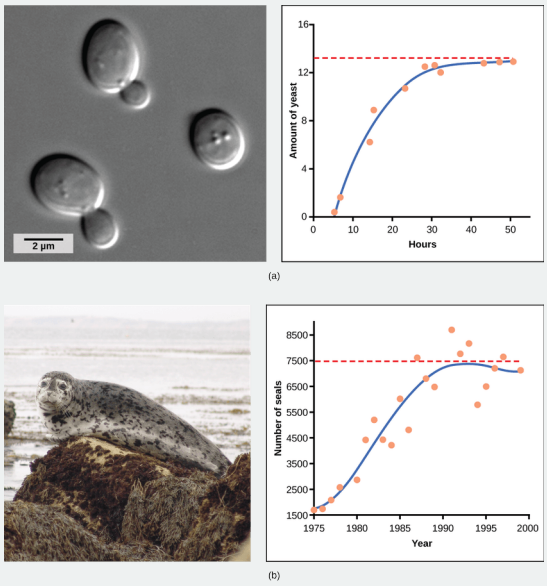


Figure 5.2.2**:** (a) Yeast grown in ideal conditions in a test tube shows a classical S-shaped logistic growth curve, whereas (b) a natural population of seals shows real-world fluctuation. The yeast is visualized using differential interference contrast light micrography. (credit a: scale-bar data from Matt Russell)

If the major food source of seals declines due to pollution or overfishing, which of the following would likely occur?

A. The carrying capacity of seals would decrease, as would the seal population.
B. The carrying capacity of seals would decrease, but the seal population would remain the same.
C. The number of seal deaths would increase, but the number of births would also increase, so the population size would remain the same.
D. The carrying capacity of seals would remain the same, but the population of seals would decrease.

Population Dynamics 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.

Population growth is regulated in a variety of ways. These are grouped into density-dependent factors, in which the density of the population affects growth rate and mortality, and density-independent factors, which cause mortality in a population regardless of population density. Wildlife biologists, in particular, want to understand both types because this helps them manage populations and prevent extinction or overpopulation.

Density-dependent Regulation

Most density-dependent factors are biological in nature and include predation, inter- and intraspecific competition, and parasites. Usually, the denser a population is, the greater its mortality rate. For example, during intra- and interspecific competition, the reproductive rates of the species will usually be lower, reducing their populations' rate of growth. In addition, low prey density increases the mortality of its predator because it has more difficulty locating its food source. Also, when the population is denser, diseases spread more rapidly among the members of the population, which affect the mortality rate.

Density dependent regulation was studied in a natural experiment with wild donkey populations on two sites in Australia.[1] On one site the population was reduced by a population control program; the population on the other site received no interference. The high-density plot was twice as dense as the low-density plot. From 1986 to 1987 the high-density plot saw no change in donkey density, while the low-density plot saw an increase in donkey density. The difference in the growth rates of the two populations was caused by mortality, not by a difference in birth rates. The researchers found that numbers of offspring birthed by each mother was unaffected by density. Growth rates in the two populations were different mostly because of juvenile mortality caused by the mother's malnutrition due to scarce high-quality food in the dense population. Figure 5.2.3 shows the difference in age-specific mortalities in the two populations.

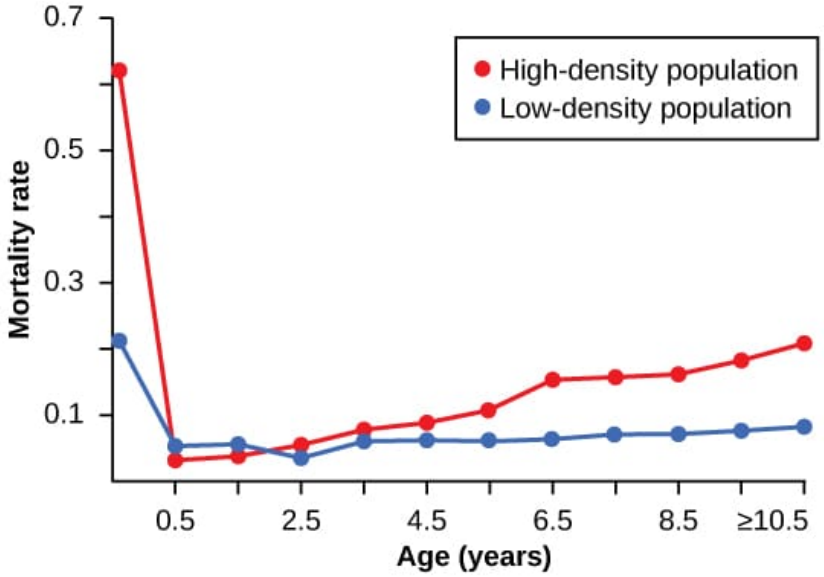


Figure 5.2.3: This graph shows the age-specific mortality rates for wild donkeys from high- and low-density populations. The juvenile mortality is much higher in the high-density population because of maternal malnutrition caused by a shortage of high-quality food.

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. For example, a population of deer affected by a harsh winter will recover faster if there are more deer remaining to reproduce.

EVOLUTION IN ACTION: Why Did the Woolly Mammoth Go Extinct?



Figure 5.2.4**:** 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)

Woolly mammoths began to go extinct about 10,000 years ago, soon after paleontologists believe humans able to hunt them began to colonize North America and northern Eurasia (Figure 5.2.4). 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.

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.

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.

Section Summary

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.

Populations are regulated by a variety of density-dependent and density-independent factors. Life-history characteristics, such as age at first reproduction or numbers of offspring, are characteristics that evolve in populations just as anatomy or behavior can evolve over time. The model of *r*- and *K*-selection suggests that characters, and possibly suites of characters, may evolve adaptations to population stability near the carrying capacity (*K*-selection) or rapid population growth and collapse (*r*-selection). Species will exhibit adaptations somewhere on a continuum between these two extremes.

Art Exercise

Figure 5.2.2: If the major food source of seals declines due to pollution or overfishing, which of the following would likely occur?

A. The carrying capacity of seals would decrease, as would the seal population.
B. The carrying capacity of seals would decrease, but the seal population would remain the same.
C. The number of seal deaths would increase, but the number of births would also increase, so the population size would remain the same.
D. The carrying capacity of seals would remain the same, but the population of seals would decrease.

Answer

A: The carrying capacity of seals would decrease, as would the seal population.

Footnotes

1. 1 David Choquenot, "Density-Dependent Growth, Body Condition, and Demography in Feral Donkeys: Testing the Food Hypothesis," *Ecology* 72, no. 3 (June 1991):805–813.
2. 2 David Nogués-Bravo et al., "Climate Change, Humans, and the Extinction of the Woolly Mammoth." *PLoS Biol* 6 (April 2008): e79, doi:10.1371/journal.pbio.0060079.
3. 3 G.M. MacDonald et al., "Pattern of Extinction of the Woolly Mammoth in Beringia." *Nature Communications* 3, no. 893 (June 2012), doi:10.1038/ncomms1881.

Glossary

birth rate
the number of births within a population at a specific point in time

carrying capacity
the maximum number of individuals of a population that can be supported by the limited resources of a habitat

death rate
the number of deaths within a population at a specific point in time

density-dependent regulation
the regulation of population in which birth and death rates are dependent on population size

density-independent regulation
the regulation of population in which the death rate is independent of the population size

exponential growth
an accelerating growth pattern seen in populations where resources are not limiting

intraspecific competition
: the competition among members of the same species

J-shaped growth curve
: the shape of an exponential growth curve

***K*-selected species**
: a species suited to stable environments that produce a few, relatively large offspring and provide parental care

logistic growth
: the leveling off of exponential growth due to limiting resources

***r*-selected species**
: a species suited to changing environments that produce many offspring and provide little or no parental care

S-shaped growth curve
: the shape of a logistic growth curve

zero population growth
: the steady population size where birth rates and death rates are equal

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5.3: 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.

Human technology and 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. Changes on a global scale including depletion of the ozone layer, desertification and topsoil loss, and global climate change are caused by human activities.

The world's human population is presently growing exponentially (Figure 5.3.1).

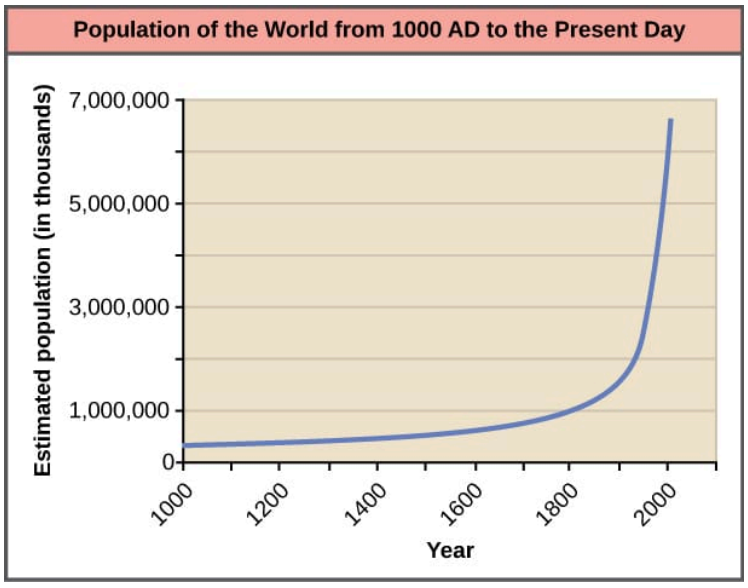


Figure 5.3.1: Human population growth since 1000 AD is exponential.

A consequence of exponential growth rate is that the time that it takes to add a particular number of humans to the population is becoming shorter. Figure 5.3.2 shows that 123 years were necessary to add 1 billion humans between 1804 and 1930, but it only took 24 years to add the two billion people between 1975 and 1999. This acceleration in growth rate will likely begin to decrease in the coming decades. Despite this, the population will continue to increase and the threat of overpopulation remains, particularly because the damage caused to ecosystems and biodiversity is lowering the human carrying capacity of the planet.

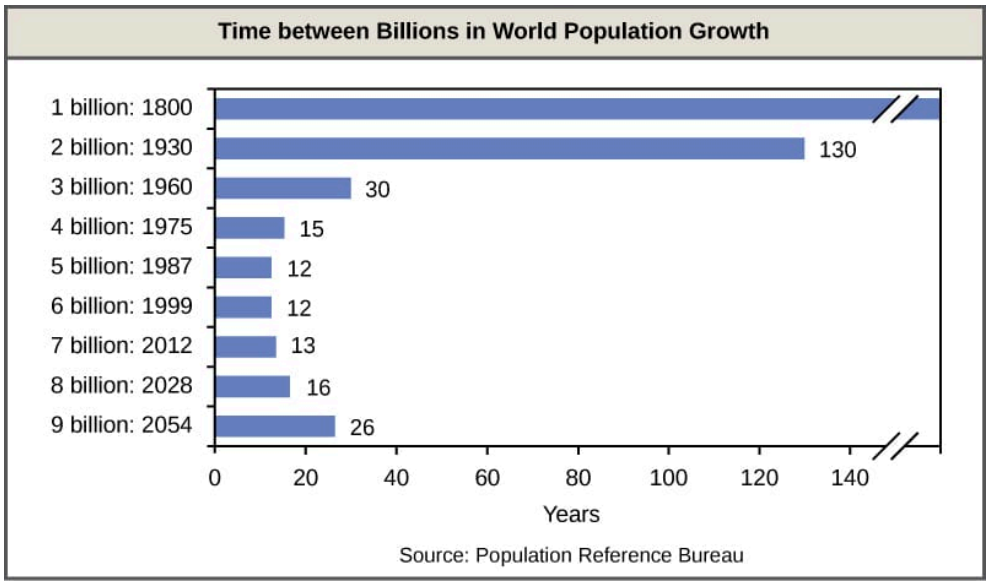


Figure 5.3.2**:** The time between the addition of each billion human beings to Earth decreases over time. (credit: modification of work by Ryan T. Cragun)

CONCEPT IN ACTION

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Watch this video of how human populations have changed over time.

Overcoming Density-Dependent Regulation

Humans are unique in their ability to alter their environment in myriad ways. This ability is responsible for human population growth because it resets the carrying capacity and overcomes density-dependent growth regulation. Much of this ability is related to human intelligence, society, and communication. Humans construct shelters to protect themselves from the elements and have developed agriculture and domesticated animals to increase their food supplies. In addition, humans use language to communicate this technology to new generations, allowing them to improve upon previous accomplishments.

Other factors in human population growth are migration and public health. Humans originated in Africa, but we have since migrated to nearly all inhabitable land on Earth, thus, increasing the area that we have colonized. Public health, sanitation, and the use of antibiotics and vaccines have decreased the ability of infectious disease to limit human population growth in developed countries. In the past, diseases such as the bubonic plaque 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. 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. The reduction in life expectancy caused by HIV/AIDS was estimated to be 7 years for 2005.[1]

Declining life expectancy is an indicator of higher mortality rates and leads to lower birth rates.

The fundamental cause of the acceleration of growth rate for humans in the past 200 years has been the reduced death rate due to a development of the technological advances of the industrial age, urbanization that supported those technologies, and especially the exploitation of the energy in fossil fuels. Fossil fuels are responsible for dramatically increasing the resources

available for human population growth through agriculture (mechanization, pesticides, and fertilizers) and harvesting wild populations.

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 5.3.3). 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. The actual growth rates in different countries are shown in Figure 5.3.3, with the highest rates tending to be in the less economically developed countries of Africa and Asia.

ART CONNECTION

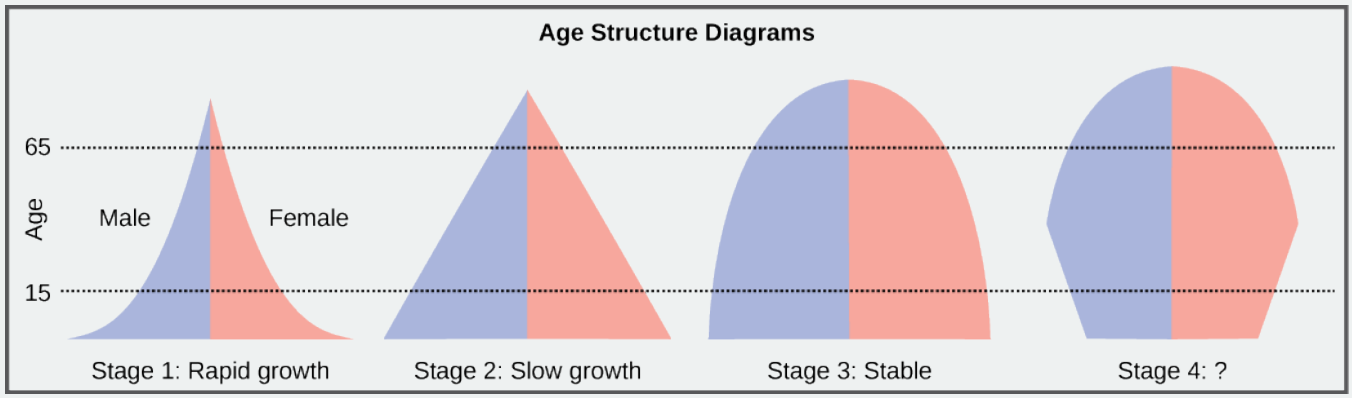


Figure 5.3.3: Typical age structure diagrams are shown. The rapid growth diagram narrows to a point, indicating that the number of individuals decreases rapidly with age. In the slow growth model, the number of individuals decreases steadily with age. Stable population diagrams are rounded on the top, showing that the number of individuals per age group decreases gradually, and then increases for the older part of the population.

Age structure diagrams for rapidly growing, slow growing, and stable populations are shown in stages 1 through 3. What type of population change do you think stage 4 represents?

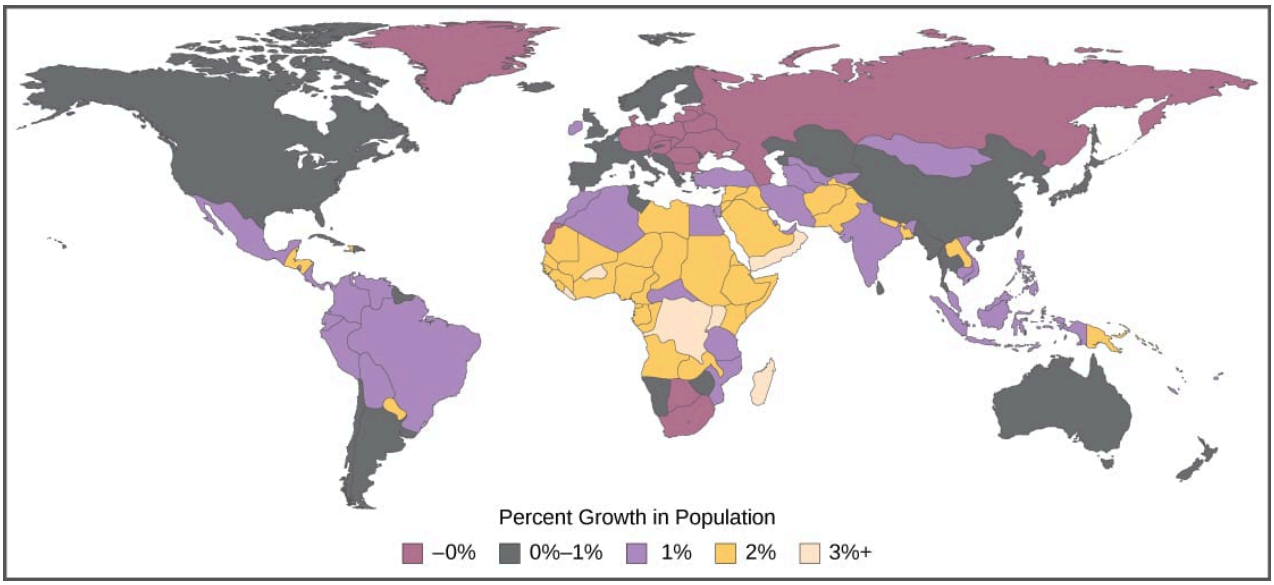


Figure 5.3.4**:** The percent growth rate of population in different countries is shown. Notice that the highest growth is occurring in less economically developed countries in Africa and Asia.

Long-Term Consequences of Exponential Human Population Growth

Many dire predictions have been made about the world's population leading to a major crisis called the "population explosion." In the 1968 book *The Population Bomb*, biologist Dr. 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."[2] While many critics view this statement as an exaggeration, 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. Family planning education programs in other countries have had highly positive effects on limiting population growth rates and increasing standards of living. In spite of population control policies, the human population continues to grow. Because of the subsequent need to produce more and more food to feed our population, inequalities in access to food and other resources will continue to widen. The United Nations estimates the future world population size could vary from 6 billion (a decrease) to 16 billion people by the year 2100. There is no way to know whether human population growth will moderate to the point where the crisis described by Dr. Ehrlich will be averted.

Another consequence of population growth is the change and degradation of the natural environment. Many countries have attempted to reduce the human impact on climate change by limiting their emission of greenhouse gases. However, a global climate change treaty remains elusive, and many underdeveloped countries trying to improve their economic condition may be less likely to agree with such provisions without compensation if it means slowing their economic development. Furthermore, the role of human activity in causing climate change has become a hotly debated socio-political issue in some developed countries, including the United States. Thus, we enter the future with considerable uncertainty about our ability to curb human population growth and protect our environment to maintain the carrying capacity for the human species.

CONCEPT IN ACTION



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

Section Summary

Earth’s human population is growing exponentially. Humans have increased their carrying capacity through technology, urbanization, and harnessing the energy of fossil fuels. The age structure of a population allows us to predict population growth. Unchecked human population growth could have dire long-term effects on human welfare and Earth’s ecosystems.

Art Connections

Figure 5.3.3: Age structure diagrams for rapidly growing, slow growing, and stable populations are shown in stages 1 through 3. What type of population change do you think stage 4 represents?

Answer

Stage 4 represents a population that is decreasing.

Footnotes

1. 1 Danny Dorling, Mary Shaw, and George Davey Smith, “Global Inequality of Life Expectancy due to AIDS,” *BMJ* 332, no. 7542 (March 2006): 662-664, doi: 10.1136/bmj.332.7542.662.
2. 2 Paul R. Erlich, prologue to *The Population Bomb*, (1968; repr., New York: Ballantine, 1970).

Glossary

age structure
the distribution of the proportion of population members in each age class

one-child policy
a policy in China to limit population growth by limiting urban couples to have only one child or face a penalty of a fine

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5.4: Community Ecology

In general, populations of one species never live in isolation from populations of other species. The interacting populations occupying a given habitat form an ecological community. The number of species occupying the same habitat and their relative abundance is known as the diversity of the community. Areas with low species diversity, such as the glaciers of Antarctica, still contain a wide variety of living organisms, whereas the diversity of tropical rainforests is so great that it 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.

Predation and Herbivory

Perhaps the classical example of species interaction is the predator-prey relationship. The narrowest definition of the predator-prey interaction 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 5.4.1). 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.

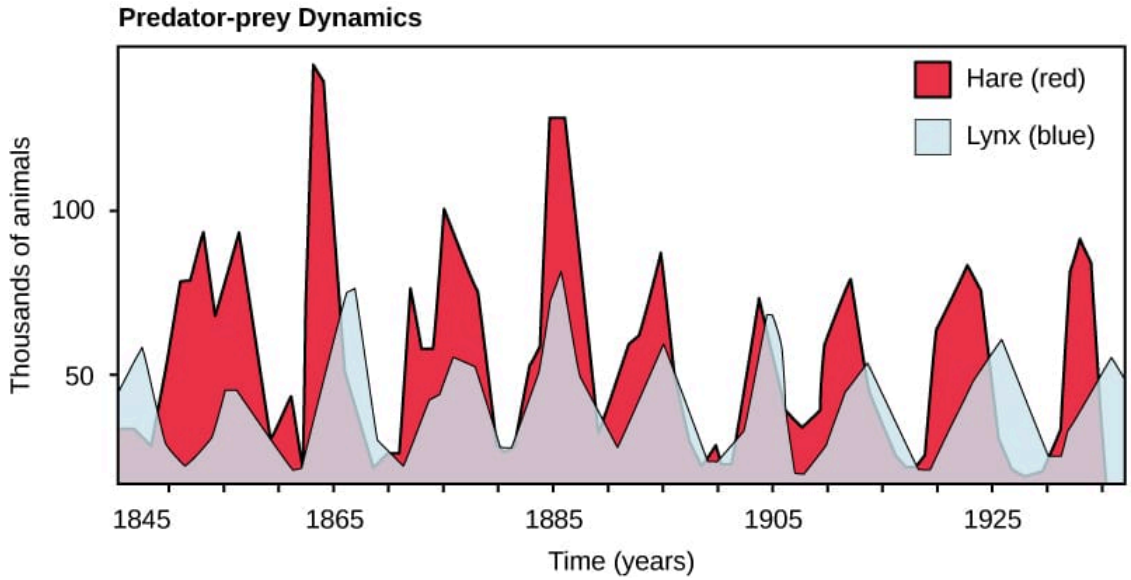


Figure 5.4.1: The cycling of snowshoe hare and lynx populations in Northern Ontario is an example of predator-prey dynamics.

Defense Mechanisms against Predation and Herbivory

Predation and predator avoidance are strong selective agents. 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 and 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 5.4.2**a**). 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 5.4.2**b**). (Biomedical scientists have purposed the chemical produced by foxglove as a heart medication, which has saved lives for many decades.)



(a) (b)

Figure 5.4.2: The (a) honey locust tree uses thorns, a mechanical defense, against herbivores, while the (b) foxglove uses a chemical defense: toxins produces 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 5.4.3**a**). In another example, the chameleon can change its color to match its surroundings (Figure 5.4.3**b**).



(a) (b)

Figure 5.4.3: (a) The tropical walking stick and (b) the chameleon use their body shape and/or coloration to prevent detection by predators. (credit a: modification of work by Linda Tanner; credit b: modification of work by Frank Vassen)

Some species use coloration 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. Fire-bellied toads produce toxins that make them distasteful to their potential predators. 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. These are only two examples of warning coloration, which is a relatively common adaptation. Warning coloration only works if a predator uses eyesight to locate prey and can learn—a naïve predator must experience the negative consequences of eating one before it will

avoid other similarly colored individuals (Figure 5.4.4).



Figure 5.4.4: The fire-bellied toad has bright coloration on its belly that serves to warn potential predators that it is toxic. (credit: modification of work by Roberto Verzo)

While some predators learn to avoid eating certain potential prey because of their coloration, other species have evolved mechanisms to mimic this coloration to avoid being eaten, even though they themselves may not be unpleasant to eat or contain toxic chemicals. In some cases of mimicry, a harmless species imitates the warning coloration of a harmful species. Assuming they share the same predators, this coloration then protects the harmless ones. Many insect species mimic the coloration of wasps, which are stinging, venomous insects, thereby discouraging predation (Figure 5.4.5).



Figure 5.4.5: One form of mimicry is when a harmless species mimics the coloration of a harmful species, as is seen with the (a) wasp (*Polistes* sp.) and the (b) hoverfly (*Syrphus* sp.). (credit: modification of work by Tom Ings)

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 5.4.6 shows a variety of foul-tasting butterflies with similar coloration.



Figure 5.4.6: Several unpleasant-tasting *Heliconius* butterfly species share a similar color pattern with better-tasting varieties, an example of mimicry. (credit: Joron M, Papa R, Beltrán M, Chamberlain N, Mavárez J, et al.)

Competitive Exclusion Principle

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**. A **niche** is the unique set of resources used by a species, which includes its interactions with other species. The competitive exclusion principle states that two species cannot occupy the same niche in a habitat: in other words, different species cannot coexist in a community if they are competing for all the same resources. This principle works because if there is an overlap in resource use and therefore competition between two species, then traits that lessen reliance on the shared resource will be selected for leading to evolution that reduces the overlap. If either species is unable to evolve to reduce competition, then the species that most efficiently exploits the resource will drive the other species to extinction. An experimental example of this principle is shown in Figure 5.4.7 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.

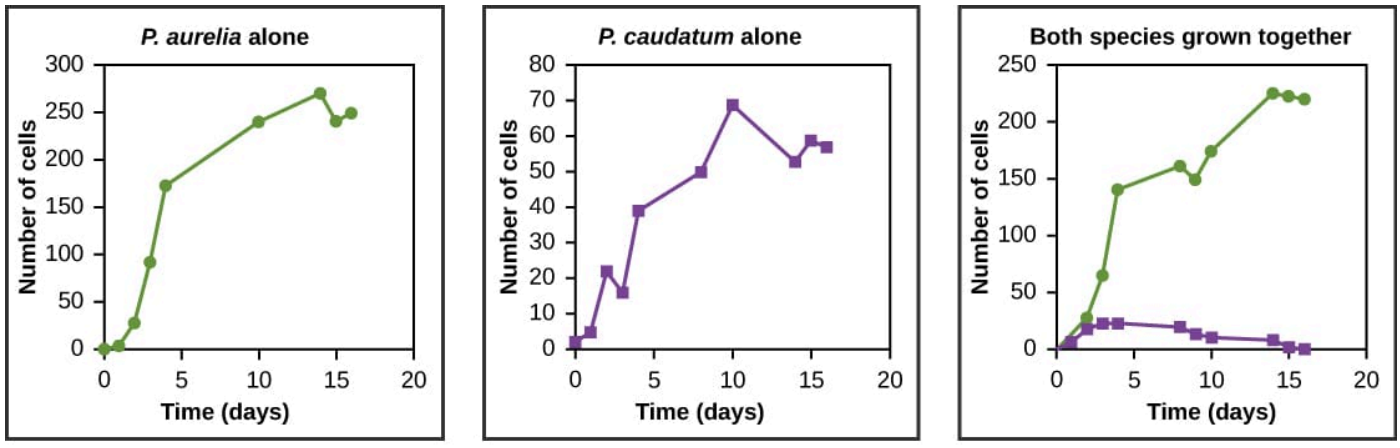


Figure 5.4.7: *Paramecium aurelia* and *Paramecium caudatum* grow well individually, but when they compete for the same resources, the *P. aurelia* outcompetes the *P. caudatum*.

Symbiosis

Symbiotic relationships are close, long-term interactions between individuals of different species. Symbioses may be commensal,

in which one species benefits while the other is neither harmed nor benefited; mutualistic, in which both species benefit; or parasitic, in which the interaction harms one species and benefits the other.

Commensalism

A commensal relationship occurs when one species benefits from a close prolonged interaction, while the other neither benefits nor is harmed. Birds nesting in trees provide an example of a commensal relationship (Figure 5.4.8). The tree is not harmed by the presence of the nest among its branches. The nests are light and produce little strain on the structural integrity of the branch, and most of the leaves, which the tree uses to get energy by photosynthesis, are above the nest so they are unaffected. The bird, on the other hand, benefits greatly. If the bird had to nest in the open, its eggs and young would be vulnerable to predators. Many potential commensal relationships are difficult to identify because it is difficult to prove that one partner does not derive some benefit from the presence of the other.



Figure 5.4.8: The southern masked-weaver is starting to make a nest in a tree in Zambezi Valley, Zambia. This is an example of a commensal relationship, in which one species (the bird) benefits, while the other (the tree) neither benefits nor is harmed. (credit: "Hanay"/Wikimedia Commons)

Mutualism

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 5.4.9**a**). 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 5.4.9**b**). 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.



(a) (b)

Figure 5.4.9: (a) Termites form a mutualistic relationship with symbiotic protozoa in their guts, which allow both organisms to obtain energy from the cellulose the termite consumes. (b) Lichen is a fungus that has symbiotic photosynthetic algae living in close association. (credit a: modification of work by Scott Bauer, USDA; credit b: modification of work by Cory Zanker)

Parasitism

A parasite is an organism that feeds off another without immediately killing the organism it is feeding on. In this relationship, 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.

The reproductive cycles of parasites are often very complex, sometimes requiring more than one host species. A tapeworm causes disease in humans when contaminated, undercooked meat such as pork, fish, or beef is consumed (Figure 5.4.10). 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. *Plasmodium falciparum* is another parasite: the protists that cause malaria, a significant disease in many parts of the world. Living inside human liver and red blood cells, the organism reproduces asexually in the human host and then sexually in the gut of blood-feeding mosquitoes to complete its life cycle. Thus malaria is spread from human to mosquito and back to human, one of many arthropod-borne infectious diseases of humans.

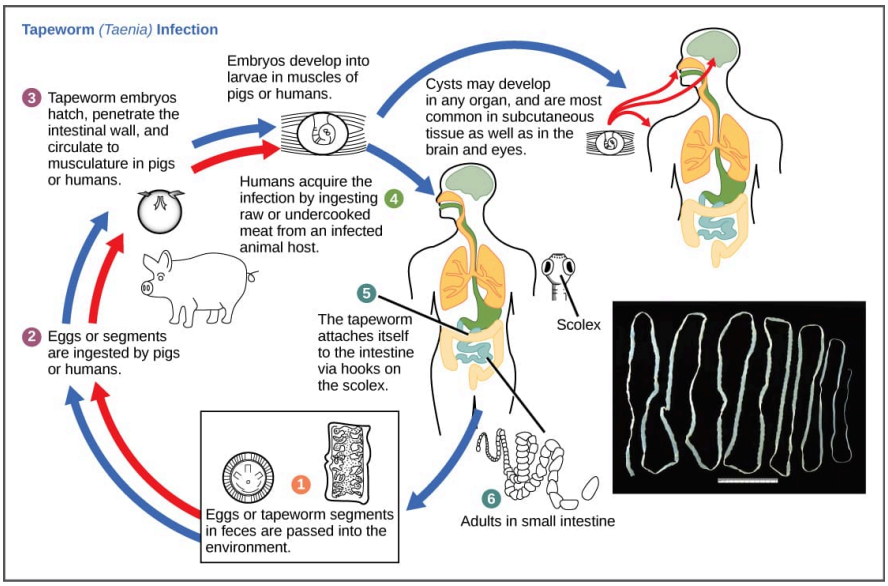


Figure 5.4.10: This diagram shows the life cycle of the tapeworm, a human worm parasite. (credit: modification of work by CDC)

CONCEPT IN ACTION

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View this YouTube Video online

To learn more about "Symbiosis in the Sea," watch this webisode of Jonathan Bird's Blue World.

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 minimize impacts on ecosystems and manage ecological communities we benefit from.

Biodiversity

Ecologists have extensively studied one of the fundamental characteristics of communities: biodiversity. One measure of biodiversity used by ecologists is the number of different species in a particular area and their relative abundance. The area in question could be a habitat, a biome, or the entire biosphere. Species richness is the term used to describe the number of species living in a habitat or other unit. Species richness varies across the globe (Figure 5.4.11). Ecologists have struggled to understand the determinants of biodiversity. Species richness is related to latitude: the greatest species richness occurs near the equator and the lowest richness occurs near the poles. Other factors influence species richness as well. Island biogeography attempts to explain the great species richness found in isolated islands, and has found relationships between species richness, island size, and distance from the mainland.

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

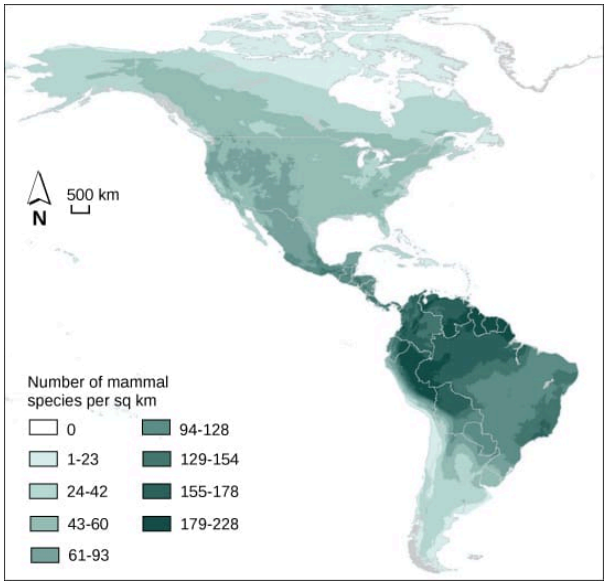


Figure 5.4.11: The greatest species richness for mammals in North America is associated in the equatorial latitudes. (credit: modification of work by NASA, CIESIN, Columbia University)

Foundation Species

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.

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



Figure 5.4.12: Coral is the foundation species of coral reef ecosystems. (credit: Jim E. Maragos, USFWS)

Keystone Species

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 5.4.13). Studies have shown that when this organism is removed from communities, mussel populations (their natural prey) increase, which completely alters the 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.



Figure 5.4.13: The *Pisaster ochraceus* sea star is a keystone species. (credit: Jerry Kirkhart)

BIOLOGY IN ACTION: Invasive Species

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 altered aquatic ecosystems, and some forests are threatened by the spread of common buckthorn (*Rhamnus cathartica*) and garlic mustard (*Alliaria petiolata*). 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. Another species, the silver carp, competes with native fish that feed on zooplankton. 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. Moreover, their presence now threatens the native fish and fisheries of the Great Lakes, which are important to local economies and recreational anglers. Asian carp have even injured humans. The fish, frightened by the sound of approaching motorboats, thrust themselves into the air, often landing in the boat or directly hitting boaters.

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.

The issues associated with Asian carp show how population and community ecology, fisheries management, and politics intersect on issues of vital importance to the human food supply and economy. Socio-political issues like the Asian carp make extensive use of the sciences of population ecology, the study of members of a particular species occupying a habitat; and community ecology, the study of the interaction of all species within a habitat.

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

Primary succession occurs when new land is formed, for example, following the eruption of volcanoes, such as those on the Big Island of Hawaii. As lava flows into the ocean, new land is continually being formed. On the Big Island, approximately 32 acres of land is added to it its size each year. Weathering and other natural forces break down the rock enough for the establishment of hearty species such as lichens and some plants, known as pioneer species(Figure 5.4.14). These species help to further break down the mineral-rich lava 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.



Figure 5.4.14: During primary succession in lava on Maui, Hawaii, succulent plants are the pioneer species. (credit: Forest and Kim Starr)

Secondary succession

A classic example of secondary succession occurs in oak and hickory forests cleared by wildfire (Figure 5.4.15). 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.

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 pine, oak, and hickory trees. These organisms are called intermediate species. Eventually, over 150 years, 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. The return of a natural ecosystem after agricultural activities is also a well-documented secondary succession process.

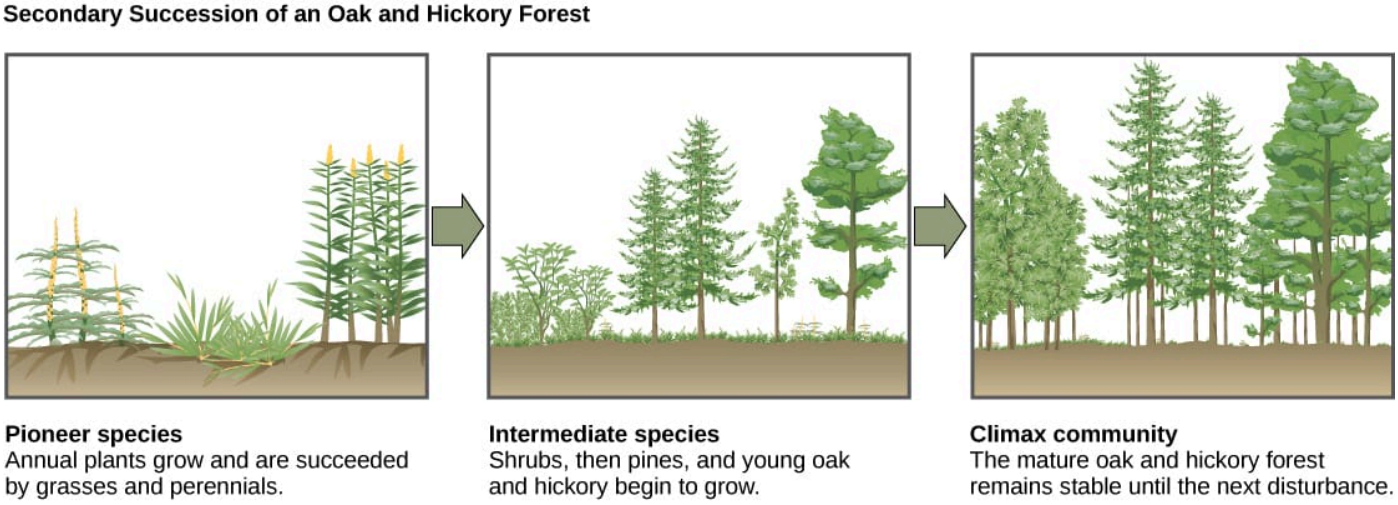


Figure 5.4.15: Secondary succession is seen in an oak and hickory forest after a forest fire. A sequence of the community present at three successive times at the same location is depicted.

Section Summary

Communities include all the different species living in a given area. The variety of these species is referred to as biodiversity. Many organisms have developed defenses against predation and herbivory, including mechanical defenses, warning coloration, and mimicry. Two species cannot exist indefinitely in the same habitat competing directly for the same resources. 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.

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5.5: Population and Community Ecology (Exercises)

Population Demographics and Dynamics

Multiple Choice

Which of the following methods will provide information to an ecologist about both the size and density of a population?

A. mark and recapture
B. mark and release
C. quadrat
D. life table

Answer

C

Which of the following is best at showing the life expectancy of an individual within a population?

A. quadrat
B. mark and recapture
C. survivorship curve
D. life table

Answer

D

Human populations have which type of survivorship curve?

A. Type I
B. Type II
C. Type III
D. Type IV

Answer

A

Free Response

Describe how a researcher would determine the size of a penguin population in Antarctica using the mark and release method.

Answer

The researcher would mark a certain number of penguins with a tag, release them back into the population, and, at a later time, recapture penguins to see what percentage was tagged. This percentage would allow an estimation of the size of the penguin population.

Population Growth and Regulation

Multiple Choice

Species with limited resources usually exhibit a(n) _____ growth curve.

A. logistic
B. logical
C. experimental
D. exponential

Answer

A

The maximum growth rate characteristic of a species is called its _____.

A. limit
B. carrying capacity
C. biotic potential
D. exponential growth pattern

Answer

C

The population size of a species capable of being supported by the environment is called its _____.

A. limit
B. carrying capacity
C. biotic potential
D. logistic growth pattern

Answer

B

Species that have many offspring at one time are usually:

A. *r*-selected
B. *K*-selected
C. both *r*- and *K*-selected
D. not selected

Answer

A

A forest fire is an example of _____ regulation.

A. density-dependent
B. density-independent
C. *r*-selected
D. *K*-selected

Answer

B

Free Response

Describe the growth at various parts of the S-shaped curve of logistic growth.

Answer

In the first part of the curve, when few individuals of the species are present and resources are plentiful, growth is exponential, similar to a J-shaped curve. Later, growth slows due to the species using up resources. Finally, the population levels off at the carrying capacity of the environment, and it is relatively stable over time.

Give an example of how density-dependent and density-independent factors might interact.

Answer

If a natural disaster such as a fire happened in the winter, when populations are low, it would have a greater effect on the overall population and its recovery than if the same disaster occurred during the summer, when population levels are high.

The Human Population

Multiple Choice

A country with zero population growth is likely to be _____.

A. in Africa
B. in Asia
C. economically developed
D. economically underdeveloped

Answer

C

Which type of country has the greatest proportion of young individuals?

A. economically developed
B. economically underdeveloped
C. countries with zero population growth
D. countries in Europe

Answer

B

Which of the following is not a way that humans have increased the carrying capacity of the environment?

A. agriculture
B. using large amounts of natural resources
C. domestication of animals
D. use of language

Answer

B

Free Response

Describe the age structures in rapidly growing countries, slowly growing countries, and countries with zero population growth.

Answer

Rapidly growing countries have a large segment of the population at reproductive age or younger. Slower growing populations have a lower percentage of these individuals, and countries with zero population growth have an even lower percentage. On the other hand, a high proportion of older individuals is seen mostly in countries with zero growth, and a low proportion is most common in rapidly growing countries.

Community Ecology

Multiple Choice

The first species to live on new land, such as that formed from volcanic lava, are called_____.

A. climax community
B. keystone species
C. foundation species
D. pioneer species

Answer

D

A symbiotic relationship where both of the co-existing species benefit from the interaction is called _____.

A. commensalism
B. parasitism
C. mutualism
D. communism

Answer

C

When an invasive species alters the community structure it is introduced to, what can the consequence be?

A. extinction of economically important species
B. reduced predation on some native species
C. increased predation on some native species
D. all of the above

Answer

D

Free Response

Describe the competitive exclusion principle and its effects on competing species.

Answer

The competitive exclusion principles states that no two species competing for the same resources at the same time and place can co-exist over time. Thus, one of the competing species will eventually dominate. On the other hand, if the species evolve such that they use resources from different parts of the habitat or at different times of

day, the two species can exist together indefinitely.

Describe the potential effects when a keystone species is removed from a community.

Answer

Removing a keystone species will have dramatic effects on the abundance of individuals in other populations, increasing some and decreasing others. This affects the interactions between populations such as competition and predator-prey relationships. In addition, the community may show a loss of diversity.

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6: The American Conservation Movement

Introduction

To most early colonists who immigrated to North America the continent was a land of unimaginably vast resources in which little effort was made to treat, minimize, or otherwise manage. This is not surprising, when one stand of trees was consumed for housing or fuel, another was nearby; when one field was eroded to the point of limited fertility, expansion further inland was relatively simple; when rivers became silted so that fisheries were impaired, one moved further upstream; and when confronted with endless herds of wild animals, it was inconceivable that one might over-consume to the point of extinction. European-settled America was a largely agrarian society and, apart from the need to keep spaces productive and clear of debris, there was little incentive to spend time and energy managing discharges to the “commons”. These attitudes persisted well into the 19th century and aspects of them are still active in the present day. While such practices could hardly be said to constitute an environmental policy, they did serve the purpose of assembling a number of groups into rethinking the way they about managing various aspects of our lives, in particular our relationship to the land and the resources it contained or provided. The Connecticut minister, doctor, and farmer **Jared Eliot** (1685-1763) wrote a series of treatises on the need for better farming methods. He summarized:

> “When our fore-Fathers settled here, they entered a Land which probably never had been Ploughed since the Creation, the Land being new they depended upon the natural Fertility of the Ground, which served their purpose very well, and when they had worn out one piece they cleared another, without any concern to amend their Land...(Carman, Tugwell, & True, 1934, p. 29).”

Although Eliot avidly instructed his fellow farmers on better methods of “field husbandry,” there is little evidence that his writings had a lasting effect (he is most known for advances in the design of the drill plough, an early planter that produced even rows of crops, increasing yields).

By 1850, the population of the United States was approaching 25 million and increasing at the rate of three to four percent per year. For comparison the population of England was about 26 million, of France 36 million, and Germany about 40 million. Although the westward migration across North America was well underway, most people still lived within a relatively narrow strip of land along the east coast. The United States was not densely populated by modern measures, yet its new status as a major global power clashed with its previous identity as an isolated "new world" of infinite spaces and endless resources. The country was also becoming more literate and urbanized; about 15 percent of the population lived in cities, a 300 percent increase from just fifty years before.

By the mid-19th century the American public was prepared to listen to the messages of various groups who had become concerned about the impacts of growth on society. Three groups had profound influences on the way we thought of ourselves in relation to the environment, on our land use policies, and on providing environmental goods and services to the growing population. These three groups, which differed in sympathies and character, are : the resource efficiency group, the transcendentalist movement, and the organized industrial interests.

Resource Efficiency

As typified by the concerns of Jared Eliot a century before, there were many who were alarmed at widespread inefficient and wasteful agricultural practices. They believed that the land could not sustain the current levels of soil erosion and infertility along with decreasing crop yields. There were barriers to expansion as well, including unyielding terrain and poor transportation to markets. By the early 1800 organized efforts wanted to understand these problems' causes. They sought to develop and implement new practices that conserved soil and wasted less, to publicly communicate their findings, and to begin building government institutions that promoted better land and resource stewardship.

Although initial conservation concerns were associated with farming, the same approach soon found its way into diverse public arena including: the management of forests and timbering, wastes from mining and smelting, the control of human disease outbreaks (most commonly associated with cholera and typhoid), and the impact of chemical exposure to workers. There were many individuals who contributed to understanding the scientific underpinnings of the environment and educating practitioners: **Eugene Hilgard** (agricultural science), **John Wesley Powell** (water rights), **George Perkins Marsh** (ecological science), **Franklin Hough** and **Gifford Pinchot** (sustainable forestry), **J. Sterling Morton** (forestry and environmental education; co-founder of Arbor

Day), **Frederick Law Olmsted** (landscape architecture), and **Alice Hamilton** (industrial hygiene), to name a few. These resource conservationists were instrumental in applying scientific methods to solving the problems of the day, problems that were rooted in our behavior toward the environment, and that had serious consequences for the well-being of people. It was as a result of these efforts that the basis for the fields of environmental science and engineering, agronomy and agricultural engineering, and public health was established. Over time these fields have grown in depth and breadth, and have led to the establishment of new areas of inquiry.

Just as importantly, several federal institutions were created to oversee the implementation of reforms and manage the government's large land holdings. Legislation forming the **Departments of the Interior** (1849), and **Agriculture** (1862), the **U.S. Forest Service** (1881), the **Geological Survey** (1879), and the **National Park Service** (1916) were all enacted during this period. It was also the time when several major conservation societies, still active today, came into being: the **Audubon Society** (1886), the **Sierra Club** (1892), and the **National Wildlife Federation** (1935). **Arbor Day** was first celebrated in 1872, and **Bird Day** in 1894.

The Transcendental Movement

The transcendental movement began in the 1830's in the U.S. in reaction to the general state of culture and society, increasing urbanism, and the rigidity of organized religions of the time. It professed a way of thinking in which the individual's unique relationship to their surroundings was valued over conformity and unreflective habits of living. But however philosophical its aims and ethereal its goals, transcendentalism had a profound connection to the natural environment. Human-environment interactions and a re-envisioning of the social contract of humanity with nature were core to its efforts. Transcendentalism resonated with an increasingly literate society, and became a major force in the development of conservation as an accepted part of the American experience.

The acknowledged leader of the transcendental movement was **Ralph Waldo Emerson** (1803-1882). In his seminal essay *Nature* (1836), Emerson sets the tone for a new way of envisioning our relation to the natural world:

> "To speak truly, few adult persons can see nature. Most persons do not see the sun. At least they have a very superficial seeing. The sun illuminates only the eye of the man, but shines into the eye and the heart of the child. The lover of nature is he whose inward and outward senses are still truly adjusted to each other; who has retained the spirit of infancy even into the era of manhood. His intercourse with heaven and earth, becomes part of his daily food. In the presence of nature, a wild delight runs through the man, in spite of real sorrows. Nature says, -- he is my creature, and maugre all his impertinent griefs, he shall be glad with me. Not the sun or the summer alone, but every hour and season yields its tribute of delight; for every hour and change corresponds to and authorizes a different state of the mind, from breathless noon to grimmest midnight. Nature is a setting that fits equally well a comic or a mourning piece. In good health, the air is a cordial of incredible virtue. Crossing a bare common, in snow puddles, at twilight, under a clouded sky, without having in my thoughts any occurrence of special good fortune, I have enjoyed a perfect exhilaration. I am glad to the brink of fear. In the woods too, a man casts off his years, as the snake his slough, and at what period so ever of life, is always a child. In the woods, is perpetual youth. Within these plantations of God, a decorum and sanctity reign, a perennial festival is dressed, and the guest sees not how he should tire of them in a thousand years. In the woods, we return to reason and faith. There I feel that nothing can befall me in life, -- no disgrace, no calamity, (leaving me my eyes,) which nature cannot repair. Standing on the bare ground, -- my head bathed by the blithe air, and uplifted into infinite space, -- all mean egotism vanishes. I become a transparent eye-ball; I am nothing; I see all; the currents of the Universal Being circulate through me; I am part or particle of God. The name of the nearest friend sounds then foreign and accidental: to be brothers, to be acquaintances, -- master or servant, is then a trifle and a disturbance. I am the lover of uncontained and immortal beauty. In the wilderness, I find something more dear and connate than in streets or villages. In the tranquil landscape, and especially in the distant line of the horizon, man beholds somewhat as beautiful as his own nature." (Emerson, 1836).

In this passage Emerson describes how his connection to the Universal Being is only made possible through communion with Nature. His metaphorical language was and remains a reminder of transcendentalism, and that our existence is dependent on the natural world.



Figure 6.1 The painting titled "The Kindred", dated 1849, depicts the artist, Thomas Cole, and poet, William Cullen Bryant. *Source: Asher Brown Durand via Wikimedia Commons*

It is difficult to fully appreciate Emerson's vision of humans and nature through language alone. As might be expected, the counter-reaction to the state of society and its attitudes toward the environment found expression in other media as well, in particular the rise of a cadre of American landscape artists. The camera had not yet been perfected, and there was no electronic media to compete for people's attention. The artists' renditions of various scenes, especially landscapes, were quite popular. In Figure 6.2 A.B. Durand (1796-1886) paints an artist and a poet out for a hike amid a lush forest scene. It captures much of the essence of transcendental thought, which influenced Durand's style intimately. The offset of the human subjects to left-of-center is purposeful: the main subject is nature, with humans merely a component. This theme carried through many of the landscapes of the period, and helped to define what became known, among others, as the "Hudson River School," whose artists depicted nature as an otherwise inexpressible manifestation of God. This is further expressed in the Frederic Church painting - In the Heart of the Andes (Figure 6.2). Here, the seemingly sole theme is the landscape itself. Closer inspection of the lower left corner, however, reveals a small party of people gathered at a cross. Their appearance is offset and virtually invisible amid the majesty of the mountains.



Figure 6.2 *The Heart of the Andes* (1859) by Hudson River School artist Frederic Edwin Church. Closer inspection of the lush landscape reveals a small party of people near a cross at the bottom left. (credit: Frederic Edwin Church via Wikimedia Commons; Public Domain)

Other notable contributors to the transcendental movement were **Henry David Thoreau** (1817-1862), **Margaret Fuller**

(1810-1850), and **Walt Whitman** (1819-1892). Thoreau was an abolitionist and the author of Walden and Civil Disobedience. Fuller was a woman's rights advocate, edited the transcendental journal The Dial and wrote *Woman in the Nineteenth Century*, which is widely considered the first American work on feminism. Whitman was an American poet, essayist, and journalist whose volume of poetry *Leaves of Grass* celebrates both the human form and the human mind as worthy of praise.

The transcendental redefinition of the social contract with the environment was holistic. It contained a new appreciation of nature as well a redefinition of human's relationships with each other. It called for: the liberation of the human mind from convention and formalism, attacks on slavery, the need for racial equality, concern for universal suffrage and women's rights, and gender equity. In many ways it was a repositioning of the ideals of the enlightenment that figured so prominently in the founding documents of the republic. These social concerns are represented today within the sustainability paradigm in the form of such issues as environmental justice, consumer behavior, and labor relations.

Transcendentalism as a formal movement diminished during the latter half of the 19th century, but it had a far-reaching influence on the way society perceived itself relative to the environment. Perhaps no one is more responsible for translating its aspirations into environmental public policy than **John Muir** (1838-1914), a Scottish-born immigrant who was heavily influenced by Emerson's writings (it is said that the young Muir carried with him a copy of *Nature* from Scotland). The two first met in 1871 during a camping trip to the Sierra Mountains of California. Upon learning of Emerson's planned departure, Muir wrote to him on May 8, 1871 hoping to convince him to stay longer, "I invite you join me in a months worship with Nature in the high temples of the great Sierra Crown beyond our holy Yosemite. It will cost you nothing save the time & very little of that for you will be mostly in Eternity" (Chou, 2003).

Muir was a naturalist, author, organizer (founder of the Sierra Club), and as it turns out a remarkably effective political activist and lobbyist. His association with **Theodore Roosevelt** (1858-1919, 26th president of the United States), began with a 1903 campaign visit by Roosevelt to California. Roosevelt sought out Muir, whose reputation was well known as a guide to the Yosemite area (see Figure 6.3).



Figure 6.3 "Roosevelt and Muir". Theodore Roosevelt and John Muir at Yosemite National Park in 1903.

It was one of Muir's special talents that he could make connections across their rather different views on the environment (he a strict preservationist, Roosevelt a practical outdoorsman). By all accounts they had frank but cordial exchanges. For example, upon viewing the giant Sequoias, Muir remarked to Roosevelt, "God has cared for these trees...but he cannot save them from fools – only Uncle Sam can do that." Roosevelt was so taken with his companion that he insisted they avoid political crowds and camp together overnight in the mountains.

The subsequent legacy of the Roosevelt administration in the name of conservation was significant, even by today's standards. Known as the "conservation president," Roosevelt was responsible for 225 million acres of land added to the U.S. Forest Service, and the creation of 50 wildlife refuges and 150 national forests representing, in total, 11 percent of the total land area of the 48 contiguous states.

The Role of Industry

During the formative period of American conservation, the behavior of industry towards the environment was either indifferent or hostile, which continues today. The industries of the day were agriculture, timber, and mining and were enabled by the transportation sector of railroads and steamboats. They had little incentive to manage their emissions to the environment responsibly, or to use natural resources wisely. Regulations were few, the science underpinning environmental impacts was nascent, the commons itself was viewed as essentially infinite, and resource exploitation and waste generation was seen as a necessary byproduct of expansion, job creation, and social well-being. And yet, as human-created organizations go, industries are extraordinarily sensitive to economic conditions. If the sustainability paradigm is to be believed, then economic viability is of paramount concern and the engagement of industrial forces must of necessity be part of its enactment. These are the engines that provide employment, and that control large quantities of capital for investment. Further, viewed from the life cycle perspective of the flow of materials, products that turn raw materials into mostly waste (defined here as a quantity of material that no one values, as opposed to salable products) are simply inefficient and reduce profitability.



Figure 6.4 "The Oregon Trail" the painting, dated 1869, depicts the westward migration of settlers via wagon trains, on horseback, and by foot. *Source: Albert Bierstadt via Wikimedia Commons.*

As noted above, industrial activities during this time were responsible for significant environmental degradation. Policy reformers of the day, such as Carl Schurz (as secretary of the Interior) turned their attention in particular to land reforms, which impacted the expansion of railroads, and forest preservation. Industry played an unquestionable role as enablers of societal shifts occurring in America by making goods and services available, increasing the wealth of the emerging middle class, and in particular providing relatively rapid access to previously inaccessible locations – in many cases the same locations that preservationists were trying to set aside. Reading, hearing stories about, and looking at pictures of landscapes of remote beauty and open spaces was alluring and stirred the imagination, but being able to actually visit these places firsthand was an educational experience that had transformative powers. Painted in 1868, Alfred Bierstadt's *The Oregon Trail* (Figure 6.4) depicts the westward migration of settlers via wagon trains, on horseback, and simply walking. This journey, not without peril, that took about six months. The next year saw the completion of the transcontinental railroad, and within a few years it became possible to complete the same journey in as little as six days in comparative comfort and safety.

Industry had a role in promoting land conservation as well, when it supported their interests. It began in 1864, with the efforts of several California citizens to have the U.S. Congress accept most of Yosemite, which had been under the "protection" of the State of California, as a national preserve. The petition cited its value "for public use, resort, and recreation". This reasoning reflected the combined interests of the resource efficiency group, preservationists, and business opportunists. Frederick Law Olmsted oversaw the initial efforts to manage the Yosemite area. He was a landscape architect most well known for the design of New York's Central Park, and an ardent believer in the ability of open spaces to improve human productivity and health. The effort was infused with renewed vigor after John Muir's arrival in the late 1860s, but it wasn't until 1906 that the park was officially designated. The movement to designate certain areas as national parks reached its zenith during the Roosevelt administration.

In the meantime, similar interests had grown to name Yellowstone as a national park, with the same basic justification as

for Yosemite. Since there were no states as yet formed in the region the pathway was more straightforward, and was made considerably easier by the lack of interest by timber and mining companies to exploit (the area was thought to have limited resource value), and the railroads who, seeing potential for significant passenger traffic, lobbied on its behalf. Thus the first national park was officially designated in 1872, only three years after the completion of the transcontinental railroad. Indeed, in relatively rapid succession the Union Pacific Railroad got behind the Yosemite efforts, and the Northern Pacific Railroad lobbied heavily for the creation of parks at Mount Rainier (1899) and Glacier (1910). By 1916, when the National Park Service was formed, sixteen national parks had been created. States too began to see value in creating and, to a degree, preserving open spaces, as evidenced by New York's Adirondack Park (1894), which was dedicated to be "forever wild."

Results of the American Conservation Movement

With the advent of the First World War, and subsequent political, social, and economic unrest that lasted for another thirty years, actions motivated by the conservation movement declined. The coalition between the resource efficiency group and those wishing to preserve nature, always uncomfortable, was further eroded when it became clear that the main reason Congress was "setting aside" various areas was mainly to better manage commercial exploitation. And yet, the period from 1850 to 1920 left a remarkable legacy of environmental reform, and laid the foundation for future advances in environmental policy. In summary, the conservation movement accomplished the following:

- Redefined the social contract between humans and the environment, establishing a legacy of conservation as part of the American character, and a national model for the preservation of natural beauty.
- Invented the concept of national parks and forests, wildlife refuges, and other sites for commercial and recreational uses by society.
- Developed the first scientific understanding of how the environment functioned, integrating the scientific approach to resource management into government policy.
- Pioneered technological practices to improve resource management.
- Established the major federal institutions with responsibility for land and resource conservation.
- Communicated the impact of pollution on human health and welfare.
- Through publications and travel, exposed many to the beauty of the natural environment and the consequences of human activities.
- Finally, although sustainability as a way of envisioning ourselves in relation to the environment was still many years away, already its three principal elements, imperfectly integrated at the time, are seen clearly to be at work.

References

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7: EVOLUTION, ITS PROCESS, AND DIVERSITY

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7.9: Evolution and it's Processes, Diversity (Exercises)

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7.1: Discovering How Populations Change

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

In the eighteenth century, ideas about the evolution of animals were reintroduced by the naturalist **Georges-Louis Leclerc, Comte de Buffon** and even by Charles Darwin's grandfather, **Erasmus Darwin**. During this time, it was also accepted that there were extinct species. At the same time, **James Hutton**, the Scottish naturalist, proposed that geological change occurred gradually by the accumulation of small changes from processes (over long periods of time) just like those happening today. 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. Lyell argued that the greater age of Earth gave more time for gradual change in species, and the process provided an analogy for gradual change in species.

In the early nineteenth century, **Jean-Baptiste Lamarck** published a book that detailed a mechanism for evolutionary change that is now referred to as **inheritance of acquired characteristics**. In Lamarck's theory, modifications in an individual caused by its environment, or the use or disuse of a structure during its lifetime, could be inherited by its offspring and, thus, bring about change in a species. While this mechanism for evolutionary change as described by Lamarck was discredited, Lamarck's ideas were an important influence on evolutionary thought. The inscription on the statue of Lamarck that stands at the gates of the Jardin des Plantes in Paris describes him as the "founder of the doctrine of evolution."

Charles Darwin and Natural Selection

The actual 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 time 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 7.1.1). 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."[1]

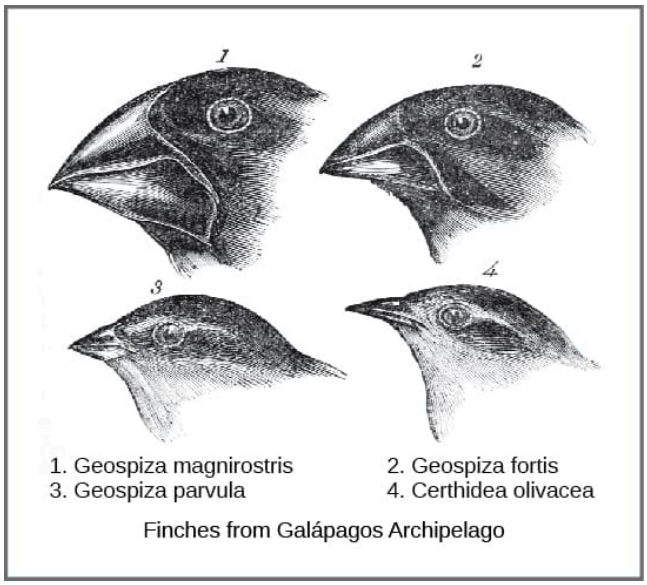


Figure 7.1.1: Darwin observed that beak shape varies among finch species. He postulated that the beak of an ancestral species had adapted over time to equip the finches to acquire different food sources. This illustration shows the beak shapes for four species of ground finch: 1. *Geospiza magnirostris* (the large ground finch), 2. *Geospiza fortis* (the medium ground finch), 3. *Geospiza parvula* (the small tree finch), and 4. *Certhidea olivacea* (the green-warbler finch).

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, the characteristics of organisms 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. The capacity for reproduction in all organisms outstrips the availability of resources to support their numbers. Thus, there is a competition for those resources in each generation. Both Darwin and Wallace's understanding of this principle came from reading an essay by the economist Thomas Malthus, who discussed this principle in relation to human populations. Third, offspring vary among each other in regard to their characteristics and those variations are inherited. 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."

Papers by Darwin and Wallace (Figure 7.1.2) 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 Species,* was published, which outlined in considerable detail his arguments for evolution by natural selection.



(a) (b)

Figure 7.1.2: (a) Charles Darwin and (b) Alfred Wallace wrote scientific papers on natural selection that were presented together before the Linnean Society in 1858.

Demonstrations of evolution by natural selection can be time consuming. One of the best demonstrations has been in the very birds that helped to inspire the theory, the Galápagos finches. Peter and Rosemary Grant and their colleagues have studied Galápagos finch populations every year since 1976 and have provided important demonstrations of the operation of natural selection. The Grants found changes from one generation to the next in the beak shapes of the medium ground finches on the Galápagos island of Daphne Major. The medium ground finch feeds on seeds. The birds have inherited variation in the bill shape with some individuals having wide, deep bills and others having thinner bills. Large-billed birds feed more efficiently on large, hard seeds, whereas smaller billed birds feed more efficiently on small, soft seeds. During 1977, a drought period altered vegetation on the island. After this period, the number of seeds declined dramatically: the decline in small, soft seeds was greater than the decline in large, hard seeds. The large-billed birds were able to survive better than the small-billed birds the following year. The year following the drought when the Grants measured beak sizes in the much-reduced population, they found that the average bill size was larger (Figure 7.1.3). This was clear evidence for natural selection (differences in survival) of bill size caused by the availability of seeds. The Grants had studied the inheritance of bill sizes and knew that the surviving large-billed birds would tend to produce offspring with larger bills, so the selection would lead to evolution of bill size. Subsequent studies by the Grants have demonstrated selection on and evolution of bill size in this species in response to changing conditions on the island. The evolution has occurred both to larger bills, as in this case, and to smaller bills when large seeds became rare.

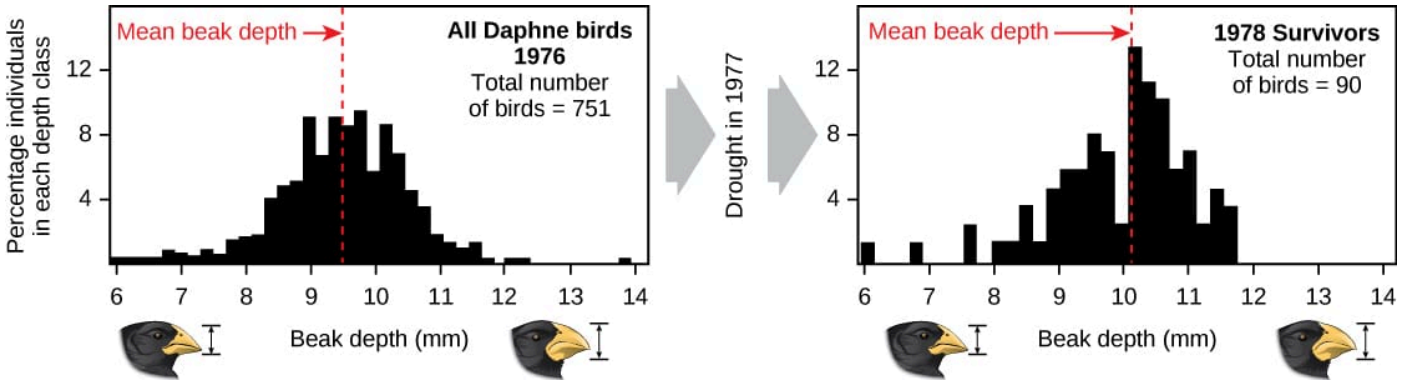


Figure 7.1.3: A drought on the Galápagos island of Daphne Major in 1977 reduced the number of small seeds available to finches, causing many of the small-beaked finches to die. This caused an increase in the finches' average beak size between 1976 and 1978. Two graphs show the number of birds on the y axis and bill depth in millimeter on the x axis. The graph on the left has data for the year 1976 with a total of 751 birds measured. The mean beak depth is about 9.5 millimeters. The graph on the right has data for the year 1978, after a drought caused the death of many birds. The total number of surviving birds measured for this data was 90, and the mean beak depth is about 10 millimeters.

Variation and Adaptation

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, selection will not lead to change in the next generation. This is critical because variation among individuals can be caused by non-genetic reasons, such as an individual being taller because of better nutrition rather than different genes.

Genetic diversity in a population comes from two main sources: mutation and sexual reproduction. Mutation, a change in DNA, is the ultimate source of new alleles or new genetic variation in any population. An individual that has a mutated gene might have a different trait than other individuals in the population. However, this is not always the case. A mutation can have one of three outcomes on the organisms' appearance (or phenotype):

- A mutation may affect the phenotype of the organism in a way that gives it reduced fitness—lower likelihood of survival, resulting in fewer offspring.
- A mutation may produce a phenotype with a beneficial effect on fitness.
- Many mutations, called neutral mutations, will have no effect on fitness.

Mutations may also have a whole range of effect sizes on the fitness of the organism that expresses them in their phenotype, from a small effect to a great effect. Sexual reproduction and crossing over in meiosis also lead to genetic diversity: when two parents reproduce, unique combinations of alleles assemble to produce unique genotypes and, thus, phenotypes in each of the offspring.

A heritable trait that aids the survival and reproduction of an organism in its present environment is called an adaptation. An adaptation is a "match" of the organism to the environment. Adaptation to an environment comes about when a change in the range of genetic variation occurs over time that increases or maintains the match of the population with its environment. The variations in finch beaks shifted from generation to generation providing adaptation to food availability.

Whether or not a trait is favorable depends on the environment at the time. The same traits do not always have the same relative benefit or disadvantage because environmental conditions can change. For example, finches with large bills were benefited in one climate, while small bills were a disadvantage; in a different climate, the relationship reversed.

Patterns of Evolution

The evolution of species has resulted in enormous variation in form and function. When two species evolve in different directions from a common point, it is called divergent evolution. Such divergent evolution can be seen in the forms of the reproductive organs of flowering plants, which share the same basic anatomies; however, they can look very different as a result of selection in different physical environments, and adaptation to different kinds of pollinators (Figure 7.1.4).

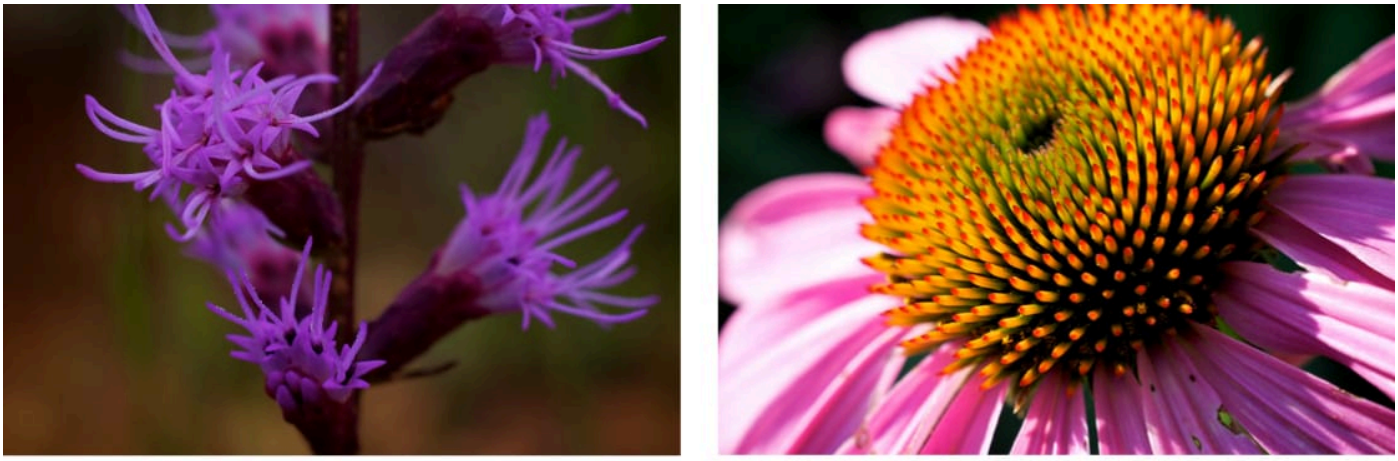


Figure 7.1.4: Flowering plants evolved from a common ancestor. Notice that the (a) dense blazing star (*Liatris spicata*) and (b) purple coneflower (*Echinacea purpurea*) vary in appearance, yet both share a similar basic morphology. (credit a, b: modification of work by Cory Zanker)

In other cases, similar phenotypes evolve independently in distantly related species. For example, flight has evolved in both bats and insects, and they both have structures we refer to as wings, which are adaptations to flight. The wings of bats and insects, however, evolved from very different original structures. When similar structures arise through evolution independently in different species it is called convergent evolution. The wings of bats and insects are called analogous structures; they are similar in function and appearance, but do not share an origin in a common ancestor. Instead they evolved independently in the two lineages. The wings of a hummingbird and an ostrich are homologous structures, meaning they share similarities (despite their differences resulting from evolutionary divergence). The wings of hummingbirds and ostriches did not evolve independently in the hummingbird lineage and the ostrich lineage—they descended from a common ancestor with wings.

The Modern Synthesis

The mechanisms of inheritance, genetics, were not understood at the time Darwin and Wallace were developing their idea of natural selection. This lack of understanding was a stumbling block to comprehending many aspects of evolution. In fact, blending inheritance was the predominant (and incorrect) genetic theory of the time, which made it difficult to understand how natural selection might operate. Darwin and Wallace were unaware of the genetics work by Austrian monk **Gregor Mendel**, which was published in 1866, not long after publication of *On the Origin of Species*. Mendel's work was rediscovered in the early twentieth century at which time geneticists were rapidly coming to an understanding of the basics of inheritance. Initially, the newly discovered particulate nature of genes made it difficult for biologists to understand how gradual evolution could occur. But over the next few decades genetics and evolution were integrated in what became known as **the modern synthesis** — the coherent understanding of the relationship between natural selection and genetics that took shape by the 1940s and is generally accepted today. In sum, the modern synthesis describes how evolutionary pressures, such as natural selection, can affect a population's genetic makeup, and, in turn, how this can result in the gradual evolution of populations and species. The theory also connects this gradual change of a population over time, called microevolution, with the processes that gave rise to new species and higher taxonomic groups with widely divergent characters, called macroevolution.

Population Genetics

Recall that a gene for a particular character may have several variants, or alleles, that code for different traits associated with that character. For example, in the ABO blood type system in humans, three alleles determine the particular blood-type protein on the surface of red blood cells. Each individual in a population of diploid organisms can only carry two alleles for a particular gene, but more than two may be present in the individuals that make up the population. Mendel followed alleles as they were inherited from parent to offspring. In the early twentieth century, biologists began to study what happens to all the alleles in a population in a field of study known as population genetics.

Until now, we have defined evolution as a change in the characteristics of a population of organisms, but behind that phenotypic change is genetic change. In population genetic terms, **evolution** is defined as a change in the frequency of an allele in a population. Using the ABO system as an example, the frequency of one of the alleles, I^A, is the number of copies of that allele divided by all the copies of the ABO gene in the population. For example, a study in Jordan found a frequency of I^A to be 26.1 percent.[2] The I^B, I^0 alleles made up 13.4 percent and 60.5 percent of the alleles respectively, and all of the frequencies add up to 100 percent. A change in this frequency over time would constitute evolution in the population.

There are several ways the allele frequencies of a population can change. One of those ways is **natural selection**. If a given allele confers a phenotype that allows an individual to have more offspring that survive and reproduce, that allele, by virtue of being inherited by those offspring, will be in greater frequency in the next generation. Since allele frequencies always add up to 100 percent, an increase in the frequency of one allele always means a corresponding decrease in one or more of the other alleles. Highly beneficial alleles may, over a very few generations, become "fixed" in this way, meaning that every individual of the population will carry the allele. Similarly, detrimental alleles may be swiftly eliminated from the gene pool, the sum of all the alleles in a population. Part of the study of population genetics is tracking how selective forces change the allele frequencies in a population over time, which can give scientists clues regarding the selective forces that may be operating on a given population. The studies of changes in wing coloration in the peppered moth from mottled white to dark in response to soot-covered tree trunks and then back to mottled white when factories stopped producing so much soot is a classic example of studying evolution in natural populations (Figure 7.1.5).

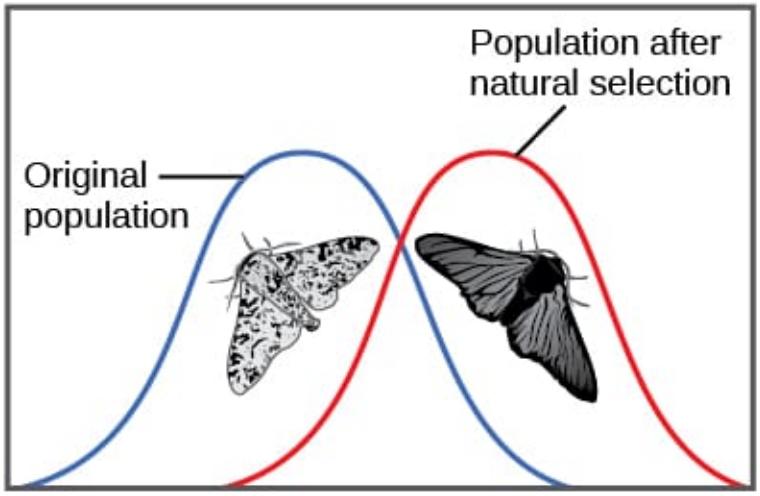


Figure 7.1.5: As the Industrial Revolution caused trees to darken from soot, darker colored peppered moths were better camouflaged than the lighter colored ones, which caused there to be more of the darker colored moths in the population. (A graph shows two moths, one light and one dark in color. The population line shifts from the light phenotype on the left to the dark one on the right in response to a darker natural environment. The text next to the graph reads: Light-colored peppered moths are better camouflaged against a pristine environment; likewise, dark-colored peppered moths are better camouflaged against a sooty environment. Thus, as the Industrial Revolution progressed in nineteenth-century England, the color of the moth population shifted from light to dark.)

In the early twentieth century, English mathematician **Godfrey Hardy** and German physician **Wilhelm Weinberg** independently provided an explanation for a somewhat counterintuitive concept. Hardy's original explanation was in response to a misunderstanding as to why a "dominant" allele, one that masks a recessive allele, should not increase in frequency in a population until it eliminated all the other alleles. The question resulted from a common confusion about what "dominant" means, but it forced Hardy, who was not even a biologist, to point out that if there are no factors that affect an allele frequency those frequencies will remain constant from one generation to the next. This principle is now known as the **Hardy-Weinberg Equilibrium**. The theory states that a population's allele and genotype frequencies are inherently stable—unless some kind of evolutionary force is acting on the population, the population would carry the same alleles in the same proportions generation after generation. Individuals would, as a whole, look essentially the same and this would be unrelated to whether the alleles were dominant or recessive. The four most important evolutionary forces, which will disrupt the equilibrium, are natural selection, mutation, genetic drift, and migration into or out of a population. A fifth factor, nonrandom mating, will also disrupt the Hardy-Weinberg equilibrium but only by shifting genotype frequencies, not allele frequencies. In nonrandom mating, individuals are more likely to mate with like individuals (or unlike individuals) rather than at random. Since nonrandom mating does not change allele frequencies, it does not cause evolution directly. Natural selection has been described. Mutation creates one allele out of another one and changes an allele's frequency by a small, but continuous amount each generation. Each allele is generated by a low, constant mutation rate that will slowly increase the allele's frequency in a population if no other forces act on the allele. If natural selection acts against the allele, it will be removed from the population at a low rate leading to a frequency that results from a balance between selection and mutation. This is one reason that genetic diseases remain in the human population at very low frequencies. If the allele is favored by selection, it will increase in frequency. Genetic drift causes random changes in allele frequencies when populations are small. Genetic drift can often be important in evolution, as discussed in the next section. Finally, if two populations of a species have different allele frequencies, migration of individuals between them will cause frequency changes in both populations. As it happens, there is no population in which one or more of these processes are not operating, so populations are always evolving, and the Hardy-Weinberg equilibrium will never be exactly observed. However, the Hardy-Weinberg principle gives scientists a baseline expectation for allele frequencies in a non-evolving population to which they can compare evolving populations and thereby infer what evolutionary forces might be at play. The population is evolving if the frequencies of alleles or genotypes deviate from the value expected from the Hardy-Weinberg principle.

Darwin identified a special case of natural selection that he called **sexual selection**. Sexual selection affects an individual's ability to mate and thus produce offspring, and it leads to the evolution of dramatic traits that often appear maladaptive in terms of survival but persist because they give their owners greater reproductive success. Sexual selection occurs in two ways: through male–male competition for mates and through female selection of mates. Male–male competition takes the form of conflicts between males, which are often ritualized, but may also pose significant threats to a male's survival. Sometimes the competition is for territory, with females more likely to mate with males with higher quality territories. Female choice occurs when females choose a male based on a particular trait, such as feather colors, the performance of a mating dance, or the building of an elaborate structure. In some cases male–male competition and female choice combine in the mating process. In each of these cases, the traits selected for, such as fighting ability or feather color and length, become enhanced in the males. In general,

it is thought that sexual selection can proceed to a point at which natural selection against a character's further enhancement prevents its further evolution because it negatively impacts the male's ability to survive. For example, colorful feathers or an elaborate display make the male more obvious to predators.

Summary

Evolution by natural selection arises from three conditions: individuals within a species vary, some of those variations are heritable, and organisms have more offspring than resources can support. The consequence is that individuals with relatively advantageous variations will be more likely to survive and have higher reproductive rates than those individuals with different traits. The advantageous traits will be passed on to offspring in greater proportion. Thus, the trait will have higher representation in the next and subsequent generations leading to genetic change in the population.

The modern synthesis of evolutionary theory grew out of the reconciliation of Darwin's, Wallace's, and Mendel's thoughts on evolution and heredity. Population genetics is a theoretical framework for describing evolutionary change in populations through the change in allele frequencies. Population genetics defines evolution as a change in allele frequency over generations. In the absence of evolutionary forces allele frequencies will not change in a population; this is known as Hardy-Weinberg equilibrium principle. However, in all populations, mutation, natural selection, genetic drift, and migration act to change allele frequencies.

Footnotes

1. 1 Charles Darwin, *Journal of Researches into the Natural History and Geology of the Countries Visited during the Voyage of H.M.S. Beagle Round the World, under the Command of Capt. Fitz Roy, R.N*, 2nd. ed. (London: John Murray, 1860).
2. 2 Sahar S. Hanania, Dhia S. Hassawi, and Nidal M. Irshaid, "Allele Frequency and Molecular Genotypes of ABO Blood Group System in a Jordanian Population," *Journal of Medical Sciences* 7 (2007): 51-58, doi:10.3923/jms.2007.51.58

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7.2: Mechanisms of Evolution

The Hardy-Weinberg equilibrium principle says that allele frequencies in a population will remain constant in the absence of the four factors that could change them. Those factors are natural selection, mutation, genetic drift, and migration (gene flow). In fact, we know they are probably always affecting populations.

Natural Selection

Natural selection has already been discussed. Alleles are expressed in a phenotype. Depending on the environmental conditions, the phenotype confers an advantage or disadvantage to the individual with the phenotype relative to the other phenotypes in the population. If it is an advantage, then that individual will likely have more offspring than individuals with the other phenotypes, and this will mean that the allele behind the phenotype will have greater representation in the next generation. If conditions remain the same, those offspring, which are carrying the same allele, will also benefit. Over time, the allele will increase in frequency in the population.

Mutation

Mutation is a source of new alleles in a population. Mutation is a change in the DNA sequence of the gene. A mutation can change one allele into another, but the net effect is a change in frequency. The change in frequency resulting from mutation is small, so its effect on evolution is small unless it interacts with one of the other factors, such as selection. A mutation may produce an allele that is selected against, selected for, or selectively neutral. Harmful mutations are removed from the population by selection and will generally only be found in very low frequencies equal to the mutation rate. Beneficial mutations will spread through the population through selection, although that initial spread is slow. Whether or not a mutation is beneficial or harmful is determined by whether it helps an organism survive to sexual maturity and reproduce. It should be noted that mutation is the ultimate source of genetic variation in all populations—new alleles, and, therefore, new genetic variations arise through mutation.

Genetic Drift

Another way a population's allele frequencies can change is genetic drift (Figure 7.2.1), which is simply the effect of chance. Genetic drift is most important in small populations. Drift would be completely absent in a population with infinite individuals, but, of course, no population is this large. Genetic drift occurs because the alleles in an offspring generation are a random sample of the alleles in the parent generation. Alleles may or may not make it into the next generation due to chance events including mortality of an individual, events affecting finding a mate, and even the events affecting which gametes end up in fertilizations. If one individual in a population of ten individuals happens to die before it leaves any offspring to the next generation, all of its genes—a tenth of the population's gene pool—will be suddenly lost. In a population of 100, that 1 individual represents only 1 percent of the overall gene pool; therefore, it has much less impact on the population's genetic structure and is unlikely to remove all copies of even a relatively rare allele.

Imagine a population of ten individuals, half with allele *A* and half with allele *a* (the individuals are haploid). In a stable population, the next generation will also have ten individuals. Choose that generation randomly by flipping a coin ten times and let heads be *A* and tails be *a*. It is unlikely that the next generation will have exactly half of each allele. There might be six of one and four of the other, or some different set of frequencies. Thus, the allele frequencies have changed and evolution has occurred. A coin will no longer work to choose the next generation (because the odds are no longer one half for each allele). The frequency in each generation will drift up and down on what is known as a random walk until at one point either all *A* or all *a* are chosen and that allele is fixed from that point on. This could take a very long time for a large population. This simplification is not very biological, but it can be shown that real populations behave this way. The effect of drift on frequencies is greater the smaller a population is. Its effect is also greater on an allele with a frequency far from one half. Drift will influence every allele, even those that are being naturally selected.

ART CONNECTION

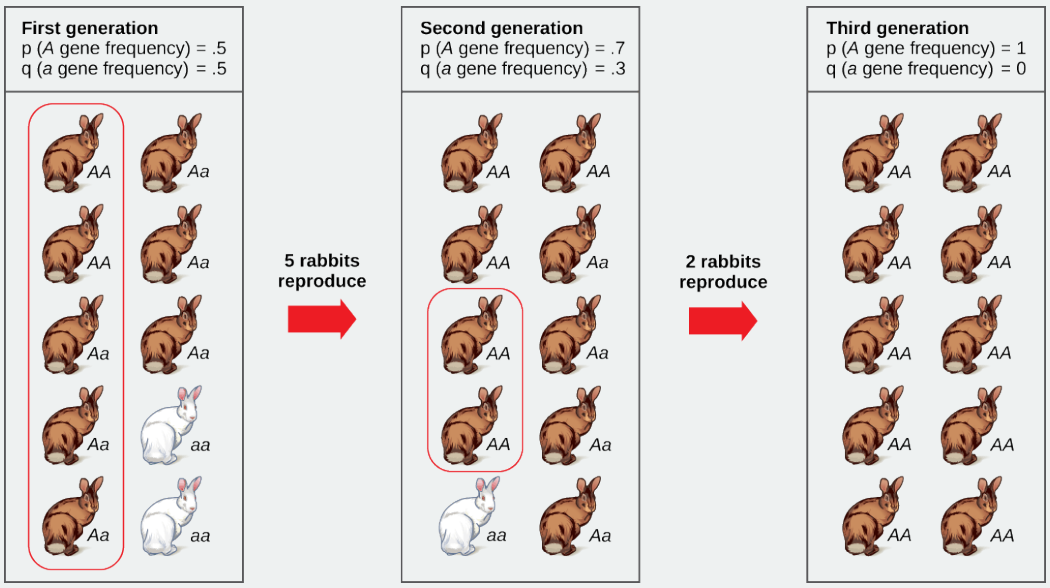


Figure 7.2.1**:** Genetic drift in a population can lead to the elimination of an allele from a population by chance. In each generation, a random set of individuals reproduces to produce the next generation. The frequency of alleles in the next generation is equal to the frequency of alleles among the individuals reproducing.

Do you think genetic drift would happen more quickly on an island or on the mainland?

Genetic drift can also be magnified by natural or human-caused events, such as a disaster that randomly kills a large portion of the population, which is known as the bottleneck effectthat results in a large portion of the genome suddenly being wiped out (Figure 7.2.2). In one fell swoop, the genetic structure of the survivors becomes the genetic structure of the entire population, which may be very different from the pre-disaster population. The disaster must be one that kills for reasons unrelated to the organism's traits, such as a hurricane or lava flow. A mass killing caused by unusually cold temperatures at night, is likely to affect individuals differently depending on the alleles they possess that confer cold hardiness.

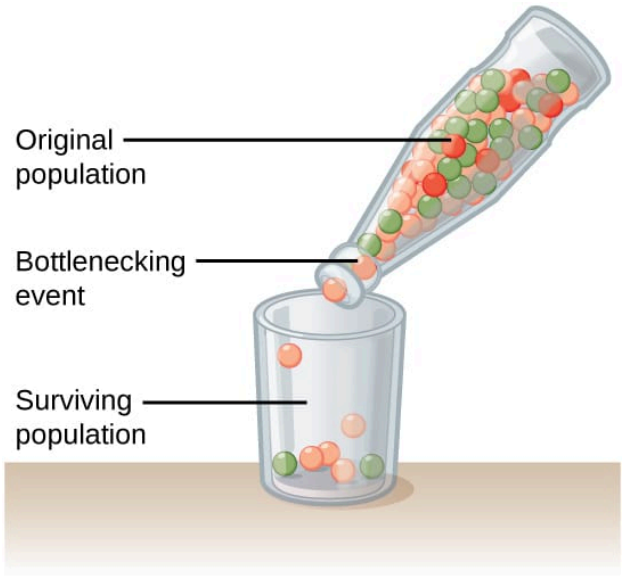


Figure 7.2.2**:** A chance event or catastrophe can reduce the genetic variability within a population.

Another scenario in which populations might experience a strong influence of genetic drift is if some portion of the population leaves to start a new population in a new location, or if a population gets divided by a physical barrier of some kind. In this situation, those individuals are unlikely to be representative of the entire population which results in the founder effect. The

founder effect occurs when the genetic structure matches that of the new population's founding fathers and mothers. The founder effect is believed to have been a key factor in the genetic history of the Afrikaner population of Dutch settlers in South Africa, as evidenced by mutations that are common in Afrikaners but rare in most other populations. This is likely due to a higher-than-normal proportion of the founding colonists, which were a small sample of the original population, carried these mutations. As a result, the population expresses unusually high incidences of Huntington's disease (HD) and Fanconi anemia (FA), a genetic disorder known to cause bone marrow and congenital abnormalities, and even cancer.[1]

CONCEPT IN ACTION

Visit this site to learn more about genetic drift and to run simulations of allele changes caused by drift.

Gene Flow

Another important evolutionary force is gene flow, or the flow of alleles in and out of a population resulting from the migration of individuals or gametes (Figure 7.2.3). While some populations are fairly stable, others experience more flux. Many plants, for example, send their seeds far and wide, by wind or in the guts of animals; these seeds may introduce alleles common in the source population to a new population in which they are rare.

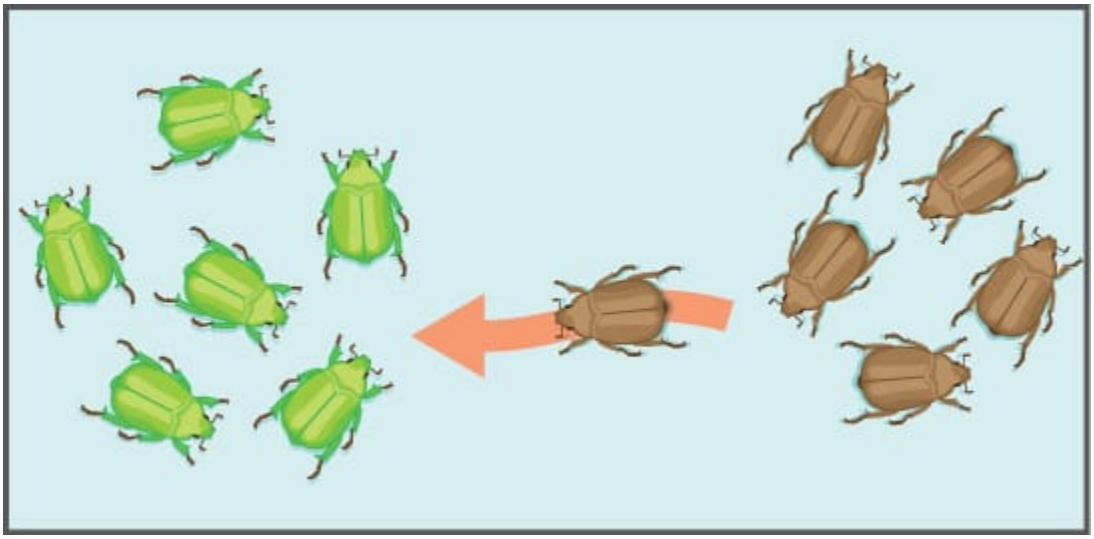


Figure 7.2.3: Gene flow can occur when an individual travels from one geographic location to another and joins a different population of the species. In the example shown here, the brown allele is introduced into the green population.

Summary

There are four factors that can change the allele frequencies of a population. Natural selection works by selecting for alleles that confer beneficial traits or behaviors, while selecting against those for deleterious qualities. Mutations introduce new alleles into a population. Genetic drift stems from the chance occurrence that some individuals have more offspring than others and results in changes in allele frequencies that are random in direction. When individuals leave or join the population, allele frequencies can change as a result of gene flow.

Art Connections

Figure 7.2.1: Do you think genetic drift would happen more quickly on an island or on the mainland?

Answer

Genetic drift is likely to occur more rapidly on an island, where smaller populations are expected to occur.

Footnotes

1. 1 A. J. Tipping et al., “Molecular and Genealogical Evidence for a Founder Effect in Fanconi Anemia Families of the Afrikaner Population of South Africa,” *PNAS* 98, no. 10 (2001): 5734-5739, doi: 10.1073/pnas.091402398.

Glossary

bottleneck effect
: the magnification of genetic drift as a result of natural events or catastrophes

founder effect
: a magnification of genetic drift in a small population that migrates away from a large parent population carrying with it an unrepresentative set of alleles

gene flow
: the flow of alleles in and out of a population due to the migration of individuals or gametes

Contributors and Attributions

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7.3: Evidence of Evolution

The evidence for evolution is compelling and extensive. Looking at every level of organization in living systems, biologists see the signature of past and present evolution. Darwin dedicated a large portion of his book, *On the Origin of Species*, identifying patterns in nature that were consistent with evolution and since Darwin our understanding has become clearer and broader.

Fossils

Fossils provide solid evidence that organisms from the past are not the same as those found today; fossils show a progression of evolution. Scientists determine the age of fossils and categorize them all over the world to determine when the organisms lived relative to each other. The resulting fossil record tells the story of the past, and shows the evolution of form over millions of years (Figure 7.3.1). For example, highly detailed fossil records have been recovered for sequences of species in the evolution of whales and modern horses. The fossil record of horses in North America is especially rich and many contain transition fossils: those showing intermediate anatomy between earlier and later forms. The fossil record extends back to a dog-like ancestor some 55 million years ago that gave rise to the first horse-like species 55 to 42 million years ago in the genus *Eohippus*. The series of fossils tracks the change in anatomy resulting from a gradual drying trend that changed the landscape from a forested one to a prairie. Successive fossils show the evolution of teeth shapes and foot and leg anatomy to a grazing habit, with adaptations for escaping predators, for example in species of *Mesohippus* found from 40 to 30 million years ago. Later species showed gains in size, such as those of *Hipparion*, which existed from about 23 to 2 million years ago. The fossil record shows several adaptive radiations in the horse lineage, which is now much reduced to only one genus, *Equus*, with several species.

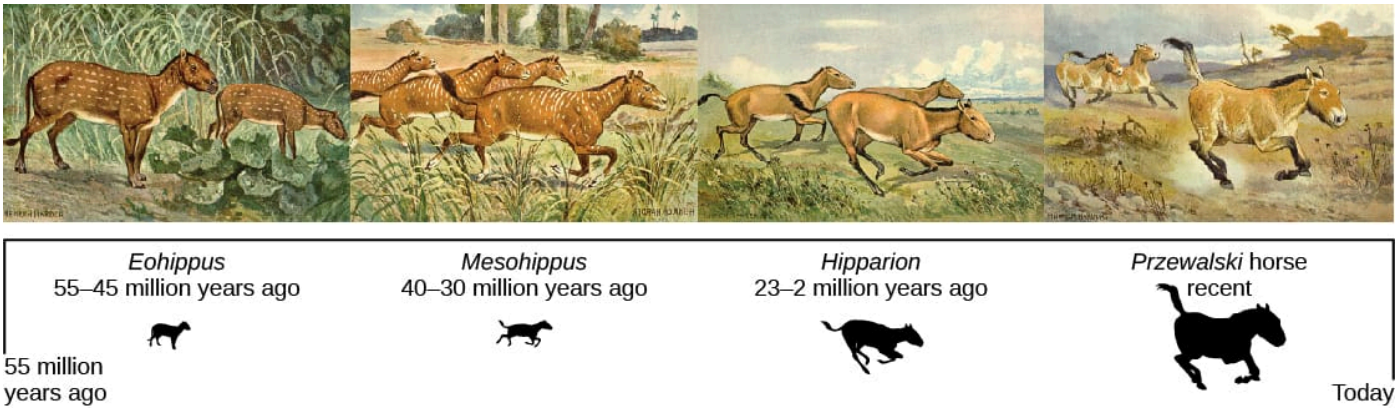


Figure 7.3.1**:** This illustration shows an artist's renderings of these species derived from fossils of the evolutionary history of the horse and its ancestors. The species depicted are only four from a very diverse lineage that contains many branches, dead ends, and adaptive radiations. One of the trends, depicted here is the evolutionary tracking of a drying climate and increase in prairie versus forest habitat reflected in forms that are more adapted to grazing and predator escape through running. Przewalski's horse is one of a few living species of horse.

Anatomy and Embryology

Another type of evidence for evolution is the presence of structures in organisms that share the same basic form. For example, the bones in the appendages of a human, dog, bird, and whale all share the same overall construction (Figure 7.3.2). That similarity results from their origin in the appendages of a common ancestor. Over time, evolution led to changes in the shapes and sizes of these bones in different species, but they have maintained the same overall layout, evidence of descent from a common ancestor. Scientists call these synonymous parts homologous structures. Some structures exist in organisms that have no apparent function at all, and appear to be residual parts from a past ancestor. For example, some snakes have pelvic bones despite having no legs because they descended from reptiles that did have legs. These unused structures without function are called vestigial structures. Other examples of vestigial structures are wings on flightless birds (which may have other functions), leaves on some cacti, traces of pelvic bones in whales, and the sightless eyes of cave animals.

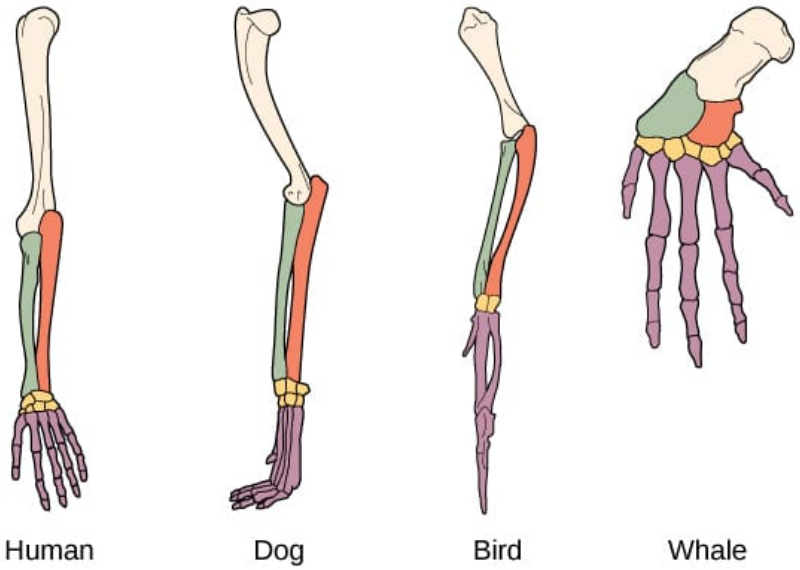


Figure 7.3.2**:** The similar construction of these appendages indicates that these organisms share a common ancestor.

Another evidence of evolution is the convergence of form in organisms that share similar environments. For example, species of unrelated animals, such as the arctic fox and ptarmigan (a bird), living in the arctic region have temporary white coverings during winter to blend with the snow and ice (Figure 7.3.3). The similarity occurs not because of common ancestry, indeed one covering is of fur and the other of feathers, but because of similar selection pressures—the benefits of not being seen by predators.



Figure 7.3.3**:** The white winter coat of (a) the arctic fox and (b) the ptarmigan's plumage are adaptations to their environments. (credit a: modification of work by Keith Morehouse)

Embryology, the study of the development of the anatomy of an organism to its adult form also provides evidence of relatedness between now widely divergent groups of organisms. Structures that are absent in some groups often appear in their embryonic forms and disappear by the time the adult or juvenile form is reached. For example, all vertebrate embryos, including humans, exhibit gill slits at some point in their early development. These disappear in the adults of terrestrial groups, but are maintained in adult forms of aquatic groups such as fish and some amphibians. Great ape embryos, including humans, have a tail structure during their development that is lost by the time of birth. The reason embryos of unrelated species are often similar is that mutational changes that affect the organism during embryonic development can cause amplified differences in the adult, even while the embryonic similarities are preserved.

Biogeography

The geographic distribution of organisms on the planet follows patterns that are best explained by evolution in conjunction with the movement of tectonic plates over geological time. Broad groups that evolved before the breakup of the supercontinent Pangaea (about 200 million years ago) are distributed worldwide. Groups that evolved since the breakup appear uniquely in regions of the planet, for example the unique flora and fauna of northern continents that formed from the supercontinent Laurasia and of the southern continents that formed from the supercontinent Gondwana. The presence of Proteaceae in Australia, southern Africa, and South America is best explained by the plant family's presence there prior to the southern supercontinent Gondwana breaking up (Figure 7.3.4).

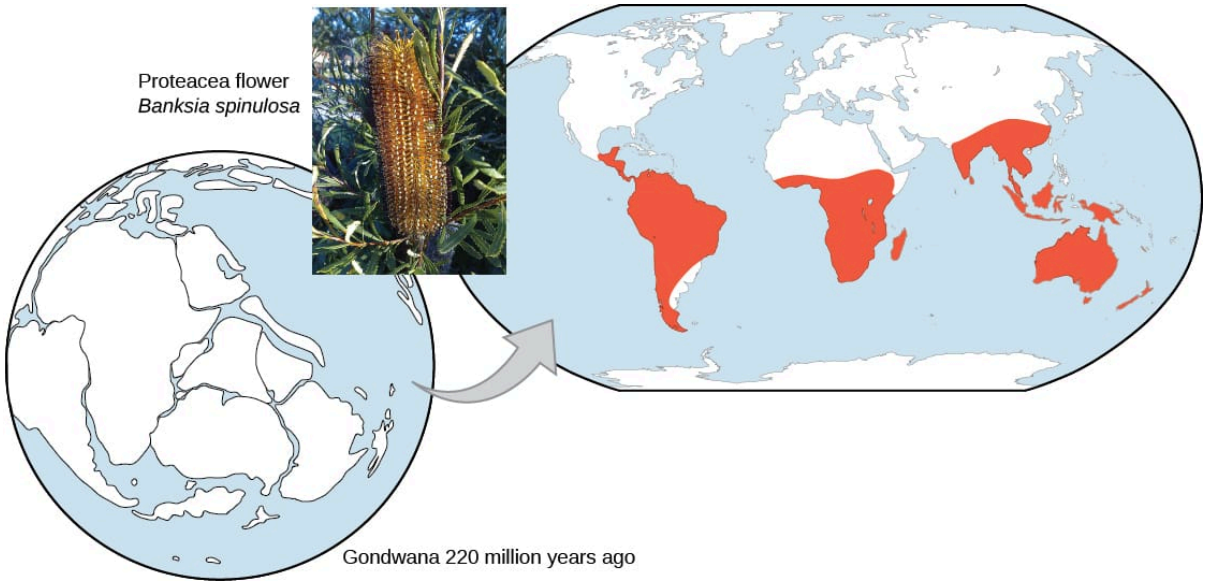


Figure 7.3.4: The Proteacea family of plants evolved before the supercontinent Gondwana broke up. Today, members of this plant family are found throughout the southern hemisphere (shown in red). (credit "Proteacea flower": modification of work by "dorofofoto"/Flickr)

The great diversification of the marsupials in Australia and the absence of other mammals reflects that island continent's long isolation. Australia has an abundance of endemic species—species found nowhere else—which is typical of islands whose isolation by expanses of water prevents migration of species to other regions. Over time, these species diverge evolutionarily into new species that look very different from their ancestors that may exist on the mainland. The marsupials of Australia, the finches on the Galápagos, and many species on the Hawaiian Islands are all found nowhere else but on their island, yet display distant relationships to ancestral species on mainlands.

Molecular Biology

Like anatomical structures, the structures of the molecules of life reflect descent with modification. Evidence of a common ancestor for all of life is reflected in the universality of DNA as the genetic material and of the near universality of the genetic code and the machinery of DNA replication and expression. Fundamental divisions in life between the three domains are reflected in major structural differences in otherwise conservative structures such as the components of ribosomes and the structures of membranes. In general, the relatedness of groups of organisms is reflected in the similarity of their DNA sequences—exactly the pattern that would be expected from descent and diversification from a common ancestor.

DNA sequences have also shed light on some of the mechanisms of evolution. For example, it is clear that the evolution of new functions for proteins commonly occurs after gene duplication events. These duplications are a kind of mutation in which an entire gene is added as an extra copy (or many copies) in the genome. These duplications allow the free modification of one copy by mutation, selection, and drift, while the second copy continues to produce a functional protein. This allows the original function for the protein to be kept, while evolutionary forces tweak the copy until it functions in a new way.

Section Summary

The evidence for evolution is found at all levels of organization in living things and in the extinct species we know about through fossils. Fossils provide evidence for the evolutionary change through now extinct forms that led to modern species. For example, there is a rich fossil record that shows the evolutionary transitions from horse ancestors to modern horses that document intermediate forms and a gradual adaptation to changing ecosystems. The anatomy of species and the embryological development of that anatomy reveal common structures in divergent lineages that have been modified over time by evolution. The geographical distribution of living species reflects the origins of species in particular geographic locations and the history of continental movements. The structures of molecules, like anatomical structures, reflect the relationships of living species and match patterns of similarity expected from descent with modification.

Glossary

vestigial structure
: a physical structure present in an organism but that has no apparent function and appears to be from a functional structure in a distant ancestor

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7.4: Species Concepts

Quantifying species diversity requires developing a definition of a species. We would not expect all members of a species to be identical, so we must consider what magnitude and types of differences between individuals would lead us to consider them members of different species. A **species concept** is, therefore, a working definition of a species and/or a methodology for determining whether or not two organisms are members of the same species. In this section, we will consider three species concepts that are commonly used by scientists. All species concepts have limitations and work better for some organismal groups than others. Each section below considers the definition of the species concept, its assumptions and limitations, and examples of groups for which that species concept does, and does not, easily apply.

The Biological Species Concept

By far the most well-known species concept is the biological species concept, which was proposed by evolutionary biologist Ernst Mayr. The **biological species concept** states that a species is a group of actually or potentially interbreeding natural populations which are reproductively isolated from other such groups. **Reproductive isolation** can occur in several ways; individuals of different groups may not mate with each other, their mating may not produce offspring, or the offspring produced may not be viable (able to survive) or fertile (able to reproduce).

In some cases, the biological species concept is straightforward and easy to apply. For instance, the western meadowlark (*Sturnella neglecta*) and the eastern meadowlark (*Sturnella magna*), both shown in Figure 7.4.1, respectively inhabit the western and eastern halves of North America. Despite the fact that their breeding ranges overlap throughout many upper midwestern states, including Michigan, Wisconsin, Illinois, Iowa, Missouri and Minnesota, the two groups do not interbreed. The courtship songs of the males of each species are distinctly different and females of each species respond to the songs of the males of their own species, leading to strong reproductive isolation between the two groups despite a high degree of similarity in appearance.



Figure 7.4.1: Males of the western meadowlark, Sturnella neglecta (left) and the eastern meadowlark Sturnella magna (right). *Images from Wikimedia Commons*[1,2]

In many cases, however, the biological species concept is difficult or impossible to use. For example, the definition's focus on interbreeding means this concept cannot be applied to asexual organisms, such as bacteria. Additionally, it can only be applied to groups for which detailed reproductive data are available, or at least obtainable. It is therefore impossible to apply the biological species concept to long-extinct species for which reproductive data do not exist and can no longer be obtained. It can also be difficult to apply the biological species concept to groups for which little is known about their reproductive biology or behavior. In these cases, extensive research would be required to determine the degree to which individuals do or do not interbreed with other groups before being able to clearly identify species boundaries. Additionally, some groups have complex patterns of

reproductive connectivity and isolation, such as the *Ensatina* salamander group shown in Figure 7.4.2. Systems like *Ensatina* are termed **ring species** because they form a ring around a particular geographic barrier, in this case, California's Central Valley. As the group spread around the valley, populations maintained reproductive connectivity (*i.e.* interbreeding) with nearby populations, but developed reproductive isolation from geographically distant populations. In the diagram below, interbreeding is shown as a gradation in color between two populations and reproductive isolation is shown as a solid line. For example, *E. oregonensis* (in red) can interbreed with *E. picta* (orange), *E. xanthoptica* (yellow), and *E. platensis* (pink), but none of the other species. Similarly, *E. xanthoptica* (yellow) can interbreed with *E. eschscholtzii* (green) and *E. oregonensis* (red), but none of the other species. In this case, the biological species concept leads to nonsensical and contradictory conclusions: *E. oregonensis*, *E. xanthoptica,* and *E. eschscholtzii* are members of the same species, but *E. oregonensis* and *E. eschscholtzii* are different species.

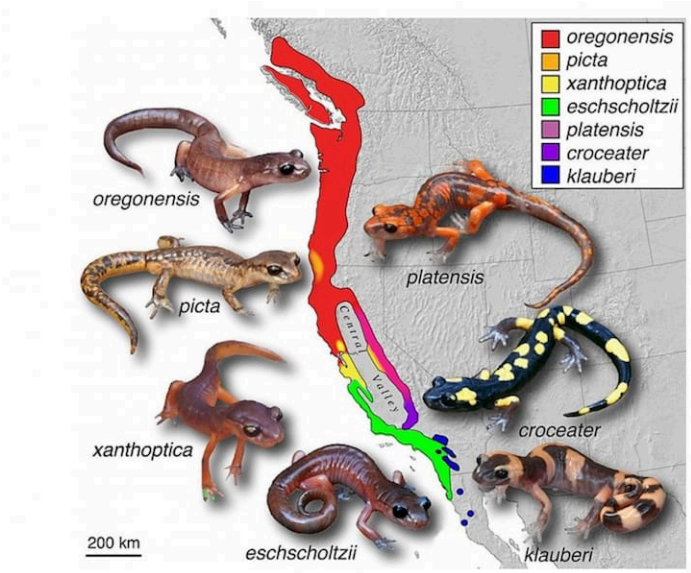


Figure 7.4.2: Range map for *Ensatina* species on the western coast of North America. Gradations in color (ex: *E. oregonensis* and *E. picta*) denote interbreeding between the two species, while solid lines (ex: *E. klauberi* and *E. escholtzii*) denote reproductive isolation. Image from Wikimedia Commons[3].

More philosophically, the biological species concept also considers species at only a single point in time (the present) and ignores the evolutionary and ecological processes that shaped reproductive isolation between groups.

The Lineage Species Concept

Due to the limitations of the biological species concept described above, other species concepts have been developed. The **lineage species concept** defines species as groups of organisms that share a pattern of ancestry and descent and which form a single branch on the tree of life Figure 7.4.3. This concept focuses more on the evolutionary history that has shaped the species as we see it today, and increasingly relies on genetic data to assign individuals to species. The lineage species concept resolves some of the problems of the biological species concept since it can be applied to asexual species and those for which detailed reproductive behavioral data are unavailable. It's reliance on genetic data makes it also difficult to apply to long-extinct species; however, recent advances in genetic analysis have allowed scientists to extract DNA from recently extinct organisms such as Neanderthals and wooly mammoths. Scientists using the lineage species concept must still consider what type and magnitude of genetic differences, and in what portions of the genome, constitute different species and must employ modern computational tools to manage the increasingly large datasets produced in genetic analyses.

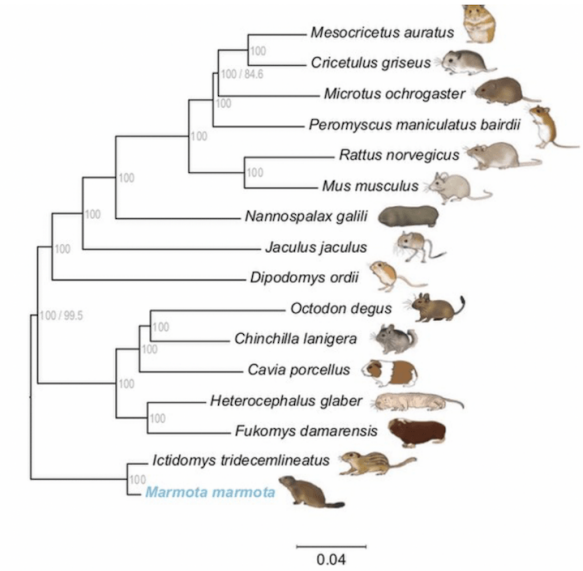


Figure 7.4.3: A phylogenetic tree of the order Rodentia (rodents), representing the lineage species concept's focus on species being identified as unique branches on a phylogenetic tree. Image from Wikimedia Commons[4]

The Morphological Species Concept

How do scientists define species in groups where there is limited or unavailable data on reproductive behavior or genetic similarity? Consider, for example, the two trilobites shown in Figure 7.4.4. Both of the fossils shown in the figure are members of the Order Phacopidae, which went extinct during the end-Devonian mass extinction event that occurred approximately 360 million years ago. Consequently, the only evidence that remains of their existence is fossils; there is no behavioral data on reproductive isolation or connectivity with other trilobites and the fossils are old enough that their DNA has degraded beyond our current analytical capabilities. How then, do we define species in trilobites? The **morphological species concept** is frequently applied in such cases, as it relies entirely on morphology (the physical structures or traits of an organism).

As you look at two photos in Fig 4, you will notice clear morphological differences. The fossil on the right has large spines jutting from both its head and rear ends (in trilobites, these are termed the cephalon and pygidium, respectively). Additionally, the spines along the side of the trilobite's thorax are much larger and more pronounced in the fossil on the right. These morphological differences lead us to categorize these fossils as members of different species. In this case, the differences are large enough that we even categorize these fossils as members of different genera and families.



Figure 7.4.4: Two trilobites in the order Phacopidae; *Hollardops mesocristata* (left) and *Cheirurus ingricus* (right). Images from Wikimedia Commons[5,6].

Since all organisms have physical traits, the morphological species can be used on any group of organisms on Earth. The major limitation to this species concept, however, is that morphology can be very misleading. Consider, for example, the shark and dolphin shown in Figure 7.4.5. These organisms have many morphological similarities in their body shape and coloration; however, we know from genetic analyses and more detailed morphological studies (on internal structures, etc) that sharks are more closely related to rays and other fish and dolphins are more closely related to whales and other mammals. The similarities that we first notice in these organisms are due to the similarities in the marine environment in which both organisms live and not to relatedness between the organisms. Consequently, the morphological species concept is often only used when other species concepts cannot be applied (for example, in the trilobate case) or in conjunction with other species concepts described above.



Figure 7.4.5: A bullshark (*Carcharhinus leucas*, left) and a bottlenose dolphin (*Tursiops truncates*, right). *Images from Wikimedia Commons*[7,8].

Linking Species Concepts

Most scientists generally agree that a species is a group of organisms that share an evolutionary and ecological history and that are distinct from other groups. The primary difference in the species concepts described above is the forms of evidence used to quantify those differences and to categorize individuals as members of a particular species. The biological species concept relies on behavioral data and emphasizes reproductive isolation between groups. The lineage species concept relies on genetic data and emphasizes distinct evolutionary trajectories between groups, which result in distinct lineages (branches on a phylogenetic tree). The morphological species concept relies on morphological data and emphasizes groups of physical traits that are unique to each species. These lines of evidence are not mutually exclusive and so multiple species concepts may be used together to define species boundaries. Regardless of the species concept used, not all organisms are easily categorized into distinct groups and so conversations around species concepts, species boundaries, and the evidence used to define them are a dynamic field of

Naming Species

Carl Linnaeus began formally naming and categorizing species in 1735 in his publication *Systema Naturae*. Linnaeus developed the **binomial nomenclature** system for naming species, which is still used by scientists today. In this system, each species is given a two-word (binomial) Latin name. The first word is the generic name, which is shared among all the species in that genus. The second word is the specific epithet and is unique among species in that genus. For instance, all juniper trees have the genus name *Juniperus* and each species has a specific epithet that identifies which juniper species it is, such as western juniper (*Juniperus occidentalis*) or California juniper (*Juniperus californica*), etc. There are many species that have the genus name *Juniperus*, and many species that have the specific epithet *occidentalis* but only one *Juniperus occidentalis*. As you may have noted in this paragraph, species names are italicized and the genus name is capitalized while the specific epithet is not. The full formal name also includes the last name of the scientist who described the species and the year in which it was named. For example, the common limpets shown in Figure 7.4.6 carry the formal scientific name of *Patella vulgata* Linnaeus, 1758.



Figure 7.4.6: Common limpets, described by Carl Linnaeus in 1758 and named *Patella vulgata*. Image from Wikimedia Commons[8].

Today, scientists have formalized guidelines they follow to choose names for new species. Scientists follow the guidelines of the International Code of Zoological Nomenclature(opens in new window) (ICZN) or the International Code of Nomenclature for Algae, Fungi and Plants(opens in new window) (ICN). These codes have strict rules for Latinizing names and descriptive terms to use in species names and for resolving conflicts in changes to scientific names. As our understanding of life on Earth expands, revisions to previous taxonomic groupings are often made and these guidelines help track changes and keep renaming or regrouping of organisms consistent.

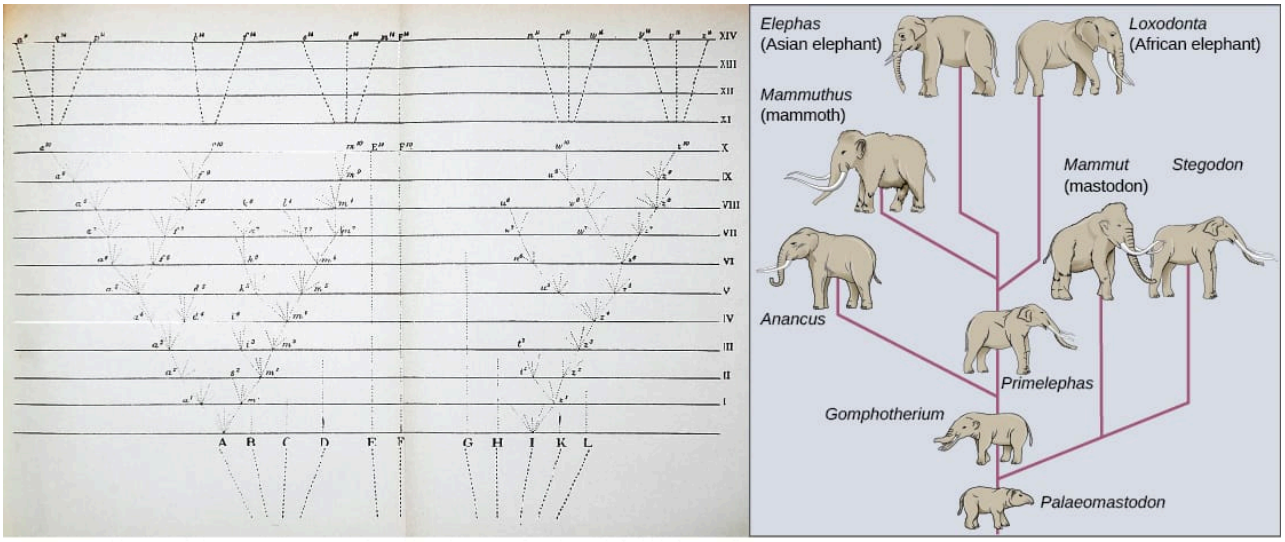
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7.5: Speciation

Given the extraordinary diversity of life on the planet there must be mechanisms for speciation: the formation of two species from one original species. Darwin envisioned this process as a branching event and diagrammed the process in the only illustration found in *On the Origin of Species* (Figure 7.5.1a). For speciation to occur, two new populations must be formed from one original population, and they must evolve in such a way that it becomes impossible for individuals from the two new populations to interbreed. Biologists have proposed mechanisms by which this could occur that fall into two broad categories. **Allopatric speciation**, meaning speciation in "other homelands," involves a geographic separation of populations from a parent species and subsequent evolution. **Sympatric speciation**, meaning speciation in the "same homeland," involves speciation occurring within a parent species while remaining in one location.

Biologists think of speciation events as the splitting of one ancestral species into two descendant species. There is no reason why there might not be more than two species formed at one time except that it is less likely and such multiple events can also be conceptualized as single splits occurring close in time.



(a) (b)

Figure 7.5.1: The only illustration in Darwin's On the Origin of Species is (a) a diagram showing speciation events leading to biological diversity. The diagram shows similarities to phylogenetic charts that are drawn today to illustrate the relationships of species. (b) Modern elephants evolved from the Palaeomastodon, a species that lived in Egypt 35–50 million years ago.

Speciation through Geographic Separation

A geographically continuous population has a gene pool that is relatively homogeneous. Gene flow, the movement of alleles across the range of the species, is relatively free because individuals can move and then mate with individuals in their new location. Thus, the frequency of an allele at one end of a distribution will be similar to the frequency of the allele at the other end. When populations become geographically discontinuous that free-flow of alleles is prevented. When that separation lasts for a period of time, the two populations are able to evolve along different trajectories. Thus, their allele frequencies at numerous genetic loci gradually become more and more different as new alleles independently arise by mutation in each population. Typically, environmental conditions, such as climate, resources, predators, and competitors, for the two populations will differ causing natural selection to favor divergent adaptations in each group. Different histories of genetic drift, enhanced because the populations are smaller than the parent population, will also lead to divergence.

Given enough time, the genetic and phenotypic divergence between populations will likely affect characters that influence reproduction enough that were individuals of the two populations brought together, mating would be less likely, or if a mating occurred, offspring would be non-viable or infertile. Many types of diverging characters may affect the reproductive isolation (inability to interbreed) of the two populations. These mechanisms of reproductive isolation can be divided into **prezygotic mechanisms** (those that operate before fertilization) and **postzygotic mechanisms** (those that operate after fertilization).

Prezygotic mechanisms include traits that allow the individuals to find each other, such as the timing of mating, sensitivity to pheromones, or choice of mating sites. If individuals are able to encounter each other, character divergence may prevent courtship rituals from leading to a mating either because female preferences have changed or male behaviors have changed. Physiological changes may interfere with successful fertilization if mating is able to occur. Postzygotic mechanisms include genetic incompatibilities that prevent proper development of the offspring, or if the offspring live, they may be unable to produce viable gametes themselves as in the example of the mule, the infertile offspring of a female horse and a male donkey.

If the two isolated populations are brought back together and the hybrid offspring that formed from matings between individuals of the two populations have lower survivorship or reduced fertility, then selection will favor individuals that are able to discriminate between potential mates of their own population and the other population. This selection will enhance the reproductive isolation.

Isolation of populations leading to allopatric speciation can occur in a variety of ways: from a river forming a new branch, erosion forming a new valley, or a group of organisms traveling to a new location without the ability to return, such as seeds floating over the ocean to an island. The nature of the geographic separation necessary to isolate populations depends entirely on the biology of the organism and its potential for dispersal. If two flying insect populations took up residence in separate nearby valleys, chances are that individuals from each population would fly back and forth, continuing gene flow. However, if two rodent populations became divided by the formation of a new lake, continued gene flow would be unlikely; therefore, speciation would be more likely.

Biologists group allopatric processes into two categories. If a few members of a species move to a new geographical area, this is called **dispersal**. If a natural situation arises to physically divide organisms, this is called **vicariance**.

Scientists have documented numerous cases of allopatric speciation taking place. For example, along the west coast of the United States, two separate subspecies of spotted owls exist. The northern spotted owl has genetic and phenotypic differences from its close relative, the Mexican spotted owl, which lives in the south (Figure 7.5.2). The cause of their initial separation is not clear, but it may have been caused by the glaciers of the ice age dividing an initial population into two.[1]

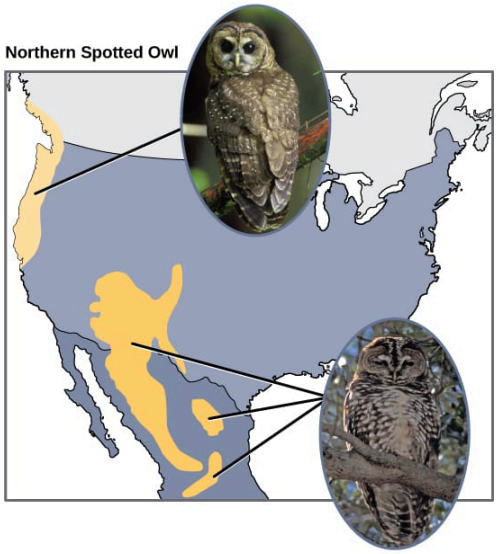


Figure 7.5.2: The northern spotted owl and the Mexican spotted owl inhabit geographically separate locations with different climates and ecosystems. The two owls are similar in appearance but with slightly different coloration. The owl is an example of incipient speciation. (credit "northern spotted owl": modification of work by John and Karen Hollingsworth, USFWS; credit "Mexican spotted owl": modification of work by Bill Radke, USFWS).

Additionally, scientists have found that the further the distance between two groups that once were the same species, the more likely for speciation to take place. This seems logical because as the distance increases, the various environmental factors would likely have less in common than locations in close proximity. Consider the two owls; in the north, the climate is cooler than in the south; the other types of organisms in each ecosystem differ, as do their behaviors and habits; also, the hunting habits and prey choices of the owls in the south vary from the northern ones. These variances can lead to evolved differences in the owls, and over time speciation will likely occur unless gene flow between the populations is restored.

In some cases, a population of one species disperses throughout an area, and each finds a distinct niche or isolated habitat.

Over time, the varied demands of their new lifestyles lead to multiple speciation events originating from a single species, which is called **adaptive radiation**. From one point of origin, many adaptations evolve causing the species to radiate into several new ones. Island archipelagos like the Hawaiian Islands provide an ideal context for adaptive radiation events because water surrounds each island, which leads to geographical isolation for many organisms (Figure 7.5.3). The Hawaiian honeycreeper illustrates one example of adaptive radiation. From a single species, called the founder species, numerous species have evolved, including the eight shown in Figure 7.5.3.

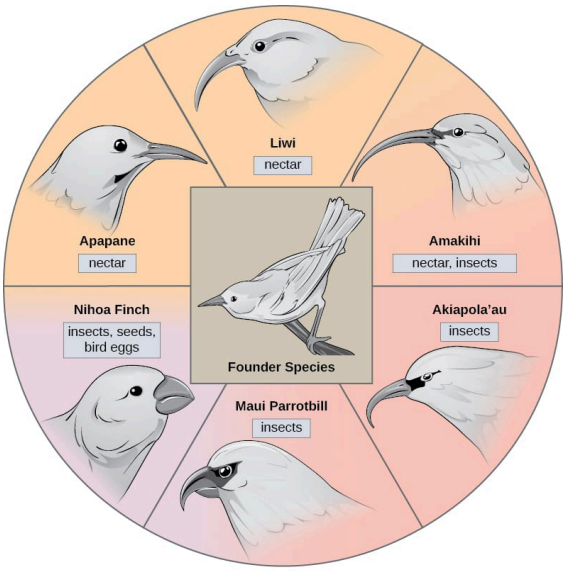


Figure 7.5.3: The honeycreeper birds illustrate adaptive radiation. From one original species of bird, multiple others evolved, each with its own distinctive characteristics.The illustration shows a wheel, with the founder species that gave rise to various honeycreeper birds at the hub. Between spokes of the wheel are six modern honeycreeper species. Five of these, the 'Apapane, Liwi, 'Amakihi, 'Akiapola'au and Maui Parrotbill, eat insects and/or nectar and have long, think beaks. The sixth bird, the Nihoa Finch, eats insects, seeds, and bird eggs, and has a short, fat beak.

Notice the differences in the species' beaks in Figure 7.5.3. Change in the genetic variation for beaks in response to natural selection based on specific food sources in each new habitat led to evolution of a different beak suited to the specific food source. The fruit and seed-eating birds have thicker, stronger beaks which are suited to break hard nuts. The nectar-eating birds have long beaks to dip into flowers to reach their nectar. The insect-eating birds have beaks like swords, appropriate for stabbing and impaling insects. Darwin's finches are another well-studied example of adaptive radiation in an archipelago.

Speciation without Geographic Separation

Can divergence occur if no physical barriers are in place to separate individuals who continue to live and reproduce in the same habitat? A number of mechanisms for sympatric speciation have been proposed and studied.

One form of sympatric speciation can begin with a chromosomal error during meiosis or the formation of a hybrid individual with too many chromosomes. **Polyploidy** is a condition in which a cell, or organism, has an extra set, or sets, of chromosomes. Scientists have identified two main types of polyploidy that can lead to reproductive isolation of an individual in the polyploid state. In some cases a polyploid individual will have two or more complete sets of chromosomes from its own species in a condition called **autopolyploidy** (Figure 7.5.4). The prefix "auto" means self, so the term means multiple chromosomes from one's own species. Polyploidy results from an error in meiosis in which all of the chromosomes move into one cell instead of separating.

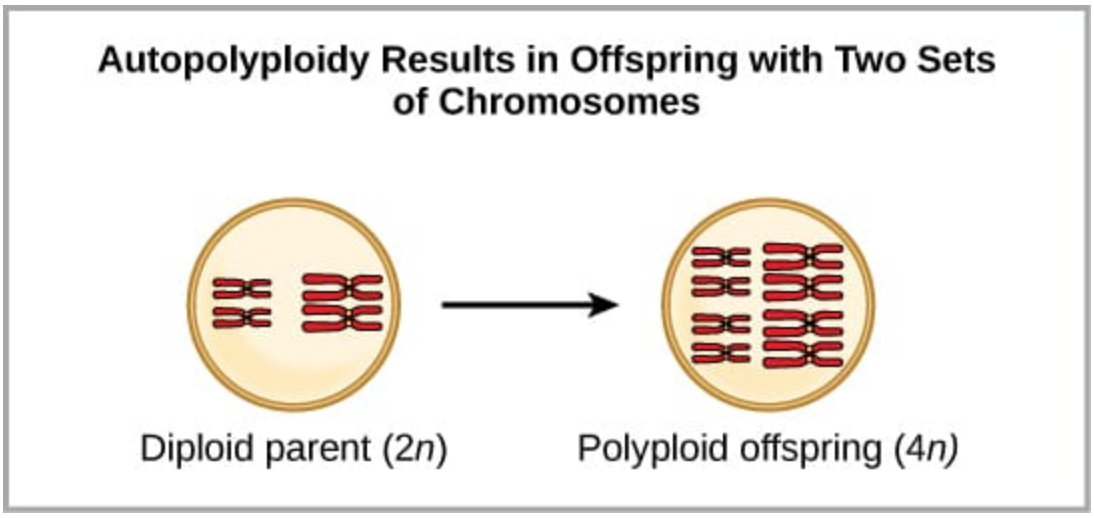


Figure 7.5.4: Autopolyploidy results when mitosis is not followed by cytokinesis. Autopolyploidy results in offspring with two sets of chromosomes. In the example shown, a diploid parent (2n) produces polyploid offspring (4n).

For example, if a plant species with $2n = 6$ produces autopolyploid gametes that are also diploid ($2n = 6$, when they should be $n = 3$), the gametes now have twice as many chromosomes as they should have. These new gametes will be incompatible with the normal gametes produced by this plant species. But they could either self-pollinate or reproduce with other autopolyploid plants with gametes having the same diploid number. In this way, sympatric speciation can occur quickly by forming offspring with $4n$ called a tetraploid. These individuals would immediately be able to reproduce only with those of this new kind and not those of the ancestral species. The other form of polyploidy occurs when individuals of two different species reproduce to form a viable offspring called an allopolyploid. The prefix “allo” means “other” (recall from allopatric); therefore, an allopolyploid occurs when gametes from two different species combine. Figure 7.5.5 illustrates one possible way an allopolyploidy can form. Notice how it takes two generations, or two reproductive acts, before the viable fertile hybrid results.

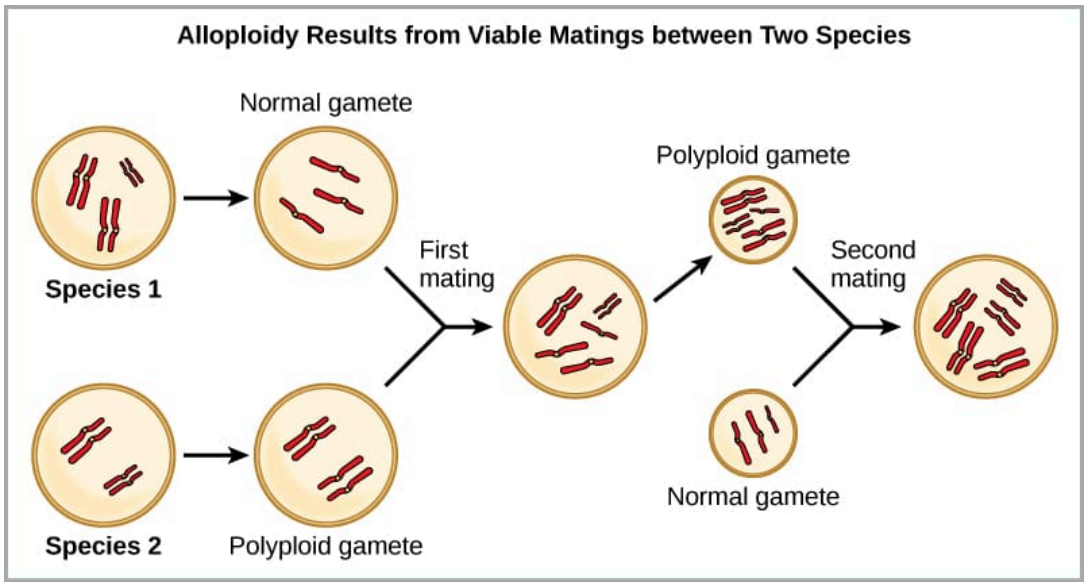
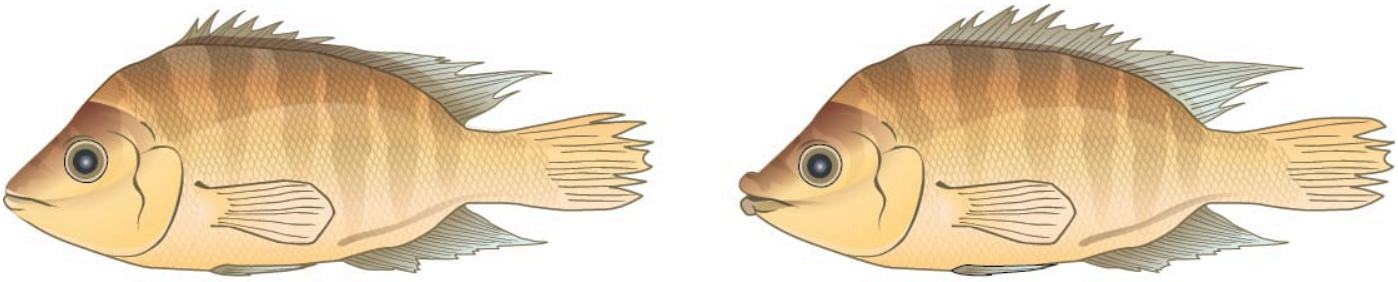


Figure 7.5.5: Alloploidy results when two species with different numbers of chromosomes mate to produce viable offspring. In the example shown, a normal gamete from one species fuses with a polyploid gamete from another. Two matings are necessary to produce viable offspring. Species one has three sets of chromosomes, and species two has two sets of chromosomes. When a normal gamete from species one (with three chromosomes) fuses with a polyploid gamete from species two (with two sets of chromosomes), a zygote with seven chromosomes results. An offspring from this mating produces a polyploid gamete, with seven chromosomes. If this polyploid gamete fuses with a normal gamete from species one, which has three chromosomes, the resulting offspring will have five viable sets of chromosomes.

The cultivated forms of wheat, cotton, and tobacco plants are all allopolyploids. Although polyploidy occurs occasionally in animals, most chromosomal abnormalities in animals are lethal; it takes place most commonly in plants. Scientists have discovered more than 1/2 of all plant species studied relate back to a species evolved through polyploidy.

Sympatric speciation may also take place in ways other than polyploidy. For example, imagine a species of fish that lived in a lake. As the population grew, competition for food also grew. Under pressure to find food, suppose that a group of these fish had the genetic flexibility to discover and feed off another resource that was unused by the other fish. What if this new food source was found at a different depth of the lake? Over time, those feeding on the second food source would interact more with each other than the other fish; therefore they would breed together as well. Offspring of these fish would likely behave as their parents and feed and live in the same area, keeping them separate from the original population. If this group of fish continued to remain separate from the first population, eventually sympatric speciation might occur as more genetic differences accumulated between them.

This scenario does play out in nature, as do others that lead to reproductive isolation. One such place is Lake Victoria in Africa, famous for its sympatric speciation of cichlid fish. Researchers have found hundreds of sympatric speciation events in these fish, which have not only happened in great number, but also over a short period of time. Figure 7.5.6 shows this type of speciation among a cichlid fish population in Nicaragua. In this locale, two types of cichlids live in the same geographic location; however, they have come to have different morphologies that allow them to eat various food sources.



Figure

: Cichlid fish from Lake Apoyeque, Nicaragua, show evidence of sympatric speciation. These two species of cichlid fish appear similar except that one has thin lips and one has thick lips. Lake Apoyeque, a crater lake, is 1800 years old, but genetic evidence indicates that the lake was populated only 100 years ago by a single population of cichlid fish. Nevertheless, two populations with distinct morphologies and diets now exist in the lake, and scientists believe these populations may be in an early stage of speciation.

Finally, a well-documented example of ongoing sympatric speciation occurred in the apple maggot fly, *Rhagoletis pomonella,* which arose as an isolated population sometime after the introduction of the apple into North America. The native population of flies fed on hawthorn species and is host-specific: it only infests hawthorn trees. Importantly, it also uses the trees as a location to meet for mating. It is hypothesized that either through mutation or a behavioral mistake, flies jumped hosts and met and mated in apple trees, subsequently laying their eggs in apple fruit. The offspring matured and kept their preference for the apple trees effectively dividing the original population into two new populations separated by host species, not by geography. The host jump took place in the nineteenth century, but there are now measurable differences between the two populations of fly. It seems likely that host specificity of parasites in general is a common cause of sympatric speciation.

Section Summary

Speciation occurs along two main pathways: geographic separation (allopatric speciation) and through mechanisms that occur within a shared habitat (sympatric speciation). Both pathways force reproductive isolation between populations. Sympatric speciation can occur through errors in meiosis that form gametes with extra chromosomes, called polyploidy. Autopolyploidy occurs within a single species, whereas allopolyploidy occurs because of a mating between closely related species. Once the populations are isolated, evolutionary divergence can take place leading to the evolution of reproductive isolating traits that prevent interbreeding should the two populations come together again. The reduced viability of hybrid offspring after a period of isolation is expected to select for stronger inherent isolating mechanisms.

Footnotes

1. 1 Courtney, S.P., et al, “Scientific Evaluation of the Status of the Northern Spotted Owl,” Sustainable Ecosystems Institute (2004), Portland, OR.

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7.6: Common Misconceptions about Evolution

Although the theory of evolution initially generated some controversy, by 20 years after the publication of *On the Origin of Species* it was almost universally accepted by biologists, particularly younger biologists. Nevertheless, the theory of evolution is a difficult concept and misconceptions about how it works abound. In addition, there are those that reject it as an explanation for the diversity of life.

CONCEPT IN ACTION

This website addresses some of the main misconceptions associated with the theory of evolution.

Evolution Is Just a Theory

Critics of the theory of evolution dismiss its importance by purposefully confounding the everyday usage of the word "theory" with the way scientists use the word. In science, a "theory" is understood to be a concept that has been extensively tested and supported over time. We have a theory of the atom, a theory of gravity, and the theory of relativity, each of which describes what scientists understand to be facts about the world. In the same way, the theory of evolution describes facts about the living world. As such, a theory in science has survived significant efforts to discredit it by scientists, who are naturally skeptical. While theories can sometimes be overturned or revised, this does not lessen their weight but simply reflects the constantly evolving state of scientific knowledge. In contrast, a "theory" in common vernacular means a guess or suggested explanation for something. This meaning is more akin to the concept of a "hypothesis" used by scientists, which is a tentative explanation for something that is proposed to either be supported or disproved. When critics of evolution say evolution is "just a theory," they are implying that there is little evidence supporting it and that it is still in the process of being rigorously tested. This is a mischaracterization. If this were the case, geneticist Theodosius Dobzhansky would not have said that "nothing in biology makes sense, except in the light of evolution."[1]

Individuals Evolve

An individual is born with the genes it has—these do not change as the individual ages. Therefore, an individual cannot evolve or adapt through natural selection. Evolution is the change in genetic composition of a population over time, specifically over generations, resulting from differential reproduction of individuals with certain alleles. Individuals do change over their lifetime, but this is called development; it involves changes programmed by the set of genes the individual acquired at birth in coordination with the individual's environment. When thinking about the evolution of a characteristic, it is probably best to think about the change of the average value of the characteristic in the population over time. For example, when natural selection leads to bill-size change in medium ground finches in the Galápagos, this does not mean that individual bills on the finches are changing. If one measures the average bill size among all individuals in the population at one time, and then measures the average bill size in the population several years later after there has been a strong selective pressure, this average value may be different as a result of evolution. Although some individuals may survive from the first time to the second, those individuals will still have the same bill size. However, there may be enough new individuals with different bill sizes to change the average bill size.

Evolution Explains the Origin of Life

It is a common misunderstanding that evolution includes an explanation of life's origins. Conversely, some of the theory's critics complain that it cannot explain the origin of life. The theory does not try to explain the origin of life. The theory of evolution explains how populations change over time and how life diversifies—the origin of species. It does not shed light on the beginnings of life including the origins of the first cells, which is how life is defined. The mechanisms of the origin of life on Earth are a particularly difficult problem because it occurred a very long time ago, over a very long time, and presumably just occurred once. Importantly, biologists believe that the presence of life on Earth precludes the possibility that the events that led to life on Earth can be repeated because the intermediate stages would immediately become food for existing living things. The early stages of life included the formation of organic molecules such as carbohydrates, amino acids, or nucleotides. If these were formed from inorganic precursors today, they would simply be broken down by living things. The early stages of life also probably included

more complex aggregations of molecules into enclosed structures with an internal environment, a boundary layer of some form, and the external environment. Such structures, if they were formed now, would be quickly consumed or broken down by living organisms.

However, once a mechanism of inheritance was in place in the form of a molecule like DNA or RNA, either within a cell or within a pre-cell, these entities would be subject to the principle of natural selection. More effective reproducers would increase in frequency at the expense of inefficient reproducers. So while evolution does not explain the origin of life, it may have something to say about some of the processes operating once pre-living entities acquired certain properties.

Organisms Evolve on Purpose

Statements such as “organisms evolve in response to a change in an environment,” are quite common. There are two easy misunderstandings possible with such a statement. First of all, the statement must not be understood to mean that individual organisms evolve, as was discussed above. The statement is shorthand for “a population evolves in response to a changing environment.” However, a second misunderstanding may arise by interpreting the statement to mean that the evolution is somehow intentional. A changed environment results in some individuals in the population, those with particular phenotypes, benefiting and, therefore, producing proportionately more offspring than other phenotypes. This results in change in the population if the characters are genetically determined.

It is also important to understand that the variation that natural selection works on is already in a population and does not arise in response to an environmental change. For example, applying antibiotics to a population of bacteria will, over time, select for a population of bacteria that are resistant to antibiotics. The resistance, which is caused by a gene, did not arise by mutation because of the application of the antibiotic. The gene for resistance was already present in the gene pool of the bacteria, likely at a low frequency. The antibiotic, which kills the bacterial cells without the resistance gene, strongly selects for individuals that are resistant, since these would be the only ones that survived and divided. Experiments have demonstrated that mutations for antibiotic resistance do not arise as a result of antibiotic application.

In a larger sense, evolution is also not goal directed. Species do not become “better” over time; they simply track their changing environment with adaptations that maximize their reproduction in a particular environment at a particular time. Evolution has no goal of making faster, bigger, more complex, or even smarter species. This kind of language is common in popular literature. Certain organisms, ourselves included, are described as the “pinnacle” of evolution, or “perfected” by evolution. What characteristics evolve in a species are a function of the variation present and the environment, both of which are constantly changing in a non-directional way. What trait is fit in one environment at one time may well be fatal at some point in the future. This holds equally well for a species of insect as it does the human species.

Evolution Is Controversial among Scientists

The theory of evolution was controversial when it was first proposed in 1859, yet within 20 years virtually every working biologist had accepted evolution as the explanation for the diversity of life. The rate of acceptance was extraordinarily rapid, partly because Darwin had amassed an impressive body of evidence. The early controversies involved both scientific arguments against the theory and the arguments of religious leaders. It was the arguments of the biologists that were resolved after a short time, while the arguments of religious leaders have persisted to this day.

The theory of evolution replaced the predominant theory at the time that species had all been specially created within relatively recent history. Despite the prevalence of this theory, it was becoming increasingly clear to naturalists during the nineteenth century that it could no longer explain many observations of geology and the living world. The persuasiveness of the theory of evolution to these naturalists lay in its ability to explain these phenomena, and it continues to hold extraordinary explanatory power to this day. Its continued rejection by some religious leaders results from its replacement of special creation, a tenet of their religious belief. These leaders cannot accept the replacement of special creation by a mechanistic process that excludes the actions of a deity as an explanation for the diversity of life including the origins of the human species. It should be noted, however, that most of the major denominations in the United States have statements supporting the acceptance of evidence for evolution as compatible with their theologies.

The nature of the arguments against evolution by religious leaders has evolved over time. One current argument is that the theory is still controversial among biologists. This claim is simply not true. The number of working scientists who reject the theory of evolution, or question its validity and say so, is small. A Pew Research poll in 2009 found that 97 percent of the 2500 scientists polled believe species evolve.[2] The support for the theory is reflected in signed statements from many scientific societies such as

the American Association for the Advancement of Science, which includes working scientists as members. Many of the scientists that reject or question the theory of evolution are non-biologists, such as engineers, physicians, and chemists. There are no experimental results or research programs that contradict the theory. There are no papers published in peer-reviewed scientific journals that appear to refute the theory. The latter observation might be considered a consequence of suppression of dissent, but it must be remembered that scientists are skeptics and that there is a long history of published reports that challenged scientific orthodoxy in unpopular ways. Examples include the endosymbiotic theory of eukaryotic origins, the theory of group selection, the microbial cause of stomach ulcers, the asteroid-impact theory of the Cretaceous extinction, and the theory of plate tectonics. Research with evidence and ideas with scientific merit are considered by the scientific community. Research that does not meet these standards is rejected.

Other Theories Should Be Taught

A common argument from some religious leaders is that alternative theories to evolution should be taught in public schools. Critics of evolution use this strategy to create uncertainty about the validity of the theory without offering actual evidence. In fact, there are no viable alternative scientific theories to evolution. The last such theory, proposed by Lamarck in the nineteenth century, was replaced by the theory of natural selection. A single exception was a research program in the Soviet Union based on Lamarck's theory during the early twentieth century that set that country's agricultural research back decades. Special creation is not a viable alternative scientific theory because it is not a scientific theory, since it relies on an untestable explanation. Intelligent design, despite the claims of its proponents, is also not a scientific explanation. This is because intelligent design posits the existence of an unknown designer of living organisms and their systems. Whether the designer is unknown or supernatural, it is a cause that cannot be measured; therefore, it is not a scientific explanation. There are two reasons not to teach nonscientific theories. First, these explanations for the diversity of life lack scientific usefulness because they do not, and cannot, give rise to research programs that promote our understanding of the natural world. Experiments cannot test non-material explanations for natural phenomena. For this reason, teaching these explanations as science in public schools is not in the public interest. Second, in the United States, it is illegal to teach them as science because the U.S. Supreme Court and lower courts have ruled that the teaching of religious belief, such as special creation or intelligent design, violates the establishment clause of the First Amendment of the U.S. Constitution, which prohibits government sponsorship of a particular religion.

The theory of evolution and science in general is, by definition, silent on the existence or non-existence of the spiritual world. Science is only able to study and know the material world. Individual biologists have sometimes been vocal atheists, but it is equally true that there are many deeply religious biologists. Nothing in biology precludes the existence of a god, indeed biology as a science has nothing to say about it. The individual biologist is free to reconcile her or his personal and scientific knowledge as they see fit. The Voices for Evolution project (http://ncse.com/voices), developed through the National Center for Science Education, works to gather the diversity of perspectives on evolution to advocate it being taught in public schools.

Section Summary

The theory of evolution is a difficult concept and misconceptions abound. The factual nature of evolution is often challenged by wrongly associating the scientific meaning of a theory with the vernacular meaning. Evolution is sometimes mistakenly interpreted to mean that individuals evolve, when in fact only populations can evolve as their gene frequencies change over time. Evolution is often assumed to explain the origin of life, which it does not speak to. It is often spoken in goal-directed terms by which organisms change through intention, and selection operates on mutations present in a population that have not arisen in response to a particular environmental stress. Evolution is often characterized as being controversial among scientists; however, it is accepted by the vast majority of working scientists. Critics of evolution often argue that alternative theories to evolution should be taught in public schools; however, there are no viable alternative scientific theories to evolution. The alternative religious beliefs should not be taught as science because it cannot be proven, and in the United States it is unconstitutional. Science is silent on the question of the existence of a god while scientists are able to reconcile religious belief and scientific knowledge.

Footnotes

1. 1 Theodosius Dobzhansky. "Biology, Molecular and Organismic." *American Zoologist* 4, no. 4 (1964): 449.
2. 2 Pew Research Center for the People & the Press, *Public Praises Science; Scientists Fault Public, Media* (Washington, DC, 2009), 37.Contributors

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7.7: Organizing Life on Earth

A **phylogeny** is the evolutionary history and the relationships among a species or group of species. The study of organisms with the purpose of deriving their relationships is called **systematics**. A "tree of life" can be constructed to illustrate when different organisms evolved and to show the relationships among different organisms, as shown in Figure 7.7.1. In this Figure you can see that all life on Earth evolved from a common ancestor, which is shown as a single point from which the three domains of Archaea, Bacteria, and Eukarya diverge and then branch repeatedly. The small, distal, branch that plants and animals (including humans) occupy in this diagram shows how recently these groups had their origin compared with other groups. Evolutionary history can be traced from the origin of life to any individual species by navigating through the evolutionary branches between the two points. The further you have to travel on the line connecting two tips, the more distantly related those two taxa are.

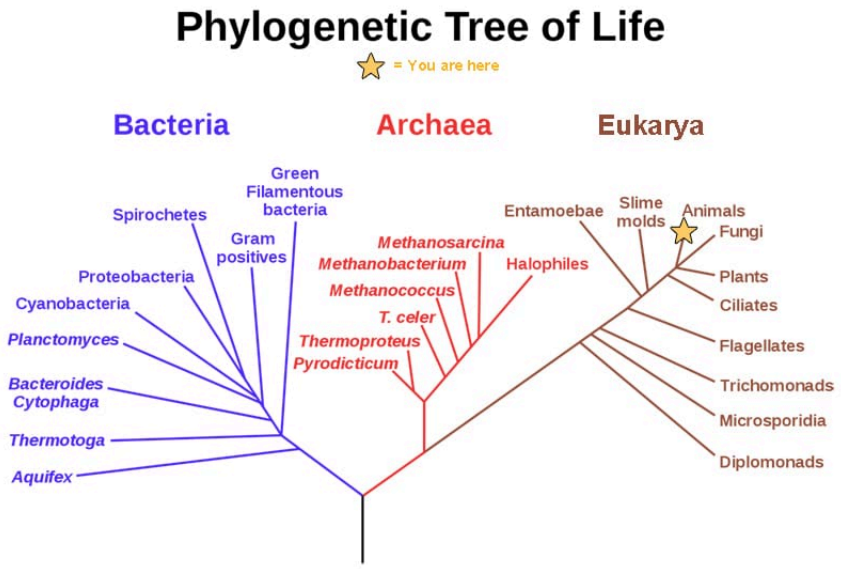


Figure 7.7.1: In the evolution of life on Earth, the three domains of life—Archaea, Bacteria, and Eukarya—branch from a single point - the common ancestor.. (credit: modification of work by Eric Gaba)

Many sub-disciplines within biology contribute to understanding how past and present life evolved over time, and together they contribute to building, updating, and maintaining the "tree of life." Information gathered may include data collected from fossils, from studying morphology, from the structure of body parts, or from molecular structure - such as the sequence of amino acids in proteins or DNA nucleotides. By considering the trees generated by different sets of data, scientists can put together the phylogeny of a species. Phylogenetic trees change as scientists discover new species as well as new character information.

The Levels of Classification

Taxonomy (which literally means "arrangement law") is the science of naming and grouping species to construct an internationally shared classification system. The taxonomic classification system (also called the **Linnaean system** after its inventor, Carl Linnaeus, a Swedish naturalist) uses a hierarchical model. A **hierarchical system** has levels and each group at one of the levels includes groups at the next lowest level, so that at the lowest level each member belongs to a series of nested groups. An analogy is the nested series of directories on the main disk drive of a computer. For example, in the most inclusive grouping, scientists divide organisms into three domains: Bacteria, Archaea, and Eukarya. Within each domain is a second level called a kingdom. Each domain contains several kingdoms. Within kingdoms, the subsequent categories of increasing specificity are: phylum, class, order, family, genus, and species.

As an example, the classification levels for the domestic dog are shown in Figure 7.7.2. The group at each level is called a taxon (plural: taxa). In other words, for the dog, Carnivora is the taxon at the order level, Canidae is the taxon at the family level, and so forth. Organisms also have a common name that people typically use, such as domestic dog, or wolf. Each taxon name is capitalized except for species, and the genus and species names are italicized. Scientists refer to an organism by its genus and species names together, commonly called a scientific name, or Latin name. This two-name system is called binomial

nomenclature. The scientific name of the wolf is therefore *Canis lupus*. Recent study of the DNA of domestic dogs and wolves suggest that the domestic dog is a subspecies of the wolf, not its own species, thus it is given an extra name to indicate its subspecies status, *Canis lupus familiaris*.

Figure 7.7.2 also shows how taxonomic levels move toward specificity. Notice how within the domain we find the dog grouped with the widest diversity of organisms. These include plants and other organisms not pictured, such as fungi and protists. At each sublevel, the organisms become more similar because they are more closely related. Before Darwin's theory of evolution was developed, naturalists sometimes classified organisms using arbitrary similarities, but since the theory of evolution was proposed in the 19th century, biologists work to make the classification system reflect evolutionary relationships. This means that all of the members of a taxon should have a common ancestor and be more closely related to each other than to members of other taxa.

Recent genetic analysis and other advancements have found that some earlier taxonomic classifications do not reflect actual evolutionary relationships, and therefore, changes and updates must be made as new discoveries take place. One dramatic and recent example was the breaking apart of prokaryotic species, which until the 1970s were all classified as bacteria. Their division into Archaea and Bacteria came about after the recognition that their large genetic differences warranted their separation into two of three fundamental branches of life.

ART CONNECTION

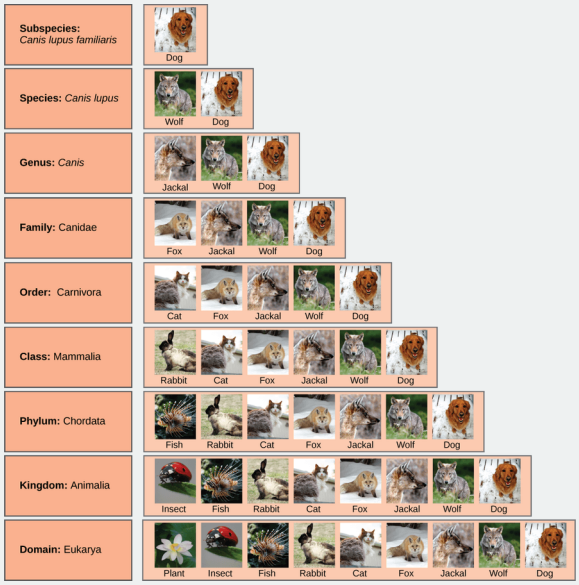


Figure 7.7.2: At each sublevel in the taxonomic classification system, organisms become more similar. Dogs and wolves are the same species because they can breed and produce viable offspring, but they are different enough to be classified as different subspecies. (credit "plant": modification of work by "berduchwal"/Flickr; credit "insect": modification of work by Jon Sullivan; credit "fish": modification of work by Christian Mehlführer; credit "rabbit": modification of work by Aidan Wojtas; credit "cat": modification of work by Jonathan Lidbeck; credit "fox": modification of work by Kevin Bacher, NPS; credit "jackal": modification of work by Thomas A. Hermann, NBII, USGS; credit "wolf" modification of work by Robert Dewar; credit "dog": modification of work by "digital_image_fan"/Flickr)

In what levels are cats and dogs considered to be part of the same group?

CONCEPT IN ACTION



Visit this site to learn more about taxonomy.

Classification and Phylogeny

Scientists use a tool called a phylogenetic tree to show the evolutionary pathways and relationships between organisms. A **phylogenetic tree** is a diagram used to reflect evolutionary relationships among organisms or groups of organisms. The hierarchical classification of groups nested within more inclusive groups is reflected in diagrams. Scientists consider phylogenetic trees to be a hypothesis of the evolutionary past because one cannot go back through time to confirm the proposed relationships.

Unlike with a taxonomic classification, a phylogenetic tree can be read like a map of evolutionary history, as shown in Figure 7.7.3. Shared characteristics are used to construct phylogenetic trees. The point where a split occurs in a tree, called a **node** or branch point, represents where a single lineage evolved into distinct new ones. Many phylogenetic trees have a single branch point at the base representing a common ancestor of all the branches in the tree. Scientists call such trees **rooted**, which means there is a single ancestral taxon at the base of a phylogenetic tree to which all organisms represented in the diagram descend from. When two lineages stem from the same branch point, they are called **sister taxa**, for example the two species of orangutans. A branch point with more than two groups illustrates a situation for which scientists have not definitively determined relationships. An example is illustrated by the three branches leading to the gorilla subspecies; their exact relationships are not yet understood. It is important to note that sister taxa share an ancestor, which does not mean that one taxon evolved from the other. The node represents a common ancestor that existed in the past, but that no longer exists. Humans did not evolve from chimpanzees (nor did chimpanzees evolve from humans) although they are our closest living relatives. Both humans and chimpanzees evolved from a common ancestor that lived, scientists believe, six million years ago and looked different from both modern chimpanzees and modern humans.

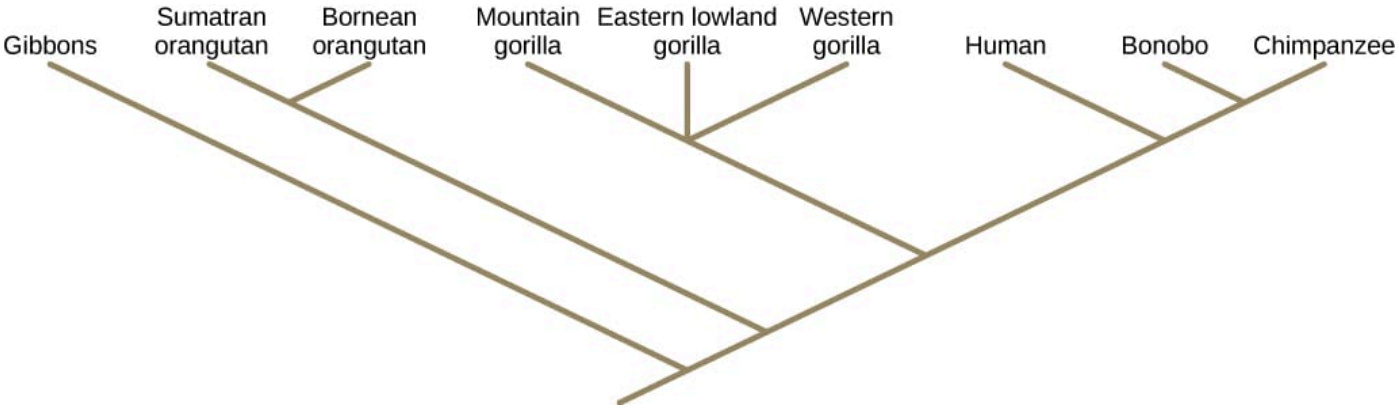


Figure 7.7.3: A phylogenetic tree is rooted and shows how different organisms, in this case the species and subspecies of living apes, evolved from a common ancestor.

The branch points and the branches in phylogenetic tree structure also imply evolutionary change. Sometimes the significant character changes are identified on a branch or branch point. For example, in Figure 7.7.4, the branch point that gives rise to the mammal and reptile lineage from the frog lineage shows the origin of the amniotic egg character. Also the branch point that gives rise to organisms with legs is indicated at the common ancestor of mammals, reptiles, amphibians, and jawed fishes.

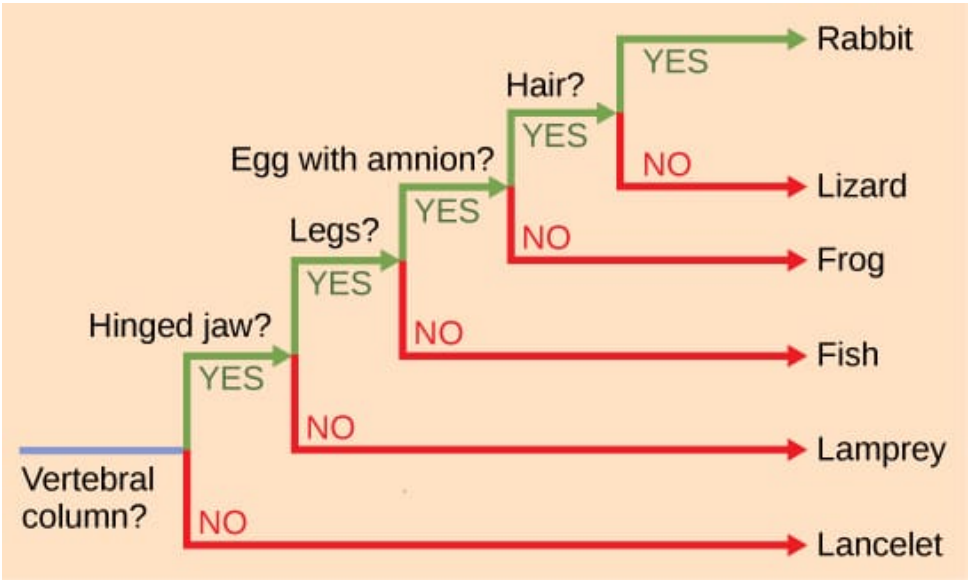


Figure 7.7.4: This phylogenetic tree is rooted by an organism that lacked a vertebral column. At each branch point, organisms with different characters are placed in different groups.

Limitations of Phylogenetic Trees

It is easy to assume that more closely related organisms look more alike, and while this is often the case, it is not always true. If two closely related lineages evolved under significantly different surroundings or after the evolution of a major new adaptation, they may look quite different from each other, even more so than other groups that are not as closely related. For example, the phylogenetic tree in Figure 7.7.4 shows that lizards and rabbits both have amniotic eggs, whereas salamanders (within the frog lineage) do not; yet on the surface, lizards and salamanders appear more similar than the lizards and rabbits.

Another aspect of phylogenetic trees is that, unless otherwise indicated, the branches do not show length of time, they show only the order in time of evolutionary events. In other words, a long branch does not necessarily mean more time passed, nor does a short branch mean less time passed— unless specified on the diagram. For example, in Figure 7.7.4, the tree does not indicate how much time passed between the evolution of amniotic eggs and hair. What the tree does show is the order in which things took place. Again using Figure 7.7.4, the tree shows that the oldest trait is the vertebral column, followed by hinged jaws, and so forth. Remember that any phylogenetic tree is a part of the greater whole, and similar to a real tree, it does not grow in only one direction after a new branch develops. So, for the organisms in Figure 7.7.4, just because a vertebral column evolved does not

mean that invertebrate evolution ceased, it only means that a new branch formed. Also, groups that are not closely related, but evolve under similar conditions, may appear more similar to each other than to a close relative.

Section Summary

Scientists continually obtain new information that helps to understand the evolutionary history of life on Earth. Each group of organisms went through its own evolutionary journey, called its phylogeny. Each organism shares relatedness with others, and based on morphologic and genetic evidence scientists attempt to map the evolutionary pathways of all life on Earth. Historically, organisms were organized into a taxonomic classification system. However, today many scientists build phylogenetic trees to illustrate evolutionary relationships and the taxonomic classification system is expected to reflect evolutionary relationships.

Art Connections

Figure 7.7.2: In what levels are cats and dogs considered to be part of the same group?

Answer

Cats and dogs are part of the same group at five levels: both are in the domain Eukarya, the kingdom Animalia, the phylum Chordata, the class Mammalia, and the order Carnivora.

Contributors

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7.8: Determining Evolutionary Relationships

Scientists collect information that allows them to make evolutionary connections between organisms. Similar to detective work, scientists must use evidence to uncover the facts. In the case of phylogeny, evolutionary investigations focus on two types of evidence: morphologic (form and function) and genetic.

Two Measures of Similarity

Organisms that share similar physical features *and* genetic sequences tend to be more closely related than those that do not. Features that overlap both morphologically and genetically are referred to as **homologous structures**; the similarities stem from common evolutionary paths. For example, as shown in Figure 7.8.1, the bones in the wings of bats and birds, the arms of humans, and the foreleg of a horse are homologous structures. Notice the structure is not simply a single bone, but rather a grouping of several bones arranged in a similar way in each organism even though the elements of the structure may have changed shape and size.



Figure 7.8.1: Bat and bird wings, the foreleg of a horse, the flipper of a whale, and the arm of a human are homologous structures, indicating that bats, birds, horses, whales, and humans share a common evolutionary past. (credit a photo: modification of work by Steve Hillebrand, USFWS; credit b photo: modification of work by U.S. BLM; credit c photo: modification of work by Virendra Kankariya; credit d photo: modification of work by Russian Gov./Wikimedia Commons)

Misleading Appearances

Some organisms may be very closely related, even though a minor genetic change caused a major morphological difference to make them look quite different. For example, chimpanzees and humans, the skulls of which are shown in Figure 7.8.2 are very similar genetically, sharing 99 percent[1] of their genes. However, chimpanzees and humans show considerable anatomical differences, including the degree to which the jaw protrudes in the adult and the relative lengths of our arms and legs.



(a) (b)

Figure 7.8.2: Chimpanzee and human skulls. (a) The chimpanzee has a prominent ridged brow, the eye and nose area is quite flat, and the maxilla and mandible (the jaw) protrude. (b) The human skull is proportionately larger than the chimpanzee, the brow is smooth, the nose and cheekbones are more prominent and the mandible and maxilla protrude only slightly. (credit a: modification of work by "Pastorius"/Wikimedia Commons)

However, unrelated organisms may be distantly related yet appear very much alike, usually because common adaptations to similar environmental conditions evolved in both. An example is the streamlined body shapes, the shapes of fins and appendages, and the shape of the tails in fishes and whales, which are mammals. These structures bear superficial similarity because they are adaptations to moving and maneuvering in the same environment—water. When a characteristic that is similar occurs by adaptive convergence (convergent evolution), and not because of a close evolutionary relationship, it is called an **analogous structure**. In another example, insects use wings to fly like bats and birds. We call them both wings because they perform the same function and have a superficially similar form, but the embryonic origin of the two wings is completely different. The difference in the development, or embryogenesis, of the wings in each case is a signal that insects and bats or birds do not share a common ancestor that had a wing. The wing structures, shown in Figure 7.8.3 evolved independently in the two lineages.

Similar traits can be either homologous or analogous. Homologous traits share an evolutionary path that led to the development of that trait, and analogous traits do not. Scientists must determine which type of similarity a feature exhibits to decipher the phylogeny of the organisms being studied.



(a) Bat wing (b) Bird wing



(c) Insect wing

Figure 7.8.3: The wing of a honey bee is similar in shape to a bird wing and a bat wing and serves the same function (flight). The bird and bat wings are homologous structures. However, the honey bee wing has a different structure (it is made of a chitinous exoskeleton, not a boney endoskeleton) and embryonic origin. The bee and bird or bat wing types illustrate an analogy—similar structures that do not share an evolutionary history. (credit a photo: modification of work by U.S. BLM; credit b: modification of work by Steve Hillebrand, USFWS; credit c: modification of work by Jon Sullivan)

Molecular Comparisons

With the advancement of DNA technology, the area of **molecular systematics**, which describes the use of information on the molecular level including DNA sequencing, has blossomed. New analysis of molecular characters not only confirms many earlier classifications, but also uncovers previously made errors. Molecular characters can include differences in the amino-acid sequence of a protein, differences in the individual nucleotide sequence of a gene, or differences in the arrangements of genes. Phylogenies based on molecular characters assume that the more similar the sequences are in two organisms, the more closely related they are. Different genes change evolutionarily at different rates and this affects the level at which they are useful at identifying relationships. Rapidly evolving sequences are useful for determining the relationships among closely related species. More slowly evolving sequences are useful for determining the relationships between distantly related species. To determine the relationships between very different species such as Eukarya and Archaea, the genes used must be very ancient, slowly evolving genes that are present in both groups, such as the genes for ribosomal RNA. Comparing phylogenetic trees using different sequences and finding them similar helps to build confidence in the inferred relationships.

Sometimes two segments of DNA in distantly related organisms randomly share a high percentage of bases in the same locations, causing these organisms to appear closely related when they are not. For example, the fruit fly shares 60 percent of its DNA with humans.[2] In this situation, computer-based statistical algorithms have been developed to help identify the actual relationships, and ultimately, the coupled use of both morphologic and molecular information is more effective in determining phylogeny.

EVOLUTION IN ACTION: Why Does Phylogeny Matter?

In addition to enhancing our understanding of the evolutionary history of species, our own included, phylogenetic analysis has numerous practical applications. Two of those applications include understanding the evolution and transmission of disease and making decisions about conservation efforts. A 2010 study[3] of MRSA (methicillin-resistant *Staphylococcus aureus*), an antibiotic resistant pathogenic bacterium, traced the origin and spread of the strain throughout the past 40 years. The study uncovered the timing and patterns in which the resistant strain moved from its point of origin in Europe to centers of infection and evolution in South America, Asia, North America, and Australasia. The study suggested that introductions of the bacteria to new populations occurred very few times, perhaps only once, and then spread from that limited number of individuals. This is in contrast to the possibility that many individuals had carried the bacteria from one place to another. This result suggests that public health officials should concentrate on quickly identifying the contacts of individuals infected with a new strain of bacteria to control its spread.

A second area of usefulness for phylogenetic analysis is in conservation. Biologists have argued that it is important to protect species throughout a phylogenetic tree rather than just those from one branch of the tree. Doing this will preserve more of the variation produced by evolution. For example, conservation efforts should focus on a single species without sister species rather than another species that has a cluster of close sister species that recently evolved. If the single evolutionarily distinct species goes extinct a disproportionate amount of variation from the tree will be lost compared to one species in the cluster of closely related species. A study published in 2007[4] made recommendations for conservation of mammal species worldwide based on how evolutionarily distinct and at risk of extinction they are. The study found that their recommendations differed from priorities based on simply the level of extinction threat to the species. The study recommended protecting some threatened and valued large mammals such as the orangutans, the giant and lesser pandas, and the African and Asian elephants. But they also found that some much lesser known species should be protected based on how evolutionary distinct they are. These include a number of rodents, bats, shrews and hedgehogs. In addition there are some critically endangered species that did not rate as very important in evolutionary distinctiveness including species of deer mice and gerbils. While many criteria affect conservation decisions, preserving phylogenetic diversity provides an objective way to protect the full range of diversity generated by evolution.

Building Phylogenetic Trees

How do scientists construct phylogenetic trees? Presently, the most accepted method for constructing phylogenetic trees is a method called **cladistics**. This method sorts organisms into **clades**, groups of organisms that are most closely related to each other and the ancestor from which they descended. For example, in Figure 7.8.4, all of the organisms in the shaded region evolved from a single ancestor that had amniotic eggs. Consequently, all of these organisms also have amniotic eggs and make a single clade, also called a monophyletic group. Clades must be **monophyletic**, wherein they include the ancestral species and all of the descendants from a branch point.

ART CONNECTION

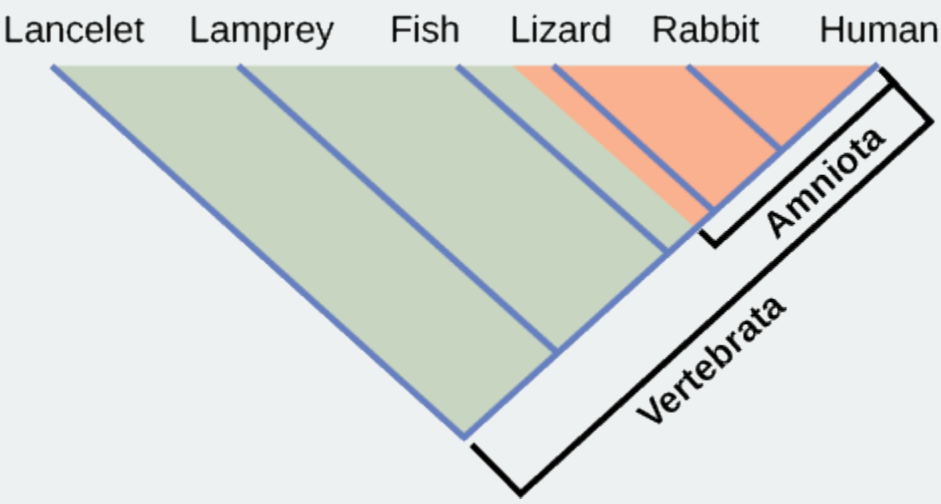


Figure 7.8.4: Lizards, rabbits, and humans all descend from a common ancestor in which the amniotic egg evolved. Thus, lizards, rabbits, and humans all belong to the clade Amniota. Vertebrata is a larger clade that also includes fish and lamprey.

Which animals in this figure belong to a clade that includes animals with hair? Which evolved first: hair or the amniotic egg?

Clades can vary in size depending on which branch point is being referenced. The important factor is that all of the organisms in the clade or monophyletic group stem from a single point on the tree. This can be remembered because monophyletic breaks down into "*mono*," meaning one, and "*phyletic*," meaning evolutionary relationship.

Shared Characteristics

Cladistics rests on three assumptions. The first is that living things are related by descent from a common ancestor, which is a general assumption of evolution. The second is that speciation occurs by splits of one species into two, never more than

two at a time, and essentially at one point in time. This is somewhat controversial, but is acceptable to most biologists as a simplification. The third assumption is that traits change enough over time to be considered to be in a different state. It is also assumed that one can identify the actual direction of change for a state. In other words, we assume that an amniotic egg is a later character state than non-amniotic eggs. This is called the **polarity of the character change**. We know this by reference to a group outside the clade: for example, insects have non-amniotic eggs; therefore, this is the older or ancestral character state. Cladistics compares ingroups and outgroups. An **ingroup** (lizard, rabbit and human in our example) is the group of taxa being analyzed. An **outgroup** (lancelet, lamprey and fish in our example) is a species or group of species that diverged before the lineage containing the group(s) of interest. By comparing ingroup members to each other and to the outgroup members, we can determine which characteristics are evolutionary modifications determining the branch points of the ingroup's phylogeny.

If a characteristic is found in all of the members of a group, it is a shared ancestral character because there has been no change in the trait during the descent of each of the members of the clade. Although these traits appear interesting because they unify the clade, in cladistics they are considered not helpful when we are trying to determine the relationships of the members of the clade because every member is the same. In contrast, consider the amniotic egg characteristic of Figure 7.8.4. Only some of the organisms have this trait, and to those that do, it is called a shared derived character because this trait changed at some point during descent. This character does tell us about the relationships among the members of the clade; it tells us that lizards, rabbits, and humans group more closely together than any of these organisms do with fish, lampreys, and lancelets.

A sometimes confusing aspect of "ancestral" and "derived" characters is that these terms are relative. The same trait could be either ancestral or derived depending on the diagram being used and the organisms being compared. Scientists find these terms useful when distinguishing between clades during the building of phylogenetic trees, but it is important to remember that their meaning depends on context.

Choosing the Right Relationships

Constructing a phylogenetic tree, or cladogram, from the character data is a monumental task that has been greatly aided by the invention of computers and software. Phylogenetic software is able to reconstruct trees such that all of the clades share the same list of derived characters. But there are other decisions to be made, for example, what if a species presence in a clade is supported by all of the shared derived characters for that clade except one? One conclusion is that the trait evolved in the ancestor, but then changed back in that one species. Also a character state that appears in two clades must be assumed to have evolved independently in those clades. These inconsistencies are common in trees drawn from character data and complicate the decision-making process about which tree most closely represents the real relationships among the taxa.

To aid in the tremendous task of choosing the best tree, scientists must use a criterion in which they determine which tree is optimal. One commonly used criterion is called **maximum parsimony**, which means that events occurred in the simplest, most obvious way. This means that the "best" tree is the one with the fewest number of character reversals, the fewest number of independent character changes, and the fewest number of character changes throughout the tree. Computer programs search through all of the possible trees to find the small number of trees with the simplest evolutionary pathways. Starting with all of the homologous traits in a group of organisms, scientists can determine the order of evolutionary events of which those traits occurred that is the most obvious and simple.

CONCEPT IN ACTION



Practice Parsimony: Go to this website to learn how maximum parsimony is used to create phylogenetic trees (be sure to continue to the second page).

These tools and concepts are only a few of the strategies scientists use to tackle the task of revealing the evolutionary history of life on Earth. Recently, newer technologies have uncovered surprising discoveries with unexpected relationships, such as the fact that people seem to be more closely related to fungi than fungi are to plants. Sound unbelievable? As the information about DNA sequences grows, scientists will become closer to mapping the evolutionary history of all life on Earth.

Section Summary

To build phylogenetic trees, scientists must collect character information that allows them to make evolutionary connections between organisms. Using morphologic and molecular data, scientists work to identify homologous characteristics and genes. Similarities between organisms can stem either from shared evolutionary history (homologies) or from separate evolutionary paths (analogies). After homologous information is identified, scientists use cladistics to organize these events as a means to determine an evolutionary timeline. Scientists apply the concept of maximum parsimony, which states that the likeliest order of events is probably the simplest shortest path. For evolutionary events, this would be the path with the least number of major divergences that correlate with the evidence.

Art Connections

Figure 7.8.3: Which animals in this figure belong to a clade that includes animals with hair? Which evolved first: hair or the amniotic egg?

Answer

Rabbits and humans belong in the clade that includes animals with hair. The amniotic egg evolved before hair, because the Amniota clade branches off earlier than the clade that encompasses animals with hair.

Footnotes

1. 1 Gibbons, A. (2012, June 13). *Science Now*. Retrieved from news.sciencemag.org/scienceno...sequenced.html
2. 2 *Background on comparative genomic analysis*. (2002, December).
3. 3 Harris, S.R. et al. 2010. Evolution of MRSA during hospital transmission and intercontinental spread. *Science* 327:469–474.

4. 4 Isaac NJ, Turvey ST, Collen B, Waterman C, Baillie JE (2007) Mammals on the EDGE: Conservation Priorities Based on Threat and Phylogeny. PLoS ONE 2(3): e296. doi:10.1371/journal.pone.0000296

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7.9: Evolution and it's Processes, Diversity (Exercises)

Discovering How Populations Change

Multiple Choice

Which scientific concept did Charles Darwin and Alfred Wallace independently discover?

A. mutation
B. natural selection
C. overbreeding
D. sexual reproduction

Answer

B

Which of the following situations will lead to natural selection?

A. The seeds of two plants land near each other and one grows larger than the other.
B. Two types of fish eat the same kind of food, and one is better able to gather food than the other.
C. Male lions compete for the right to mate with females, with only one possible winner.
D. all of the above

Answer

D

What is the difference between micro- and macroevolution?

A. Microevolution describes the evolution of small organisms, such as insects, while macroevolution describes the evolution of large organisms, like people and elephants.
B. Microevolution describes the evolution of microscopic entities, such as molecules and proteins, while macroevolution describes the evolution of whole organisms.
C. Microevolution describes the evolution of populations, while macroevolution describes the emergence of new species over long periods of time.
D. Microevolution describes the evolution of organisms over their lifetimes, while macroevolution describes the evolution of organisms over multiple generations.

Answer

C

Population genetics is the study of _____.

A. how allele frequencies in a population change over time
B. populations of cells in an individual
C. the rate of population growth
D. how genes affect embryological development

Answer

A

Free Response

If a person scatters a handful of plant seeds from one species in an area, how would natural selection work in this situation?

Answer

The plants that can best use the resources of the area, including competing with other individuals for those resources, will produce more seeds themselves and those traits that allowed them to better use the resources will increase in the population of the next generation.

Explain the Hardy-Weinberg principle of equilibrium.

Answer

The Hardy-Weinberg principle of equilibrium states that a population's allele frequencies are inherently stable. Unless an evolutionary force is acting upon the population, the population would carry the same genes at the same frequencies generation after generation, and individuals would, as a whole, look essentially the same.

Mechanisms of Evolution

Multiple Choice

Galápagos medium ground finches are found on Santa Cruz and San Cristóbal islands, which are separated by about 100 km of ocean. Occasionally, individuals from either island fly to the other island to stay. This can alter the allele frequencies of the population through which of the following mechanisms?

A. natural selection
B. genetic drift
C. gene flow
D. mutation

Answer

C

In which of the following pairs do both evolutionary processes introduce new genetic variation into a population?

A. natural selection and genetic drift
B. mutation and gene flow
C. natural selection and gene flow
D. gene flow and genetic drift

Answer

B

Free Response

Describe natural selection and give an example of natural selection at work in a population.

Answer

The theory of natural selection stems from the observation that some individuals in a population survive longer and have more offspring than others, thus passing on more of their genes to the next generation. For example, a big, powerful male gorilla is much more likely than a smaller, weaker gorilla to become the population's silverback, the pack's leader who mates far more than the other males of the group. The pack leader will, therefore, father more offspring, who share half of his genes, and are thus likely to also grow bigger and stronger like their father.

Over time, the genes for bigger size will increase in frequency in the population, and the population will, as a result, grow larger on average.

Evidence of Evolution

Multiple Choice

The wing of a bird and the arm of a human are examples of _____.

A. vestigial structures
B. molecular structures
C. homologous structures
D. analogous structures

Answer

C

The fact that DNA sequences are more similar in more closely related organisms is evidence of what?

A. optimal design in organisms
B. adaptation
C. mutation
D. descent with modification

Answer

D

Free Response

Why do scientists consider vestigial structures evidence for evolution?

Answer

A vestigial structure is an example of a homologous structure that has apparently been reduced through evolution to a non-functional state because its function is no longer utilized by the species exhibiting it; therefore, any mutations which might reduce its structure are not selected against. The fact that the species has vestiges of the structure rather than no structure at all is evidence that it was present in an ancestor and evolved to non-functionality through accumulation of random mutations.

Speciation

Multiple Choice

Which situation would most likely lead to allopatric speciation?

A. A flood causes the formation of a new lake.
B. A storm causes several large trees to fall down.
C. A mutation causes a new trait to develop.
D. An injury causes an organism to seek out a new food source.

Answer

A

What is the main difference between dispersal and vicariance?

A. One leads to allopatric speciation, whereas the other leads to sympatric speciation.
B. One involves the movement of the organism, whereas the other involves a change in the environment.
C. One depends on a genetic mutation occurring, whereas the other does not.
D. One involves closely related organisms, whereas the other involves only individuals of the same species.

Answer

B

Which variable increases the likelihood of allopatric speciation taking place more quickly?

A. lower rate of mutation
B. longer distance between divided groups
C. increased instances of hybrid formation
D. equivalent numbers of individuals in each population

Answer

B

Free Response

Why do island chains provide ideal conditions for adaptive radiation to occur?

Answer

Organisms of one species can arrive to an island together and then disperse throughout the chain, each settling into different niches, exploiting different food resources and, evolving independently with little gene flow between different islands.

Two species of fish had recently undergone sympatric speciation. The males of each species had a different coloring through which females could identify and choose a partner from her own species. After some time, pollution made the lake so cloudy it was hard for females to distinguish colors. What might take place in this situation?

Answer

It is likely the two species would start to reproduce with each other if hybridization is still possible. Depending on the viability of their offspring, they may fuse back into one species.

Common Misconceptions about Evolution

Multiple Choice

The word “theory” in theory of evolution is best replaced by _____.

A. fact
B. hypothesis
C. idea
D. alternate explanation

Answer

A

Why are alternative scientific theories to evolution not taught in public school?

A. more theories would confuse students
B. there are no viable scientific alternatives
C. it is against the law
D. alternative scientific theories are suppressed by the science establishment

Answer

B

Free Response

How does the scientific meaning of “theory” differ from the common, everyday meaning of the word?

Answer

In science, a theory is a thoroughly tested and verified set of explanations for a body of observations of nature. It is the strongest form of knowledge in science. In contrast, a theory in common usage can mean a guess or speculation about something, meaning that the knowledge implied by the theory may be very weak.

Explain why the statement that a monkey is more evolved than a mouse is incorrect.

Answer

The statement implies that there is a goal to evolution and that the monkey represents greater progress to that goal than the mouse. Both species are likely to be well adapted to their particular environment, which is the outcome of natural selection.

Organizing Life on Earth

Multiple Choice

What is a phylogeny a description of?

A. mutations
B. DNA
C. evolutionary history
D. organisms on Earth

Answer

C

What do scientists in the field of systematics accomplish?

A. discover new fossil sites
B. organize and classify organisms
C. name new species
D. communicate between field biologists

Answer

B

Which statement about the taxonomic classification system is correct?

A. There are more domains than kingdoms.
B. Kingdoms are the top category of classification.
C. A phylum may be represented in more than one kingdom.

D. Species are the most specific category of classification.

Answer

D

Which best describes the relationship between chimpanzees and humans?

A. chimpanzees evolved from humans
B. humans evolved from chimpanzees
C. chimpanzees and humans evolved from a common ancestor
D. chimpanzees and humans belong to the same species

Answer

C

Which best describes a branch point in a phylogenetic tree?

A. a hypothesis
B. new lineage
C. hybridization
D. a mating

Answer

B

Free Response

How does a phylogenetic tree indicate major evolutionary events within a lineage?

Answer

The phylogenetic tree shows the order in which evolutionary events took place and in what order certain characteristics and organisms evolved in relation to others. It does not generally indicate time durations.

List the different levels of the taxonomic classification system.

Answer

Domain, Kingdom, Phylum, Class, Order, Family, Genus, and Species.

Determining Evolutionary Relationships

Multiple Choice

Which statement about analogies is correct?

A. They occur only as errors.
B. They are synonymous with homologous traits.
C. They are derived by response to similar environmental pressures.
D. They are a form of mutation.

Answer

C

What kind of trait is important to cladistics?

A. shared derived traits
B. shared ancestral traits
C. analogous traits
D. parsimonious traits

Answer

A

What is true about organisms that are a part of the same clade?

A. They all share the same basic characteristics.
B. They evolved from a shared ancestor.
C. They all are on the same tree.
D. They have identical phylogenies.

Answer

B

Which assumption of cladistics is stated incorrectly?

A. Living things are related by descent from a common ancestor.
B. Speciation can produce one, two, or three new species.
C. Traits change from one state to another.
D. The polarity of a character state change can be determined.

Answer

B

A monophyletic group is a _____.

A. phylogenetic tree
B. shared derived trait
C. character state
D. clade

Answer

D

Free Response

Dolphins and fish have similar body shapes. Is this feature more likely a homologous or analogous trait?

Answer

Dolphins are mammals and fish are not, which means that their evolutionary paths (phylogenies) are quite separate. Dolphins probably adapted to have a similar body plan after returning to an aquatic lifestyle, and therefore this trait is probably analogous.

Describe maximum parsimony.

Answer

Maximum parsimony hypothesizes that events occurred in the simplest, most obvious way, and the pathway of evolution probably includes the fewest major events that coincide with the evidence at hand.

How does a biologist determine the polarity of a character change?

Answer

The biologist looks at the state of the character in an outgroup, an organism that is outside the clade for which the phylogeny is being developed. The polarity of the character change is from the state of the character in the outgroup to the second state.

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8: CONSERVATION BIOLOGY AND BIODIVERSITY

Conservation biology is the management of nature and of Earth's biodiversity with the aim of protecting species, their habitats, and ecosystems from excessive rates of extinction and the erosion of biotic interactions. It is an interdisciplinary subject drawing on natural and social sciences, and the practice of natural resource management.

8.1: Biodiversity

8.2: The Importance of Biodiversity to Human Life

8.3: Threats to Biodiversity

8.4: Preserving Biodiversity

8.5: Review Questions

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8.1: Biodiversity

Traditionally, ecologists have measured **biodiversity**, a general term for the number of species present in the biosphere, by taking into account both the number of species and their relative abundance to each other. Biodiversity can be estimated at a number of levels of organization of living organisms. These estimation indices, which came from information theory, are most useful as a first step in quantifying biodiversity between and within ecosystems; they are less useful when the main concern among conservation biologists is simply the loss of biodiversity. However, biologists recognize that measuring species diversity may help focus efforts to preserve the biologically or technologically important elements of biodiversity.

The Lake Victoria cichlids provide an example with which we can begin to understand biodiversity. The biologists studying cichlids in the 1980s discovered hundreds of cichlid species representing a variety of specialized habitat types and specific feeding strategies. These included eating plankton floating in the water, scraping/eating algae from rocks, eating insect larvae from the lake bottom, and eating the eggs of other species of cichlid. The cichlids of Lake Victoria are the product of a complex adaptive radiation. An **adaptive radiation** is a rapid (less than three million years in the case of the Lake Victoria cichlids) branching through speciation of a phylogenetic clade into many closely related species. Typically, the species "radiate" into different habitats and niches. The Galápagos Island finches are an example of a modest adaptive radiation with 15 species. The cichlids of Lake Victoria are an example of a spectacular adaptive radiation that formerly included about 500 species.

At the time biologists were making this discovery, some species began to quickly disappear. A culprit in these declines was the Nile perch, a species of large predatory fish that was introduced to Lake Victoria by fisheries to feed the people living around the lake. The Nile perch was introduced in 1963, but its populations did not begin to surge until the 1980s. The perch population grew by consuming cichlids, driving species after species to the point of **extinction** (the disappearance of a species). In fact, there were several factors that played a role in the extinction of perhaps 200 cichlid species in Lake Victoria: the Nile perch, declining lake water quality due to agriculture and land clearing on the shores of Lake Victoria, and increased fishing pressure. Scientists had not even catalogued all of the species present — so many unnamed species were lost. The diversity is now a shadow of what it once was.

The cichlids of Lake Victoria are a thumbnail sketch of contemporary rapid species loss that occurs all over Earth that is caused primarily by human activity. Extinction is a natural process of macroevolution that occurs at the rate of about one out of 1 million species becoming extinct per year. The fossil record reveals that there have been five periods of mass extinction in history with much higher rates of species loss, and the rate of species loss today is comparable to those periods of mass extinction. However, there is a major difference between the previous mass extinctions and the current extinction we are experiencing: human activity. Specifically, three human activities have a major impact: 1) habitat destruction, 2) introduction of exotic species, and 3) over-harvesting. Predictions of species loss within the next century range from 10 percent to 50 percent in a tiny amount of time based on geological timescales. Extinctions on this scale have only happened five other times in the history of the planet, and these extinctions were caused by cataclysmic events that changed the course of the history of life in each instance.

Types of Biodiversity

Scientists generally accept that the term biodiversity describes the number and kinds of species and their abundance in a given location or on the planet. Species can be difficult to define, but most biologists still feel comfortable with the concept and are able to identify and count eukaryotic species in most contexts. Biologists have also identified alternate measures of biodiversity, some of which are important for planning how to preserve biodiversity.

Genetic diversity is one of those alternate concepts. **Genetic diversity**, or genetic variation defines the raw material for evolution and adaptation in a species. A species' future potential for adaptation depends on the genetic diversity held in the genomes of the individuals in populations that make up the species. The same is true for higher taxonomic categories. A genus with very different types of species will have more genetic diversity than a genus with species that are genetically similar and have similar ecologies. If there were a choice between one of these genera of species being preserved, the one with the greatest potential for subsequent evolution is the most genetically diverse one.

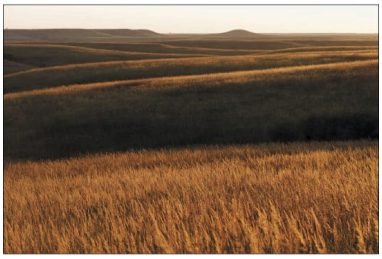
Many genes code for proteins, which in turn carry out the metabolic processes that keep organisms alive and reproducing. Genetic diversity can be measured as **chemical diversity** the wide variety of metabolic compounds, both primary (such as sugars and amino acids) and secondary (such as terpenoids, alkaloids, and phenolics). This chemical diversity has potential benefit for humans as a source of pharmaceuticals, so it provides one way to measure diversity that is important to human health and welfare.

Humans have generated diversity in domestic animals, plants, and fungi, among many other organisms. This diversity is also suffering losses because of migration, market forces, and increasing globalism in agriculture, especially in densely populated regions such as China, India, and Japan. The human population directly depends on this diversity as a stable food source, and its decline is troubling biologists and agricultural scientists.

It is also useful to define **ecosystem diversity**, meaning the number of different ecosystems on the planet or within a given geographic area (Figure 8.1.1). Whole ecosystems can disappear even if some of the species might survive by adapting to other ecosystems. The loss of an ecosystem means the loss of interactions between species, the loss of unique features of coadaptation, 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. 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 elsewhere, but the hugely productive ecosystem that was responsible for creating the most productive agricultural soils in the United States is now gone. As a consequence, native soils are disappearing or must be maintained and enhanced at great expense.



(a)



(b)

Figure 8.1.1: The variety of ecosystems on Earth—from (a) coral reef to (b) prairie—enables a great diversity of species to exist. (credit a: modification of work by Jim Maragos, USFWS; credit b: modification of work by Jim Minnerath, USFWS)

Current Species Diversity

Despite considerable effort, knowledge of the species that inhabit the planet is limited and always will be because of a continuing lack of financial resources and political willpower. A recent estimate suggests that name eukaryotic species (about 1.5 million species) account for less than 20 percent of the total number of eukaryote species present on the planet (approximately 8.7 million species). Estimates of prokaryotic species numbers are largely guesses, but biologists agree that science has only begun to catalog their diversity. Even with what is known, there is no central repository of names or samples of the described species; therefore, there is no way to be sure that the current 1.5 million descriptions is accurate, and instead is a best guess based on the opinions of taxonomic experts. Given that Earth is losing species at an accelerating pace, science is very much in the place it was with the Lake Victoria cichlids, and knowing little about what is being lost. Table 8.1.1 presents recent estimates of biodiversity in different groups.

Table 8.1.1: Estimates of the Numbers of Described and Predicted Species by Taxonomic Group.

Estimates of the Numbers of Described and Predicted Species by Taxonomic Group.

	Mora et al. 2011[1]		Chapman 2009[2]		Groombridge & Jenkins 2002[3]	
	Described	Predicted	Described	Predicted	Described	Predicted
Animalia	1,124,516	9,920,000	1,424,153	6,836,330	1,225,500	10,820,000
Chromista	17,892	34,900	25,044	200,500	—	—

	Mora et al. 2011[1]		Chapman 2009[2]		Groombridge & Jenkins 2002[3]	
Fungi	44,368	616,320	98,998	1,500,000	72,000	1,500,000
Plantae	224,244	314,600	310,129	390,800	270,000	320,000
Protozoa	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 ways, and the internet is facilitating that effort. Nevertheless, it has been pointed out that at the current rate of new species descriptions (which according to the State of Observed Species Report is 17,000 to 20,000 new species per year), it will take close to 500 years to finish describing life on this planet.[4] Over time, the task becomes both increasingly difficult and increasingly easier as extinction removes species from the planet.

Naming and counting species may seem like an unimportant pursuit given the other needs of humanity, but determining biodiversity it is not simply an accounting of species. Describing a species is a complex process through which biologists determine an organism's unique characteristics and whether or not that organism belongs to any other described species or genus. It allows biologists to find and recognize the species after the initial discovery, and allows them to follow up on questions about its biology. In addition, the unique characteristics of each species make it potentially valuable to humans or other species on which humans depend.

Patterns of Biodiversity

Biodiversity is not evenly distributed on Earth. Lake Victoria contained almost 500 species of cichlids alone, ignoring the other fish families present in the lake. All of these species were found only in Lake Victoria; therefore, the 500 species of cichlids were endemic. **Endemic species** are found in only one location. Endemics with highly restricted distributions are particularly vulnerable to extinction. Higher taxonomic levels, such as genera and families, can also be endemic. Lake Michigan contains about 79 species of fish, many of which are found in other lakes in North America. What accounts for the difference in fish diversity in these two lakes? Lake Victoria is an ancient tropical lake, while Lake Michigan is a recently formed temperate lake. Lake Michigan in its present form is only about 7,000 years old, while Lake Victoria in its present form is about 15,000 years old, although its basin is about 400,000 years in age. Biogeographers have suggested that latitude and age are two factors that explain biodiversity patterns on the planet.

One of the oldest observed patterns in ecology is that species biodiversity in almost every taxonomic group increases as latitude declines. In other words, biodiversity increases closer to the equator, as seen in an amphibian species example in Figure 8.1.2.

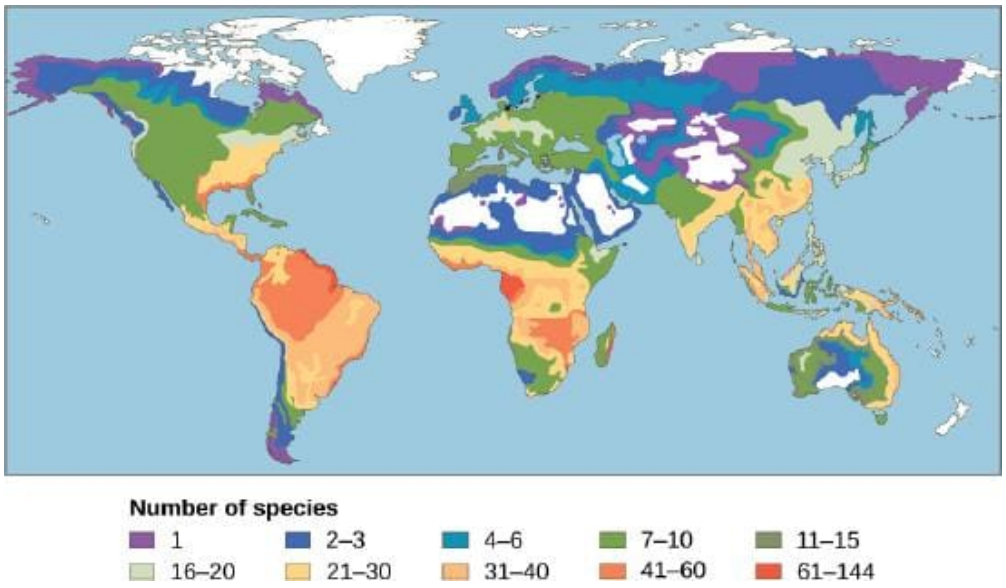


Figure 8.1.2: The number of amphibian species across the globe. Global amphibian species richness demonstrates that biodiversity is highest near the tropics and decreases toward northern and southern latitudes. A similar pattern is observed for most taxonomic groups. The white areas indicate a lack of data in this particular study. (Credit: OpenStax, CC BY 4.0)

It is not yet clear why biodiversity increases closer to the equator, but scientists have several hypotheses. One factor may be the greater age of the ecosystems in the tropics versus those in temperate regions; the temperate regions were largely devoid of life or were drastically reduced during the last glaciation. The idea is that greater age provides more time for speciation. Another possible explanation is the increased direct energy the tropics receive from the sun versus the decreased intensity of the solar energy that temperate and polar regions receive. Tropical ecosystem complexity may promote speciation by increasing the number of ecological niches in the tropics relative to higher latitudes. An **ecological niche** is the specific role and position a species occupies within its ecosystem. The greater heterogeneity in ecological niches provides more opportunities for coevolution, specialization, and perhaps greater selection pressures leading to population differentiation. However, this hypothesis suffers from some circularity — ecosystems with more species encourage speciation, but how did they get more species to begin with?

The tropics have been perceived as being more stable than temperate regions which have a pronounced climate and day-length seasonality. The tropics have their own forms of seasonality, such as rainfall, but they are generally assumed to be more stable environments than temperate. This stability might promote speciation into highly specialized niches. Regardless of the mechanisms, it is certainly true that all levels of biodiversity are greatest in the tropics. Additionally, the rate of endemism is highest in the tropics and there are more biodiversity “hotspots.” However, this richness of diversity also means that knowledge of species is unfortunately very low, and there is a high potential for biodiversity loss with destruction of tropical ecosystems.

Conservation of Biodiversity

In 1988, British environmentalist Norman Myers developed a conservation concept to identify areas rich in species and at significant risk for species loss: biodiversity hotspots. **Biodiversity 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 endemic plant species and 70 percent of the area disturbed by human activity. There are now 34 biodiversity hotspots (Figure 8.1.3) containing large numbers of endemic species, which include half of Earth’s endemic plants.

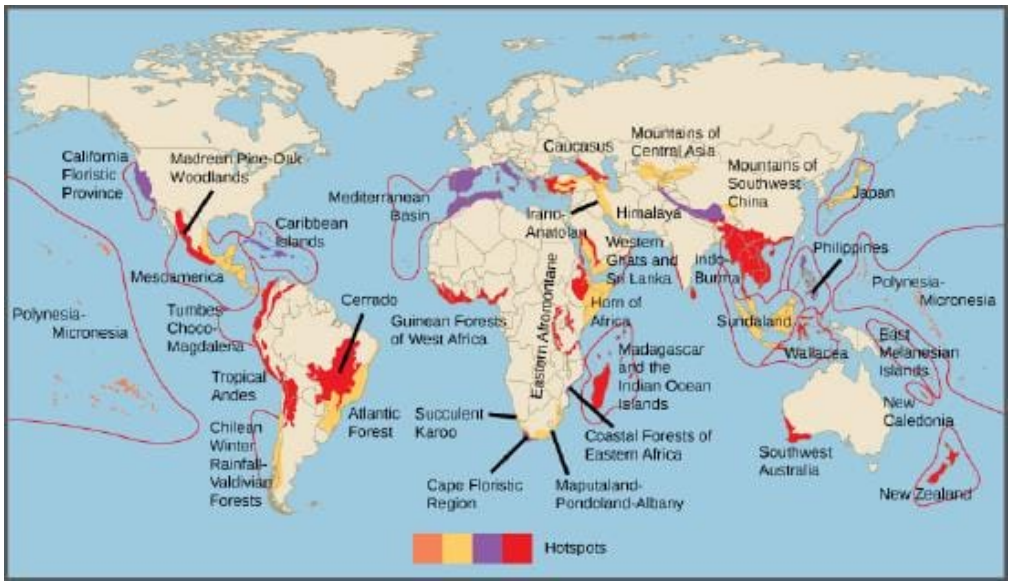


Figure 8.1.3: Conservation International has identified 34 biodiversity hotspots, which cover only 2.3 percent of the Earth's surface but have endemic to them 42 percent of the terrestrial vertebrate species and 50 percent of the world's plants. Most hotspots occur in coastal regions and on islands. Some of the hotspots include New Zealand, Madagascar, Thailand, Vietnam, the west coast of Central America, and southwest Austrailia. Some other areas indicated are the California cost, labeled as the California floristic province, the Mediterranean Basin, and the Carribean islands. (Credit: OpenStax, CC BY 4.0)

Biodiversity Change through Geological 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 continuously ongoing: speciation and extinction. Both are natural "birth" and "death" processes of macroevolution. When speciation rates begin to outstrip extinction rates, the number of species will increase; likewise, the number of species will decrease when extinction rates begin to overtake speciation rates. Throughout Earth's history, these two processes have fluctuated—sometimes leading to dramatic changes in the number of species on Earth as reflected in the fossil record (Figure 8.1.4).

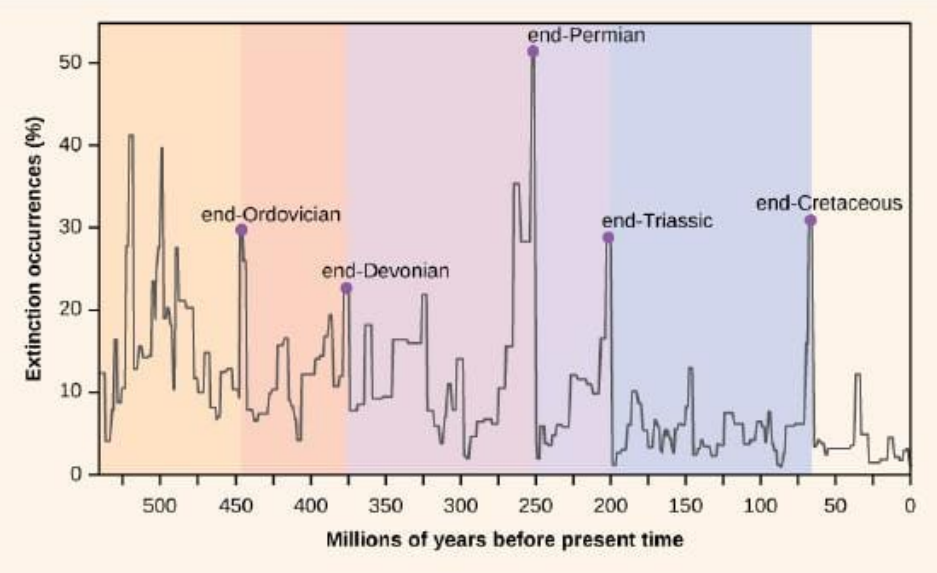


Figure 8.1.4: Biodiversity change through geological time on Earth as based in the fossil record. Percent extinction occurrences versus time in millions of years before present time, starting 550 million years ago. Sudden and dramatic losses of biodiversity, called mass extinctions, have occurred five times. Extinction occurrences increase and decrease in a cyclical manner. At the lowest points on the cycle, extinction occurrences were between 2% and 5% percent. Spikes in the number of extinctions occurred at the end of geological periods: end-Ordovician, 450 million years ago; end-Devonian, 374 million years ago; end-Permian, 252 million years ago; end-Triassic, 200 million years ago; and end-Cretaceous, 65 million years ago. During these spikes, extinction occurrences approximately ranged from 22% to 50%. (Credit: OpenStax, CC BY 4.0)

Paleontologists have identified five strata in the fossil record that appear to show sudden and dramatic (greater than half of all extant species disappearing from the fossil record) losses in biodiversity. These are called mass extinctions. There are many lesser, yet still dramatic, extinction events, but the five mass extinctions have attracted the most research. 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 Phanerozoic (since 542 million years ago). In most cases, the hypothesized causes are still controversial; however, the most recent mass extinction event seems clear.

The Five Mass Extinctions

The fossil record of the mass extinctions was the basis for defining periods of geological history, so they typically occur at the transition point between geological periods. The transition in fossils from one period to another reflects the dramatic loss of species and the gradual origin of new species. These transitions can be seen in the rock strata. Table 8.1.2 provides data on the five mass extinctions.

Table 8.1.2: The five mass extinctions in Earth's history.

The five mass extinctions in Earth's history.

Geological Period	Mass Extinction Name	Time (millions of years ago)
Ordovician–Silurian	end-Ordovician O–S	450–440
Late Devonian	end-Devonian	375–360
Permian–Triassic	end-Permian	251
Triassic–Jurassic	end-Triassic	205
Cretaceous–Paleogene	end-Cretaceous K–Pg (K–T)	65.5

Recent Extinctions

The Pleistocene Extinction

The Pleistocene Extinction is one of the lesser extinctions, and a recent one. It appears to have happened in a relatively restricted time period at the end of the last glaciation period, 10,000 – 12,000 years ago. It is marked by the loss of North American and Eurasian **megafauna** - large vertebrate animals. In North America the losses were quite dramatic and included the woolly mammoths (with an extant population existing until about 4,000 years ago in isolation on Wrangel Island, Canada), mastodon, giant beavers, giant ground sloths, saber-toothed cats, and the North American camel In the early 1900s, scientists first suggested the possibility that over-hunting caused the rapid extinction of these large animals. Research into this hypothesis continues today.

In general, the timing of the Pleistocene Extinction is correlated with the arrival of paleo-humans as long as 40,000 years ago. A competing hypothesis points to climate-change events. The extinctions began in Australia just after the arrival of humans in the area, about 40,000 to 50,000 years ago. This included: a marsupial lion, a giant one-ton wombat, and several giant kangaroo species. In North America, the extinctions of almost all of the large mammals occurred 10,000–12,000 years ago. All that are left are the smaller mammals such as bears, elk, moose, and cougars. Finally, on many remote oceanic islands, the extinctions of many species occurred coincidentally with human arrivals. Not all of the islands had large animals, but when there were large animals, they were often forced into extinction. Madagascar was colonized about 2,000 years ago and the large mammals that lived there subsequently became extinct. Eurasia and Africa do not show this pattern, but they also did not experience a recent arrival of hunter-gatherer humans. Rather, humans arrived in Eurasia hundreds of thousands of years ago. This topic remains an area of active research in building hypotheses and research. It seems clear that even if climate played a role, in most cases human hunting precipitated the extinctions.

The Holocene Extinction

Since the beginning of the Holocene period, approximately 11,700 years ago (9,700 BCE), there have been many extinctions of individual species recorded in human writings. Most of these occurred due to the disruptive activities of modern *Homo sapiens*, and are coincident with the expansion of the European colonies since the 1500's.

One of the earlier and popularly known examples is the dodo bird. The odd pigeon-like bird lived in the forests of Mauritius (an island in the Indian Ocean) and became extinct around 1662. The dodo was hunted for its meat by sailors and was easy prey because it approached people without fear (the dodo had not evolved with humans). Pigs, rats, and dogs brought to the island by European ships also killed dodo young and eggs.

Steller's sea cow became extinct in 1768; it was related to the manatee and probably once lived along the northwest coast of North America. Steller's sea cow was first discovered by Europeans in 1741 and was overhunted for meat and oil. The last sea cow was killed in 1768. That amounts to just 27 years between the sea cow's first contact with Europeans and extinction of the species!

Since 1900, a variety of species have gone extinct, including the following:

- In 1914, the last living passenger pigeon died in a zoo in Cincinnati, Ohio. This species had once darkened the skies of North America during its migrations, but it was overhunted and suffered from habitat loss that resulted from the clearing of forests for farmland.
- The Carolina parakeet, once common in the eastern United States, died out in 1918. It suffered habitat loss and was hunted to prevent it from eating orchard fruit. (The parakeet ate orchard fruit because its native foods were destroyed to make way for farmland.)
- The Japanese sea lion, which inhabited a broad area around Japan and the coast of Korea, became extinct in the 1950s due to fishermen.
- The Caribbean monk seal was distributed throughout the Caribbean Sea but was driven to extinction via hunting by 1952.

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 extinct species of vertebrates after 1500 AD, 86 of which were driven extinct by overhunting or overfishing.

Estimates of Present-Time Extinction Rates

Estimates of extinction rates are hampered by the fact that most extinctions are probably happening without observation. The extinction of a bird or mammal is likely to be noticed by humans, especially if it has been hunted or used in some other way. But there are many organisms that are of less interest to humans (not necessarily of less value) and many that are undescribed.

The background extinction rate is estimated to be about one per million species per year (E/MSY). For example, assuming there are about ten million species in existence, the expectation is that ten species would become extinct each year (each year represents ten million species per year).

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. However, this value may be an underestimate for three reasons. First, many species would not have been described until much later in the time period, so their loss would have gone unnoticed. Second, the number of recently extinct vertebrate species is increasing because extinct species now are being described from skeletal remains. And third, some species are probably already extinct even though conservationists are reluctant to name them as such. Taking these factors into account raises the estimated extinction rate closer to 100 E/MSY. The predicted rate by the end of the century is 1500 E/MSY.

A second approach to estimating present-time extinction rates is to correlate species loss with habitat loss by 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. An example of a species-are curve can be seen in Figure 8.1.5. Island biogeography tudies have shown that the number of species present increases as the size of the island increases. This phenomenon has also been shown to hold true in other island-like habitats as well, such as the mountain-top tepuis of Venezuela, which are surrounded by tropical forest. Turning this relationship around, if the habitat area is reduced, the number of species living there will also decline. Estimates of extinction rates based on habitat loss and species-area relationships have suggested that with about 90 percent habitat loss an expected 50 percent of species would become extinct. Species-area estimates have led to species extinction rate calculations of about 1000 E/MSY and higher. In general, actual observations do not show this amount of loss and suggestions have been made that there is a delay in extinction. Recent work has also called into question the applicability of the species-area relationship when estimating the loss of species. This work argues that the species-area relationship leads to an overestimate of extinction rates. A better relationship to use may be the endemics-area relationship. Using this method would bring estimates down to around 500 E/MSY in the coming century, however it is still important to note that this value is still 500 times the background rate.

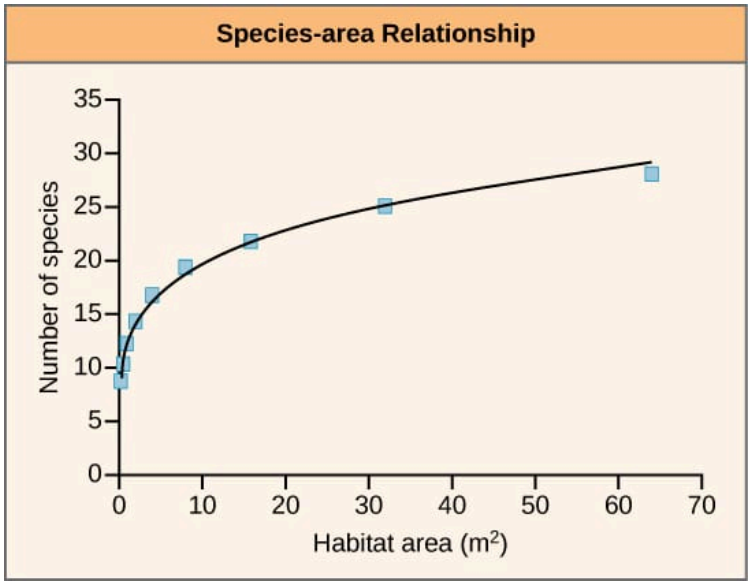


Figure 8.1.5: A species-area relationship curve demonstrates that as the geographic habitat area increases, the total number of unique species increases, and levels off over time. (Credit: Image by OpenStax, CC BY 4.0)

Chapter Summary

Biodiversity exists at multiple levels of organization and is measured in different ways depending on the scientific goals of those taking the measurements. These measurements include numbers of species, genetic diversity, chemical diversity, and ecosystem diversity. The number of described species is estimated to be 1.5 million with about 17,000 new species being described each year. Estimates for the total number of species on Earth vary but are on the order of 10 million. Biodiversity is negatively correlated with latitude for most taxa, meaning that biodiversity is higher in the tropics. The mechanism for this pattern is not known with certainty, but several plausible hypotheses have been advanced.

Five mass extinctions with losses of more than 50 percent of extant species are observable in the fossil record. Biodiversity recovery times after mass extinctions vary, but may be as long as 30 million years. Recent extinctions are recorded in written history and are the basis for one method of estimating contemporary extinction rates. The other method uses measures of habitat loss and species-area relationships. Estimates of contemporary extinction rates vary, but some rates are as high as 500 times the background rate, as determined from the fossil record, and are predicted to rise.

Footnotes

- 1Mora Camilo et al., "How Many Species Are There on Earth and in the Ocean?" *PLoS Biology* (2011), doi:10.1371/journal.pbio.1001127.
- 2Arthur D. Chapman, *Numbers of Living Species in Australia and the World*, 2nd ed. (Canberra, AU: Australian Biological Resources Study, 2009). www.environment.gov.au/system/files/pages/2ee3f4a1-f130-465b-9c7a-79373680a067/files/nlsaw-2nd-complete.pdf/.
- 3Brian Groombridge and Martin D. Jenkins. *World Atlas of Biodiversity: Earth's Living Resources in the 21st Century*. Berkeley: University of California Press, 2002.
- 4International Institute for Species Exploration (IISE), *2011 State of Observed Species (SOS)*. Tempe, AZ: IISE, 2011. Accessed May, 20, 2012.

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8.2: The Importance of Biodiversity to Human Life

It may not be clear why biologists are concerned about biodiversity loss. When biodiversity loss is thought of as the extinction of the passenger pigeon, the dodo bird, and even the woolly mammoth, the loss may appear to be an emotional one. But is the loss practically important for the welfare of the human species? From the perspective of evolution and ecology, the loss of a particular individual species is unimportant (however, we should note that the loss of a keystone species can lead to ecological disaster). Extinction is a normal part of macroevolution. But the *accelerated extinction rate* translates into the loss of tens of thousands of species within our lifetimes, and it is likely to have dramatic effects on human welfare through the collapse of ecosystems and in added costs to maintain food production, clean air and water, and human health.

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 undomesticated living things on the planet. Biologists recognize the human species is embedded in ecosystems and is dependent on them, just as every other species on the planet is dependent. Technology smooths out the extremes of existence, but ultimately the human species cannot exist without a supportive ecosystem.

Human Health

Archeological evidence indicates that humans have been using plants for medicinal uses for thousands of years. A Chinese document from approximately 2800 BC is believed to be the first written account of herbal remedies, and such references occur throughout the global historical record. Contemporary indigenous societies that live close to the land often retain broad knowledge of the medicinal uses of plants growing in their area. Most plants produce secondary plant compounds, which are toxins used to protect the plant from insects and other animals that eat them, but some of which also work as medication.

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 (Figure 8.2.1). Many medicines 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. Antibiotics, which are responsible for extraordinary improvements in health and lifespans in developed countries, are compounds largely derived from fungi and bacteria.



Figure 8.2.1: *Catharanthus roseus*, the Madagascar periwinkle, has various medicinal properties. Among other uses, it is a source of vincristine, a drug used in the treatment of lymphomas. (credit: Forest and Kim Starr)

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 medicines improve people's lives. Pharmaceutical companies are always looking for new compounds synthesized by living organisms that can function as medicines. It is estimated that 1/3 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 derived from natural compounds. The opportunities for new medications will be reduced in direct proportion to the disappearance of species.

Agricultural Diversity

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 potatoes grown in that region belong to seven species and the number of varieties likely is in the thousands. Even the Inca capital of Machu Picchu had numerous gardens growing varieties of potatoes. 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 topography, 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 human-generated 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 also demonstrates risks of low crop diversity. The tragic Irish potato famine occurred when the single variety grown in Ireland became susceptible to a potato blight, wiping out the entire crop. The loss of the potato crop led to mass famine and the related deaths of over one million people, as well as mass emigration of nearly two million people.

Disease resistance is a chief benefit of 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. The ability to create new crop varieties relies on the diversity of varieties available and the accessibility 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 food supply.

Since the 1920s, government agriculture departments have maintained seed banks of crop varieties as a way of maintaining crop diversity. A **seed bank** stores seeds to preserve plant genetic diversity. This system has flaws because over time, seed banks are lost through accidents, and there is no way to replace them. A major global seed bank opened in 2008 on Spitsbergen island in Norway, known as the Svalbard Global Seed Vault (Figure 8.2.2). It 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. 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.



Figure 8.2.2: The Svalbard Global Seed Vault is a storage facility for seeds of Earth's diverse crops. (credit: Mari Tefre, Svalbard Global Seed Vault)

Crop success is largely dependent on the **quality of the soil**. Although some agricultural soils are rendered sterile using controversial cultivation and chemical 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. If farmers had to maintain arable soil using alternate means, the cost of food would be much higher than it is now. 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.

Plant pollination is another key ecosystem service, provided by various species of bees, other insects, and birds. One estimate indicates that honey bee pollination provides the United States a $1.6 billion annual benefit. Honey bee populations in North America have been suffering large losses caused by a syndrome known as colony collapse disorder, whose cause is unclear. (Evidence suggests the possible culprits may be the invasive varroa mite coupled with the *Nosema* gut parasite and acute paralysis virus.) Loss of these species would render it very difficult, if not impossible, to grow any of the 150 United States crops requiring pollination, including grapes, oranges, lemons, peppers, most brassica (broccoli and cauliflower), and many berries, melons, and nuts.

Finally, humans compete for their food with **crop pests**, most of which are insects. Pesticides control these competitors, however they are costly and lose their effectiveness over time as pest populations adapt and evolve. They also lead to collateral damage by killing non-pest species and risking the health of consumers and agricultural workers. 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 found that in 74 percent of studies that looked for an effect of landscape complexity on natural enemies of pests, the greater the complexity, the greater the effect of pest-suppressing organisms. An experimental study found that introducing multiple enemies of pea aphids (an important alfalfa pest) increased the yield of alfalfa significantly. This study shows the importance of landscape diversity via the question of whether a diversity of pests is more effective at control than one single pest; the results showed this to be the case. Loss of diversity in pest enemies will inevitably make it more difficult and costly to grow food.

Wild Food Sources

In addition to growing crops and raising animals for food, humans obtain food resources from wild populations, primarily fish populations. For approximately 1 billion people worldwide, aquatic resources provide the main source of animal protein. Since 1990, global fish production has declined, sometimes dramatically. Unfortunately, and despite considerable effort, few fisheries on the planet are managed for sustainability.

Fishery extinctions rarely lead to complete extinction of the harvested species, but rather to a radical restructuring of the marine ecosystem. This occurs when a dominant species is so over-harvested that it ecologically becomes a minor player. 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 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 as larger species are fished to extinction. The ultimate outcome could clearly be the loss of aquatic systems as food sources.

Psychological and Moral Value

Finally, it has been clearly shown that humans benefit psychologically from living in a biodiverse world. A chief proponent of this idea is Harvard entomologist E. O. Wilson. He argues that human evolutionary history has adapted us to live in a natural environment and that city environments generate psychological stressors that affect human health and well-being. There is considerable research into the psychological regenerative benefits of natural landscapes that suggests the hypothesis may hold some truth. In addition, there is a moral argument that humans have a responsibility to inflict as little harm as possible on other species.

Chapter Summary

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. More medicines will undoubtedly be discovered in nature. Loss of biodiversity will impact the number of pharmaceuticals available to humans.

Crop diversity is a requirement for food security, and it is being lost. The loss of wild relatives to crops also threatens breeders' abilities to create new varieties. 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. Wild food sources are mainly aquatic, but few of these resources are being managed for sustainability. Fisheries' ability to provide protein to human populations is threatened when extinction occurs.

Biodiversity may provide important psychological benefits to humans. Additionally, there are moral arguments for the maintenance of biodiversity.

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8.3: Threats to Biodiversity

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 those resources are being removed unsustainably from the environment. The three greatest proximate 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. A fourth major cause of extinction, anthropogenic (human-caused) climate change, has not yet had a large impact, but it is predicted to become significant during this century. Global climate change is also a consequence of human population needs for energy and the use of fossil fuels to meet those needs (Figure 8.3.1). Environmental issues, such as toxic pollution, have specific targeted effects on species, but are not generally seen as threats at the magnitude of the others.

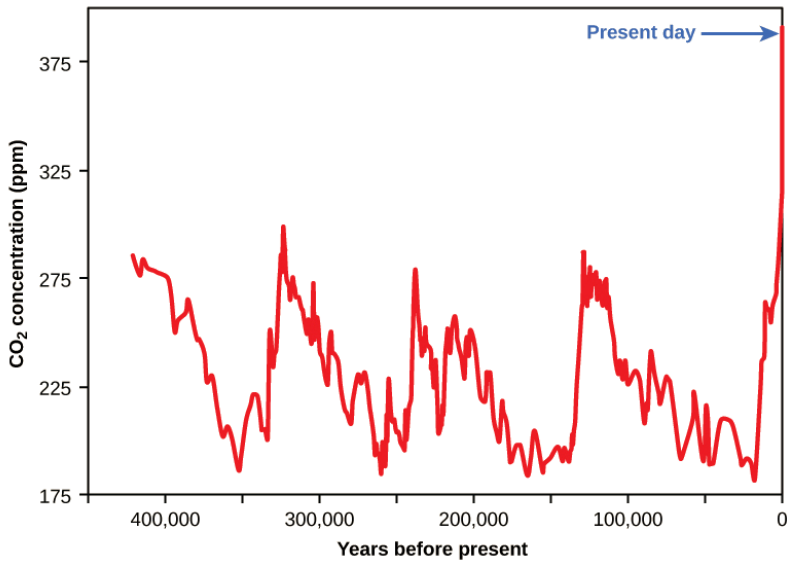


Figure 8.3.1: Atmospheric carbon dioxide concentration in parts per million over time (years before present). Historically, carbon dioxide levels have fluctuated in a cyclical manner, from about 280 parts per million at the peak to about 180 parts per million at the low point. This cycle repeated every one hundred thousand years or so, from about 425,000 years ago until recently. Prior to the industrial revolution, the atmospheric carbon dioxide concentration was at a low point on the cycle. Since then, the carbon dioxide level has rapidly climbed to its current level of 395 parts per million. This carbon dioxide level is far higher than any previously recorded levels. 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 replace certain functions that were once performed by the natural ecosystem. 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 within the range of a species and, unless they are one of the few species that do well in human-built environments, the species will become extinct. Human destruction of habitats (habitats generally refer to the part of the ecosystem required by a particular species) accelerated in the latter half of the twentieth century. Consider the exceptional biodiversity of Sumatra: it is home to one species of orangutan, a species of critically endangered elephant, and the Sumatran tiger, but half of Sumatra’s forest is now gone. The neighboring island of Borneo, home to 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 8.3.2). 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 percent. Much loss (2.4 percent) occurred in the humid tropics where forest loss is primarily from timber extraction. These losses certainly also represent the extinction of species unique to those areas.



Figure 8.3.2: An oil palm plantation in Sabah province Borneo, Malaysia, replaces native forest habitat that a variety of species depended on to live. (credit: Lian Pin Koh)

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 10 percent of the imported timber stream in the United States, which is the world's largest consumer of wood products, is potentially 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; therefore, 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. Certification applies to specific products, not to a producer; some producers' products may not have certification while other products are certified. There are certifications other than the FSC, but these are run by timber companies 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.

Habitat destruction can affect ecosystems other than forests. Rivers and streams are important ecosystems and are frequently the target of habitat modification through building and from damming or water removal. Damming of rivers affects flows and access to all parts of a river. Altering a flow regime can reduce or eliminate populations that are adapted to seasonal changes in flow. For example, an estimated 91 percent of river lengths in the United States have been modified with damming or bank modifications. 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.

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, the biological growth of the resource is less than the potential growth of the profits made from fishing if that time and money were invested elsewhere. In these cases—whales are an example—economic forces will drive toward fishing the population to extinction.

CONCEPT IN ACTION

The U.S. Fish & Wildlife Service report on "Threatened & Endangered Species Active Critical Habitat" of endangered and threatened species in the United States also includes an online mapper.

For the most part, fishery extinction is not equivalent to biological extinction—the last fish of a species is rarely fished out of the ocean. But there are some instances in which true extinction is a possibility. Whales have slow-growing populations and are at risk of complete extinction through hunting. Also, there are some species of sharks with restricted distributions that are at risk of extinction. The groupers are another population of generally slow-growing fishes that, in the Caribbean, includes a number of species that are at risk of extinction from overfishing.

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.

Exotic 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.

CONCEPT IN ACTION

Explore this interactive global database of exotic or invasive species.

Lakes and islands are particularly vulnerable to extinction threats from introduced species. In Lake Victoria, the intentional

introduction of the Nile perch was largely responsible for the extinction of about 200 species of cichlids. The accidental introduction of the brown tree snake via aircraft (Figure 8.3.3) 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 8.3.3: The brown tree snake, Boiga irregularis, is an exotic species that has caused numerous extinctions on the island of Guam since its accidental introduction in 1950. (credit: NPS)

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 ship ballast. The zebra mussels in the Great Lakes have cost the industry 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 of 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*, which causes the disease chytridiomycosis (Figure 8.3.4). 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.



Figure 8.3.4: This Limosa harlequin frog (*Atelopus limosus*), an endangered species from Panama, died from a fungal disease called chytridiomycosis. The red lesions are symptomatic of the disease. (credit: Brian Gratwicke)

Early evidence suggests that another fungal pathogen, *Geomyces destructans*, introduced from Europe is responsible for white-nose syndrome, which infects cave-hibernating bats in eastern North America and has spread from a point of origin in western New York State (Figure 8.3.5). 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.



Figure 8.3.5: 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)

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 hypothesized to continue 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. These gases decrease the degree to which Earth is able to radiate heat energy created by the sunlight that enters the atmosphere. The changes in climate and energy balance

caused by increasing greenhouse gases are complex and our understanding of them depends on predictions generated from detailed computer models. Scientists generally 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. However, there is still debate and a lack of understanding about specific outcomes. Scientists disagree about the likely magnitude of the effects on extinction rates, with estimates ranging from 15 to 40 percent of species committed to extinction by 2050. Scientists do agree 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 with their adapted climate norms, but also to face habitat gaps along the way. 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.

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

Climate gradients will also move up mountains, eventually crowding species higher in altitude and eliminating the habitat for those species adapted to the highest elevations. Some climates will completely disappear. The rate of warming appears to be accelerated in the arctic, which is recognized as a serious threat to polar bear populations that require sea ice to hunt seals during the winter months: seals are the only source of protein available to 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 8.3.6).



Figure 8.3.6: 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.

Summary

The core threats to biodiversity are human population growth and unsustainable resource use. To date, the most significant causes of extinction are habitat loss, introduction of exotic species, and overharvesting. Climate change is predicted to be

a significant cause of extinction in the coming century. Habitat loss occurs through deforestation, damming of rivers, and other activities. Overharvesting is a threat particularly to aquatic species, but the taking of bush meat in the humid tropics threatens many species in Asia, Africa, and the Americas. Exotic species have been the cause of a number of extinctions and are especially damaging to islands and lakes. Exotic species' introductions are increasing because of the increased mobility of human populations and growing global trade and transportation. Climate change is forcing range changes that may lead to extinction. It is also affecting adaptations to the timing of resource availability that negatively affects species in seasonal environments. The impacts of climate change are currently greatest in the arctic. Global warming will also raise sea levels, eliminating some islands and reducing the area of all others.

Contributors and Attributions

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8.4: 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.

Measuring Biodiversity

The technology of molecular genetics and data processing and storage are maturing to the point where cataloguing the planet's species in an accessible way is now feasible. **DNA barcoding** is one molecular genetic method, which takes advantage of rapid evolution in a mitochondrial gene (cytochrome c oxidase 1) present in eukaryotes, except for plants, to identify species using the sequence of portions of the gene. However, plants may be barcoded using a combination of chloroplast genes. Rapid mass sequencing machines make the molecular genetics portion of the work relatively inexpensive and quick. Computer resources store and make available the large volumes of data. Projects are currently underway to use DNA barcoding to catalog museum specimens, which have already been named and studied, as well as testing the method on less-studied groups. As of mid 2017, close to 200,000 named species had been barcoded. Early studies suggest there are significant numbers of undescribed species that looked too much like sibling species to previously be recognized as different. These now can be identified with DNA barcoding.

Numerous computer databases now provide information about named species and a framework for adding new species. However, as already noted, at the present rate of description of new species, it will take close to 500 years before the complete catalog of life is known. Many, perhaps most, species on the planet do not have that much time.

There is also the problem of understanding which species known to science are threatened and to what degree they are threatened. This task is carried out by the non-profit **IUCN** which, as previously mentioned, maintains the Red List—an online listing of endangered species categorized by taxonomy, type of threat, and other criteria (Figure 8.4.1). The Red List is supported by scientific research. In 2011, the list contained 61,000 species, all with supporting documentation.

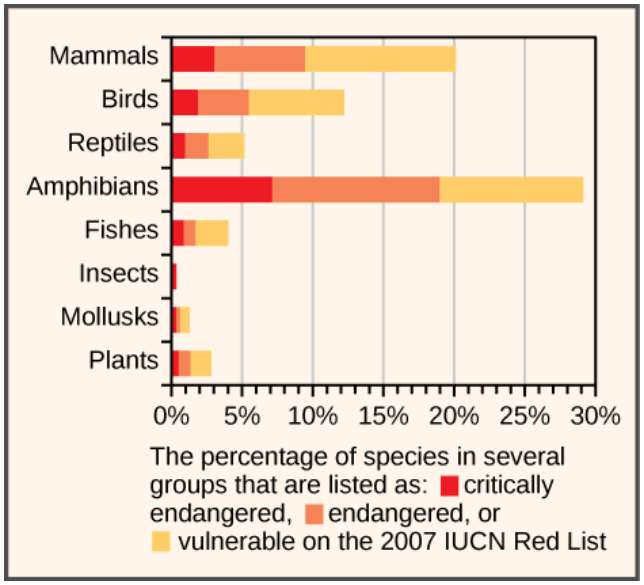


Figure 8.4.1: The 2007 IUCN Red List of critically endangered, endangered, or vulnerable species within various taxonomic groups. The amphibians face the highest risk. (Credit: work by OpenStax, CC BY 4.0)

Which of the following statements is **NOT** supported by this graph?

a. There are more vulnerable fishes than critically endangered and endangered fishes combined.
b. There are more critically endangered amphibians than vulnerable, endangered and critically endangered reptiles combined.
c. Within each group, there are more critically endangered species than vulnerable species.
d. A greater percentage of bird species are critically endangered than mollusk species.

Changing Human Behavior

Legislation throughout the world has been enacted to protect species. 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 approximately 33,000 listed species from being transported across nations' borders, thus protecting them from being caught or killed when international trade is involved. 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. Illegal wildlife trade is monitored by another non-profit: **Trade Records Analysis of Flora and Fauna in Commerce (TRAFFIC)**.

Within many countries there are laws that protect endangered species and regulate hunting and fishing. In the United States, the **Endangered Species Act (ESA)** was enacted in 1973. Species at risk are listed by the Act; the U.S. Fish & Wildlife Service is required by law to develop plans that protect the listed species and bring them back to sustainable numbers. The Act, 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 it is listed. Additionally, species may be controversially taken off the list without necessarily having had a change in their situation. More fundamentally, the approach to protecting individual species rather than entire ecosystems is both inefficient and focuses efforts on a few highly visible and often charismatic species, perhaps at the expense of other species that go unprotected. At the same time, the Act has a critical habitat provision outlined in the recovery mechanism that may benefit species other than the one targeted for management.

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).

As already mentioned, the private non-profit sector plays a large role in the conservation effort both in North America and around the world. The approaches range from species-specific organizations to the broadly focused IUCN and TRAFFIC. The Nature Conservancy takes a novel approach. It purchases land and protects it in an attempt to set up preserves for ecosystems.

Although it is focused largely on reducing carbon and related emissions, the Paris Climate Agreement is a significant step toward altering human behavior in a way that should affect biodiversity. If the agreement is successful in its goal of halting global temperature rise, many species negatively affected by climate change may benefit. Assessments of the accord's implementation will not take place until 2023, and measurement of its effects will not be feasible for some time. However, the agreement, signed by over 194 countries, represents the world's most concerted and unified effort to reduce greenhouse gas emissions, embrace alternative energy sources, and ease climate pressure on ecosystems.

Conservation in Preserves

Establishment of wildlife and ecosystem preserves is one of the key tools in conservation efforts. 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. Preserves can be effective in the short term for protecting both species and ecosystems, but they face challenges that scientists are still exploring to strengthen their viability as long-term solutions to the preservation of biodiversity *and* the prevention of extinction.

How Much Area to Preserve?

Due to the way protected lands are allocated and the way biodiversity is distributed, it is challenging to determine how much land or marine habitat should be protected. The IUCN World Parks Congress estimated that 11.5 percent of Earth's land surface was covered by preserves of various kinds in 2003. We should note that this area is greater than previous goals; however, it only includes 9 out of 14 recognized major biomes. Similarly, individual animals or types of animals are not equally represented on preserves. For example, high quality preserves include only about 50 percent of threatened amphibian species. To guarantee that all threatened species will be properly protected, either the protected areas must increase in size, or the percentage of high quality preserves must increase, or preserves must be targeted with greater attention to biodiversity protection. Researchers indicate that more attention to the latter solution is required.

Preserve Design

There has been extensive research into optimal preserve designs for maintaining biodiversity. The fundamental principle behind much of the research has been 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. The fundamental conclusion was that biodiversity on an island was a function of the origin of species through migration, speciation, and extinction on that island. Islands farther from a mainland are harder to get to, so migration is lower and the equilibrium number of species is lower. Within island populations, evidence suggests that the number of species gradually increases to a level similar to the numbers on the mainland from which the species is suspected to have migrated. In addition, smaller islands are harder to find, so their immigration rates for new species are typically lower. Smaller islands are also less geographically diverse so all things being equal, there are fewer niches to promote speciation. And finally, smaller islands support smaller populations, so the probability of extinction is higher.

As islands get larger, the number of species able to colonize the island and find suitable niches on the island increases, although the effect of island area on species numbers is not a direct correlation. Conservation preserves can be seen as “islands” of habitat within “an ocean” of non-habitat. For a species to persist in a preserve, the preserve must be large enough to support it. The critical size depends, in part, on the home range that is characteristic of the species. A preserve for wolves, which range hundreds of kilometers, must be much larger than a preserve for butterflies, which might range within ten kilometers during its lifetime. But larger preserves 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.

Preserves perform better when there are buffer zones around them of suboptimal habitat. The buffer allows organisms to exit the boundaries of the preserve without immediate negative consequences from predation or lack of resources. One large preserve is better than the same area of several smaller preserves because there is more core habitat unaffected by edges. 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 between them so that individuals (and their genes) can move between the preserves, for example along rivers and streams, will make the smaller preserves behave more like a large one. 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, biological, and ecological specifications of a preserve, there are a variety of policy, legislative, and enforcement specifications related to uses of the preserve for functions other than protection of species. These can include anything from timber extraction, mineral extraction, regulated hunting, human habitation, and nondestructive human recreation. Many of these policy decisions are made based on political pressures rather than conservation considerations. 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 areas of the tropics.

Limitations on Preserves

Some of the limitations on preserves as conservation tools are evident from the discussion of preserve design. Political and economic pressures typically make preserves smaller, rather than larger, so setting aside areas that are large enough is difficult. If the area set aside is sufficiently large, there may not be sufficient area to create a buffer around the preserve. In this case, an area on the outer edges of the preserve inevitably becomes a riskier suboptimal habitat for the species in the preserve. Enforcement of protections is also a significant issue in countries without the resources or political will to prevent poaching and illegal resource extraction.

Climate change will create inevitable problems with the *location* of preserves. The species within them may migrate to higher latitudes as the habitat of the preserve becomes less favorable. Scientists are planning for the effects of global warming on future preserves and striving to predict the need for new preserves to accommodate anticipated changes to habitats; however, the end effectiveness is tenuous since these efforts are prediction based.

Finally, an argument can be made that conservation preserves indicate that humans are growing more separate from nature, and that humans only operate in ways that do damage to biodiversity. Creating preserves may reduce the pressure on humans outside the preserve to be sustainable and non-damaging to biodiversity. On the other hand, properly managed, high quality preserves present opportunities for humans to witness nature in a less damaging way, and preserves may present some financial benefits to local economies. Ultimately, the economic and demographic pressures on biodiversity are unlikely to be mitigated by preserves alone. In order to fully benefit from biodiversity, humans will need to alter activities that damage it.

Habitat Restoration

Habitat restoration holds considerable promise as a mechanism for restoring and maintaining biodiversity. Of course, once a species has become extinct, its restoration is impossible. However, restoration can improve the biodiversity of degraded ecosystems. Reintroducing Gibbon wolves, a top predator, to Yellowstone National Park in 1995 led to dramatic changes in the ecosystem that increased biodiversity (Figure 8.4.2). The wolves function to suppress elk and coyote populations and provide more abundant resources to the guild of carrion eaters. The reintroduction of wolves led to a change in the grazing behavior of elk who no longer grazed exposed stream and riverbeds in order to avoid predation. Reducing elk populations allowed for the revegetation of riparian areas, which increased the species diversity of that habitat. In one location, the Lamar Riverbed, willow and cottonwood seedlings recolonized after decreased elk grazing. The seedlings decreased erosion and provided shading to the creek, which improved fish habitat. Beavers also benefited by gaining acces to an abundant supply of food and building materials. The wolves also reestablished their dominance amongst the park's carnivores, and the coyote population size decreased as a result. This led to increased population sizes of the coyote prey, including pronghorn antelope, foxes, and other small mamammals. In addition, the abundance, population health, and diversity of carrion-eating species also increased as a result of the wolve's predatory activities. In this habitat, the wolf is considered a **keystone species**, meaning a species that is instrumental in maintaining diversity in an ecosystem. Removing a keystone species from an ecological community may cause a collapse in diversity. The results from the Yellowstone experiment suggest that restoring a keystone species 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 those species; likewise, it also makes sense to attempt to return them to their ecosystem if they have been removed.

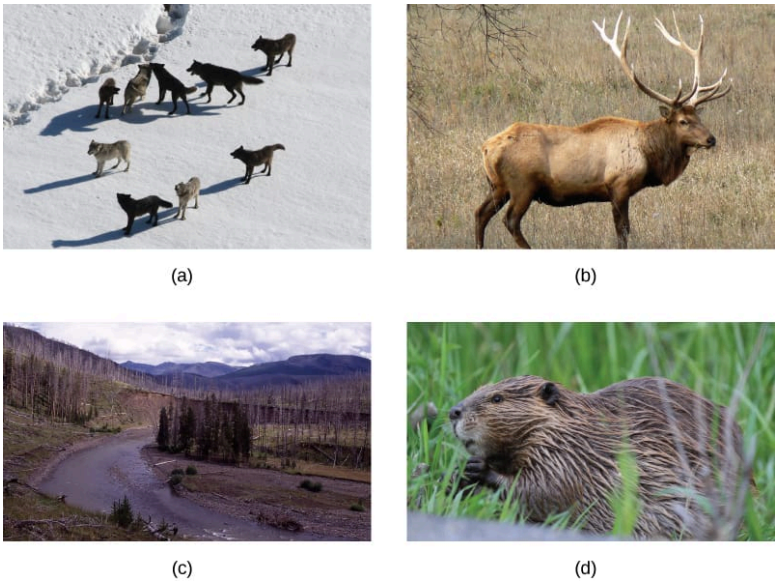


Figure 8.4.2: Animals and habitat who were affected by the reintroduction of wolves into Yellowstone National Park, 1995. (a) The keystone species, Gibbon wolves. (b) Elk. (c) The Lamar Riverbed. (d) Beaver may also have benefited from the habitat change. (credit a: modification of work by Doug Smith, NPS; credit c: modification of work by Jim Peaco, NPS; credit d: modification of work by “Shiny Things”/Flickr)

Other large-scale restoration experiments underway involve dam removal, which is a national movement that is accelerating in importance. 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 and because many dams no longer provide the benefit and functions that they did when they were first built. The measured benefits of dam removal include restoration of naturally fluctuating water levels (the purpose of dams is frequently to reduce variation in river flows), which leads to increased fish diversity and improved water quality. In the Pacific Northwest, dam removal projects are expected to increase populations of salmon, which is considered a keystone species because it transports key nutrients to inland ecosystems during its annual spawning migrations. In other regions such as the Atlantic coast, dam removal has allowed the return of 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. 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 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 and gaining strength. 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. However, captive breeding programs have yielded some success stories, such as the California condor reintroduction to the Grand Canyon and the reestablishment of the Whooping Crane along the Midwest flyway.

Unfortunately, zoo facilities are far too limited to contemplate captive breeding programs for the numbers of species that are now at risk. Education is another 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; at present, the results tend to be mixed.

Chapter Summary

New technological methods such as DNA barcoding and information processing and accessibility are facilitating the cataloging of the planet's biodiversity. There is also a legislative framework for biodiversity protection. International treaties such as CITES regulate the transportation of endangered species across international borders. Legislation within individual countries protecting species and agreements on global warming have had limited success; the Paris Climate accord is currently being implemented as a means to reduce global climate change.

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. The non-profit sector is also very active in conservation efforts in a variety of ways.

Conservation preserves are a major tool in biodiversity protection. Presently, 11 percent of Earth's land surface is protected in some way. The science of island biogeography has informed the optimal design of preserves; however, preserves have limitations imposed by political and economic forces. In addition, climate change will limit the effectiveness of preserves in the future. A downside of preserves is that they may lessen the pressure on human societies to function more sustainably outside the preserves.

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. Zoos have attempted to take a more active role in conservation and can have a limited role in captive breeding programs. Zoos also have a useful role in education.

Footnotes

- 1 Robert H. MacArthur and Edward O. Wilson, E. O., *The Theory of Island Biogeography* (Princeton, N.J.: Princeton University Press, 1967).

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8.5: Review Questions

5. With an extinction rate of 100 E/MSY and an estimated 10 million species, how many extinctions are expected to occur in a century?

a. 100
b. 10,000
c. 100,000
d. 1,000,000

6. An adaptive radiation is_____.

a. a burst of speciation
b. a healthy level of UV radiation
c. a hypothesized cause of a mass extinction
d. evidence of an asteroid impact

7. The number of currently described species on the planet is about _____.

a. 17,000
b. 150,000
c. 1.5 million
d. 10 million

8.A mass extinction is defined as _____.

a. a loss of 95 percent of species
b. an asteroid impact
c. a boundary between geological periods
d. a loss of 50 percent of species

9. A secondary plant compound might be used for which of the following?

a. a new crop variety
b. a new drug
c. a soil nutrient
d. a pest of a crop pest

10. Pollination is an example of _____.

a. a possible source of new drugs
b. chemical diversity
c. an ecosystem service
d. crop pest control

11. What is an ecosystem service that performs the same function as a pesticide?

a. pollination
b. secondary plant compounds
c. crop diversity
d. predators of pests

12. Which two extinction risks may be a direct result of the pet trade?

a. climate change and exotic species introduction
b. habitat loss and overharvesting
c. overharvesting and exotic species introduction
d. habitat loss and climate change

13. Exotic species are especially threatening to what kind of ecosystem?

a. deserts
b. marine ecosystems
c. islands
d. tropical forests

14. Certain parrot species cannot be brought to the United States to be sold as pets. What is the name of the legislation that makes this illegal?

a. Red List
b. Migratory Bird Act
c. CITES
d. Endangered Species Act (ESA)

15. What was the name of the first international agreement on climate change?

a. Red List
b. Montreal Protocol
c. International Union for the Conservation of Nature (IUCN)
d. Kyoto Protocol

16. About what percentage of land on the planet is set aside as a preserve of some type?

a. 1 percent
b. 6 percent
c. 11 percent
d. 15 percent

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9: WEATHER, CLIMATE, AND CLIMATE CHANGE

9.1: Weather and Climate

9.2: Climate Systems, and Long Term Climate Change

9.3: The Atmospheric Blanket and Its Warming Effect

9.4: How Do We Measure Climate Change?

9.5: The Skeptic's Corner- Climate Change Misinformation

9.5.1: The Basics of Climate Change

9.5.2: Back to the Present and Future of Climate Change

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- 2.9: Atoms, Isotopes, Ions, and Molecules - Covalent Bonds and Other Bonds and Interactions by Boundless (now LumenLearning) is licensed CC BY-SA 4.0.

9.1: Weather and Climate

Learning Objectives

By the end of this section, you will be able to do the following:

- Define climate, global climate change, weather

All biomes are universally affected by global climactic conditions. Scientists who study climate have noted a series of marked changes that have gradually become increasingly evident during the last sixty years. **Global climate change** is the term used to describe altered global weather patterns due largely to rising levels of atmospheric carbon dioxide, and include worldwide increases in temperature and climactic changes.

Climate and Weather

A common misconception about global climate change is that a specific weather event occurring in a particular region (for example, a very cool week in June in central Indiana) provides evidence of global climate change. However, a cold week in June is a weather-related event and not a climate-related one. These misconceptions often arise because of confusion over the terms climate and weather.

Climate refers to the long-term, predictable atmospheric conditions of a specific area. The climate of a biome is characterized by having consistent seasonal temperature and rainfall ranges. Climate does not address the amount of rain that fell on one particular day in a biome or the colder-than-average temperatures that occurred on one day. In contrast, **weather** refers to the conditions of the atmosphere during a short period of time. Weather forecasts are usually made for 48-hour cycles. Long-range weather forecasts are available but can be unreliable.

To better understand the difference between climate and weather, imagine that you are planning an outdoor event in northern Wisconsin. You would be thinking about *climate* when you plan the event in the summer rather than the winter because you have long-term knowledge that any given Saturday in the months of May to August would be a better choice for an outdoor event in Wisconsin than any given Saturday in January. However, you cannot determine the specific day that the event should be held on because it is difficult to accurately predict the weather on a specific day. Climate can be considered “average” weather that takes place over many years.

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9.2: Climate Systems, and Long Term Climate Change

Climate Systems

Although almost anything can happen with the weather, climate is more predictable. The weather on a particular winter day in San Diego may be colder than on the same day in Lake Tahoe, but, on average, Tahoe's winter climate is significantly colder than San Diego's. Climate then is the long-term average of weather and can be described by its air temperature, humidity, wind speed and direction, and the type, quantity, and frequency of precipitation. Climate can change, but only over long periods of time

LATITUDE

The main factor influencing the climate of a region is latitude because different latitudes receive different amounts of solar radiation. Figure $9.2.1$ shows that sunlight hits Earth's surface at different angles, and depending on this angle the radiation is intensely spread over a small area at perpendicular angles, and spread out over a larger area at more oblique angles. As a result the equator receives the most solar radiation, the sun is directly overhead at midday and the days are equally long year-round. In contrast, polar regions receive the least solar radiation and in winter there are extended periods of continuous darkness that can range from 24 hours at the polar circles to six months at the poles. As sunlight travels through increasingly oblique angles to reach Earth, the radiation is filtered through increasingly thicker wedges of atmosphere, making the sunlight much less intense. Sunlight hitting Earth's surface at increasingly oblique angles is further reduced by any ice and snow which reflects the radiation back to the atmosphere.

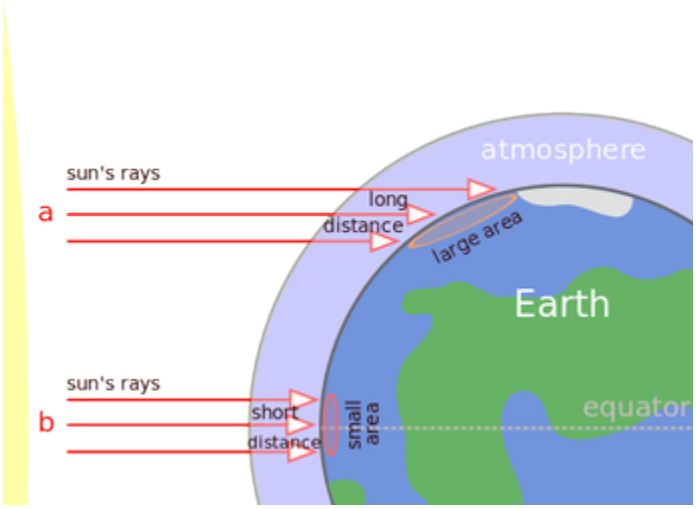


Figure $9.2.1$: Variation of solar intensity by latitude. Parallel red arrows representing sun's rays strike the spherical Earth at two locations. At the equator (labeled b), the rays travel a short distance through a thin layer of the atmosphere and hit directly, concentrating solar energy over a small surface area. At a high polar latitude (labeled a), the rays hit at a shallow oblique angle, traveling a long distance through a thicker layer of the atmosphere and spreading the same solar energy over a much larger surface area. (Image credit: Oblique rays 02 Pengo.svg by Peter Halasz, used under CC BY-SA 2.5)

The amount of sunlight hitting any given spot on Earth also changes throughout the year because Earth's axis of rotation is tilted 23.5° relative to its path around the Sun. This causes climate variations known as **seasons**. In Figure $9.2.2$ this tilt is represented by the symbol for epsilon, ε. This tilt is also responsible for **solstices** - an astronomical event that happens twice a year (in June and December) when the Sun reaches its highest or lowest point in the sky, resulting in the days with the most and least daylight hours. During the June solstice the Northern hemisphere is tilted closest to the Sun and it marks the longest day and shortest night of the year. During the December solstice the Northern hemisphere is tilted furthest away from the Sun and it marks the shortest day and longest night of the year.

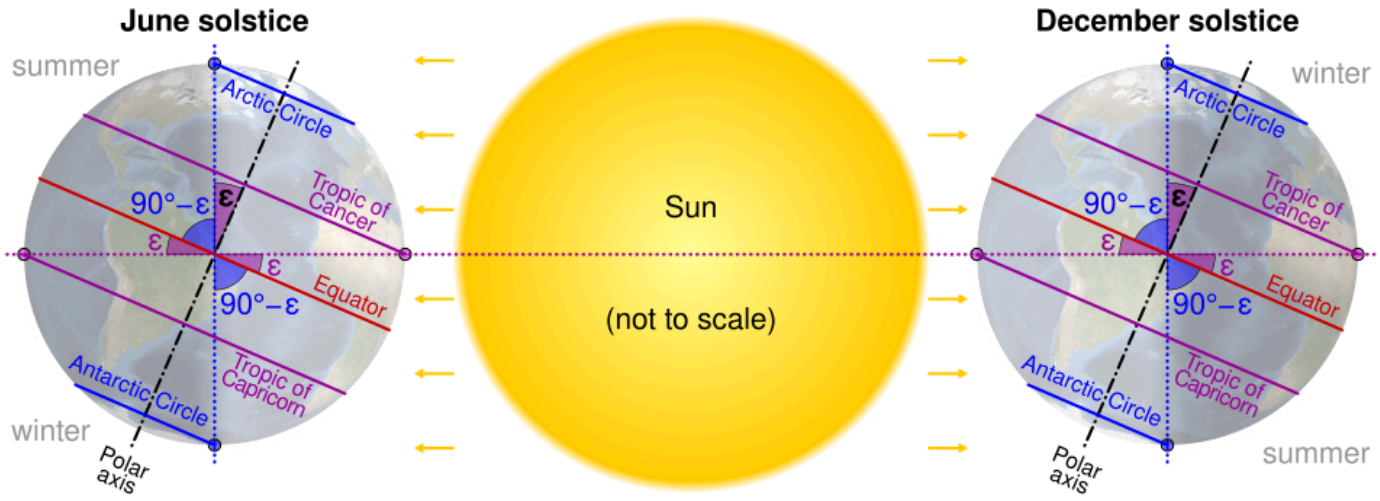


Figure 9.2.2: Earth's axial tilt and lighting conditions during the June and December solstices, showing how the tilt changes seasonal sunlight exposure across major lines of latitude.. (Image credit: Axial tilt vs tropical and polar circles.svg by Cmglee, dedicated to the public domain under CC0 1.0)

ATMOSPHERIC CIRCULATION

The differences in solar radiation hitting Earth's tropics (between the Tropics of Cancer and Capricorn) and polar regions, drives the majority of Earth's atmospheric circulation. Figure 9.2.3 diagrams the three-cell model of global atmospheric circulation, showing how heat is redistributed across the planet.

- **Surface Winds and Pressure Belts:** At the equator (0°), the Intertropial Convergence Zone (ITC**Z)** creates a band of low pressure. Moving poleward, permanent high-pressure zones settle near 30° N and 30° S. Between these zones, surface winds are deflected by the Coriolis effect, producing the Northeasterly Trade Winds and Southeasterly Trade Winds in the topics, and the Westerlies in the mid-latitudes.
- **Convection Cells:** The atmosphere is divided into three distinct vertical convection loops flanking the globe: one near the equator (Hadley cells), one in the middle (the mid-latitude cell, Ferrel), and one near high latitudes (the polar cell). The equatorial cell is a thermal cell and driven solely by solar heating. Wet moist air rises near the equator, and cold dry air to fall at the tropics at +/- 30° latitude. The polar cell is also a thermal cell, but is driven by extreme cold rather than heat. It is characterized by cold dense air sinking directly over the poles (90°), and flowing along the surface toward 60° latitude, warming up slightly, and then rising. Air in the mid-latitude cell moves as a result of being sandwiched between the equatorical and polar cells. The air in this cell rises where it is relatively cold (60°) and sinks where it is relatively warm (30°), spinning like a mechanical gear wedged between the two other powerful cells.
- **The Tropopause:** The tropopause altitude varies by latitude, sinking lower over the arctic zone (around 5–10 km) and rising higher over the temperate zone (up to 15 km). The **tropopause** is the thin boundary layer that marks the absolute upper ceiling of the troposphere. It separates the turbulent troposphere below from the calm stratosphere above. The tropopause acts as a structural cap on Earth's weather. The stratosphere above contains less dense air, and because gravity pulls atmospheric gases down toward the Earth's surface, roughly 75–80% of the entire atmosphere's mass is squeezed into the troposphere.

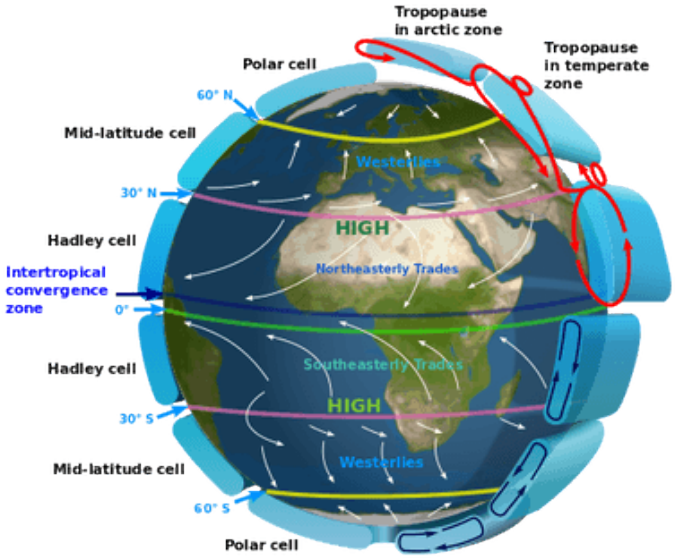


Figure 9.2.3: Three-cell model of global atmospheric circulation detailing pressure zones, convective cells, and prevailing surface wind belts.

Visual Note: While the blue convective cell shapes in this diagram appear higher near the top, note that the curved red arrows show the true height of the troposphere ceiling: it is physically compressed lower over the cold Arctic zone and expands much higher over the warmer temperate zone. (Image credit: Earth Global Circulation - en.svg by Kaidor via Wikimedia Commons, used under CC BY-SA 3.0)

PREVAILING WINDS

The prevailing winds are the bases of the Hadley, Ferrell, and Polar Cells. These winds greatly influence the climate of a region because they bring the weather from the locations they come from. Local winds also influence local climate. For example, breezes from the Great Lakes actively moderate regional temperatures by keeping coastal areas significantly cooler in the summer and milder in the winter.

OCEAN CIRCULATION

Large patterns in the ocean's surface water movement are called **currents**, and are caused by prevailing surface winds and the Coriolis effect. The ocean currents transfer heat as well. These patterns can be seen in Figure 9.2.4 where clockwise movement of water and heat occur in the Northern hemisphere, and anti-clockwise movement occurs in the Southern hemisphere. A large, circular system of rotating ocean currents that stretch across an entire ocean basin is known as a **gyre**. The temperature of the water offshore influences the temperature of coastal locations, particularly if the winds come off the sea. Cool waters along the western United States is caused by the clockwise rotating ocean current that bring cold water from the arctic toward the equator, causing the coastal regions of California, Oregon, and Washington to be cool.

Large patterns in ocean water also form deep currents, and are driven by differences in water density. Colder water holds more salt and is more dense than warmer water which holds less salt and is less dense. Cold dense ocean water will sink and then travel along the ocean floor until it hits a landmass/continent where it is forced up to the surface (called an **upwelling**), creating a three-dimensional movement of water. Upwellings also bring cold, deep water up to the ocean surface and contribute to the cool coastal temperatures. The same ocean current moderating the West coast's temperatures also brings warm, tropical water to Eastern Japan. In the Atlantic Ocean, the northern ocean current brings warm water from the tropics to the southern states. This current is called the **Gulf Stream** because it originates in the Gulf of Mexico and flows out like a massive, fast-moving river or "stream" through the ocean. This warm moisture is a major reason why the southern states experience humid conditions and tornadoes in the summer and autumn. The Gulf Stream also impacts Europe by bringing warm water northward, making the northward land mass warmer than expected.

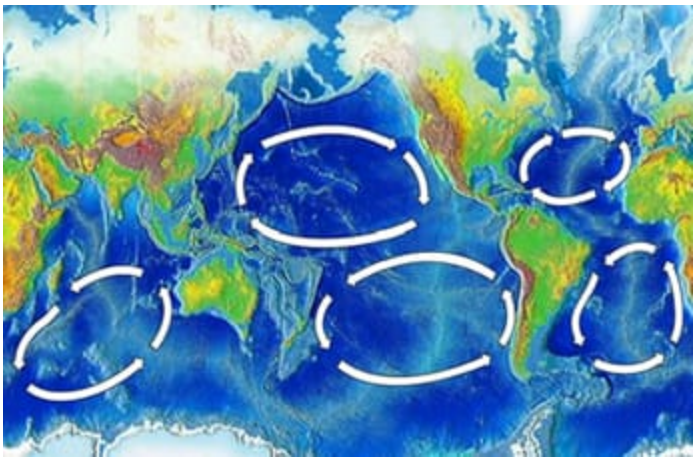


Figure 9.2.4: Global distribution of ocean currents and gyres, denoted by white elliptical outlines, displaying their regulatory impact on coastal regional climates. (Image credit: Geosciences LibreTexts / Lumen Learning, used under open educational license).

Short Term Changes

El Niño Southern Oscillation (ENSO)

Short term changes in climate are common. The largest and most important of these is the oscillation between El Niño and La Niña conditions. This cycle is called the **ENSO (El Niño southern oscillation)**. The ENSO drives changes in climate that are felt around the world about every two to seven years.

In a normal year, the trade winds blow across the Pacific Ocean near the equator from east to west (toward Asia). A low pressure cell rises above the western equatorial Pacific. Warm water in the western Pacific Ocean and raises sea levels by one-half meter. Along the western coast of South America, the Peru Current carries cold water northward, and then westward along the equator with the trade winds. Upwelling brings cold, nutrient-rich waters from the deep sea.

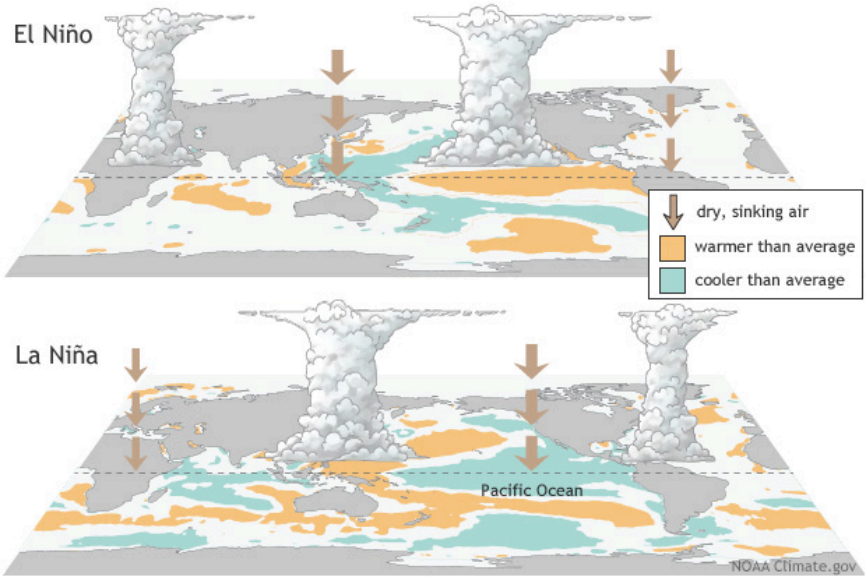
In an **El Niño** year, when water temperature reaches around 28 degrees C (82 degrees F), the trade winds weaken or reverse direction and blow east (toward South America)**.** Warm water is dragged back across the Pacific Ocean and piles up off the west coast of South America. With warm, low-density water at the surface, upwelling stops. Without upwelling, nutrients are scarce and plankton populations decline. Since plankton form the base of the food web, fish cannot find food, and fish numbers decrease as well. All the animals that eat fish, including birds and humans, are affected by the decline in fish.

By altering atmospheric and oceanic circulation, El Niño events change global climate patterns, as shown in Figure 9.2.5.

- Some regions receive more than average rainfall, including the west coast of North and South America, the southern United States, and Western Europe.
- Drought occurs in other parts of South America, the western Pacific, southern and northern Africa, and southern Europe.

An El Niño cycle lasts one to two years. Often normal circulation patterns resume. Sometimes circulation patterns bounce back quickly and extremely, called **La Niña**. In a La Niña year trade winds moves from east to west and warm water piles up in the western Pacific Ocean, as in a normal year. Ocean temperatures along coastal South America are colder than normal (instead of warmer, as in El Niño). Cold water reaches farther into the western Pacific than normal (Figure 9.2.5).

Other important oscillations are smaller and have a local, rather than global, effect. The North Atlantic Oscillation mostly alters climate in Europe. The Mediterranean also goes through cycles, varying between being dry at some times, and warm and wet at others.



Figure

: Comparison of atmospheric circulation, sea surface temperature anomalies, and precipitation zones during El Niño and La Niña events. The top panel shows an El Niño event: warm water anomalies (shaded orange) stretch eastward across the central and eastern equatorial Pacific, accompanied by rising warm air and towering rain clouds over the central Pacific and South America, while dry, sinking air (indicated by brown downward arrows) settles over Indonesia and the western Pacific. The bottom panel shows a La Niña event: cooler-than-average sea surface temperatures (shaded teal) dominate the central and eastern equatorial Pacific, pushing the warm water pooling and rising rain clouds far to the west over Indonesia, while dry, sinking air settles over the central Pacific. A legend identifies brown arrows as dry, sinking air, orange shading as warmer than average, and teal shading as cooler than average water. (Image credit: NOAA Climate.gov, Public Domain)

ALTITUDE AND MOUNTAIN RANGES

Air pressure and air temperature decrease with altitude. The closer that air molecules are packed together, the more likely they are to collide, and these collisions give off heat and warm the air. As one travels up in altitude, the air thins, and as the air molecules are more spread out they are less likely to collide. For example, at the base of the Rocky Mountains is Lakewood CO at 1,682 meters (5,518 feet), which has an average annual temperature of 17°C (62°F); To the West in the mountains is Climax CO at 3,460 meters (11,300 feet), which has an average annual temperature of 5.4°C (42°F).

Mountain ranges modulate the climate of surrounding regions as well, including through the **rain-shadow effect**. This occurs where moist moving air encounters mountain ranges. The air is too heavy to travel over the mountains and is forced up the mountain slopes where it expands and cools. The dry air causes an arid environment on the leeward side of the range. Mountain ranges also separate coastal regions from the rest of the continent. Since a maritime air mass may have trouble rising over a mountain range, the coastal area will have a maritime climate but the inland area on the leeward side will have a continental climate.

Climate Change in Earth History

For the past two centuries, climate has been relatively stable. People placed their farms and cities in locations that were in a favorable climate without thinking that the climate could change. But climate has changed throughout Earth history, and a stable climate is not the norm. In recent years, Earth's climate has begun to change again. Most of this change is warming because of human activities that release greenhouse gases into the atmosphere. The effects of warming are already being seen and will become more extreme as temperature rise.

Climate has changed throughout Earth history. Much of the time Earth's climate was hotter and more humid than it is today, but climate has also been colder, as when glaciers covered much more of the planet. The most recent ice ages were in the Pleistocene Epoch, between 1.8 million and 10,000 years ago. Glaciers advanced and retreated in cycles, known as glacial and interglacial periods. With so much of the world's water bound into the ice, sea level was about 125 meters (395 feet) lower than it is today.

Many scientists think that we are now in a warm, interglacial period that has lasted about 10,000 years.

For the past 2,000 years, climate has been relatively mild and stable when compared with much of Earth's history. Why has climate stability been beneficial for human civilization? Stability has allowed the expansion of agriculture and the development of towns and cities.

Fairly small temperature changes can have major effects on global climate. The average global temperature during glacial periods was only about 5.5 degrees C (10 degrees F) less than Earth's current average temperature. Temperatures during the interglacial periods were about 1.1 degrees C (2.0 degrees F) higher than today**.**

What causes Earth's climate to change over long periods of time?

Causes of Long-term Climate Change

Climates have changed over time, prior to the human existence. This section considers the forces that cause climate to change over long periods of time.

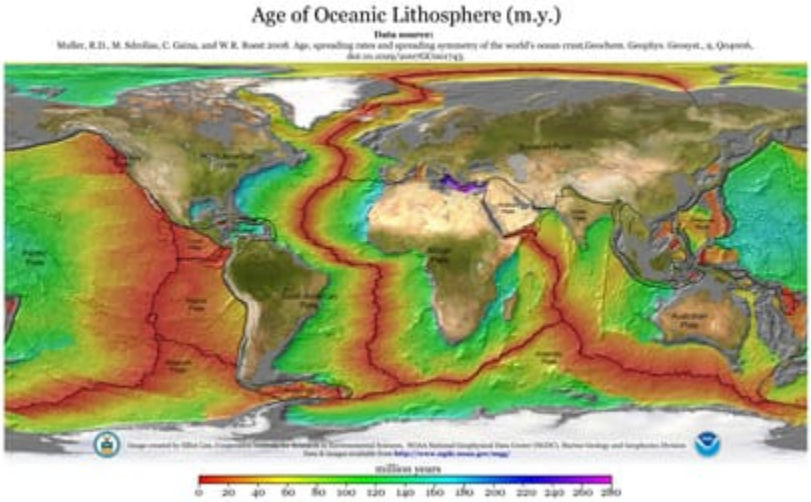


Figure 9.2.6: Global map detailing the structural age of the oceanic lithosphere in millions of years, tracking seafloor spreading outward from divergent mid-ocean ridges. (Image credit: Age of oceanic lithosphere by R.D. Müller, M. Sdrolias, C. Gaina, and W.R. Roest via Wikimedia Commons, used under CC BY-SA 3.0)

Plate Tectonics

Earth's outer shell is broken into large, rigid slabs of rock called **tectonic plates**. These plates float on a hot, semi-fluid layer of Earth's mantle and are in constant, slow motion. The movement of these plates, typically just a few centimeters per year, shapes the planet's surface and drives most major geological activity.They also can can alter climate. Over millions of years as seas open and close, ocean currents may distribute heat differently. For example, when all the continents were joined into the supercontinent known as Pangaea, nearly all locations experienced a continental climate. As continents separate heat was more evenly distributed. When continents are located near the poles ice can accumulate. Increasing amounts of ice increase how much solar radiation is reflected, and lowers the global temperature. In this manner, plate tectonic movements may help start ice ages when Earth's temperature get low enough.

Volcanic Eruptions

Plate motions also trigger volcanic eruptions, which release gasses and dust into the atmosphere. Volcanic eruptions occur over the course of days, but the solids and gases released during an eruption influence the climate over a the course of years and cause short-term climate changes. The gases and solids released by volcanic eruptions can include carbon dioxide, water vapor, sulfur dioxide, hydrogen sulfide, hydrogen, and carbon monoxide. Generally, volcanic eruptions cool the climate.

Milankovitch Cycles

The regular variations in the Earth's position relative to the sun are known as **Milankovitch cycles** (Figure 9.2.7). These are long-term, cyclical variations in Earth's orbit and tilt that alter the amount and distribution of solar energy reaching the planet. These orbital changes repeat over tens of thousands of years and act as the primary natural driver of Earth's historical ice ages and warm periods. The length of Milankovitch cycles range between 19,000 and 100,000 years, and as a result one would expect to see some predictable changes in the Earth's climate at a minimum of every 19,000 years.

One Milankovitch cycle is Eccentricity, and refers to changes in the shape of the Earth's orbit as it goes around the Sun. The orbit varies from more circular to more elliptical in a cycle lasting between 90,000 and 100,000 years. When the orbit is more elliptical, there is a greater difference in solar radiation between winter and summer. A second Milankovitch cycle is called Precession, and refers to how Earth wobbles on its axis of rotation. This cycle lasts 27,000 years and at one extreme the Northern Hemisphere points toward the Sun when the Earth is closest to the Sun. When this happens summers are much warmer and winters are much colder than now. At the opposite extreme, the Northern Hemisphere points toward the Sun when it is farthest from the Sun. This results in chilly summers and warmer winters than now. The last Milankovitch cycle is Obliquity, which refers to how Earth's tilt on its axis varies between 22.1° and 24.5° degrees. This cycle lasts 41,000 years. Seasons are caused by the tilt of Earth's axis of rotation, which is at a 23.5° angle now. The smaller the tilt angle, the smaller the temperature difference between summers and winters. When these three variations are charted out, a climate pattern of about 100,000 years emerges. Ice ages correspond closely with Milankovitch cycles. Since glaciers can form only over land, ice ages only occur when landmasses cover the polar regions. Therefore, Milankovitch cycles are also connected to plate tectonics.

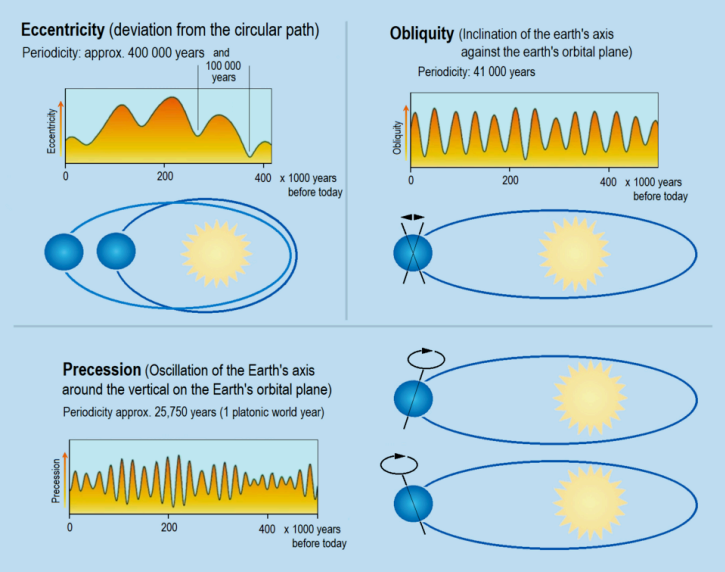


Figure 9.2.7: The three Milankovitch cycles: orbital eccentricity, axial obliquity, and rotational precession. Eccentricity - the graphic below the graph demonstrates how the Earth's orbit fluctuates between a nearly circular path (inner dark blue circle) and a more elongated, oval elliptical path (outer light blue ellipse) around the Sun. Obliquity - the globe diagram highlights the tilt angle variation (shifting between a minimum of 22.1° and a maximum of 24.5°). A higher tilt angle sharpens and accentuates seasonal extremes in both hemispheres. Precession - the two stacked diagrams on the right illustrate the slow, conical "wobble" of Earth's rotational axis. This wobble alters the direction the axis points in space over time, which changes the timing of the seasons relative to Earth's distance from the Sun.(Image credit: Milankovitch cycles by Philippe Rekacewicz via Wikimedia Commons / GRID-Arendal, used under CC BY-NC-SA 3.0)

CHANGES IN ATMOSPHERIC GREENHOUSE GAS LEVELS

Other important drivers of climate change are greenhouse gases, and they have been a consistent component of Earth's atmosphere for billions of years. However, human's recent activities in altering levels of atmospheric greenhouse gasses has played a significant role in recent climate change. For this reason we will consider how greenhouse gases act as a climate change driver independently in the next section.

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9.3: The Atmospheric Blanket and Its Warming Effect

The Earth's atmosphere is an extremely thin shell compared with the size of our planet Figure 9.3.1. The primary gases in the atmosphere by volume are nitrogen (78.1%), oxygen (20.9%), and argon (0.9%). These figures don't include water vapor, which varies significantly with location and altitude but averages about 0.4% of the atmosphere globally. Other naturally occurring gases include carbon dioxide (CO_2), ozone, and methane, which all occur in trace amounts. Although CO_2, methane, and ozone occur naturally, human activities are increasing their concentrations.

This blanket of atmosphere sustains life in many fundamental ways. First, it is vital to the cycle of plant and animal life. Plants grow by taking carbon dioxide from the atmosphere. In the process of photosynthesis, they use energy from the sun to synthesize carbon dioxide with water and release oxygen to the atmosphere. Plants incorporate the carbon into sugars that store energy and into structural materials such as cellulose, while they release the oxygen back into the atmosphere. When animals, including human beings, consume plant material (or other animals), they digest it: that is, they take in oxygen, which reacts with the food to release its stored energy. In the process, animals and humans convert some of the carbon back into carbon dioxide and re-exhale it into the atmosphere.

Water vapor is a crucial part of the atmospheric composition. Water vapor is produced primarily from evaporation from the oceans, surface soils, and subsurface aquifers and then spreads around the planet. It is the water vapor in the atmosphere that forms clouds and rain, thus creating rivers, lakes, glaciers, and ski slopes.

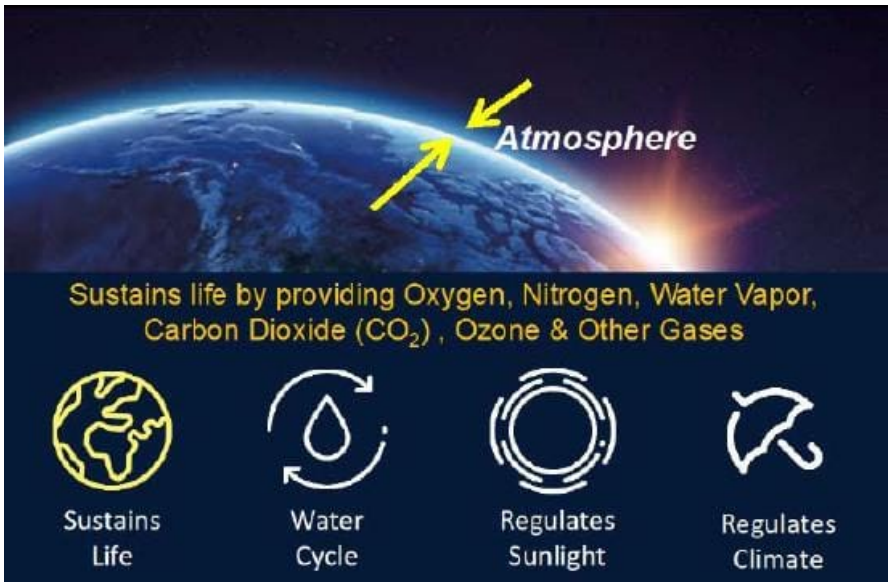


Figure 9.3.1. Earth's atmosphere is a thin, fragile shell. The atmosphere carries out many functions including: sustaining life, cycling water, regulating sunlight, and regulaing climate. Image by V. Ramanathan. Icons designed by Freepik from Flaticon.com.

Most important for our purposes, the atmosphere plays a crucial role in determining the temperature of our plane. It works similarly to how a human-made greenhouse allows solar radiation in to the greenhouse, but traps heat inside. The atmosphere's role in this is referred to as the **greenhouse effect**, and the atmospheric gasses responsible for this are known as **greenhouse gasses**. The most abundant greenhouse gasses in Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide and ozone, and unlike other gasses, greenhouse gasses absorb the radiation emitted from Earth's surface. Without these greenhouse gases, our planet would be about as cold as Mars — far too cold to support liquid water and life. At the other extreme, without clouds, ice, and snow to reflect sunlight, the planet would be so hot that it would be uninhabitable. The atmosphere's composition keeps Earth's temperature at just the right level for water to be present in the planet in all three phases: gaseous water vapor, liquid water, and solid ice and snow crystals. All three forms of water are essential for the survival of *Homo sapiens* and most other species on Earth, and therefore the atmosphere protects life.

Earth's Energy Budget, and the Natural Greenhouse Effect

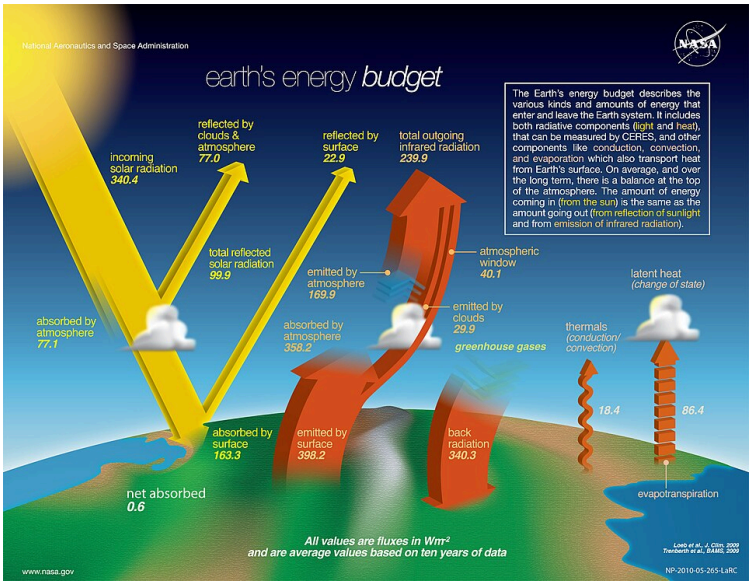


Figure 9.3.2: Earth's energy budget, with incoming and outgoing radiation (Values are shown in W/m^2). Satellite instruments (CERES) measure the reflected solar and emitted infrared radiation fluxes. The energy balance determines Earth's climate.

Year 2021 update: Net absorbed energy (shown as 0.6) rose to above 1.0 W/m^2 based on independent CERES and ocean heat content measurements. "Earth's Energy Budget Diagram" by NASA (NASA Langley Research Center), based on data from Loeb et al., *Journal of Climate*, 2009, and Trenberth et al., *Bulletin of the American Meteorological Society (BAMS)*, 2009. Public Domain.

Earth's atmosphere plays a fundamental role in determining the levels of heat and energy on its surface by modulating the amounts of solar radiation received and lost. The solar radiation that ultimately hits Earth's atmosphere and surface is called **solar irradiation**, and is expressed in terms of the energy rate per unit of its surface area, or watts per square meter (W/m^2). Tracking these gains and losses is known as **Earth's Energy Budget** (Figure 9.3.2), which also includes how energy moves through Earth's climate systems. About 29% of solar irradiation is reflected back into space by the atmosphere, the land surface, and the sea surface. The primary climate variables responsible for this 29% are clouds, snow cover, ice sheets, sea ice, glaciers, and atmospheric oxygen and nitrogen. In general, whiter substances (clouds, ice, and snow) reflect more solar radiation. Earth absorbs the remaining 71% of solar irradiance, which heats the land, ocean surface, and atmosphere. Some of this energy escapes as emitted infrared radiation. This **infrared radiation** is commonly referred to as heat energy because the infrared radiation emitted by any substance depends on its temperature. The higher an object's temperature, the more heat energy it emits.

Not all of the emitted heat energy escapes to space. The greenhouse gases in the intervening atmosphere absorb (trap) some of this heat energy. As a result, the heat energy leaving the planet is reduced by the intervening atmosphere. This trapping of heat energy that otherwise would have escaped to space is referred to as the **greenhouse effect**. The atmospheric greenhouse gases trap heat energy and re-radiate some of it back to the surface. The surface absorbs this re-radiated heat energy, causing the Earth to warm some more. The Earth will continue to warm until it reaches a temperature at which the net incoming solar energy equals the heat energy emitted to space by the warmer surface and the atmosphere.

Thus, the surface temperature of a planet is primarily determined by two factors: the net amount of incoming solar energy it receives, and the heat-trapping properties of any greenhouse gases in its atmosphere. Increasing the concentration of greenhouse gases shifts the balance between incoming solar energy and outgoing heat energy, resulting in a warmer planet.

The Greenhouse Effect, a Metaphorical Blanket

The trapping of heat by the Earth's atmosphere is typically referred to as the "greenhouse effect." This metaphor compares the heat-trapping gases in the atmosphere to the glass panes of a greenhouse, which allow solar radiation to enter but slow down outgoing infrared heat radiation. Although this name has become standard, it's not the best metaphor for understanding the effects of climate pollutants. In fact, the main reason it's warmer inside a real greenhouse is not because it traps radiated heat energy, but because its walls and roof keep warm air from escaping and colder outside air from entering.



Figure 9.3.3: The role of atmospheric greenhouse gasses can be metaphorically thought of as a blanket. Image by Matthew Henry via Unsplash. Licensed under CC0 / Public Domain.

A more scientifically accurate metaphor for the warming effect of the atmosphere is the blanket effect. On a cold night, a blanket (the atmosphere) warms us by trapping some of the heat energy radiated by the body (the planet's surface) and thus prevents some of it from escaping to the rest of the room (space). However, following well-established tradition, we will retain the terms greenhouse effect and greenhouse gases throughout this book.

Experimental validation of the atmospheric greenhouse effect

How do we know the greenhouse effect is real? One way is to look at the energy absorbed and emitted by the Earth. Satellites routinely measure the incoming solar energy and the outgoing heat energy from the planet. Independently, the heat energy emitted by the surface has been estimated using observed surface temperatures on land and sea.

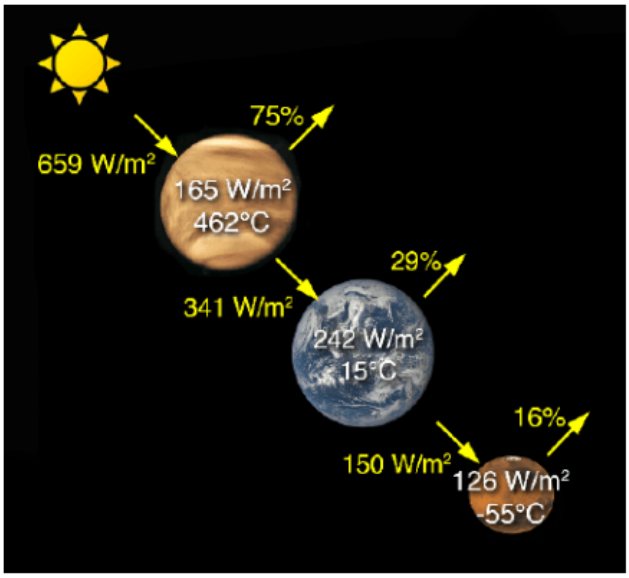


Figure 9.3.4 Comparison of the planetary energy budgets, reflections percentages, and surface temperatures of Venus, Earth, and Mars. Image by NASA. Public Domain.

Globally, measurements show that the Earth's surface emits heat energy at 390 W/m^2. However, satellite measurements during

the 1980s showed that the heat energy escaping to space through the atmosphere was only 260 W/m^2 (Figure 9.3.4). Thus, the atmosphere traps about one-third of the surface-emitted heat energy. Clouds decrease the energy that escapes by an additional 25 W/m^2; thus, the net heat energy escaping to space (with clouds) is 235 W/m^2.

We can use another, more whole-system approach to validate the greenhouse effect: comparing planet Earth with its neighbors, Venus and Mars. On one hand, the average surface temperature of Earth is 15°C. The Venusian surface, on the other hand, is searing hot at 462°C, and well above the melting point of lead. Why is this the case? The first obvious suggestion would be that Venus is hot because it is so close to the sun. Indeed, Venus is close to the sun, and its incoming solar energy is 659 W/m^2, compared with 341 W/m^2 for Earth. But there is a second factor to consider: Venus is completely cloud covered and as a result reflects as much as 75% of its incoming solar energy. Taking this into account, we find that Venus actually absorbs solar energy of 165 W/m^2, slightly less than the amount of solar energy that Earth absorbs (242 W/m^2). On that basis, we would expect Venus to be cooler than the Earth. The only remaining explanation for Venus's searing hot surface temperature is the greenhouse effect of the CO_2 in its atmosphere. It turns out that the concentration of CO_2 on Venus is about 200,000 times more than that on Earth, creating a superstrong CO_2 greenhouse effect, which maintains Venus's hot temperature.

Mars, on the other hand, is much farther from the sun and receives less than half the solar energy that Earth receives. Mars is nearly cloud-free (except for some dust clouds), and it reflects only 18% of its incoming solar energy. The net effect is that the solar energy that Mars absorbs (125 W/m^2) is only half of that absorbed by Earth. This is the primary reason for the frigid average temperature on Mars (−55°C). Mars's atmosphere is mostly CO_2, and the amount of CO_2 on Mars is actually about 15 times larger than that on Earth. However, the higher level of this greenhouse gas is not enough to compensate for the lower incoming solar energy.

Earth in the Goldilocks Zone

The above exercise illustrates an important message about the optimal climate on Earth. The surface temperature is determined by a delicate balance between the amount of incoming solar energy, the reflected solar energy, and the greenhouse gases in the atmosphere. As we saw earlier, water vapor has the strongest warming effect of the naturally occurring greenhouse gases. At the same time, clouds made up of condensed water vapor have a net cooling effect. If water vapor plays such a significant role in our climate, why do discussions of climate change mostly focus on emissions of carbon dioxide? Where does the water vapor greenhouse effect fit in this picture?

While carbon dioxide is emitted by geological processes (and more recently, human activities), the concentration of water vapor is primarily governed by surface and atmospheric temperatures. The warmer the atmosphere, the higher the concentration of water vapor, assuming there is an abundant source (such as oceans or water "cooked out" from minerals deep in the Earth's interior).

Because the concentration of water vapor depends on temperature, climate scientists refer to it as a climate feedback that amplifies warming, rather than a direct cause of warming. If there were no carbon dioxide in the Earth's atmosphere, temperatures would fall to the point that most of the water vapor would condense or crystallize out of the Earth's atmosphere as well. Without carbon dioxide, there would be very little water vapor greenhouse effect and the Earth would be much cooler, if not frozen.

Thus, the Earth seems to have just the right amount of incoming solar radiation, clouds, and CO_2 to maintain an equitable climate. Among the three planets, Earth is the only one whose temperature is not too hot, not too cold, but "just right" for Goldilocks's porridge—and for life (Figure 9.3.5).

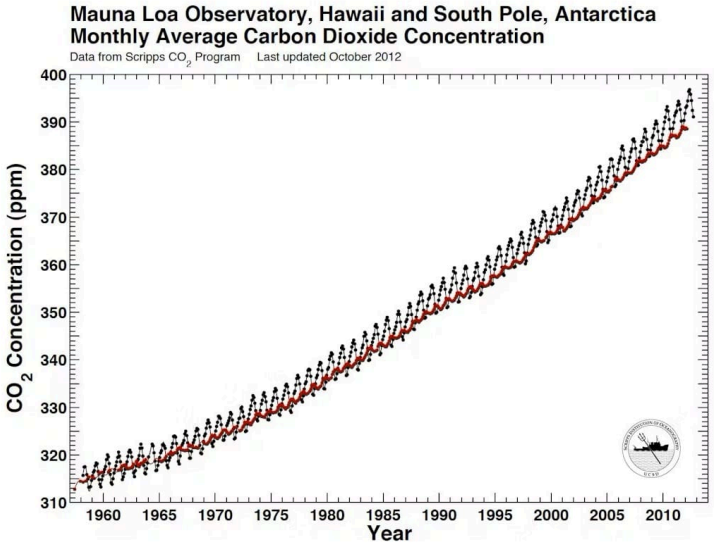


Figure 9.3.5 Conceptual representation of the planetary habitable zone, or "Goldilocks Zone." The illustration uses the children's fable to explain how a planet's distance from its host star must be "just right" to sustain life. Image adapted by NOAA Science On a Sphere from NASA.

Increasing CO_2 Levels Over the Natural Greenhouse Effect

While the natural greenhouse effect is vital for maintaining life on Earth, humans have added an enormous amount of carbon dioxide to the atmosphere since the dawn of the Industrial Revolution in the late 1700's. As of 2017 we have dumped 2,200,000,000,000 (2.2 trillion) tons of carbon dioxide into the atmosphere over the past 240 years. About 45% of that carbon dioxide still remains in the air today. That leaves a 990 billion ton blanket of human-generated carbon dioxide in the thin atmospheric shell. That is equivalent to the weight of about 490 billion cars circling the planet all the time.

How do we know the weight of the human-made CO_2? From direct measurements initiated by Charles David Keeling a scientist at the Scripps Institution of Oceanography (UC San Diego). This wiggly curve is called the Keeling Curve and shows the concentration of carbon dioxide in the atmosphere (Figure 9.3.6). When Keeling first started making measurements in 1958, the atmospheric carbon dioxide concentration was 313 parts per million (**ppm**). That is, out of every million molecules in the atmosphere, 313 were carbon dioxide molecules.



Figure

The Keeling Curve shows the monthly average atmospheric carbon dioxide (

) concentrations measured in parts per million (ppm) at Mauna Loa Observatory, Hawaii (black upper line) and the South Pole, Antarctica (red lower line) from 1958 through 2012. The data shows a steady, continuous long-term increase in global carbon dioxide alongside strong seasonal fluctuations in the northern hemisphere. Image by the Scripps Institution of Oceanography. CC BY 4.0.

Passing a major threshold

In the year 2016, we passed a major threshold. Based on measurements of ancient air bubbles trapped in ice and other data, scientists estimate that the concentration of CO_2 before 1850 was 275 ppm. That concentration has since increased steadily, shooting past 300 ppm by 1950, 369 ppm by 2000, and 400 ppm by 2016. Carbon dioxide concentration was about 410 ppm in 2018, meaning that humans have now increased the overall concentration of carbon dioxide by nearly 50% since the preindustrial era. Crossing the threshold of 400 parts per million signifies that the planet could be transitioning into an era of major climate changes The increase is seen everywhere on the planet: the ocean surface, mountaintops, and deserts. Whether the data are collected in Hawaii, the Arctic, or the Antarctic, the findings are the same. Basically, the additional CO_2 has covered the planet like a blanket.

How did that happen? Air travels fast. Pollution from North America travels to Europe in days; pollution from Asia travels to North America in a week; and pollution from South America travels to the Antarctic in a few weeks. Air takes a few years to travel from the Arctic to the Antarctic. Travel times for pollution are much shorter than the lifetime of the CO_2 molecule in the air, which is 100 to 1,000 years. That's why the CO_2 increase is found everywhere on the planet. Carbon dioxide is what scientists refer to as **a well-mixed gas** — one that remains in the atmosphere much longer than the time it takes to spread around the world.

What is the take-home message?

The atmosphere connects every part of the world with every other part in a matter of days or weeks. Therefore, we can only solve the climate change problem through global cooperation.

Greenhouse gases as pollutants

Why do we call carbon dioxide and other anthropogenic greenhouse gases "pollutants"? Pollute means "contaminate something with a harmful or toxic substance." Carbon dioxide is a natural component of the atmosphere and a vital part of the respiration cycle that sustains life, so how can it be a pollutant? Although carbon dioxide and most other greenhouse gases exist naturally in the atmosphere, human emissions are increasing their concentrations, causing warming that will most definitely have harmful

impacts, as we will see later in this chapter. The harmful impacts of these emissions make it appropriate to refer to greenhouse gases as “pollutants.”

What are the sources for the observed increase in CO_2?

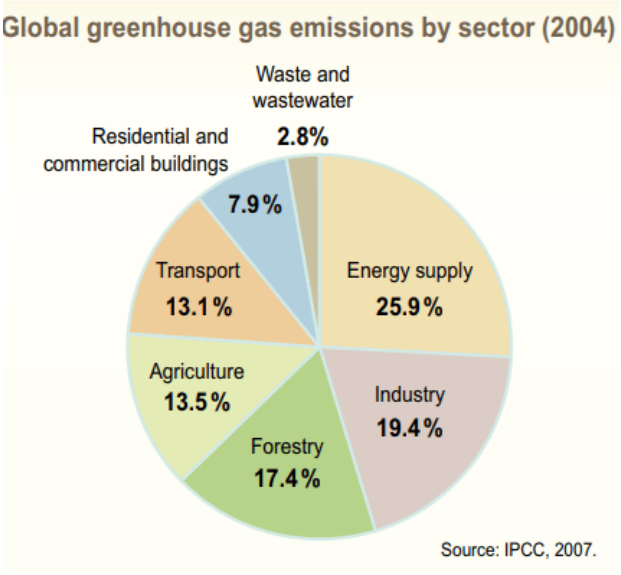


Figure 9.3.7 Global greenhouse gas emissions by economic sector in 2004, illustrated by percentage of total anthropogenic emissions. The largest contributor is the energy supply sector at 25.9%, followed by industry (19.4%), forestry (17.4%), agriculture (13.5%), transport (13.1%), residential and commercial buildings (7.9%), and waste/wastewater (2.8%). Image adapted from the IPCC (2007) via UNEP/GRID-Arendal. Public Domain.

Many human activities that address our basic needs, development, and well-being are sources of greenhouse gases. Global greenhouse gas emissions by economic sector in 2004 is shown in Figure 9.3.7. Most of the energy used by society since the Industrial Revolution has come from fossil fuels: coal, oil, and natural gas. Burning fossil fuels emits the largest amount of CO_2 by far, contributing an estimated 34 billion tons in 2016. Major anthropogenic sources of carbon dioxide include the following:

- Using fossil fuels to produce electricity: In 2016, 65% of electricity worldwide was generated by burning fossil fuels, including 38% from coal and 23% from natural gas. Coal emits roughly twice as much CO_2 per unit of electricity generated as natural gas, so burning coal to generate electricity is particularly concerning.
- Transportation: There are about 1 billion motor vehicles in use around the world, the vast majority of which use oil-based fuels. Aviation and commercial shipping are also major emitters of carbon dioxide.
- Residential and commercial buildings and activities: In addition to indirect emissions from electricity use, buildings can be a direct source of CO_2 emissions, primarily through heating. In developed countries, natural gas is frequently used for space heating, water heating, and cooking. The least affluent 3 billion, with limited access to fossil fuels, frequently burn wood or animal dung for heating and cooking, which also release CO_2.
- Industrial processes: A range of industrial processes, in particular cement and steel production, emit significant amounts of CO_2. Cement production alone is estimated to have been responsible for 2 billion tons of CO_2 emissions in 2016.
- Land use: Changes in land use, in particular burning forests to clear land for farming, grazing, or housing, also emit significant amounts of carbon dioxide. Over the decade 2007–2016, CO_2 emissions from land use averaged about 5 billion tons per year.

How much additional heat energy is trapped by the 990-billion-ton CO_2 blanket?

As of 2010, the heat-trapping effect of human-emitted carbon dioxide was about 860 terawatts (1 **terawatt** equals 1,000 billion watts—that’s a 1 followed by 12 zeros). This represents about 50 times our total global rate of energy consumption! To understand the enormity of 860 terawatts, let’s look at another statistic. The heat energy trapped by our human-made blanket is equivalent to burning 40 trillion 60-watt lightbulbs every second, every day, every month, every year. We are trapping an enormous amount of

heat in the land, oceans, and atmosphere. Based on fundamental physics, the temperature of the planet and the atmosphere will be forced to increase until the extra 860 terawatts are radiated away into space. If we continue to increase the concentration of CO_2 in the atmosphere, even more heat will be trapped, forcing the planet to warm even further. This, in a nutshell, is the cause of global warming.

Is CO_2 the only important anthropogenic greenhouse gas?

Until 1975, we thought that CO_2 was the only source of anthropogenic warming. Then the greenhouse effect of chlorofluorocarbons (CFCs)—a group of artificially produced molecules used as refrigerants, solvents, and propellants—was discovered in 1975. Soon after, a host of other anthropogenic gases (more than 20) were added to the list of climate-warming gases. The most important of these, in terms of their warming impact, are methane, ozone, nitrous oxide, and another group of refrigerants known as hydrofluorocarbons (HFCs). The sources of these pollutants are the following:

- Methane (CH_3) is the main natural gas that we use for power generation, heating, and cooking. Natural gas leaks (called “fugitive emissions”) at production and processing facilities and through distribution pipes are a significant source of methane emissions. Another major source is methane produced by bacteria in the guts of cattle, sheep, and goats. Wet rice agriculture (rice paddy fields), wood burning, landfills, and sewage water treatment plants are among the other significant sources.
- CFCs (chlorofluorocarbons) and HFCs (hydrofluorocarbons) are artificially produced for refrigeration and air conditioning. CFCs have been phased out by international treaty since the late 1980s, but work to phase out HFCs is just beginning.
- Ozone is not directly emitted by human activities, but fossil-fuel power plants and automobile engines emit gases known as ozone precursors (methane, nitrogen oxides, and volatile organic compounds) that react with sunlight to produce ozone in the lower atmosphere.
- Nitrous oxide is released by bacteria in the soil. Nitrogen-based fertilizers used in agriculture increase the activity of soil bacteria and their nitrous oxide emissions. The IPCC estimates that as of 2010 (the IPCC data is available for only up to 2010), CO_2 has trapped 1.8 W/m2 of heat, which is 860 terawatts when integrated over the surface area of the whole planet. All of the anthropogenic non-CO_2 gases have added another 1.2 W/m2, bringing the total heat trapped by all anthropogenic greenhouse gases to 3 W/m2 (about 1,500 terawatts).

Is the climate responding to this added heat?

According to the data, Earth's climate is responding to this added heat. Scientists have collected data at Earth's surface, in the atmosphere (using aircraft and balloons), and from space using satellites. The entire atmosphere, most of the land surface, and the oceans to depths of as much as a kilometer have warmed to unprecedented levels compared with the temperatures of the last 100,000 years.

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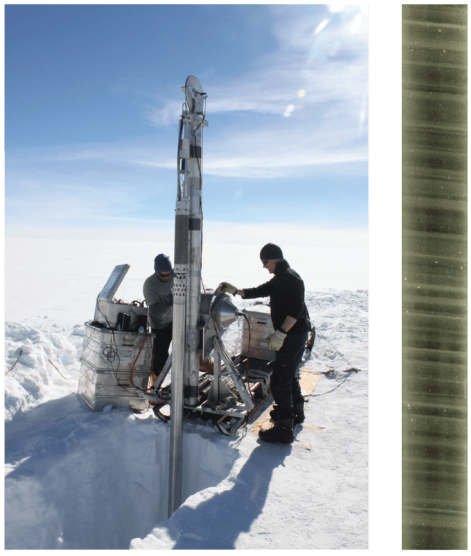
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9.4: How Do We Measure Climate Change?

Evidence for Global Climate Change

Since scientists cannot go back in time to directly measure climatic variables, such as average temperature and precipitation, they must instead indirectly measure temperature. To do this, scientists rely on historical evidence of Earth's past climate.

Antarctic ice cores are a key example of such evidence for climate change. These ice cores are samples of polar ice obtained by means of drills that reach thousands of meters into ice sheets or high mountain glaciers. Viewing the ice cores is like traveling backwards through time; the deeper the sample, the earlier the time period. Trapped within the ice are air bubbles of atmospheric gasses and other biological evidence that can reveal Earth's historic climate. Antarctic ice cores have been collected and analyzed to indirectly estimate the temperature of the Earth over the past 400,000 years (Figure 9.4.1).



(a) (b)

Figure 9.4.1: Field extraction of a glacial ice cylinder (a) and a close-up section highlighting localized atmospheric bubbles trapped during ancient snow compaction (b). (credit: a: Helle Astrid Kjær; b: National Ice Core Laboratory, USGS)

Figures $PageIndex2$ and $PageIndex3$ show examples of ice-core analyses of atmospheric carbon dioxide and methane levels respectively, over the past 400,000 years. These results are based on ice core studies in addition to global air monitoring sites. Atmospheric carbon dioxide has risen and fallen in periodic cycles between 180 and 300 parts per million (ppm) by volume, prior to the Industrial Revolution. In a similar manner, atmospheric levels of methane cycled at significantly lower levels in the same timeframe. This data is important for putting recent human greenhouse generating activity into context of the past 400,000 years. As greenhouse gasses affect the amount of energy in Earth's climate systems, and as human's have significantly increased the levels of atmospheric greenhouse gasses, humans are the primary driver of climate change since the mid-20th century.

Interactive Content

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Figure 9.4.2: Interactive timeline tracking long-run atmospheric carbon dioxide concentrations ((CO_2)) in parts per million (ppm). Data sets combine historical ice core records with modern daily atmospheric monitoring networks. Image from Our World in Data. NOAA Global Monitoring Laboratory - Trends in Atmospheric Carbon Dioxide (2026); EPA based on various sources (2022) – with major processing by Our World in Data. Licensed under CC BY 4.0

Interactive Content

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Figure 9.4.3: Interactive timeline tracking the annual concentration of atmospheric methane in parts per billion per volume (ppbv). Data sets combine historical ice core records with modern daily atmospheric monitoring networks. Image from Our World in Data. NOAA Global Monitoring Laboratory - Trends in Atmospheric Methane (2026); EPA based on various sources (2022) – with major processing by Our World in Data. Licensed under CC BY 4.0.

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9.5: The Skeptic's Corner- Climate Change Misinformation

It is important to address climate skeptics, as their repeated claims can cause people to distrust their own views and the near-unanimous views of climate scientists. A phenomenal website, Skeptical Science(opens in new window), addresses the ideas of climate change skeptics in a systematic and comprehensive manner. It's the source for the use of "The Skeptic's Corner" in this book.

Greenhouse Gasses are Just Plant Food

The Skeptics - But isn't the CO_2 we emit into the atmosphere just plant food?

This argument is used by many who say that we shouldn't worry about dumping CO_2 from burning fossil fuels into the atmosphere. As with some arguments, there is partial truth in the statement. Of course, CO_2 is plant "food," as Rubisco fixes it in photosynthesis, so increasing CO_2 in very controlled experiments (in which all other conditions are fixed) will increase its fixation as it outcompetes O_2 as a substrate. This is true only for C3 plants. Experiments have shown that increasing CO_2 for C4 plants (discussed in the next chapter section), which have a mechanism for pre-concentrating CO_2 as bicarbonate, will not result in the same increase in CO_2 fixation. A complete analysis shows that this description of CO_2 as plant food is incomplete and misleading — an example of a logical fallacy. Several applicable logical fallacies are described below:

- **Half-truth (Cherry-picking Fallacy)** – The argument selectively presents only one fact (that CO_2 benefits plants) while ignoring other relevant facts, such as how excessive CO_2 contributes to global warming, ocean acidification, and extreme weather, which can harm ecosystems, including plants.
- **Hasty Generalization** – Just because CO_2 benefits plants in some cases doesn't mean that increasing CO_2 indefinitely is beneficial. It overlooks the complex ecological and climatic consequences.
- **Oversimplification** – The argument reduces a complex scientific issue to a single, misleading cause-and-effect relationship for climate change.
- **Straw Man Fallacy** (in some contexts) – If this argument is used to dismiss concerns about climate change without addressing the broader scientific consensus, it misrepresents the issue and creates a weaker version of the opponent's position

Other, indirect factors not discussed by those who use the simple argument that CO_2 is simply plant food are listed below (summarized from an excellent video by Andrew Dressler(opens in new window) on this topic).

- Weed growth, which competes for sun, nutrients, and water, would increase, necessitating even more toxic herbicides. This is especially true for C4 plants like corn and sorghum, which gain no advantage from elevated CO_2 levels. In addition, studies show that they can become more resistant to herbicides as they experience more optimal growing conditions.
- The effects of increased CO_2 on plants do not persist, as they adapt at the biochemical level to the increased levels. For example, C3 plants decrease the amount of Rubisco they make, especially over longer time periods.
- Plants also need other nutrients, such as nitrogen and phosphorus, so increasing CO_2 alone will not increase plant growth when other nutrients become rate-limiting.
- Stomata opening size and frequency decrease with increasing CO_2, a logical outcome given increased CO_2 availability. This means less CO_2 enters the cell per unit time, but also less O_2 and H_2O (g) leaves. Plants need H_2O primarily for cooling, which occurs with the evaporation as H_2O (l) → H_2O (g), an exothermic and exergonic process that requires heat from the plant. This cooling in plants is analogous to sweating in animals. In field studies, plants getting extra CO_2 are warmer than adjacent plants that aren't. So plants can benefit from extra CO_2 when water-stressed, but they are disadvantaged by the heat stress accompanying global and localized warming.
- Also, as less water enters the roots when stomata are closed, fewer soil nutrients are taken up by the plant. The result of plants growing faster due to increased CO_2 is less nutritious plants that contain more nonstructural sugars, which are deleterious to human health. Hence, all foods—plant and animal alike—will provide less nutrition. This also includes proteins, such as Rubisco, the main protein in consumed plants, which is decreased.
- Metal ions (the ionome), such as iron, zinc, and calcium, are also decreased, as are vitamins. Total mineral content is reduced by (opens in new window) about 8% in C3 plants such as rice and wheat.
- Faster-growing plants have reduced tolerance to insect and fungal pests. At higher CO_2, the number of aphids significantly

increases. The best previous geological example of a rapid increase in atmospheric CO_2 with no preceding warming of the climate is the **Paleocene/Eocene thermal maximum (PETM)**, which occurred about 56 million years ago. Plant fossils from that time show significant insect damage.

- Higher CO_2 levels increase global temperatures, which can lead to excessive and extreme precipitation events that cause flooding, as well as increased droughts. Droughts decrease crop yield. Elevated temperatures in the absence of drought are also bad for plants. Large yield decreases in wheat and rice are observed with increased temperature and CO_2.

In short, for C3 plants, a rise in CO_2 might be temporarily beneficial for plants but destructive for us.

Three recent studies have quantified these effects and shown that the positive growth response of C3 plants to increased CO_2 has already turned negative. as the Earth warms. Here are links to the three studies.

1. Transition from positive to negative indirect CO_2 effects on the vegetation carbon uptake(opens in new window)
2. Shifts in vegetation activity of terrestrial ecosystems attributable to climate trends(opens in new window)
3. Inhibitive Effects of Recent Exceeding Air Temperature Optima of Vegetation Productivity and Increasing Water Limitation on Photosynthesis Reversed Global Greening(opens in new window)

Finally, data presented in Figure 9.5.1 clearly shows the reduction in plant protein and micronutrients at elevated $CO_{2\ atm}$ levels (568 to 590 ppm compared to present levels of 427 on 2/27/25). The data were obtained through a multiyear study at free-air CO_2 enrichment (FACE) facilities under field conditions in China and Japan. In this technique, rings of pipes or towers are set up around plots of crops, forests, or grasslands. These release controlled amounts of CO_2 into the air, raising the concentration around the plants (often to levels expected later this century) while leaving other environmental factors — like sunlight, wind, temperature, and rainfall — unchanged. The names to the right in the bar graph are particular rice lines (cultivars). The decreased availability of nutrients for herbivores will affect the entire food chain. Similar effects were seen for B vitamin content.

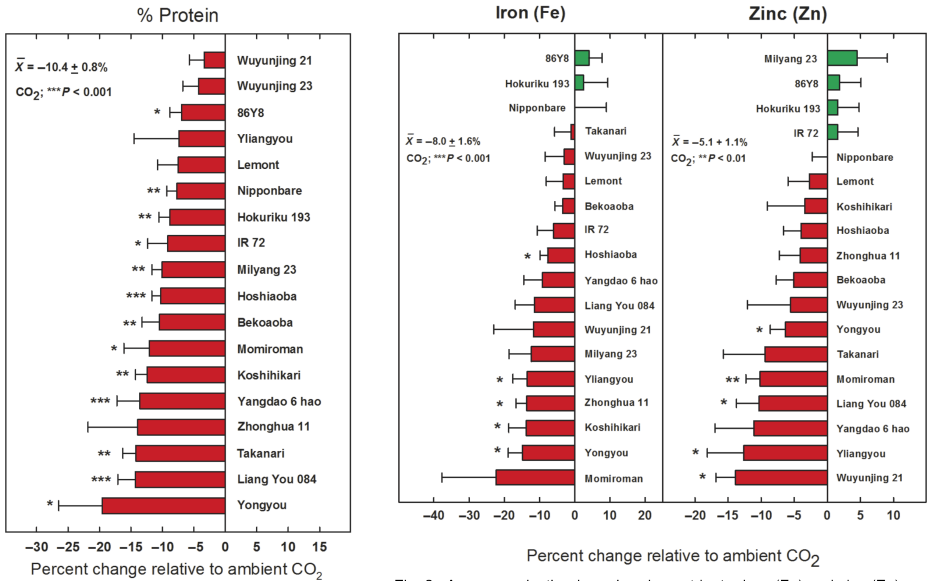


Figure 9.5.1: Reduction in plant protein and micronutrients relative to $CO_{2\ atm}$. Chunwu Zhu *et al.* Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains, with potential health consequences for the poorest rice-dependent countries. *(left)* Average reduction in grain protein at elevated relative to ambient [CO_2] for 18 cultivated rice lines of contrasting genetic backgrounds grown in China and Japan using free-air CO_2 enrichment (FACE) technology. (right) Average reduction in grain micronutrients, iron (Fe), and zinc (Zn) concentration at elevated relative to ambient [CO_2] for 18 cultivated rice lines of contrasting genetic backgrounds grown in China and Japan using FACE technology. Bars are ±SE. *P < 0.05 and **P < 0.01 for a given cultivar. CO_2; **P < 0.01 is based on all cultivars.Bars are ±SE. *P < 0.05 and **P < 0.01 .S *ci. Adv.* 4, eaaq1012(2018).DOI:10.1126/sciadv.aaq1012. Distributed under a Creative Commons Attribution-NonCommercial License 4.0 (CC BY-NC).

Climate Justice: The Emitters and the Affected

The Skeptic's Corner: Climate Change Misinformation

Why should we make changes to reduce fossil fuel emissions when China is the biggest emitter of CO_2?

We present a series of graphs below, taken from CO_2 Emissions - Our World in Data, to show which countries have emitted the most CO_2 in the past and now. In a just world, those countries that have emitted the most should move swiftly and forcefully not only to reduce emissions but also to support other countries' transitions to clean fuels and to help them with climate change mitigation and adaptation. We don't wish to demonize the fossil fuel industry and those who work in it. The use of fossil fuels, which are high-energy, high-density, and cheap fuel (because of historically massive subsidies), has lifted billions out of poverty over time. We had no alternative to fossil fuels until recently. Most did not realize how significantly fossil fuel use would affect our present and future climate, human health, and the entire biosphere. Yet, we can't just stop using fossil fuels without inflicting great economic pain on those who can least afford it. To help those currently suffering and those who will suffer most in the future, and to help ourselves, our children, and our grandchildren, we must move away from using fossil fuels as soon as possible through a planned drawdown of their use.

In Figure 9.5.2 you can see the annual carbon dioxide emissions based on country and the world as a whole. Although China has the highest emissions, they have been emitting for far less time than the U.S.

Interactive Content

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this Interactive Content online

Figure 9.5.2: Interactive line chart comparing annual territorial carbon dioxide (CO_2) emissions in tonnes across selected nations and the global total from 1750 to 2024. Image from Our World in Data / Global Carbon Budget. Licensed under CC BY 4.0.

The US still leads the world in total CO_2 emitted since the Industrial Revolution, as seen in the cumulative carbon dioxide emissions in Figure 9.5.3. The U.S. also has the greatest GDP. In 2022, Pakistan suffered tragic flooding exacerbated by climate change. Up to a third of the country was underwater. In a just world, the biggest emitters would aid the rest of the world.

Interactive Content

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this Interactive Content online

Figure 9.5.3: Interactive line chart comparing annual territorial carbon dioxide (CO_2) emissions in tonnes across selected nations and the global total from 1750 to 2024. Image from Our World in Data / Global Carbon Budget. Licensed under CC BY 4.0.

In Figure 9.5.4 you can see the inequality is evident as the wealthiest people (high and upper-middle income) collectively contribute 86% of CO_2 emissions.

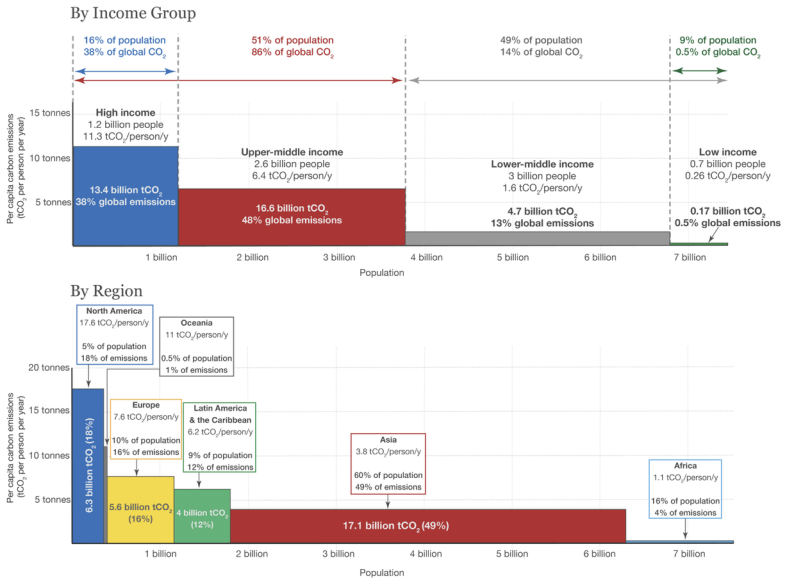


Figure 9.5.4: CO_2 emissions by country and income since the Industrial Revolution. ("Global CO_2 emissions by income and region" by Our World in Data is licensed under CC BY 4.0)

What science says

Since the beginning of the Industrial Revolution, the United States has emitted by far the most CO_2 per capita, and China is not even close.

This is All Part of Normal Climate Change Cycles

The Skeptic's Corner: Climate Change Misinformation

Climate has always changed. Our present period is no different, so action is unnecessary.

Indeed, the Earth has been subject to cycles of glaciation and deglaciation for hundreds of thousands of years. Luckily, we can determine atmospheric CO_2 levels dating back hundreds of thousands of years by measuring the entrapped CO_2 in ice cores from Antarctica and Greenland. In addition, we've been able to infer temperatures over this time frame using proxies including tree rings and fossils. Figure 9.5.5 shows how atmospheric CO_2 and temperature have varied over the last 800000 years using Antarctic ice core data.

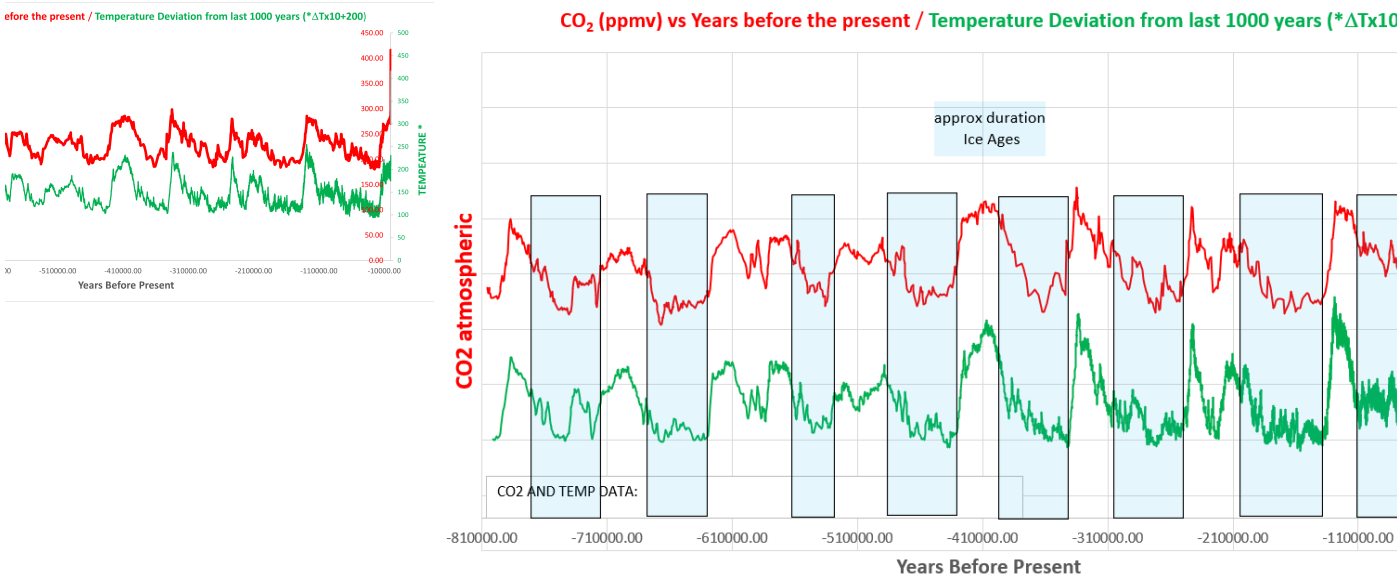


Figure 9.5.5: Atmospheric CO_2 concentrations (ppm, red) and temperature deviations from the past 1000 years (green) using ice core data and temperature proxies. The bottom figure shows the same graph with the duration of the repeated ice ages shown in light blue. A("CO_2 vs Years Before Present and Temperature Deviation" by user *gandyd* via Wikimedia Commons is licensed under CC BY-SA 3.0).

Figure 9.5.5 shows:

- Both atmospheric CO_2 and temperature change are periodic. So yes, it is true that "climate changes," as climate change skeptics argue.
- Both CO_2 and temperature change in synchrony. An obvious question is: what changes first? Does temperature change drive CO_2 changes or vice versa? More on that in a bit.
- **The CO_2 levels in more recent times (on the right-hand side of the graph) have soared to levels not seen in the last 800,000 years**! CO_2 emissions from the burning of fossil fuels cause this change.

Over those 800,000 years, the Earth has experienced cycles of glaciation/deglaciation, including recurring ice ages. Figure ({9{.}5{.}\eatSpaces{6} \endSpaces}\) below shows a depiction of the last ice age, which peaked 21,000 years ago. At that time, the ice cap over New York City was about 1 mile high as CO_2 was 185 ppm!

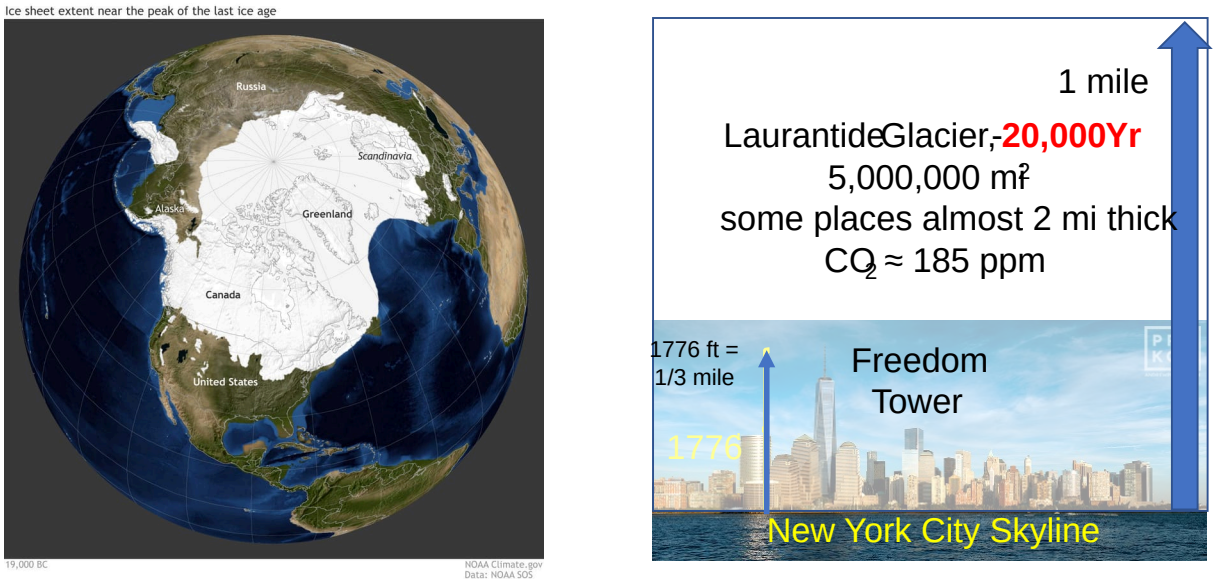


Figure 9.5.1: The Laurentide glacier during the last ice age. A) Modeled Northern Hemisphere continental ice sheet extent near the peak of the last ice age, circa 19,000 BC. Glacial coverage spans across large swaths of North America, Greenland, and Northern Europe. Image by NOAA Climate.gov, based on data provided by NOAA Science on a Sphere. Public Domain. B) Conceptual diagram comparing the thickness of the Laurentide Ice Sheet during the Last Glacial Maximum (circa 20,000 years ago) against the modern New York City skyline. At 1 mile thick, the ice sheet would stand roughly three times higher than the Freedom Tower (1,776 feet). Data compiled from the Encyclopædia Britannica and NOAA paleoclimate archives. CC BY-SA 4.0.

By 5000 BCE, the glacier had retreated to more modern levels, leaving ice over the Arctic Ocean and Greenland. CO_2 levels were around 260 ppm at the time. A change of just 100 ppm in CO_2 was sufficient to melt the Northern Hemisphere glaciers. The image above is not "Northern Hemisphere-Centric," since the great glaciers were confined to the Northern Hemisphere during the ice ages. That's because glaciers grow over land, and most of the land on the planet is in the Northern Hemisphere. The video below shows an animation of the Northern Hemisphere ice shield from 19,000 BCE to now, with a projected future assuming little action to reduce CO_2 emissions. Pay special attention to the graphs, which also show sea level changes.

Blue Marble 3000

This visualization has been developed at the Zurich University of Applied Sciences by Adrian Meyer and Karl Rege. It shows the earth starting at the last glacial maximum 21'000 years ago and ends 1'000 years in the future. Further Information.

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Video courtesy of NASA / Goddard Space Flight Center Scientific Visualization Studio, Public Domain.

A landmark study by Jessica E. Tierney *et al.* in 2020 (Glacial Cooling and Climate Sensitivity Revisited) shows that during the last ice age the average global temperature was 6 degrees Celsius (11°F) cooler than today, which in the 20th century was 14°C (57°F). The Arctic, however, was much colder (about 14 °C or 25 °F colder). The group also came up with an estimate of **climate sensitivity**, the increase in temperature with increasing CO_2. That value represents a **rise of 3.4 °C (6.1 °F) per doubling of CO_2**. In 1896, Arrhenius, recognizing that CO_2 was a greenhouse gas, calculated that doubling atmospheric CO_2 would cause a rise of 4-5 °C. No one can say we haven't known!

A new value for climate sensitivity, indicating a **warming of 4.8 °C (8.6 °F) per doubling of CO2,** was determined by Hansen et

al. (opens in new window)(2023) using more precise data on temperatures and CO_2 concentrations derived from isotopic analyses of ice core samples. If this value holds, the environment needed for human life and our present society is seriously jeopardized unless we take immediate measures to stop emissions and cool the planet. In addition, the rate of increase in global and ocean temperatures has accelerated after 2010, and the likely culprit is a decrease in toxic SO_2 aerosols emitted by ocean vessels in the North Pacific and Atlantic Oceans, as well as in China, due to the reduction of dirty coal-burning facilities. Aerosols reflect incident solar light and increase cloud formation, both of which help cool the planet. Paradoxically, reducing anthropogenic aerosols, while great for cardiovascular and pulmonary health, will accelerate global warming. India would be much warmer now if not for the high aerosol concentrations from smog that cover many of its large cities and countryside.

What the science shows

Climate, CO_2, and temperature have always changed over geological time, but the present rise in anthropogenic CO_2 over such a brief period is unprecedented. This has led to CO_2 levels far exceeding those during the warmer interglacial periods when Northern Hemisphere glaciers retreated.

The Ice Ages, CO_2, and Temperature

The Skeptic's Corner: Yes, CO_2 has increased, but its effects have plateaued, so no worries about additional fossil fuel emissions!

This is the argument of a preeminent physicist with expertise in spectroscopy but not in climate science. He states that the absorption of emitted infrared light by CO_2 (atm) has peaked because its concentration is high enough to saturate the absorption (0% transmittance), so extra CO_2 would have no effect. If so, we can continue burning fossil fuels without worrying about their effects on global warming.

Climate scientists have refuted this idea using three main arguments.

1. Spectral line widening prevents saturation

Beer's Law states that $A_{667\ cm^{-1}\ or\ 15\ \mu M} = \varepsilon bc$, where c is the concentration. If there is sufficient CO_2 to absorb all the IR light at 15 μM, the signal saturates, and additional CO_2 won't absorb any more IR light. It would escape into space without further warming of the planet. However, the main absorbance band at 15 μM is broad and widens with increasing CO_2, so additional CO_2 can still absorb and trap IR at the wavelengths (or "wings") surrounding the main 15 μM peak. This is illustrated in Figure 9.5.7 below.

Figure 9.5.7: IR transmission spectra of CO_2 with increasing CO_2. Drag the sliders to see the band broaden in real time. The dashed blue line shows the pre-industrial baseline (280 ppm) for comparison. *Claude* (Claude Sonnet 4.6) [Large language model]. Retrieved May 2, 2025, from https://claude.ai.

The main peak broadens due to collisions with molecules (most notably O_2 and N_2). At higher pressure (lower altitude, as in the troposphere), there are more collisions per second, and the wings are wider as the energy levels for the absorption are perturbed. You can see this by dragging the pressure slider — lower pressure (higher altitude) narrows the band. Another factor leading to broadening is the Doppler effect. If a photon and CO_2 are moving in different directions during absorption, the photon's frequency changes slightly, leading to band broadening. You likely associate the Doppler effect with a shifting frequency of a siren moving away from you.

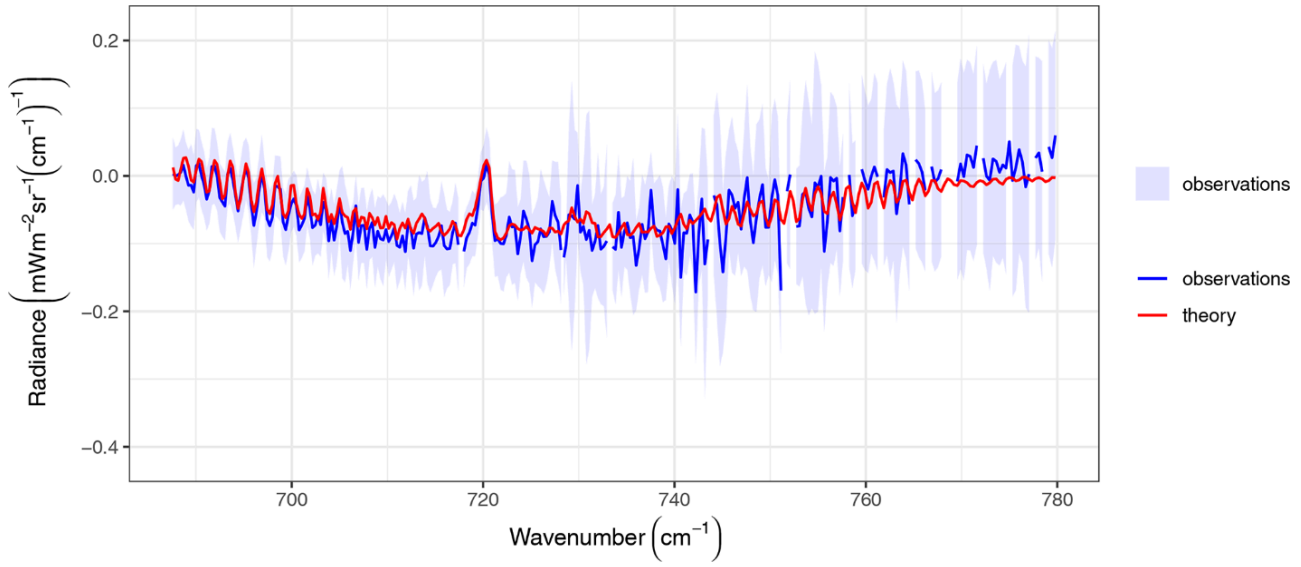
It is well known that doubling the CO_2 concentration does not double the temperature. This assumes a linear relationship between the two. Rather, a doubling of CO_2 produces a net increase but far less than a doubling of the temperature change, so the relationship is logarithmic in CO_2, not linear. This suggests some but not complete saturation of the CO_2 infrared absorption. We've explored **climate sensitivity**, the increase in temperature with increasing CO_2, earlier in this section, and showed that a doubling of CO_2 gives an increase of 3.4 °C (6.1 °F) or possibly even higher. Climate sensitivity is included in all climate models, so any saturation effect is already accounted for.

2. CO_2 is distributed in the upper troposphere and stratosphere

CO_2 is not only near the ground where it is emitted. In the upper troposphere and stratosphere, its concentration is lower, and the atmosphere is much less "saturated," yet infrared light is still absorbed. Moreover, at these heights, less heat is radiated back into space, as colder objects radiate less.

3. Direct satellite data show a decrease in IR radiation from the atmosphere with increasing CO_2

This is clearly the "smoking gun" to refute the saturation argument. Figure 9.5.8 below shows the annual mean radiance differences from the Earth due to CO_2 increases. The data are from the Atmospheric Infrared Sounder (AIRS) satellite (blue line) and are compared with theory (red line) during 2003–2012.



Figures 9.5.8: Annual mean radiance differences (in $\mathrm{mW\,m^{-2}\,sr^{-1}\,(cm^{-1})^{-1}}$) due to CO_2 increase from the AIRS observations (blue line) and from theory (red line) and standard deviations for the AIRS observations (blue shading), illustrating the direct impact of CO_2 increase on the spectral radiances during the 2003–2012 period. João Teixeira, R. Chris Wilson, and Heidar Th. Thrastarson. Atmospheric Chemistry and Physics. 24, 6375–6383, 2024. Creative Commons Attribution 4.0 License.

Here is the significance of these observations taken directly from the paper: "This figure is focused on the 680-to-780 $\mathrm{cm^{-1}}$ spectral range, which represents the R branch of the 15 µm CO_2 band and is a spectral region where the CO_2 signal is particularly significant. In this spectral region, enhanced absorption in the troposphere, where temperature decreases with height, reduces outgoing "infrared" radiation (y-axis values are negative). From a broader climate perspective, the reduction in outgoing radiation drives the increase in global surface temperature necessary for the overall climate system to re-establish energy balance at the top of the atmosphere, and, as such, it is a critical component of global warming. During this period, the measured monthly mean CO_2 mole fraction at Mauna Loa increased on average by approximately 2 ppm $\mathrm{yr^{-1}}$".

The main proponent of the saturation argument is leading the present US administration's efforts to refute the overwhelming scientific consensus on the primary cause of current climate change: CO2 emitted by burning fossil fuels.

Past Climate Anomalies

The Skeptic's Corner: Climate Change Misinformation

In recorded human history, there have been other periods of climate change, so we shouldn't worry about the present! Look at the Little Ice Ages!

Several dramatic but short-lived (in geological time) climate changes have punctuated recorded human history. Let's look at two, mostly to equip you to address climate skeptics. They also show the sensitivity of our climate to subtle changes.

The Little Ice Ages

Actual and proxy temperature records show a mild period in Europe from around 950-1100, followed by colder weather, especially from 1450 to 1850. The latter period is called the "Little Ice Age," although no significant expansion of the Northern Hemisphere ice shield occurred. It was especially cold worldwide in 1816 when much of the world experienced a "year without summer." The effect in 1816 had a clear cause: the eruption of Mount Tambora in Indonesia on April 10, 1815.

In addition to this identifiable influence in 1816, a cool period was reported in the Northern Hemisphere from about 1800 to 1820, beginning before the Tambora eruption. Also, a low period of the sun's irradiance, the Dalton Minimum, occurs from 1790 to 1860. Proxies for solar activity in the 1600s also show small drops in solar irradiance, as discussed below. The dip in global average temperatures following the Medieval Warm Period is shown in Figure 9.5.9.

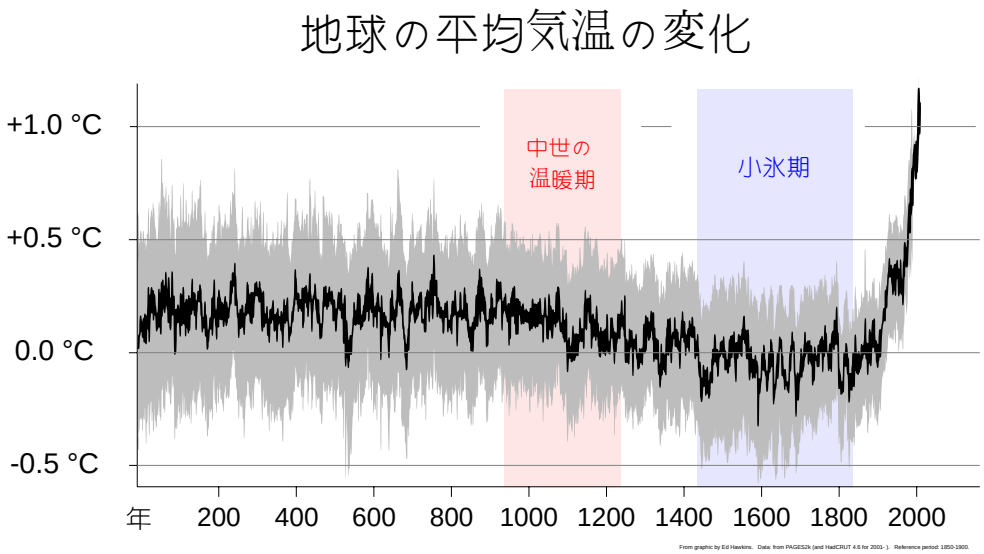


Figure 9.5.9: Reconstructed global average temperature anomalies over the past two millennia, highlighting the relative localized variability of the "Medieval Warm Period" and the "Little Ice Age" compared to rapid modern warming. ("2000+ year global temperature including Medieval Warm Period and Little Ice Age" by Ed Hawkins, using data from PAGES2k and HadCRUT, is licensed under CC BY-SA 4.0).

Modern climate change has been captured in literature and art. One example is a painting showing "Ice Fairs" on the Thames in London, shown in Figure 9.5.10.



Figure 9.5.10: Historical depiction of the 1683–1684 London Frost Fair on the ice of the frozen River Thames during the peak of the Little Ice Age. A crowd of people in period attire are gathered on the thick ice around makeshift tents, wooden shanties, and flags, participating in winter sports and ice fishing against a hazy city backdrop. ("A Frost Fair on the Thames at Temple Stairs" by Abraham Hondius, 1684, image courtesy of the London Museum, Public Domain).

Many factors probably contributed to the Little Ice Ages, including a drop in solar irradiance. A newer explanation has also been proposed. Marine records show that the waters near Greenland and the Nordic seas were warmer, due to a strengthening of the Atlantic Meridional Overturning Circulation (AMOC). This would have caused the loss of Arctic ice in the late 1300s and 1400s, cooling the water and diluting its salinity since ice, when it crystallized with a tetrahedral hydrogen-bonded coordination of water, excludes salt. This would have collapsed the AMOC and its heat transfer to the northern waters, leading to rapid and prolonged cooling. An analogous strengthening of the AMOC was observed between 1960 and 1980, which was attributed to a long-duration high-pressure system over Greenland. A similar event might have occurred to kick-start the Little Ice Age. Tree rings indicate higher solar irradiance before the Little Ice Age, which may be associated with the initial strengthening of the AMOC.

The Little Ice Ages also affected China and may have contributed to crop failure in 1644, when the Ming Dynasty fell. An Arctic hurricane in 1588 helped destroy the Spanish Armada. The Great Fire of London in 1666 was preceded by a very dry summer following an exceptionally cold winter. Food production was severely disrupted, potentially leading to significant social change in Europe and elsewhere as the Plague shattered societal and cultural norms.

The 1816 eruption of Mount Tambora in present-day Indonesia greatly exacerbated the effects of cooling. The ash and SO_2 aerosols blocked solar irradiance. Droughts, floods, cholera epidemics, famine, and migration from Europe to the US and East to West partly arose from this event.

One of the worst times to be alive: 536

Historians report that in 536 AD, parts of Europe, the Middle East, and Asia experienced 24 hours of darkness for up to 18 months. Summer temperatures plummeted. Famines occurred for a few years after. It snowed in China in the summer. The worst effects were in the Northern Hemisphere, but they were worldwide. It was probably the most pronounced cooling in the last 2000 years. To make matters worse, a pandemic erupted around 541, spreading from southern Asia to northern Europe. It had a huge effect on the Byzantine Empire and is known as the Justinian (bubonic) Plague after the Byzantine emperor. Crop failures, trade expansion, and an influx of rodents driven by the cold temperatures could have led to and exacerbated the plague.

This second, more severe example of cooling was shorter-lived on a geological timescale. Temperatures fell in the summer by about 1.5-2.5^{0}C. A "smoking gun" has been linked to this cooling: a volcanic explosion in Iceland. In addition, another eruption occurred in 540, which lowered the temperature by 1.5-2.50C, and another in 547. The combined effects of climate change and the plague led to a significant economic decline in Europe. Signs of airborne lead in the ice at 640, originating from silver mining, suggest a recovery in economic growth. You should ask yourself how the modern world copes with such an occurrence.

What the science shows

The Little Ice Ages and the climate changes preceding and following the Justinian plague had multiple causes, including volcanic eruptions, small changes in solar irradiance, and shifts in North Atlantic Ocean currents and associated weather patterns. These short-term climate changes had disastrous effects on people's lives and the economic health of societies. Predicted future warming arising from CO_2 emitted from fossil fuel use (and other greenhouse gas causes) would bring far worse immediate and potentially irreversible consequences. As people who know the causes of climate change, we must act with due diligence and speed to avert the worst climate future.

Solar Activity and Climate Change

The Skeptic's Corner: Climate Change Misinformation

It's not CO_2 levels that cause any observed increases in temperature. The sun's activity is changing. It always has and always will. There's nothing we can do about it.

We have discussed how the orbital forcing of the climate kick-started each of the recurring ice ages in the Pleistocene. Some effects of the change in solar activity independent of the sun's orbit have been noted above. Specifically, we have shown that it cannot account for present warming. We present a series of graphs from the NOAA (National Oceanic and Atmospheric Administration) in the collective Figure $9.5.11$ below to show the actual change in solar activity over recent times. Comments are shown at the bottom of each graph.

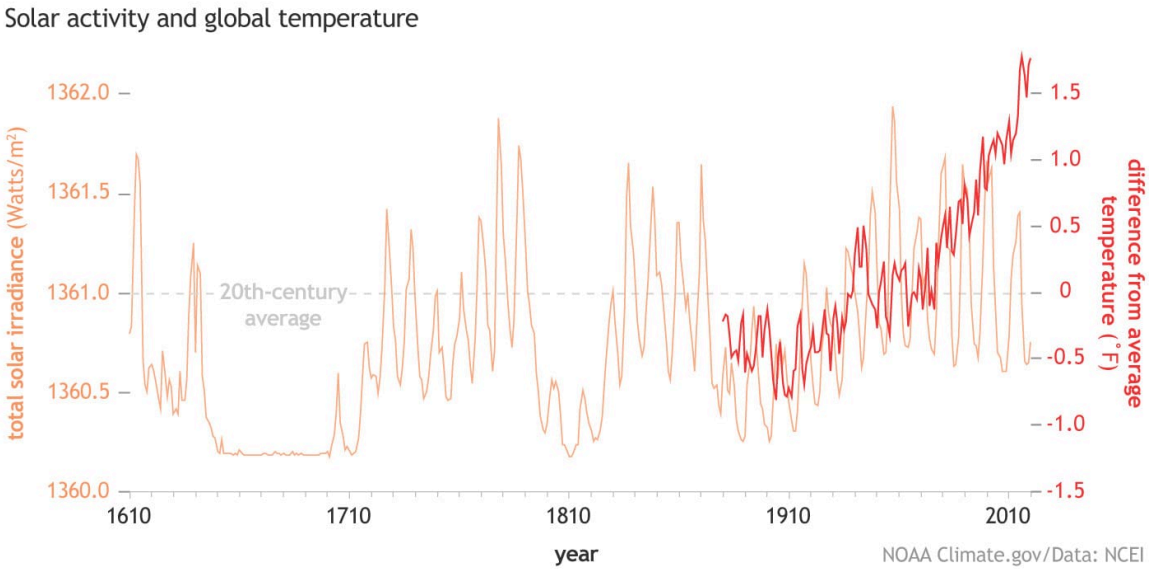


Figure $9.5.11a$: Total solar irradiance (in Watts/m²) and global temperature differences (in °F) from 1610 to 2010. Dark red to the right are actual temperature differences

The maximum % spread between the lowest and highest is very small. Such a small change shouldn't have such dramatic effects on climate unless sustained, as it was from around 1630-1700. Hence, this decline in solar activity likely contributed to the Little Ice Age. The regular rise and fall (spikes) are associated with the 11-year sunspot cycle activity. Note that the rise in average temperature since 1910 (shown in red) cannot be accounted for by a change in solar activity. Figure $9.5.11b$ below shows the irradiance over time with the Maunder and Dalton minimums labeled.

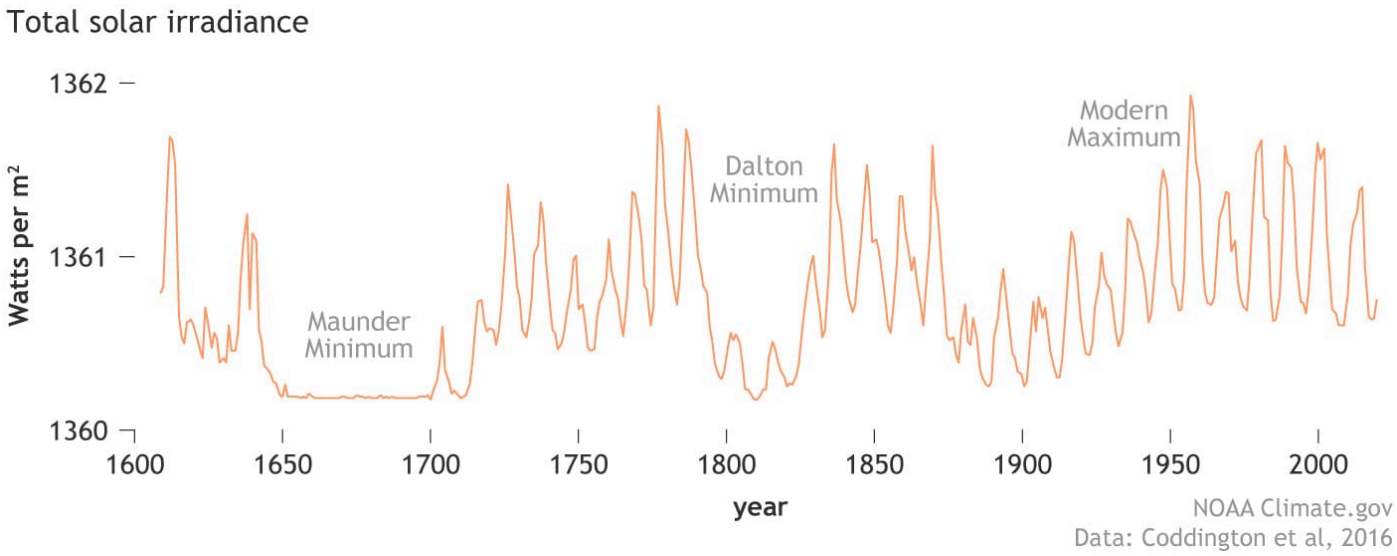


Figure $9.5.11b$: Irradiance over time with the Maunder and Dalton minimums

The above graph shows that the irradiance decreased by about 0.06% (although other values have been reported as high as 0.22%) during the Maunder Minimum, which occurred in the Little Ice Age. The average decrease in terrestrial temperatures was 1.0-2 ^{0}C.

Figure $9.5.11c$ below shows a best fit average temperature difference (dark red line) compared to the 1800-1960 average.

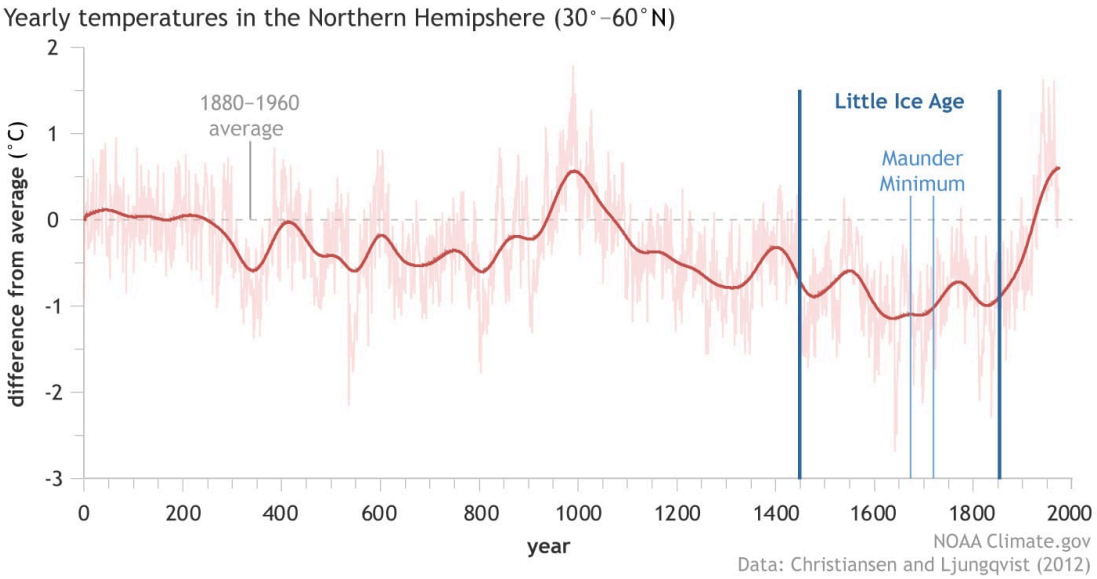


Figure $9.5.11c$: Yearly temperatures in the Northern Hemisphere from 1850 to present, with a notable increase in recent years. Best fit average temperature difference (dark red line) compared to the 1800-1960 average.

Note that the averages are lower during the Little Ice Age, with the lowest values and the lowest spike temperatures near and in the Maunder Minimum. A lowering of just 1 ^{0}C had profound effects on Europe's climate.

Figure $9.5.11d$ below shows irradiance change from 1980 to 2020 through 4 solar cycles.

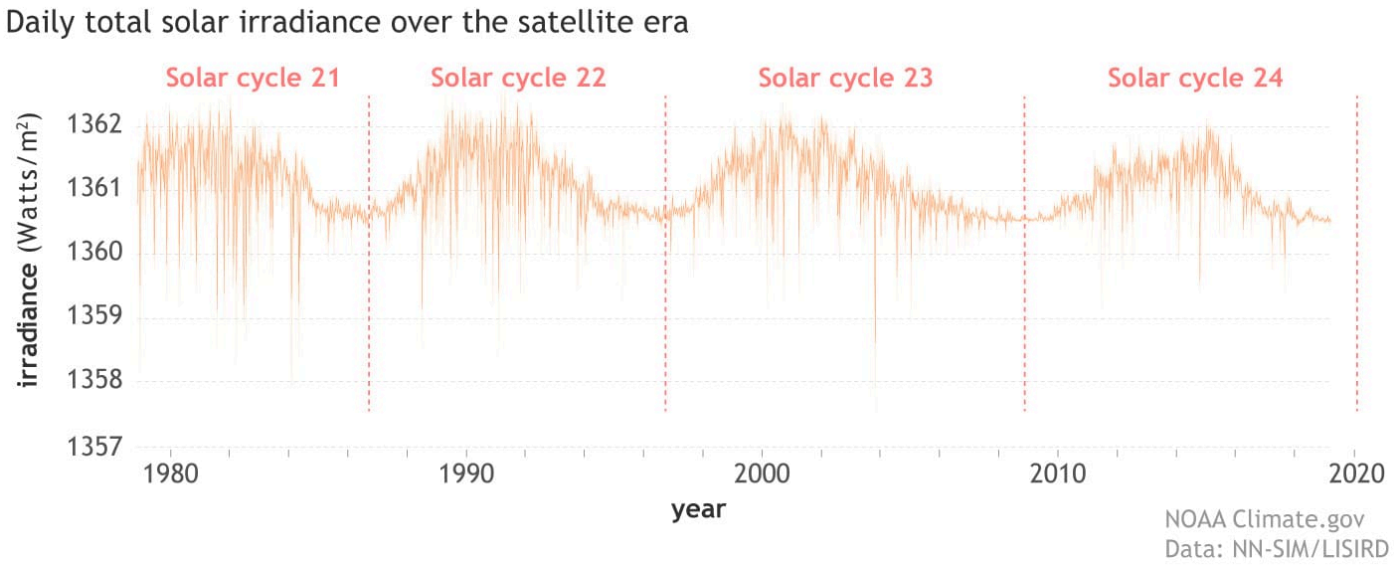


Figure $9.5.11d$: Irradiance change from 1980 to 2020 through 4 solar cycles.

The graph shows the 11-year repeat of sunspot activity and resulting solar irradiance. Although activity dropped in 2020 (not shown in the figure), it was the **second-warmest year** on record since 1880.

Finally, Figure $9.5.11e$ below shows irradiance over the last 10,000 years (from the end of the last Ice Age) until 0 CE.

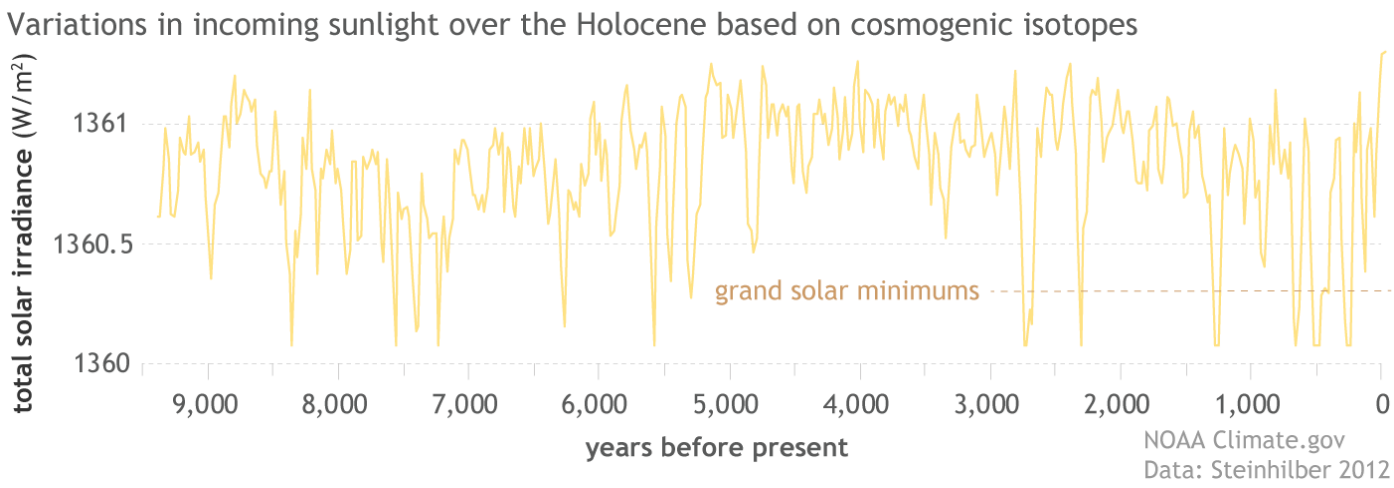


Figure $9.5.11e$: Irradiance over the last 10,000 years.

This graph does not show the effects of orbital climate forcing. Rather, it shows that solar activity did not change significantly for the 10,000 years before 0 CE.

So the climate warming we see now can't be attributed to changes in solar irradiance. We have injected a massive amount of CO_2, approximately 1.5 trillion tons, into the atmosphere since the Industrial Revolution from using fossil fuels. Not all of that is still in the atmosphere, but enough to raise CO_2 to levels not seen for 3 million years. Based on the relationship between CO_2 and temperature across the ice ages, science can predict when conditions might exist to initiate and propagate the next ice age. The data arising from these models, illustrated in Figure $9.5.11f$, show how much incoming solar radiation (insolation) must arrive at the Earth (watts/m^2) to trigger the next ice age.

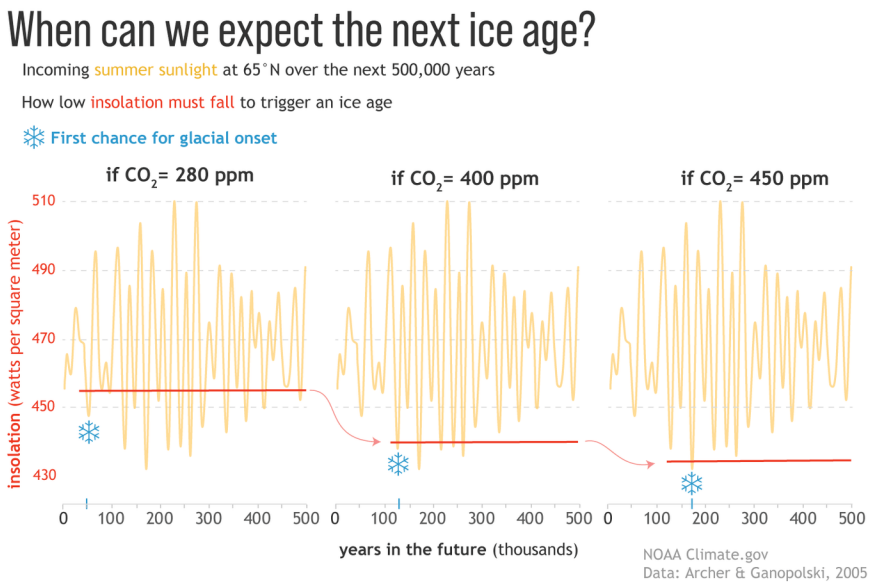


Figure $9.5.11f$: Incoming solar radiation required to trigger the next ice age.

As shown on the left side of the figure, if CO_2 were 280 ppm (typical of peaks in past interglacial periods), it would require repeated drops in insolation below the threshold of about 455 watts/m^2 (red line) to initiate glaciation. As of June, 2026, we are at 430 ppm and rising. If it rises to 450 ppm, as it surely will in the absence of carbon capture, it would require much less insolation to produce an ice age, since the greenhouse effect of higher CO_2 would warm the atmosphere. The right graph shows there is little chance of another ice age in the absence of large and sustained volcanic activity or an asteroid impact that would block solar radiation.

What science says

Changes in solar irradiance (not changes in Earth's orbital dynamics) **cannot** account for warming since the Industrial Revolution. They have contributed to short-term (geological time-scale) cooling during the Little Ice Ages.

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9.5.1: The Basics of Climate Change

Search Fundamentals of Biochemistry

Learning Goals

(Learning Goals written by Claude, Anthropic)

By the end of this chapter, students should be able to:

The Greenhouse Effect and Earth's Energy Balance

- Explain how greenhouse gases — especially CO_2, CH_4, and N_2O — trap infrared radiation emitted by Earth, using IR spectroscopy and blackbody radiation principles to connect molecular properties to planetary warming, and calculate the Earth Energy Imbalance (~1 W/m^2) to appreciate its magnitude.
- Define Global Warming Potential (GWP_{100}), compare the values, atmospheric lifetimes, and climate contributions of CO_2, CH_4, and N_2O, and explain why CO_2 remains the primary long-term concern despite methane's higher per-molecule potency.
- Rebut the argument that "CO_2 absorption is saturated" using three lines of evidence: spectral line broadening at higher pressures and Doppler effects, continued absorption in the upper troposphere and stratosphere, and direct satellite measurements showing decreased outgoing IR radiation at CO_2 absorption wavelengths.

Climate History: Ice Ages, Orbital Forcing, and CO_2

- Interpret ice core and ocean sediment proxy data to describe the synchronous relationship between atmospheric CO_2 and temperature over 800,000 years, explain what the Milankovitch cycles (eccentricity, obliquity, precession) do and do not explain, and identify why present CO_2 levels are unprecedented in at least 3 million years.
- Explain how small orbital temperature increases trigger deglaciation through AMOC slowdown, Southern Ocean warming, and CO_2 release from ocean stores — making CO_2 the driver of the bulk of subsequent warming — and rebut the skeptic argument that "temperature rises before CO_2."
- Describe the role of dust, iron deposition, and phytoplankton primary production as feedback mechanisms that amplify or dampen glacial cycles through their effects on ocean CO_2 uptake.

Deep-Time Climate: Key Events and Sensitivity

- Describe the Paleocene–Eocene Thermal Maximum (PETM, ~56 MYA) and the Eocene–Oligocene Transition (EOT, ~33 MYA) as case studies in rapid CO_2-driven climate change, comparing PETM CO_2 release rates (~1.5 Pg/year) to present emissions (~25 Pg/year).
- Distinguish equilibrium climate sensitivity (ECS, ~3.4 °C per CO_2 doubling) from Earth System Sensitivity (ESS, ~5–8 °C), explain what each includes, and connect the higher ESS value to the long-term consequences of sustained CO_2 elevation.
- Explain why AMOC weakening (projected ~50% by 2100) represents a major climate risk, describing its consequences for European weather, North American sea levels, tropical precipitation, ocean carbon uptake, and atmospheric CO_2.

Introduction

We've known for a long time that burning fossil fuels and releasing CO_2 into the atmosphere would warm our climate. Perhaps the first paper addressing this-"Circumstances affecting the Heat of the Sun's Rays"-was published in 1856, before the US Civil War, by the woman scientist Eunice Foote. John Tyndall (of the Tyndall effect) published a more comprehensive work on greenhouse gases in 1859. Given the complexity of the biosphere's climate, it was not until the 1980s that climate models became sophisticated enough for scientists like James Hansen to become convinced and alarmed enough to discuss, in Congressional hearings, the role of anthropogenic (human-caused) CO_2 released into the atmosphere as a cause of ever-worsening global warming. The knowledge of human-induced climate change has been politicized and subjected to an orchestrated campaign of misinformation and disinformation by fossil fuel companies and their political contributors. We have delayed global action for so long that we must act immediately and aggressively to address climate change before we reach climatic conditions so austere for

humans that parts of the world become uninhabitable. Homo sapiens evolved in a world dominated by repetitive glaciation and deglaciation. Hans Joachim Schellnhuber, an atmospheric physicist, climatologist, and founding director of the Potsdam Institute for Climate Impact Research, has stated that humans have so affected the world that we have eliminated the possibility of the next glaciation cycle.

Many readers might not be familiar with the data and models that support the evidence for human-caused climate change. They may not be aware that climate scientists are almost unanimously supportive of climate data and models. As in any field, however, you will find outliers whose ideas carry disproportionate weight among climate change skeptics. Hence, we provide basic data to show the relationships among increasing atmospheric CO_2 levels, global warming, drought and flooding, ocean acidification, and biodiversity loss. We also provide supportive information, allowing users to address questions from those who question the reality of present human-induced climate change. We don't shy away from using basic physics either, since most students studying biochemistry at the level covered in this book have also studied physics and biology. In subsequent sections, we will address the biochemical consequences of climate change and how biochemistry can help mitigate it.

Greenhouse Effect

Before the advent of the Industrial Revolution, the Earth's climate was fairly constant since the last ice age, which peaked about 22,000 years ago (YA) and ended about 12,000 YA. There have been short (on a geological time scale) cooling periods since the end of the last ice age. Humans evolved around 200,000 years ago, with modern civilizations arising about 4000 BCE, so it could be said that humans are ice-age peoples (a distinctly Northern Hemisphere perspective). Humans have benefited from a fairly stable climate since then.

The sun's energy warms the Earth. If the Earth did not radiate back into space an amount of energy equal to what it receives, it would slowly and continually warm. The Earth reflects energy as light. In addition, as the Earth is heated by the sun, it emits infrared radiation (as do all warm objects). Earth's temperatures are stable when the energy it emits equals the energy it receives from the sun. This is illustrated in Figure 9.5.1.1.

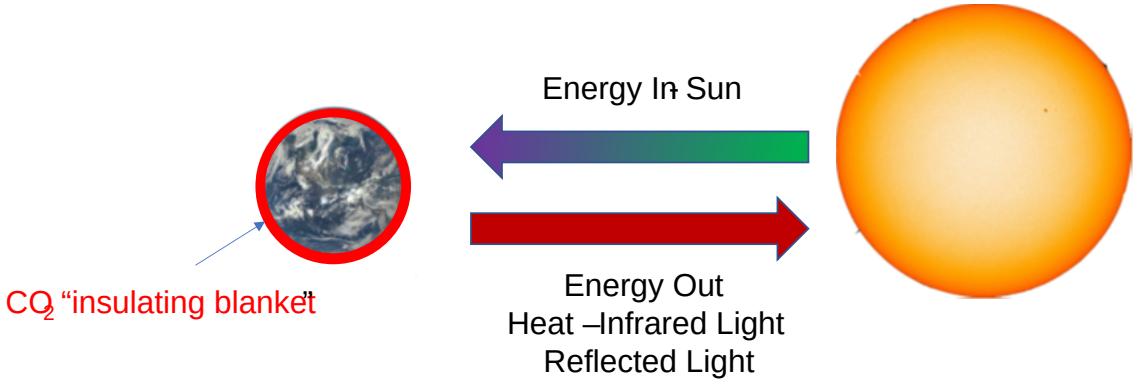
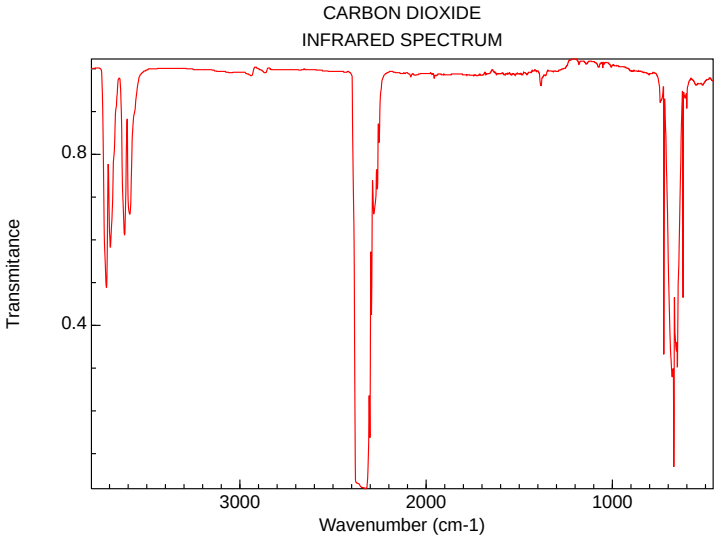


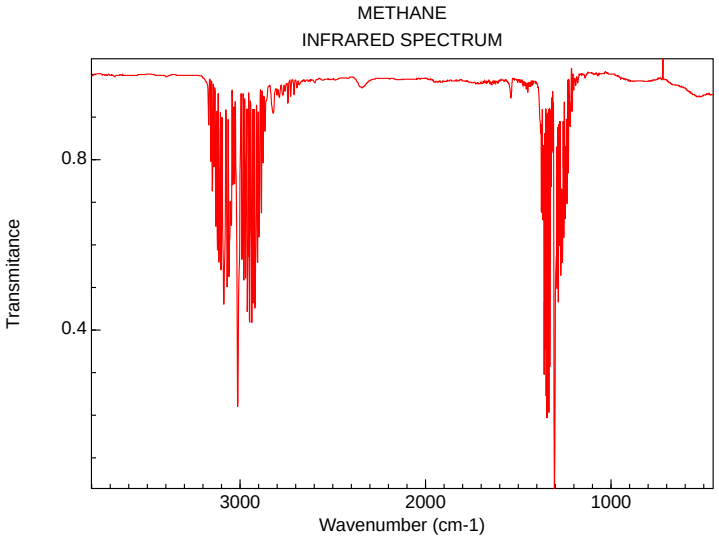
Figure 9.5.1.1: Energy balance for Earth as it absorbs and emits solar radiation

Relatively constant levels of atmospheric CO_2 have enabled our stable climate; this trace atmospheric gas has hovered around 280 parts per million (ppm) until the start of the Industrial Revolution in 1770. CO_2 is a greenhouse gas, which, as anyone who has run an IR spectrum knows, absorbs in the infrared. CO_2 in the atmosphere absorbs some of the infrared radiation emitted by the Earth, allowing the Earth to be warmer than it would be in its absence. The CO_2 effectively acts as an insulating blanket. In fact, without CO_2 or other "greenhouse" gases, the Earth would be completely covered by snow.

Other greenhouse gases in the atmosphere include methane and nitrous oxide. The IR spectra of these gases are shown in Figure 9.5.1.2. Students who have taken organic chemistry labs and obtained IR spectra of samples always blank the instrument to remove spectral signals from both CO_2 and H_2O.



NIST Chemistry WebBook (https://webbook.nist.gov/chemistry)



NIST Chemistry WebBook (https://webbook.nist.gov/chemistry)

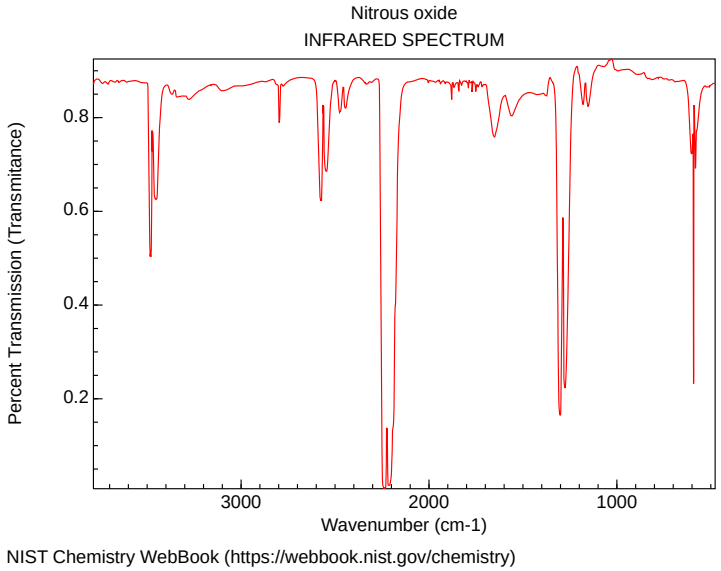


Figure 9.5.1.2: IR spectra of some greenhouse gases. NIST (ex: https://webbook.nist.gov/cgi/cbook.c...ndex=1#IR-SPEC)

Let's look at the relationship between the IR spectra of CO_2 and the spectra emitted by the sun and the Earth. You have probably heard of a blackbody radiator in introductory physics classes. It is a hypothetical object that absorbs 100% of all electromagnetic radiation that falls on it without transmitting or reflecting it (hence it appears black). In addition, it emits light energy that depends only on its temperature, not on its chemical composition.

The surface of the Sun is about 5778 K. The peak of blackbody radiation for a body at that temperature is at approximately 0.5 μm (500 nm), which falls in the middle of the visible spectrum. The Earth, with an average temperature of 288 K, emits at a peak of about 10-15 μM in the IR region. The blackbody radiation curves emitted by the Sun and the Earth are shown in the Figure 9.5.1.3 PHET simulation below. Move the blackbody temperature slider to see the effect on the emitted blackbody radiation. You will have to change the -/+ icons to see the Earth's IR spectra in comparison to the Sun.

Figure 9.5.1.3: PHET Interactive Simulations. University of Colorado, Boulder. https://phet.colorado.edu/en/simulat...ectrum/credits

Play with the slider and magnifying glass icons to view the Earth's emission spectrum (peak at 8.3 μM, spanning 5-16 μM). This overlaps with the CO_2 IR absorption peak (Figure 2) centered at 667 cm^{-1} (15 μM) with a wavelength range span of about 500–850 cm⁻¹ (12-20 μM). The Sun's spectrum shows little intensity at 10-15 μm, so it contributes little to CO_2 absorbance at those wavelengths. Its light just passes through the atmosphere until it strikes Earth.

Since the start of the Industrial Revolution, humans have been releasing ever-increasing amounts of CO_2 into the atmosphere from burning fossil fuels, methane from agricultural practices, and natural gas production. As of January 2025, CO_2 levels have reached 427 ppm, while methane has increased to 1900 parts per billion (ppb) or 1.9 ppm.

Interactive graphs showing atmospheric CO_2 and methane over time are shown in Figures 9.5.1.4 below.

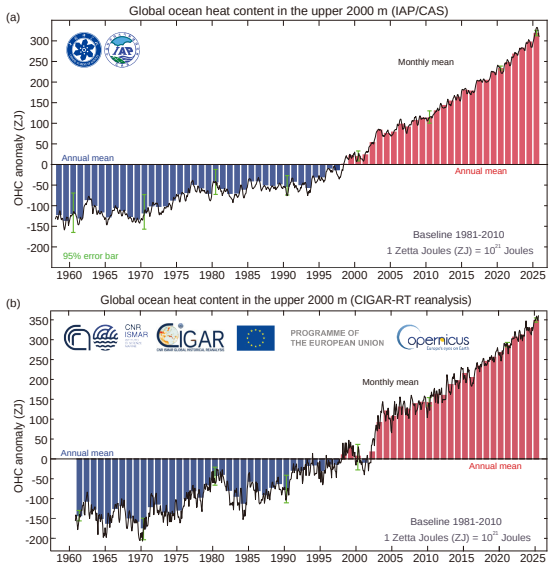
Figures 9.5.1.4: Atmospheric CO_2 and methane over the last 800,000 years. Our World in Data.

Increasing atmospheric methane contributes about 20% of the global warming effect of more concentrated CO2, as it has a strong IR absorption spectrum. It has a short atmospheric half-life (about 20 years) compared to CO_2 (hundreds of years). Nitrous oxide (N_2O) is also a powerful greenhouse gas that depletes stratospheric ozone. Our increased use of synthetic fertilizers and manure is the primary anthropogenic source of N_2O. Its emissions are accelerated by poorly drained farmlands.

The net effect is that the Earth is no longer in energy balance. The net contributions of energy input and output are expressed as energy/sec/m^2 of the Earth's surface area. Hence, the units are Joule/s·m^2 = Watts/m^2, where 1 Watt is 1 J/s. From around 2005

to 2019, the average **Earth Energy Imbalance (EEI)** (or budget) was about +460 x 10^{12} W or 460 terawatts (TW) = 4.6 x 10^{14} W. Dividing this by the surface area of the planet (5.1 x 10^{14} m^2) gives an average global value of +0.90 ± 0.15 W/m^2 (or J/(m^2s)). Newer, more refined estimates indicate it is +1 W/m^2, with most of the excess energy stored in Earth's Oceans, which have a high specific heat capacity and cover 71% of Earth's surface. Most of the remaining excess energy is used to warm landmasses and melt ice sheets and glaciers. 1 W/m^2 might not seem like a lot, but it is (pardon the pun), astronomically big.

Figures 9.5.1.5 below shows the general, continual increase in the ocean heat content (OHC) in zetaJoules (ZJ, 10^{21} J) of the upper 2000 m of the ocean since 1960, with a dramatic acceleration since 2000.



Figures 9.5.1.5: Global upper 2000 m OHC from 1958 through 2025 according to (a) IAP/CAS, (b) CIGAR-RT (from 1961 through 2025), and (c) Copernicus Marine (from 2005 through 2025) (1 ZJ = 10^{21} J). In panels (a) and (b), the black curves represent monthly time series, while the histograms show annual anomalies. Pan, Y., Cheng, L., Abraham, J. *et al.* Ocean Heat Content Sets Another Record in 2025. *Adv. Atmos. Sci.* (2026). https://doi.org/10.1007/s00376-026-5876-0. Creative Commons Attribution 4.0 International License. http://creativecommons.org/licenses/by/4.0/. Here is a link to the Heat Content in the top 700 meters of the ocean - Our World in Data

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The atomic bomb dropped on Hiroshima released about 1.8 x 10^{13} Joules (some estimates are as high as 9 x 10^{13} Joules) of energy. Assume for the sake of calculation that this energy was released in 1 second over the planet's entire surface (5.1 x 10^{14} m^2). The Earth energy imbalance for that one explosion was 0.035 J/m^2•s (0.176 J/m^2•s for the higher estimate). The ratios of the present imbalance (+1 W/m2) to the distributed bomb's imbalances are 1/0.035 = 28x for the lower-energy-estimate bomb or 1/0.176 = 5.7 for the higher-energy-estimate. Hence, the present imbalance, 1 J/m^2s from human-caused climate change, is equivalent to detonating 6-28 Hiroshima-type atomic bombs every second. Other estimates are lower and closer to 600 bombs per day. Regardless, these values should give you a dramatic sense of the imbalance and how unsustainable it is.

Figure 9.5.1.6 below represents the Earth's energy budget.

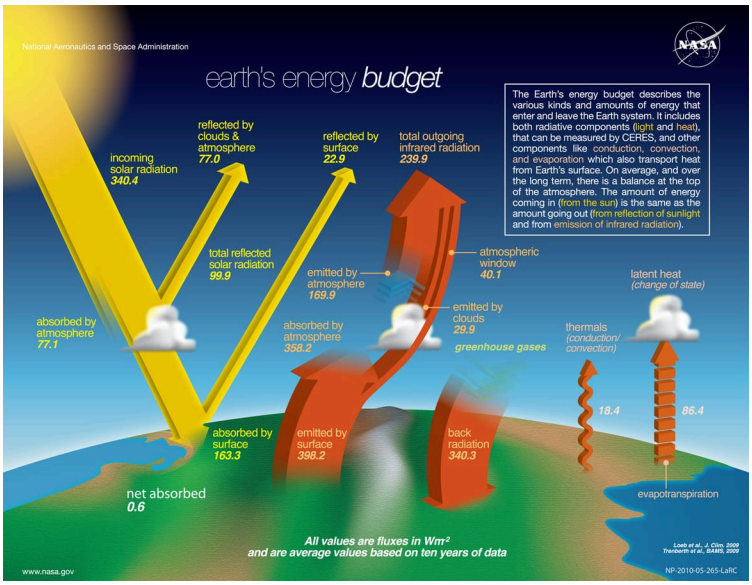


Figure 9.5.1.6: Earth's energy budget, with incoming and outgoing radiation (Values are shown in W/m^2). Satellite instruments (CERES) measure the reflected solar and emitted infrared radiation fluxes. **Year 2021 update**: Net absorbed energy (shown as 0.6) rose to above 1.0 W/m^2 based on independent CERES and ocean heat content measurements. (see Fig. 1 in Loeb et al.(2021), Geoph. Res. Let 48 (13), doi:10.1029/2021GL093047). Public Domain

Global Warming Potential

The **global warming potential (GWP)** calculates the total contribution of all emitted greenhouse gases. It is expressed in units of CO_2 equivalents. It accounts for the contributions of other greenhouse gases, such as CH_4 and nitrous oxide (N_2O), each with unique IR absorption spectra (as shown in Figure 2 above) and atmospheric half-lives. The IPCC uses a 100-year time frame for the calculation of the GWP, which is often abbreviated as GWP100, and uses this formula:

$$\mathrm{CO_2\ equivalent\ kg} = \mathrm{CO_2\ kg} + (\mathrm{CH_4\ kg} \times 28) + (\mathrm{N_2O}kg \times 265) \tag{9.5.1.1}$$

- CO_2 has a GWP of 1 by definition since it is the reference. Its time frame in the atmosphere (100s to 1000 years) doesn't matter since it is the reference.
- CH_4 has a GWP of around 27-30 over 100 years, reflecting its higher IR absorbance but lower lifetime (around 12 years).
- N_2O has a GWP of around 265-273 over a 100-year timescale and a lifetime of around 109 years.

Water is also a greenhouse gas, as you can attest on humid days, and its lack in the atmosphere over deserts leads to a large temperature drop at night. It's very different than other greenhouse gases. Its concentration varies widely (from 40 ppm to 40,000 or more) depending on humidity and precipitation events, which remove it from the atmosphere. The amount of water in the atmosphere increases with rising global temperatures, leading to more intense precipitation events and further warming in a positive feedback loop. Its concentration in the atmosphere changes significantly on time scales of hours and days, so its atmospheric half-life is short. In contrast, the half-life of CO_2 in the atmosphere is measured in decades to centuries.

The basis for methane's contribution to climate change needs a clearer explanation. Given its IR absorption spectra, it is a very potent greenhouse gas. Many oil companies have indicated a commitment to decreasing methane leakage from pipelines, which would be helpful. Still, these efforts may distract from the fact that CO_2 is the biggest problem. Over 20 years (not 100 as in the GWP calculations above), methane is 80 times as potent as CO_2. Those numbers sound ominous (80X and 20 years, which is not long away)! But you shouldn't compare the two on a kg/kg basis, as the warming from CO_2 could last 1000 years, whereas that from methane lasts only 20 years, after which it disappears. Given its short atmospheric lifetime, the long-term climate effect of methane depends on the rate at which it is added to the atmosphere (megatons/year). Still, for CO_2, it is the net mass added over a longer time, which has a cumulative effect. CO_2 effects continue to increase, but methane effects wane quickly. So you can't easily compare warming over the first 20 years. Consequently, the delay in acting on methane is minimal compared to that in acting on CO_2.

Methane accounts for about 30% of net warming, and about 60% of it is likely from human activities. As we hit the IPCC Paris target of 1.5 °C, about 30% of that, or about 0.45 °C, is from methane; hence, 0.27 °C comes from human sources. Decreasing human sources of methane will help. But we can't use our efforts to remove methane to avoid or slow down the push for net-zero CO2 emissions.

Climate changes over the last million years

Note: In the next few sections, the word "Skeptics" will be used. It is important to address climate skeptics, as their repeated claims can cause people to distrust their own views and the near-unanimous views of climate scientists. A phenomenal website, Skeptical Science, addresses the ideas of climate change skeptics in a systematic and comprehensive manner. It's the source for the use of "The Skeptic's Corner" in this book.

The Skeptic's Corner: Climate Change Misinformation

Climate has always changed. Our present period is no different, so action is unnecessary.

Indeed, the Earth has been subject to cycles of glaciation and deglaciation for hundreds of thousands of years. Luckily, we can determine atmospheric CO_2 levels dating back hundreds of thousands of years by measuring the entrapped CO_2 in ice cores from Antarctica and Greenland. In addition, we've been able to infer temperatures over this time frame using proxies (tree rings, fossils, and more, as described in section 31.2). Figure $9.5.1.7$ shows how atmospheric CO_2 and temperature have varied over the last 800000 years using Antarctic ice core data.



Figure 9.5.1.7: Atmospheric CO_2 concentrations (ppm, red) and temperature deviations from the past 1000 years (green) using ice core data and temperature proxies. The bottom figure shows the same graph with the duration of the repeated ice ages shown in light blue. Antarctic Ice Cores Revised 800K YrCO2 Data. Bereiter, B.; Eggleston, S.; Schmitt, J.; Nehrbass-Ahles, C.; Stocker, T.F.; Fischer, H.; Kipfstuhl, S.; Chappellaz, J. http://ncdc.noaa.gov/paleo/study/17975

Several key features of the graph should be apparent:

- Both atmospheric CO_2 and temperature change (ΔT) are periodic. So yes, it is true that "climate changes," as climate change skeptics argue.
- Both CO_2 and ΔT change in synchrony. An obvious question is: what changes first? Does ΔT drive CO_2 changes or vice versa? More on that in a bit.
- **The CO_2 levels in more recent times (on the right-hand side of the graph) have soared to levels not seen in the last 800,000 years**! CO_2 emissions from the burning of fossil fuels cause this change.

Here is an interactive animation that shows the evolution of CO_2 and scaled temperature changes (not absolute) over the years, making the lock-step similarities in their changes more evident (graph produced by Claude - Anthropic, using data from Bereiter, B. et al.

Figure 9.5.1.7*zoom* below zooms in to show both $CO_{2\ atm}$ and temperature values (look at changes, not actual values) since 1000 CE. The light blue-shaded region represents the "Little Ice Ages".

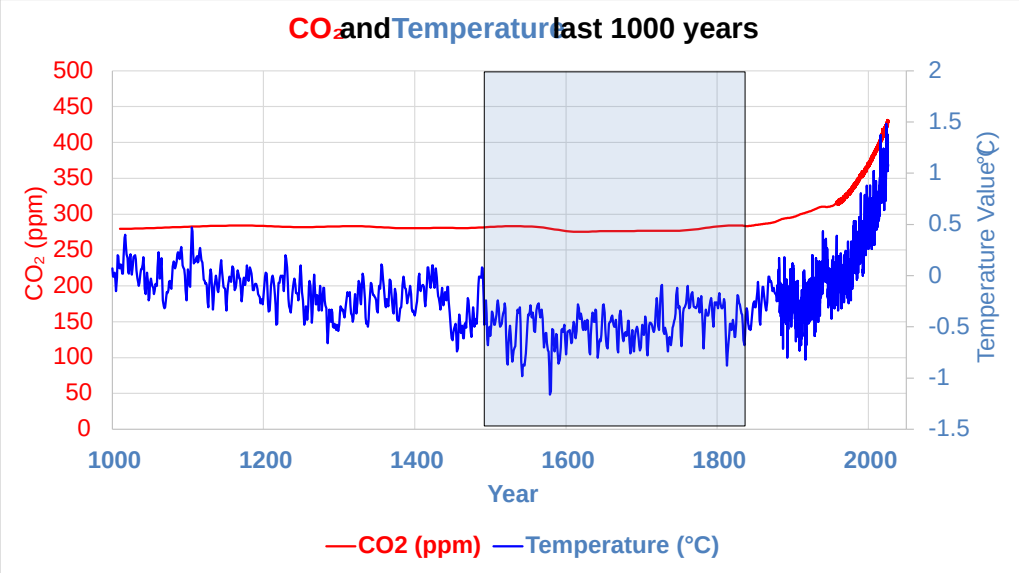


Figure 9.5.1.7*zoom*: $CO_{2\ atm}$ (blue) and temperature values (red, look at changes, not actual values) since 1000 CE. Note that they generally proceed in lockstep. Data and data sources from the 2 Degrees Institute.

Over those 800K years, the Earth has experienced cycles of glaciation/deglaciation, including recurring ice ages. Figure ({9{.}5{.}1{.}\eatSpaces{8} \endSpaces}\) below shows a depiction of the last ice age, which peaked 21,000 years ago (left). At that time, the ice cap over New York City was higher the Free Tower (1776 feet) as CO_2 was 185 ppm!

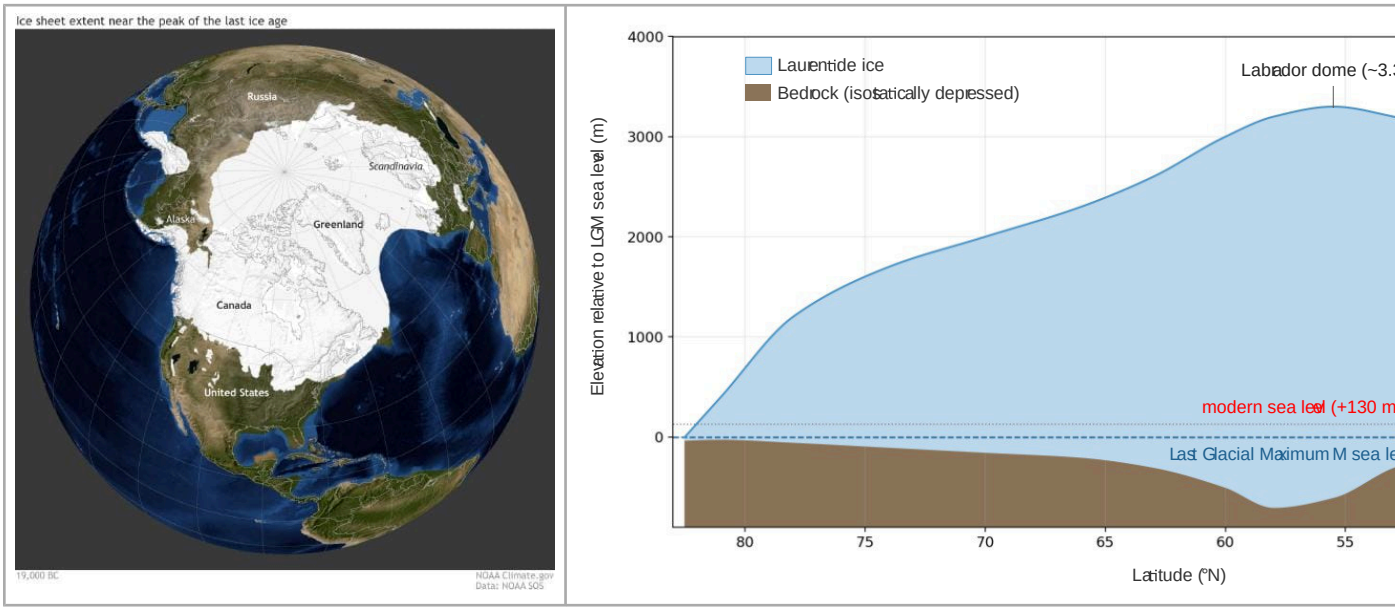


Figure 9.5.1.8: Left Panel - The Laurentide Ice Shield during the last ice age. Right Panel - its North-South Cross-Section at the Last Glacial Maximum (~21 kya) along ~74° W — Arctic Ocean → Labrador dome → New York City → terminal moraine. Based on ICE-6G_C (Peltier et al. 2015) and Dyke (2002). Vertical exaggeration ~500×. Sources: Peltier, Argus & Drummond (2015) J. Geophys. Res. — ICE-6G_C (VM5a); Dyke (2002); Lambeck et al. (2014) PNAS; NYC ice thickness ~600 m per revised estimates (NYT 2018, Merguerian). Graphic by Claude (Anthropic).

By 5000 BCE, the glacier had retreated to more modern levels, leaving ice over the Arctic Ocean and Greenland (see the interactive simulation of the deglaciation). CO_2 levels were around 260 ppm at the time. A change of just 100 ppm in CO_2 was

sufficient to melt the Northern Hemisphere glaciers. The image above is not "Northern Hemisphere-Centric," since the great glaciers were confined to the Northern Hemisphere during the ice ages. That's because glaciers grow over land, and most of the land on the planet is in the Northern Hemisphere. (Our climate studies won't include when one continent - Pangea- existed.) The video below shows an animation of the Northern Hemisphere ice shield from 19,000 BCE to now, with a projected future assuming little action to reduce CO_2 emissions. Pay special attention to the graphs, which also show sea level changes.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Best estimates by Tierney et al. now show that during the last ice age, the average global temperature was 6 degrees Celsius (11°F) cooler than today, which in the 20th century was 14°C (57°F). The Arctic, however, was much colder (about 14 °C/25 °F colder). The group also came up with an estimate of **climate sensitivity**, the increase in temperature with increasing CO_2. That value represents a **rise of 3.4 °C (6.1 °F) per doubling of CO_2**. In 1896, Arrhenius, recognizing that CO_2 was a greenhouse gas, calculated that doubling atmospheric CO_2 would cause a rise of 4-5 °C. No one can say we haven't known!

A new value for climate sensitivity, indicating a **warming of 4.8 °C (8.6 °F) per doubling of CO2,** was determined by Hansen et al. (2023) using more precise data on temperatures and CO_2 concentrations derived from isotopic analyses of ice core samples. If this value holds, the environment needed for human life and our present society is seriously jeopardized unless we take immediate measures to stop emissions and cool the planet. In addition, the rate of increase in global and ocean temperatures has accelerated after 2010, and the likely culprit is a decrease in toxic SO_2 aerosols emitted by ocean vessels in the North Pacific and Atlantic Oceans, as well as in China, due to the reduction of dirty coal-burning facilities. Aerosols reflect incident solar light and increase cloud formation, both of which help cool the planet. Paradoxically, reducing anthropogenic aerosols, while great for cardiovascular and pulmonary health, will accelerate global warming. India would be much warmer now if not for the high aerosol concentrations from smog that cover many of its large cities and countryside.

What the science shows

Climate, CO_2, and temperature have always changed over geological time, but the present rise in anthropogenic CO_2 over such a brief period is unprecedented. This has led to CO_2 levels far exceeding those during the warmer interglacial periods when Northern Hemisphere glaciers retreated.

The Ice Ages, CO_2, and Temperature

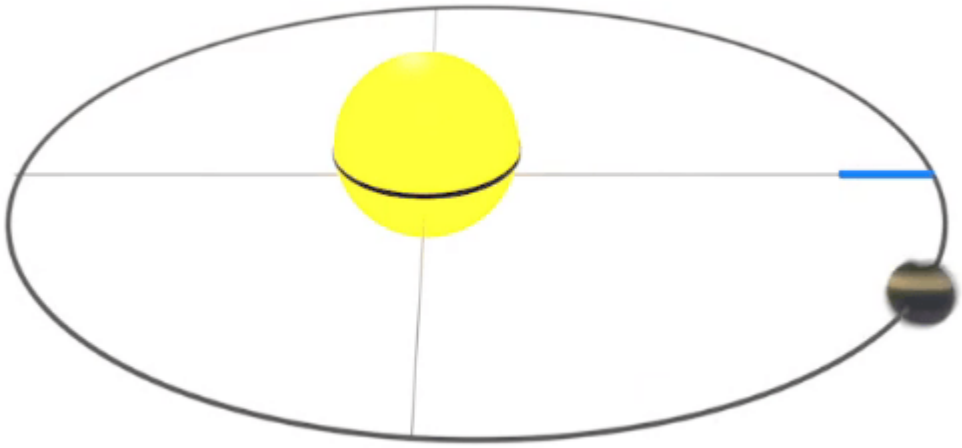
The Skeptic's Corner: Climate Change Misinformation

It's not CO_2 levels that are causing the observed increases in temperature. CO_2 levels are rising as temperatures increase, so we don't have to worry about them. It's a natural process requiring no action to reduce fossil fuel use. Why reduce it if it doesn't cause global warming?

Data and models show that the global increase in temperature is mainly driven by rising CO_2 levels (and not rising temperatures driving rising CO_2). That raises the question of what initiates deglaciation. It turns out that cyclic increases in solar irradiance that increase temperatures, especially in the Northern Hemisphere, start deglaciation. A prime factor is changes in the Earth's orbital dynamics around the Sun. As you know, the orientation of the Earth's rotation axis remains generally fixed and pointed in the same orientation as the Earth rotates around the Sun. This fixed orientation leads to Earth's annual spring, summer, fall, and winter cycles. In winter, the Northern Hemisphere is pointed away from the Sun, leading to decreased solar irradiance per square meter and causing winter there. When the Earth is on the opposite side of the Sun, the axis points in the same direction but

tilts towards the Sun, leading to summer in the Northern Hemisphere. However, the Earth's orbital dynamics do change cyclically over long periods. These long-term changes in the Earth's orbital shape (eccentricity), tilt (obliquity), and wobble (precession) are called the Milankovitch Cycle and are illustrated in Figure 9.5.1.8. These cycles cause small temperature increases that start deglaciation. **Click on each image below** to download and view short videos illustrating these orbital changes.

Change in eccentricity (orbital shape) - (100,000 yr cycle)



Change in obliquity (tilt) (41,000 yr cycle)



Axial precession (wobble) (26,000 yr cycle)



Figure 9.5.1.8: The Milankovitch cycle showing changes in the Earth's orbital dynamics with respect to the sun. https://climate.nasa.gov/news/2948/m...arths-climate/

Based on these cycles, Milankovitch calculated that recurring ice ages should occur approximately every 41000 years. Ice ages occurred at this interval, from about 3 million years ago (MYA) to 1 million years ago (MYA). About 800,000 years ago (mid-Pleistocene), they lengthened to about 100,000 years, corresponding to the Earth's eccentricity cycle. The increased cycle duration led to longer-lasting glaciers that moved further south into the Northern Hemisphere. This shift can't be accounted for solely by Earth's orbital eccentricity, since the change in solar irradiance wouldn't have been sufficient to cause it.

CORRECTION - 3/23/26: One likely explanation for the increase in time between ice ages during this **Mid-Pleistocene Transition (MPT)** was proposed by John A. Clark et al. It goes like this. Before extensive glaciation, the Earth's surface was exposed to significant weathering. This converted the outer rock layer in the Northern Hemisphere into broken rock, dirt, and dust, collectively called **regolith**. When ice sheets initially formed on the regolith, the ice slid more readily over it (lower frictional resistance), leading to faster ice-sheet spread and thinner ice sheets that melted more easily during deglaciation. The formation/melting of the ice shields was mostly affected (forced) by the obliquity of Earth's axis, which changed over a 40,000-year cycle.

Over time, the soft regolith was eroded and transported by the advancing glaciers. This left bare rock. Subsequent cycles of glaciation formed ice shields that moved more slowly and thus became thicker. These required longer melting times, supporting a shift to a 100 Kyr cycle. The glaciers then grew over 2 or more obliquity cycles. Evidence supporting this includes the absence of ancient regolith and the exposure of bedrock in Canada and Scandinavia. Punctuating these rhythmic orbital and ice-age cycles are other events, such as large volcanic eruptions and asteroid impacts, that can produce minor to major climate changes and resulting mass extinctions.



March, 2026. New ice core data from Antarctica offers another explanation for the 40Kyr-to-100Kyr transition during the Mid-Pleistocene and supports the role of the oceans in storing and releasing heat. These findings also increase our understanding of current climate change. Marks-Peterson et al. analyzed ice-core data from the Allan Hills Blue Ice Area (BIA) that formed over a continuous 3-million-year period. (These types of analyses will be discussed in subsequent chapter sections.) They could directly measure CO_2 and methane in individual ice core layers and determine the age of each vertical layer using ^{40}Ar dating. An old, long ice core is difficult to analyze because ice pressure fuses layers, making measurements more challenging. Given this compression, *an entire glaciation cycle would be condensed into a single layer in*

this analysis.

The data covered a different time sampling than the 800,000-year continuous ice core record (from EPICA Dome C and others) shown in Figure 4 above, which shows CO_2 changing from about 180 ppm during glacial maxima to ~280 ppm during interglacial periods, a net change of ~80-100 ppm. The paper examined whether the long-term baseline (a center with periodic increases and decreases) for CO_2 and CH_4 changed over 3 million years, though with lower time resolution due to compression, as described above.

The analysis showed no significant variation in average CO_2 across the Mid-Pleistocene transition, as CO_2 remained consistently low. The same finding was obtained for the **Pliocene-Pleistocene Transition** (~2.6 MYa) when CO_2 was about 250 ppm. CO_2 declined by only about 20 ppm (from roughly 250 ppm to 230 ppm) across the entire Pleistocene. Methane did not change. Yet average temperatures dropped more than 2 °C globally and 3.5 °C in the Antarctic. So, relative stability in CO_2 occurred from the start of Northern Hemisphere glaciation (around 2.6 MYA at the start of the Pleistocene) and the Mid-Pleistocene transition. Hence, CO_2 changes during these times can't solely contribute to changes in glaciation cycles from 40kYr to 100 kyr.

During these times, the extent of the Northern Hemisphere ice sheets increased dramatically. Hence, other factors contribute to cooling during these transitions. (Reminder: the Pleistocene Epoch,2.6 million–11,700 years ago, is the period of the ice ages, while the Holocene (11,700 years ago–present) is the current warm period, although many think we are in a new Epoch called the Anthropocene, representing human-driven environmental changes.) The pre-Industrial Revolution average CO_2 level of around 280 falls within the Pleistocene average range determined in the paper. Our present value of around 432 (6/13/26) is disastrously high and without precedent over the last 3 million.

The authors suggest that over time frames of millions of years (not the recurrent glaciation cycles over the last 800 MYr, which were driven by orbital and regolith changes), other factors, such as changes in the ocean circulation, increases in ice sheet reflection (albedo), feedback caused by plants, and additional geological changes. CO_2 remains tightly coupled to temperature on orbital timescales (the glacial cycles), but the long-term cooling trend appears to have been driven by other mechanisms. The data is consistent with the regolith explanation offered above for the 40KYr to 100KYr change in glaciation cycles.

Figure 9.5.1.9 shows how a combination of tilt angle, precession axis, and orbital shape at around 200 KYA (narrow rectangle across all the graphs) combined to lead to low glacial ice volume (bottom graph).

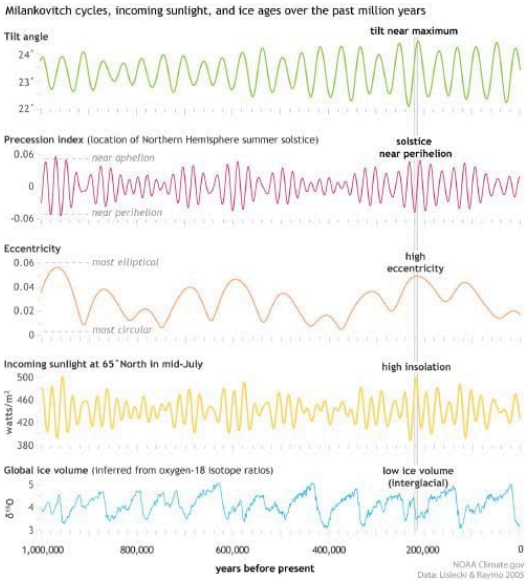


Figure 9.5.1.9: Milankovitch cycle contribution to ice volume over the past 1M years

If orbital changes (or **forcing**) trigger deglaciation, what is the role of increasing levels of the greenhouse gas CO_2, which covary with temperature (see Figure 3)? Temperature increases derived from orbital and hence solar "forcing" seem to precede CO_2 increases for short periods (perhaps 100 - 200 years). After that, CO_2 accounts for almost all of

the global temperature increase during deglaciation, with CO_2 and temperature rising together. A global increase of about 0.3 °C due to the Milankovitch cycle leads to greater Northern Hemisphere irradiance. This causes some localized melting of the Northern ice shield, leading to higher ocean temperatures in the Northern Hemisphere. These increases slow a major ocean current, the **Atlantic Meridional Overturning Circulation (AMOC)**, inhibiting the burial and return of cold water in tropical and southern oceans. This, in turn, led to a warming in the south, accompanied by the release of large amounts of CO2 stored in the oceans (see Carbon Cycle in 31.3). The release of this greenhouse gas was then responsible for most of the warming that led to massive degradation. This "interhemispheric see-saw" heat transfer from northern to southern waters is key. For most of the warming during glacial melting, CO_2 and temperature change synchronously.

Recent Updates: April 16, 2026

The graphic information and explanation of the AMOC in Figure 9.5.1.10 below were made using Claude AI.

Figures 9.5.1.10The AMOC. Anthropic. (2025). *Claude* (Claude Sonnet 4.6) [Large language model]. Retrieved May 2, 2025, from https://claude.ai.



April 15, 2026

Unfortunately, a recent report shows the AMOC has a 50% chance of weakening over this century. Here is the abstract and reference to the paper:

"Climate models show considerable discrepancies in their future projections around the Atlantic, mainly due to uncertainties in the fate of the Atlantic Meridional Overturning Circulation (AMOC). Climate models suggest a 32 ± 37% reduction in AMOC strength by 2100 (90% probability, Shared Socioeconomic Pathways 2-4.5 scenario). [The newer, most refined model] gives an estimate of the AMOC slowdown of 51 ± 8% (90% probability), i.e., a weakening ~ 60% stronger than suggested by the multimodel mean. This more substantial weakening of AMOC has key implications for future adaptation strategies. Valentin Portmann *et al*. project a ~50% weakening of the AMOC by the end of this century. *Sci. Adv*. **12**, eadx4298 (2026).DOI:10.1126/sciadv.adx4298

Here are some consequences of a slowing of the AMOC:

- a cooler, stormier climate, drier summers, and wetter winters in Europe, counteracting some of the warming in that area;
- the accumulation of warm water on the eastern North American coast, causing higher sea level rise compared to other regions (as warm water has a greater volume);
- major disruption of tropical rains, causing flooding and droughts in different regions, including the Amazon and tropical Africa;
- a strong decline in ecosystem mass over the North Atlantic, affecting the size and location of fish;
- a dangerous positive feedback loop of less CO_2 deposited and sequestered in the ocean, increasing atmospheric CO_2;
- changes in the jet stream with stronger westerly winds in mid-latitudes and an extension of the jet stream over the North Atlantic, having significant effects on weather and climate;
- In a more positive effect, the Arctic ice cap would likely expand.

Interpreting climate data is difficult. For example, measurements of $^{15}N/^{14}N$ ratios showed that gases like N_2 and, by extension, CO_2 could rapidly diffuse through the compacting snow (firn, comprising the top 50-100 meters of the ice cap) until they became trapped in the solid ice beneath it. This would lead to "newer" CO_2 in older ice samples, and the conclusion that temperature changes preceded changes in CO_2. The data are corrected to address the "apparent" time shift.

The CO_2 trapped in bubbles in Antarctic ice core samples reflects global CO_2 levels, given atmospheric circulation. However, the temperatures measured from the same core samples (see Chapter 31.2) represent **local** (Antarctic) temperatures. Ice core samples from Greenland and ocean sediment samples from around the world determine temperatures at different locations over

time. All of this data is required to model the climate. Taken together, they lead us to our present interpretation of the relationship between CO_2 and temperature rise over time.

What the science shows

Increased solar irradiance on Earth, resulting from cyclic changes in the Earth's orbit, leads to short, small temperature increases in the Northern Hemisphere. These increases lead to the release of the greenhouse gas CO_2 from the oceans, causing synchronous global warming and subsequent deglaciation.

So when skeptics say that temperature increases precede CO_2 increases, you can acknowledge they did, but that the bulk of the warming is attributed to increasing CO_2 released from ocean stores, leading to synchronous temperature increases and deglaciation. Using chemical terms, small temperature increases from orbital forcing catalyzed the release of large amounts of dissolved CO_2 from the ocean. Chapter 31.3 will explore the carbon cycle in greater detail and examine its effects on CO_2 levels.

Recent Updates: April 10, 2026

The Skeptic's Corner: Yes, CO_2 has increased, but its effects have plateaued, so no worries about additional fossil fuel emissions!

This is the argument of a preeminent physicist with expertise in spectroscopy but not in climate science. He states that the absorption of emitted infrared light by CO_2 (atm) has peaked because its concentration is high enough to saturate the absorption (0% transmittance), so extra CO_2 would have no effect. If so, we can continue burning fossil fuels without worrying about their effects on global warming. Climate scientists have refuted this idea using three main arguments.

1. Spectral line widening prevents saturation

Beer's Law states that $A_{667\ cm^{-1}\ or\ 15\ \mu M} = \varepsilon bc$, where c is the concentration. If there is sufficient CO_2 to absorb all the IR light at 15 μM, the signal saturates, and additional CO_2 won't absorb any more IR light. Hence IR emitted by the Earth at 15 μM wavelength escape into space without further warming of the planet. However, the main absorbance band at 15 μM is broad and widens with increasing CO_2, so additional CO_2 can still absorb and trap IR at the wavelengths (or "wings") surrounding the main 15 μM peak. This is illustrated in Figures 9.5.1.11 below.

Figure 11: IR transmission spectra of CO_2 with increasing CO_2. Drag the sliders to see the band broaden in real time. The dashed blue line shows the pre-industrial baseline (280 ppm) for comparison. *Claude* (Claude Sonnet 4.6) [Large language model]. Retrieved May 2, 2025, from https://claude.ai.

The main peak broadens due to collisions with molecules (most notably O_2 and N_2). At higher pressure (lower altitude, as in the troposphere), there are more collisions per second, and the wings are wider as the energy levels for the absorption are perturbed. You can see this by dragging the pressure slider — lower pressure (higher altitude) narrows the band. Another factor leading to broadening is the Doppler effect. If a photon and CO_2 are moving in different directions during absorption, the photon's frequency changes slightly, leading to band broadening. You likely associate the Doppler effect with a shifting frequency of a siren moving away from you.

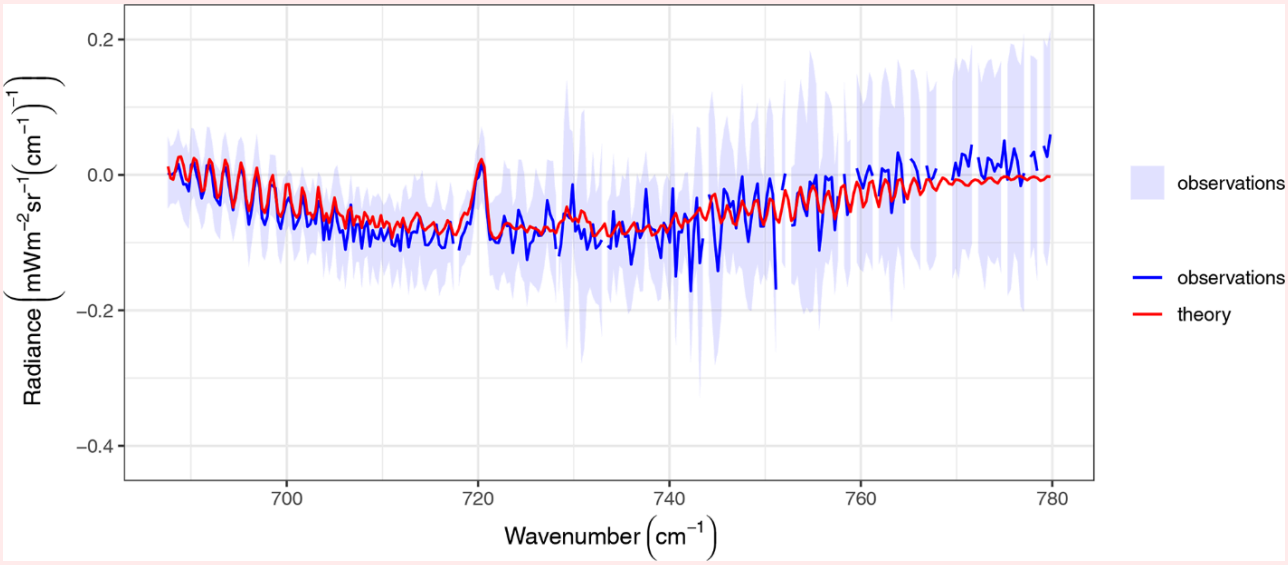
It is well known that doubling the CO_2 concentration does not double the temperature. This assumes a linear relationship between the two. Rather, a doubling of CO_2 produces a net increase but far less than a doubling of the temperature change, so the relationship is logarithmic in CO_2, not linear. This suggests some but not complete saturation of the CO_2 infrared absorption. We've explored **climate sensitivity**, the increase in temperature with increasing CO_2, earlier in this section, and showed that a doubling of CO_2 gives an increase of 3.4 °C (6.1 °F) or possibly even higher. Climate sensitivity is included in all climate models, so any saturation effect is already accounted for.

2. CO_2 is distributed in the upper troposphere and stratosphere

CO_2 is not only near the ground where it is emitted. In the upper troposphere and stratosphere, its concentration is lower, and the atmosphere is much less "saturated," yet infrared light is still absorbed. Moreover, at these heights, less heat is radiated back into space, as colder objects radiate less.

3. Direct satellite data show a decrease in IR radiation from the atmosphere with increasing CO_2

This is clearly the "smoking gun" to refute the saturation argument. Figure 9.5.1.12 below shows the annual mean radiance differences from the Earth due to CO_2 increases. The data are from the Atmospheric Infrared Sounder (AIRS) satellite (blue line) and are compared with theory (red line) during 2003–2012.



Figures 9.5.1.12: Annual mean radiance differences (in $\text{mW m}^{-2}\,\text{sr}^{-1}\,(\text{cm}^{-1})^{-1})^{-1}$) due to CO_2 increase from the AIRS observations (blue line) and from theory (red line) and standard deviations for the AIRS observations (blue shading), illustrating the direct impact of CO_2 increase on the spectral radiances during the 2003–2012 period. João Teixeira, R. Chris Wilson, and Heidar Th. Thrastarson. Atmospheric Chemistry and Physics. 24, 6375–6383, 2024. https://doi.org/10.5194/acp-24-6375-2024. Creative Commons Attribution 4.0 License.

Here is the significance of these observations taken directly from the paper: "This figure is focused on the 680-to-780 cm^{-1} spectral range, which represents the R branch of the 15 µm CO_2 band and is a spectral region where the CO_2 signal is particularly significant. In this spectral region, enhanced absorption in the troposphere, where temperature decreases with height, reduces outgoing "infrared" radiation (y-axis values are negative). From a broader climate perspective, the reduction in outgoing radiation drives the increase in global surface temperature necessary for the overall climate system to re-establish energy balance at the top of the atmosphere, and, as such, it is a critical component of global warming. During this period, the measured monthly mean CO_2 mole fraction at Mauna Loa increased on average by approximately 2 ppm yr^{-1}".

The main proponent of the saturation argument is leading the present US administration's efforts to refute the overwhelming scientific consensus on the primary cause of current climate change: CO2 emitted by burning fossil fuels.

We refute another of his arguments, that increasing CO_2 is good for the planet since it is merely plant food, in another section.

Termination of the Ice Ages

How did the ice ages terminate? Contributions from orbital forcing derived from the Milankovitch cycle also play a role. Another factor seems to be dust derived from regolith, produced by glacier movement, as mentioned above. How can that hypothesis be tested? Using proxies for dust, namely iron and long-chain n-alkanes (derived from plant waxes) that have been deposited in sediments. First, look at a graph of CO_2 and temperature changes and superimpose those on iron and long-chain fatty acid levels, as shown in Figure 9.5.1.13.

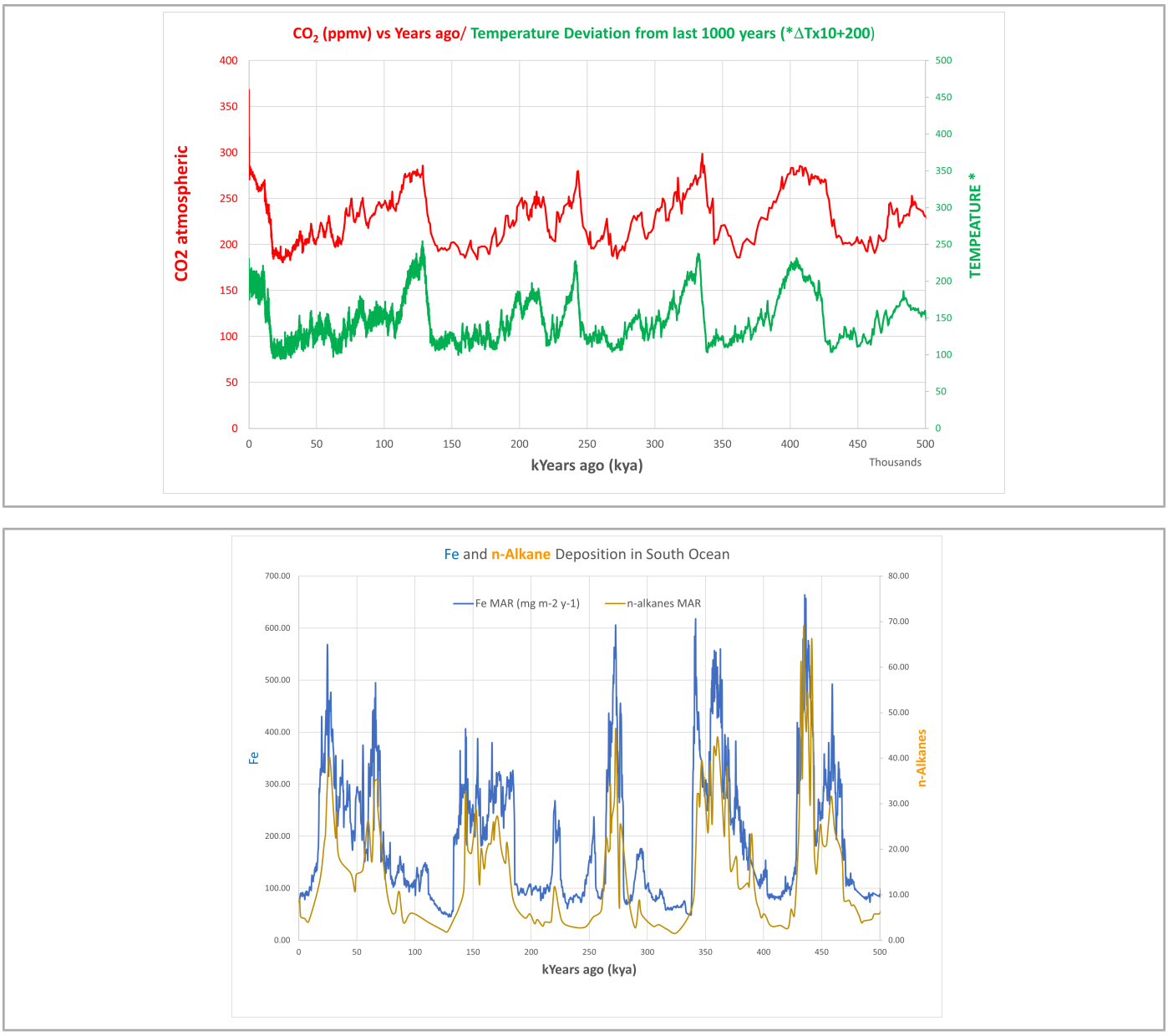


Figure 9.5.1.13: Fe and n-alkane deposition compared to CO_2 and temperatures in the Southern Ocean over the last 500,000 years. Note that the x-axis shows time in kYA going to the right. (so the past is towards the right).

A close examination of the two vertically aligned graphs from around 120 K to 130 KYA shows that iron and n-alkane depositions are at a minimum while CO_2 and temperature are peaking! What explains this negative correlation? It depends on the biosphere's intimate connection to the nonbiological world (an arbitrary distinction).

Iron and n-alkanes are circulated and delivered in dust. The long-chain alkanes, highly abundant in waxes and enriched in odd-carbon-number chains, were presumably derived from leaf waxes, which prevent water loss from plants, especially at higher temperatures. Dust deposits were first observed in geological time during the transition from the warmer Pliocene (5.3 to 2.6 MYA) to the Pleistocene (2.6 MYA to 11.7 KYA; see Figure 8 below). During the warmer Pliocene, the difference between global and atmospheric temperatures was smaller, and with this smaller temperature gradient, winds capable of transporting dust globally would be diminished. Also, the warmer Pliocene (5.3 to 2.6 MYA) would have had more rain, which would have removed dust from the global circulation.

As temperatures cooled in the Pleistocene (2.6 MYA to 11.7KYA), cycles of glaciation would produce more dust-containing regolith (rocks, soil, and dust) at the southern ends of the ice shield, which would be dispersed by stronger global winds driven by higher

temperature gradients and less rainfall. Dust contains carbon (for example, long-chain fatty acids) and, perhaps more importantly, iron, which is needed for oceanic phytoplankton growth. Without Fe, the uptake of CO_2 by phytoplankton (primary production) would not occur, leading to increased CO_2 in the atmosphere. Stronger regional atmospheric winds would increase nutrient upwelling and deep-ocean CO_2 release. The CO_2 would enter the atmosphere more readily in the absence of iron dust deposition.

In summary:

- High CO_2 and high temperature (lower global temperature gradients, more rain) are associated with lower dust levels, as indicated by proxies Fe and n-alkanes. Low dust levels reduce the deposition of Fe and n-alkanes in the ocean, thereby decreasing phytoplankton primary production and CO_2 fixation into biomass. This leads to increased CO_2 transfer from the ocean to the atmosphere, thereby increasing atmospheric temperature. This is an example of a positive feedback loop (higher temperatures leading to higher temperatures).
- Low CO_2 and low temperature (higher global temperature gradients, stronger winds, less rain) are associated with high dust deposition of Fe and n-alkanes. This increases phytoplankton primary production and decreases CO_2 flux from the ocean to the atmosphere, forming a negative feedback loop.

By the end of a glacial deposition cycle, dust, blown by stronger winds from higher temperature gradients, was increasingly deposited on the ice sheets. In addition to increasing the sheets' heat absorption, it would also decrease their reflectivity (albedo). Both effects would promote ice sheet melting. Also, a cooler planet during the glacial maximum had less precipitation, which, along with lower CO_2, would lead to more plant and tree death, increasing soil erosion and desertification, both effects which would have increased dust production and its deposition on ice sheets. Then, when CO_2 rose to 280 ppm, plant life renewed, and dust levels dropped.

Climate change from 66 million years ago to now

Antarctic ice core data cover the last 2 million (M) years. Ocean sediment data can go back 66 million years (MYA), just before the dinosaurs died following the massive asteroid impact that formed the Chicxulub crater, buried beneath the Yucatán Peninsula in Mexico. A brief review of geological eras, periods, and epochs is shown below in Figure 9.5.1.14

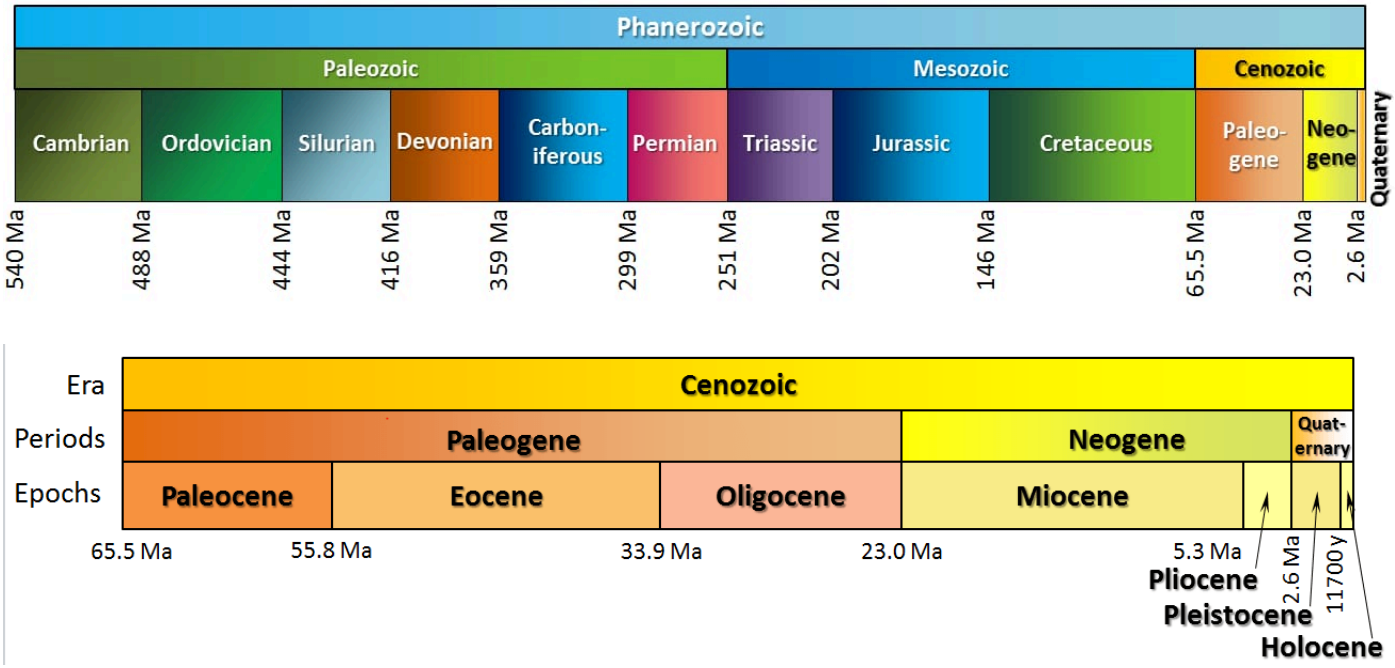


Figure 9.5.1.14: Geological Era, Periods and Epochs

CO_2 levels and associated temperatures derived from ocean sediment cores going back to 66 MYA are shown in Figure 9.5.1.10.

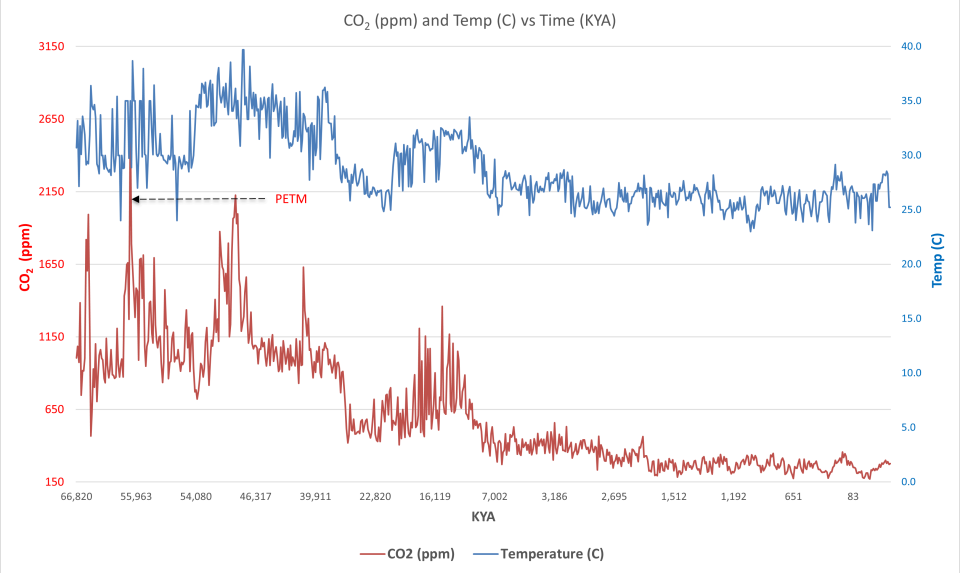


Figure 9.5.1.14 CO_2 levels (red) and temperatures (blue) derived from ocean sediment cores going back to 66 MYA = 66,000 KYA. Data from Rae et al. Annual Review of Earth and Planetary Sciences, 49, 2021

Again, note the parallel rise and fall of CO_2 and temperature. Eventually, they fell further during the Pliocene (5.3 to 2.6 MYA) and Pleistocene (2.6 MYA to 11.7KYA) epochs, with cyclic glacial/interglacial periods we've discussed above. Northern hemisphere glaciation started in the late Miocene (10 to 6 MYA), and both poles of the planet had glacial sheets.

The time frame shown in Figure 9 encompasses the Cenozoic era (from 65 MYA, when the dinosaurs died, to the present). CO_2 levels were much higher than today in the greenhouse Paleocene and Eocene eras, but decreased to about 500 ppm in the Oligocene (34 MYA). An almost stepwise drop in CO_2 and temperature occurred during the **Eocene-Oligocene transition (EOT)**, about 33 MYA. Data show the development of large ice sheets in Antarctica at that time. Before the EOT (33 MYA), Antarctica was ice-free, as shown in the recreation in Figure 9.5.1.15.



Figure 9.5.1.15: Reconstruction of the West Antarctic mid-Cretaceous temperate rainforest. Image credit: J. McKay / Alfred-Wegener-Institut / CC-BY 4.0. https://www.sci.news/othersciences/p...ing-09921.html

Proxy temperature data indicate that the transition was most likely driven by decreased CO_2, with some orbital forcing probably involved. Present models still struggle to explain the EOT (33 MYA) transition, but it is clear that both CO_2 and temperature

decreased. Where did the CO_2 go? Most assuredly into the oceans.

To understand that, we need to know a bit about the carbon cycle, which we will discuss in more detail in the next chapter. Let's briefly discuss the role of atmospheric CO_2 and its interaction with the ocean. The main atmospheric gases, N_2 and O_2, are present at very low concentrations in the ocean because they are nonpolar and generally unreactive. CO_2 is also a nonpolar trace gas, but unlike other nonpolar gases, it can readily react with water to form HCO_3^- and CO_3^{-2}, which are abundant in ocean reserves. Hence, ocean chemistry of CO_2 largely determines atmospheric CO_2 levels. The coupled reactions of CO_2 are shown below.

$$\mathrm{CO_2(\ g,\ atm) \leftrightarrow CO_2(aq,\ ocean)} \tag{9.5.1.2}$$

$$\mathrm{CO_2(aq,\ ocean\ ) + H_2O(I,\ ocean\ ) \leftrightarrow H_3O^+(aq) + HCO_3^-(aq)} \tag{9.5.1.3}$$

$$\mathrm{H_2O(I) + HCO_3^-(aq) \leftrightarrow H_3O^+(aq) + CO_3{}^{2-}(aq,\ sparingly\ soluble\ )} \tag{9.5.1.4}$$

This chemistry helps determine the ocean's pH. Figure 9.5.1.16 shows atmospheric CO_2 and ocean pH levels over the last 66 million years.

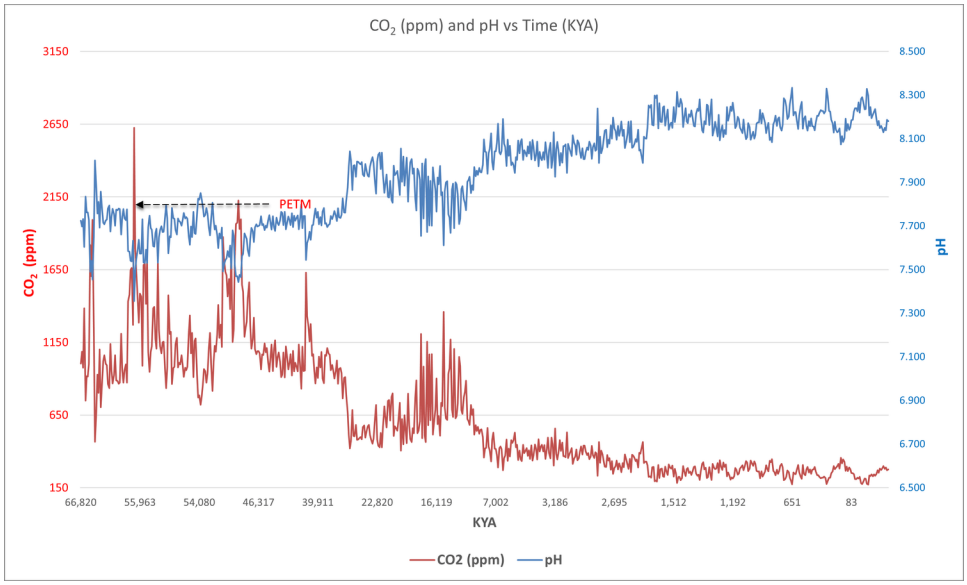


Figure 9.5.1.16: Atmospheric levels of CO_2 and ocean pH over the last 66 million years

Before the EOT at 34 MYA, atmospheric CO_2 levels were higher and ocean pH levels lower (around 7.7). After the EOT (33 MYA), atmospheric CO2 is much lower, and ocean pH is higher (more basic, 7.9, rising to 8.1). What happened to the CO_2 is a bit unclear. Atmospheric CO_2 decreased as it moved into the oceans, but wouldn't that have lowered pH based on the chemical equations presented above? It would have, but it turns out that the ocean alkalinity is determined not just by H_3O^+ produced by the equations above but by the dissolved inorganic carbon ions, HCO_3^- (aq) and CO_3^{2-} (aq), which are conjugate bases. Increased HCO_3^- (aq) and SiO_4^{-2} (aq) from weathering solid carbonates and silicates that entered the oceans would raise ocean pH.

A little review of introductory chemistry helps here.

Let's take bicarbonate, the weak conjugate base of the weak acid carbonic acid. HCO_3^- can act as both an acid and base.

Rx 1: Acts as an acid: HCO_3^- (aq) + H_2O (l) ↔ H_3O^+(aq) + CO_3^{2-} (aq)

$$K_{a2} = \frac{[\mathrm{H_3O^+}]\,[\mathrm{CO_3^{2-}}]}{[\mathrm{HCO_3^-}]} = 4.7 \times 10^{-11} \tag{9.5.1.5}$$

Rx 2: Acts as a base: HCO_3^- (aq) + H_2O (l) ↔ H_2CO_3 (aq) + OH^- (aq)

$$K_{b2} = \frac{[H_2CO_3]\,[OH^-]}{[HCO_3^-]} = 2.2 \times 10^{-8} \tag{9.5.1.6}$$

The equilibrium constant for the reaction of HCO_3^- as a base is much larger, so bicarbonate is a stronger base than an acid.

Whatever the mechanism of CO_2 drawdown, it led to lower temperatures during the EOT transition. The ocean's increased alkalinity also consumed H_3O^+, increasing ocean pH.

Figure 9.5.1.17 summarizes planetary temperatures across geological time.

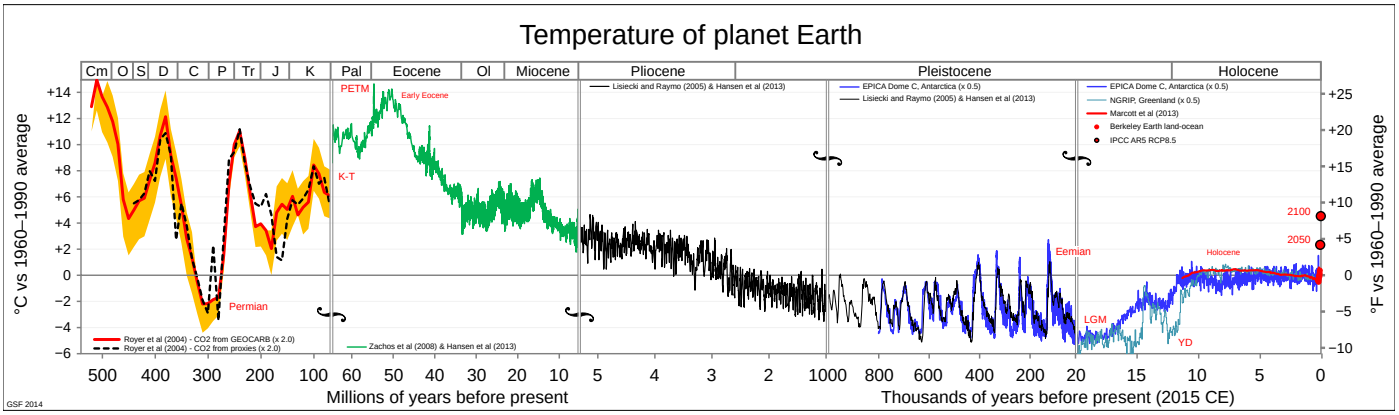


Figure 9.5.1.17: Earth's temperature over 500 million years. https://commons.wikimedia.org/wiki/F...alaeotemps.png. (Excel available). Creative Commons Attribution-Share Alike 3.0 Unported

Several key features should be noted. The last time CO_2 was as high as today (415 ppm) was about 3 million years ago. Repetitive cycles of glaciation/deglaciation are obvious in the Pleistocene (2.6 MYA to 11.7 KYA).

Note: This figure has been misinterpreted, leading to misinformation in the popular press and some podcasts, as it shows a general decrease in atmospheric CO_2 levels since the end of the dinosaurs (65 MYA). Climate skeptics would say the Earth is way cooler than in the past, which is true, but none of us would like to live in the time of the dinosaurs! Homo sapiens likely originated about 300K years ago and left Africa in waves, with the first around 150KYA and the most consequential around 60 KYA. We evolved, lived, and developed civilizations in climatic conditions set by CO_2 levels much lower than today's. The figure shows that our current CO_2 levels most closely resemble those of 3-4 million years ago. At that time, Earth's temperature was likely 3 °C above today's level, and the seas were 25 meters higher than they are today. In addition, the steep slope of the present CO_2 rise appears to be unprecedented in Earth's historical record.

At around 56 MYA, a temperature spike of about 5^0 - $9\ ^0$F (or even more) on an already warmer planet occurred over about a 100 K-year timeframe. This is known as the **Paleocene/Eocene thermal maximum (PETM)**. It is the closest example to the current rate of CO_2 injection into the atmosphere, so it gives us a basis for what we may see with our current CO_2 spike. The poles warmed to nearly $70\ ^0$F, and alligators and palm trees were found there. The warming also led to the spread of tropical rainforests away from the equator, allowing the evolution and proliferation of new plant species, including flowering plants, and an incredible biodiversity of insects, birds, and other animals that relied on them. Flowering plants produce fruits, which helped drive the evolution of mammals and the first true primates, including the tiny Teilhardina magnoliana. It may have resembled the picture in Figure 9.5.1.18 below. (https://en.wikipedia.org/wiki/Teilhardina). Big eyes and hands would help them find fruit in tropical forests.



Figures 9.5.1.18: Teilhardina magnoliana

The temperature increase was caused by a dramatic spike in CO_2 from deep-sea volcanoes and vents, which also led to a dramatic drop in ocean pH as measured by the loss of deep-sea $CaCO_3$ (chalk). Methane hydrates were also released. These environmental and biosphere changes are visually evident in geological deep-sea sediment records as shown in Figure 9.5.1.19.

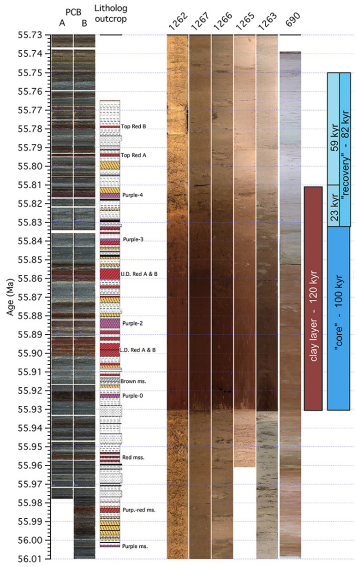


Figure 9.5.1.19: Overview of the Paleocene–Eocene Thermal Maximum (PETM, 55.5 MYA) data from deep-sea records and the terrestrial Polecat Bench
(PCB) drill core against age. Westerhold et al. Clim. Past, 14, 303–319, 2018. https://doi.org/10.5194/cp-14-303-2018. Creative Commons Attribution 3.0 License

Sediment cores were taken at various sites (1262, 1267, 1266, 1265, 1263, and 690) and arranged from left to right in order of water depth, from deep to shallow. Note that 55.93 million years ago, at the start of the PETM, there was a sharp transition from light brown/gray, enriched in chalk, to dark brown, enriched in clay. Ocean acidification dissolved the chalk. It took over 100,000 years to recover.

This very short time frame is called the **Paleocene/Eocene Thermal Maximum (PETM**, 55.5 MYA), which shows that very quick spikes (on the geological time scale) can and do occur. Approximately 1.5 petagrams (10^{15}) of CO_2 were released annually during

the PETM. We are now releasing about 25 petagrams per year. Our current rate of warming is much higher than during the PETM (55.5 MYA). The best candidates for the source of CO_2 responsible for the PETM are volcanoes, the oceans, and permafrost. Methane hydrates (a solid form of methane found in low-temperature, high-pressure waters) might also be another factor.

The PETM and the period that followed enabled the optimal evolution of primates. That time might be called the Age of the Primates (analogous to the Age of the Dinosaurs). Figure 13 shows that the onset of the Oligocene was accompanied by much lower temperatures due to CO_2 drawdown. This decimated primate habitats, except in tropical rainforests. Primates disappeared completely from North America but thrived in Africa. Tectonic forces generated the African Rift Valley, characterized by diverse geology and a less homogeneous, more fractured landscape, which again posed new challenges but also provided new habitats for the evolution of primates and the eventual appearance of Homo Sapiens.

Update from December 3, 2023, Science

In December 2023, a refinement of CO_2, temperature, and sea-level-rise data since the demise of the dinosaurs 65 million years ago was published. (The geological interval from 66 million years ago to now is called the Cenozoic Era and consists of 3 periods: the Paleogene until 23 MYA, the Neogene until 2.6 MYA, and the Quaternary.) A group, the Cenozoic Carbon Dioxide Proxy Integration Project (CenCO2PIP) Consortium, reviewed and reevaluated all "proxy" measurements used to determine past climate conditions (we will discuss proxies using isotope ratios in ice cores and sediments as proxies for actual CO_2, temperature, and sea level changes in the next few sections). Figure 9.5.1.20 below shows the revised data, representing our best. For this work, pay close attention to graphs A (CO_2), B (relative temperature changes), and C (sea level changes). Note that CO_2 levels in 2022 were last seen 14 million years ago!

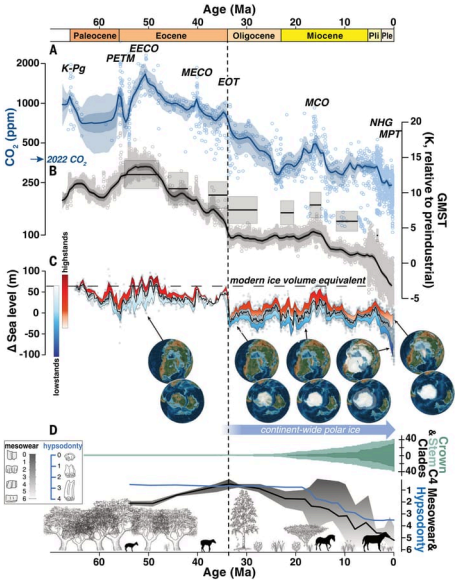


Figure 9.5.1.20: Category 1 paleo-CO_2 record compared to global climate signals. From The Cenozoic CO_2 Proxy Integration Project (CenCO_2PIP) Consortium, Toward a Cenozoic history of atmospheric CO_2.*Science***382**, eadi5177(2023). DOI:10.1126/science.adi5177. Reprinted with permission from AAAS.

The legend below is directly taken from the Science article. The vertical dashed line indicates the onset of continent-wide glaciation in Antarctica.

(**A**) Atmospheric CO_2 estimates (symbols) and 500-kyr mean statistical reconstructions (median and 50 and 95% credible intervals: dark and light-blue shading, respectively). Major climate events are highlighted: K-PG, Cretaceous/Paleogene boundary; PETM, Paleocene Eocene Thermal Maximum; EECO, Early Eocene Climatic Optimum; MECO, Middle Eocene Climatic Optimum; EOT, Eocene/Oligocene Transition; MCO, Miocene Climatic Optimum; NHG, onset of Northern Hemisphere Glaciation; and MPT, Mid-Pleistocene Transition. The 2022 annual average atmospheric CO_2 of 419 ppm is indicated for reference.

(**B**) Global mean surface temperatures estimated from benthic $\delta^{18}O$ data following Westerhold *et al.* (solid line, individual proxy estimates as symbols, and statistically reconstructed 500-kyr mean values shown as the continuous curve, with 50 and 95% credible intervals) and from surface temperature proxies (gray boxes).

(**C**) Sea level, with gray dots displaying raw data; the solid black line reflects median sea level in a 1-Myr running window. High- and lowstands are defined within a running 400-kyr window, with lower and upper bounds of highstands defined by the 75th and 95th percentiles and lower and upper bounds of lowstands defined by the 5th and 25th percentiles in each window. Globes depict select paleogeographic reconstructions and the growing presence of ice sheets in polar latitudes.

(**D**) Crown ages show that C_4 clades, with CCMs adapted to low CO_2, initially diversified in the early Miocene, and then rapidly radiated in the late Miocene. Flora transitioned from dominantly forested and woodland to open grassland habitats based on fossil phytolith abundance data. North American equids typify hoofed animal adaptations to new diets and environments, including increased mesowear (black line; note the inverted scale), hypsodonty (blue line), and body size.

The results reconfirm the strong correlation between CO_2 and temperature over geologic time, but there are some time intervals when they were out of synchrony. One example is from 37 to 34 MYA, around the Eocene-Oligocene transition (EOT), as described above. In Figure 15, CO_2 didn't change much as the Earth cooled prior to the EOT. In contrast, CO_2 levels dropped sharply during the Oligocene, while temperatures remained flat. The start of the Oligocene also saw a large drop (55 m) in sea levels, coincident with the EOT, the fall in temperatures, and the rise in glaciation. The authors state that some of the divergences in CO2 and temperatures are likely not directly related to CO_2 but to other variables, such as changes in "paleogeography" arising from continental drift, plate tectonics, etc., that might have altered ocean currents, as well as changes in the reflectivity of sunlight. In addition, the proxies used for those times might have been affected by unaccounted-for changes in seawater composition and pH.

This extensive data presented an opportunity of calculate the climate sensitivity (how much temperature changes with a doubling of CO_2) as we discussed above. The value calculated by Tierney was about 3.4 °C (6.1 °F), although Hansen's recent estimate is higher. This particular value is the equilibrium climate sensitivity (ECS), which includes relatively fast feedbacks like cloud cover and sea ice that act over 100s of years. The value calculated in the new study is not as fine-grained (coarser) at resolutions of 1000s of years, so instead they calculate a much longer-term climate sensitivity called the Earth Systems Sensitivity (ESS) that includes long-term (geological time) events such as changes in continent-wide ice sheets. The value of ESS is between 5°C (9°F) and 8°C (14.4°F), much higher than the ECS widely accepted today. A doubling of CO_2 without some mechanism for drawdown, if sustained over geological time, would transform the world of the distant future. It would be similar to conditions during the Paleocene/Eocene Thermal Maximum (PETM), when the poles warmed to near 70°F, allowing alligators and palm trees to occur there.

This chapter is divided into two sections. Read Chapter 01B, "Back to the Present and Future of Climate Change," to see where we are and where we are headed!

Summary

(Summary written by Claude, Anthropic)

This chapter introduces the fundamental science behind climate change, focusing on how human activities have altered the Earth's energy balance and disrupted long-established climate patterns. Key points include:

- **Historical Foundations and Urgency:**
    - Early studies by Eunice Foote and John Tyndall laid the groundwork for understanding the greenhouse effect.
    - Modern climate models (developed since the 1980s) and recent observations confirm that anthropogenic CO_2 emissions are driving rapid global warming, necessitating immediate and aggressive action.
- **The Greenhouse Effect and Energy Imbalance:**
    - Earth's climate is maintained by a balance between incoming solar radiation and outgoing infrared radiation.
    - Greenhouse gases such as CO_2, methane (CH_4), and nitrous oxide (N_2O) absorb infrared radiation, effectively insulating the planet.
    - Pre-industrial CO_2 levels (~280 ppm) have risen to 427 ppm as of January 2025, upsetting this balance and storing excess energy primarily in the oceans.
    - The current energy imbalance is significant—equivalent to detonating several Hiroshima-type atomic bombs every second—illustrating the unsustainability of current trends.
- **Global Warming Potential (GWP):**

- GWP is a metric used to compare the warming effects of different greenhouse gases in CO_2-equivalents over a 100-year period.
- Although CH_4 is more potent on a per-mass basis over short time frames, CO_2 remains the principal concern due to its long atmospheric lifetime and cumulative impact.

- **Climate Variability Over Geological Time:**
  - Ice core data reveal that while CO_2 and temperature have fluctuated naturally over the past 800,000 years, the recent rapid rise in CO_2 levels is unprecedented.
  - The chapter discusses glacial-interglacial cycles, highlighting how relatively small changes in CO_2 (100 ppm) historically corresponded with major shifts in global climate.

- **Orbital Forcing and Feedback Mechanisms:**
  - The Milankovitch cycles (changes in Earth's eccentricity, obliquity, and precession) initiate small temperature increases that trigger deglaciation.
  - These temperature rises lead to the release of CO_2 from the oceans, amplifying warming through positive feedback loops.
  - Dust feedbacks are also explored, showing how variations in dust deposition can either enhance or mitigate warming by influencing phytoplankton growth and planetary albedo.

- **Long-Term Climate Change and Carbon Cycle Interactions:**
  - The chapter reviews data spanning from 66 million years ago to the present, illustrating how CO_2 levels and global temperatures have paralleled each other over geological time.
  - Major events such as the Paleocene–Eocene Thermal Maximum (PETM) are discussed, providing context for the rapid changes occurring today.
  - The interactions between atmospheric CO_2 and ocean chemistry are detailed through chemical equilibria, explaining shifts in ocean pH and alkalinity that accompany changes in CO_2 concentrations.

- **Implications for Future Climate:**
  - Updated data indicate that equilibrium climate sensitivity (ECS) and the longer-term Earth Systems Sensitivity (ESS) may be higher than previously estimated, suggesting that a doubling of CO_2 could eventually raise global temperatures by 5–8 °C.
  - The chapter concludes by emphasizing the critical need to address CO_2 emissions to avoid future climate scenarios that could jeopardize human habitability and ecosystem stability.

Overall, this chapter provides a comprehensive framework that combines historical context, physical principles, and biochemical processes to explain current climate change. It lays the groundwork for understanding how climate dynamics are interconnected with global biogeochemical cycles, setting the stage for further exploration of climate mitigation and adaptation strategies in subsequent sections.

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9.5.2: Back to the Present and Future of Climate Change

Search Fundamentals of Biochemistry

Learning Goals

(Learning goals written by Claude, Anthropic)

By the end of this chapter, students should be able to:

Anthropogenic Forcing and Historical Climate Context

- Explain why the rapid rise in atmospheric CO_2 since the Industrial Revolution (~1760) cannot be attributed to natural factors such as changes in orbital mechanics, solar irradiance, volcanic activity, or land use changes alone—and describe how NASA climate models demonstrate that only the addition of anthropogenic greenhouse gas forcing accurately reproduces observed global temperature increases since 1880, while also explaining why the seasonal zig-zag in the CO_2 record reflects Northern Hemisphere photosynthesis and why rising methane (now contributing up to ~20% of observed warming) compounds the problem.
- Place the Little Ice Ages (c. 1450–1850) and the 536 AD cooling event in mechanistic context: explain how small decreases in solar irradiance (Maunder Minimum, ~0.06% decrease), multiple volcanic eruptions (Mount Tambora 1815, Iceland ~536 AD), and changes in the Atlantic Meridional Overturning Circulation (AMOC) contributed to these historical cooling events—and use these examples to explain the climate system's sensitivity to relatively small radiative forcings, while arguing that none of these mechanisms can account for current warming and that predicted anthropogenic warming would produce far more severe and potentially irreversible consequences.
- Explain the concept of climate sensitivity and Earth's Energy Imbalance (EEI): describe how EEI has risen from ~+0.6 W/m^2 in 2000 to ~+1.0 W/m^2 in 2021 and the implications of Hansen et al.'s 2023 revised climate sensitivity estimate of 4.8°C per CO_2 doubling for the feasibility of keeping warming below 1.5°C—and explain the paradoxical warming effect of reducing sulfate aerosols (required by clean air legislation), noting that aerosols that cool the planet through solar reflection and cloud formation also cause severe cardiovascular, pulmonary, and cancer diseases.

Climate Projections, Scenarios, and Justice

- Compare and contrast the IPCC RCP/SSP climate scenarios and the newer CMIP7 emission-based scenarios: explain how the RCP framework characterized scenarios by radiative forcing (W/m^2), the SSP framework added socioeconomic and political dimensions, and CMIP7 replaces these with scenarios named by emission trends (Very Low through High, including High-to-Low and Low-to-Negative trajectories)—and explain why the previously included RCP 8.5 scenario has been retired as the most likely worst-case in CMIP7 given current clean energy progress, while still serving a legitimate purpose as an upper boundary condition analogous to Monte Carlo scenario modeling in finance.
- Describe the inequity of historical CO_2 emissions and its implications for climate justice: explain how the United States has emitted the most cumulative CO_2 per capita since the Industrial Revolution despite China being the current largest net emitter, how the wealthiest 20% of the global population contributes ~86% of emissions, how countries like Pakistan suffer disproportionate climate impacts despite minimal historical contributions, and articulate why the largest historical emitters bear the greatest responsibility for emissions reduction, financing clean energy transitions in developing nations, and supporting climate mitigation and adaptation globally.

The Sulfur Cycle and Climate Feedbacks

- Describe the biochemistry of dimethylsulfide (DMS) and dimethylsulfoniopropionate (DMSP) production and their roles in the global sulfur cycle and climate: explain how DMSP is synthesized from methionine via methylation, transamination, or decarboxylation pathways in marine phytoplankton, algae, bacteria, and some higher plants (using enzymes such as MMT, DSYB/DsyB, and DDSC); how DMSP lyase (Ddd) cleaves DMSP to release DMS; how DMS is released to the atmosphere where it forms sulfate aerosols that reflect solar radiation, promote cloud formation, and cool local climate; and why intracellular DMSP at millimolar concentrations also functions as an osmolyte for marine organisms in hyperosmotic seawater environments.

Back to the Recent Past and Present

Let's return to more recent human history and the anthropogenic forcing of our climate. Figure 9.5.2.1 shows atmospheric CO_2 levels since 1000. Zoom in on the steep rise in CO_2 that started around 1760 with the Industrial Revolution

Figure 9.5.2.1: An interactive graph of atmospheric CO_2 over more recent times.

Zoom in on the steep rise in CO_2 that started around 1760 with the Industrial Revolution. Figure 9.5.2.1: Interactive graph of atmospheric CO_2 vs time over the last 1000 years. Historical CO_2 record from the Law Dome DE08, DE08-2, and DSS ice cores. Credits: D.M. Etheridge, L.P. Steele, R.L. Langenfelds, R.J. Francey and the Division of Atmospheric Research, CSIRO, Aspendale, Victoria, Australia. 2 Degrees Institute. https://www.2degreesinstitute.org/. Also, https://www.co2levels.org/

Orbital mechanics **cannot** explain the planet's warming over the brief (geological) period since the Industrial Revolution. Neither can volcanic activity, changes in solar activity, changes in land use (for example, deforestation that slows photosynthesis and CO_2 removal from the atmosphere), or even aerosols released by burning fossil fuels (which would decrease global temperature by increasing the reflection of sunlight). Click on Figure 9.5.2.2 to see an animated explanation of which factors best explain the global temperature increase since 1880. The results are clear: It's us!

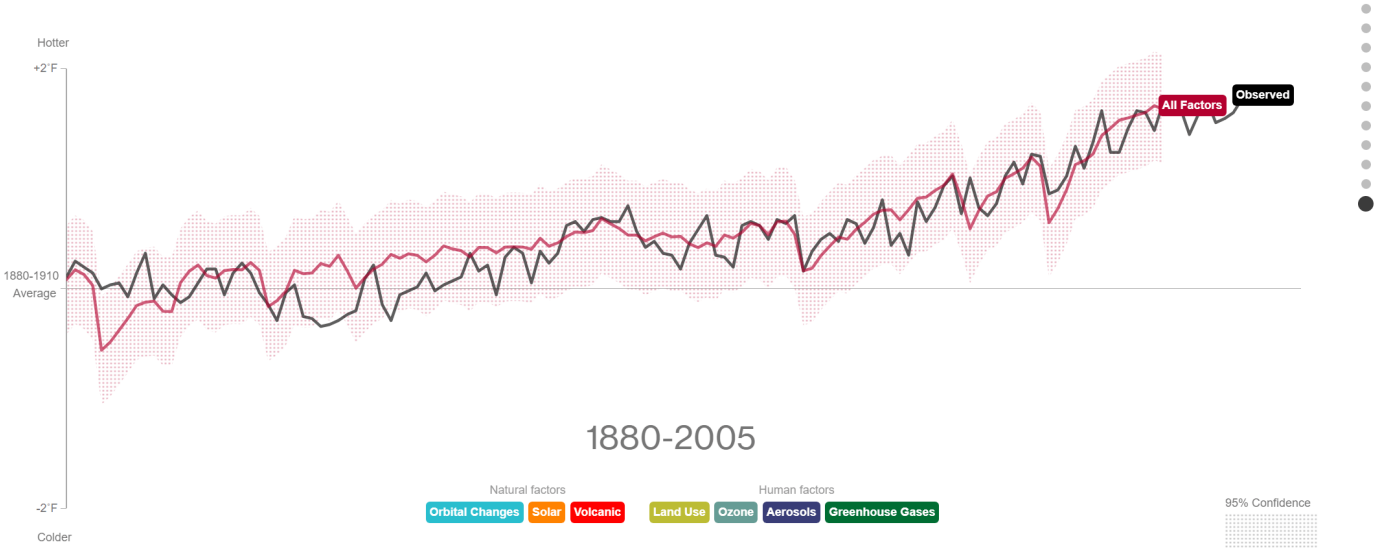


Figure 9.5.2.2: Factors contributing to global warming based on NASA data and NASA's Goddard Institute for Space Studies (GISS) climate models.

Unfortunately, other greenhouse gases have also risen since 1975, as shown in Figure 9.5.2.3.

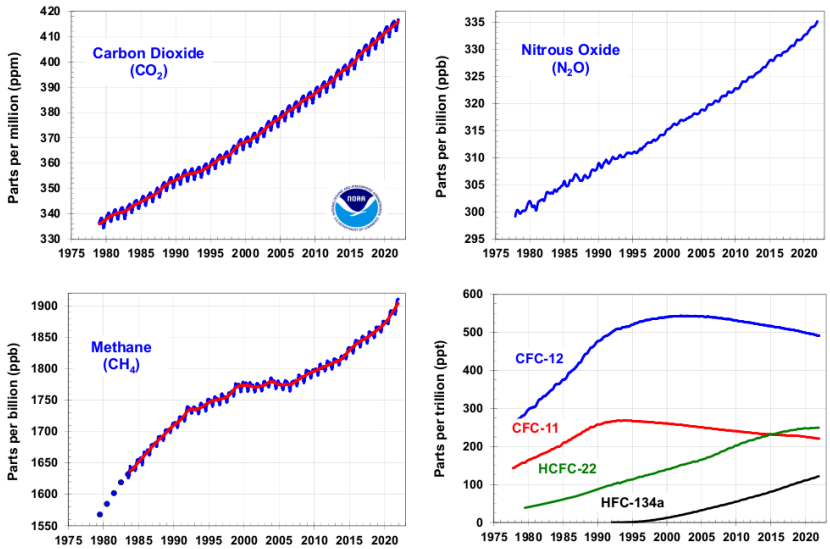


Figure 9.5.2.3: Rise in greenhouse gases since 1975. https://www.co2.Earth/annual-ghg-index-aggi

Take special note of the zig-zag nature of the CO_2 curve. The curve dips slightly in the summer, when plants in the Northern Hemisphere actively remove CO_2. Increasing methane now accounts for up to 20% of the warming observed. Figure 9.5.2.4 shows an interactive graph of a very worrisome rise of atmospheric methane with time.

Figure 9.5.2.4: Interactive graph of atmospheric CH_4 vs time over the last 1000 years. 2 Degrees Institute. https://www.2degreesinstitute.org/

Present-day warming is unequivocally caused by humans burning fossil fuels.

Past Climate Anomalies

The Skeptic's Corner: Climate Change Misinformation

In recorded human history, there have been other periods of climate change, so we shouldn't worry about the present! Look at the Little Ice Ages!

Several dramatic but short-lived (in geological time) climate changes have punctuated recorded human history. Let's look at two, mostly to equip you to address climate skeptics. They also show how sensitive our climate is to subtle changes.

The Little Ice Ages

Actual and proxy temperature records show a mild period in Europe from around 950-1100, followed by colder weather, especially from 1450 to 1850. The latter period is called the "Little Ice Age," although no significant expansion of the Northern Hemisphere ice shield occurred. It was especially cold worldwide in 1816 when much of the world experienced a "year without summer." The effect in 1816 had a clear cause: the eruption of Mount Tambora in Indonesia on April 10, 1815.

In addition to this identifiable influence in 1816, a cool period was reported in the Northern Hemisphere from about 1800 to 1820, beginning before the Tambora eruption. Also, a low period of the sun's irradiance, the Dalton Minimum, occurs from 1790 to 1860. Proxies for solar activity in the 1600s also show small drops in solar irradiance, as discussed below. The dip in global average temperatures following the Medieval Warm Period is shown in Figure 9.5.2.5.

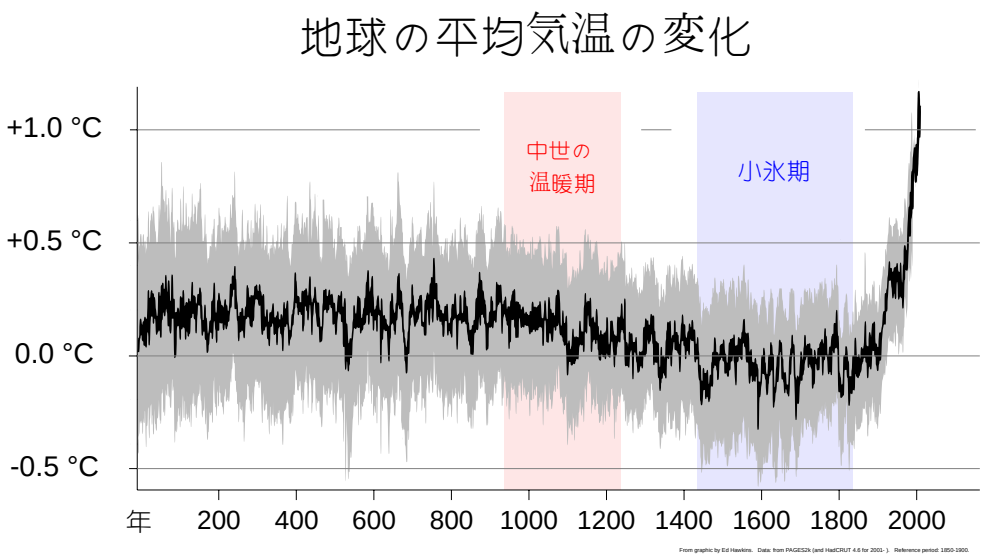


Figure 9.5.2.5: Dip in global average temperatures following the Medieval Warm Period, By RCraig09 - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/inde...curid=87832845

Modern climate change has been captured in literature and art. One example is a painting showing "Ice Fairs" on the Thames in London, shown in Figure 9.5.2.6.



Figure 9.5.2.6:https://commons.wikimedia.org/wiki/F...enell.jpgdfdfd

Many factors probably contributed to the Little Ice Ages, including a drop in solar irradiance. A newer explanation has also been proposed. Marine records show that the waters near Greenland and the Nordic seas were warmer, due to a strengthening of the Atlantic Meridional Overturning Circulation (AMOC). This would have caused the loss of Arctic ice in the late 1300s and 1400s, cooling the water and diluting its salinity since ice, when it crystallized with a tetrahedral hydrogen-bonded coordination of water, excludes salt. This would have collapsed the AMOC and its heat transfer to the northern waters, leading to rapid and prolonged cooling. An analogous strengthening of the AMOC was observed between 1960 and 1980, which was attributed to a long-duration high-pressure system over Greenland. A similar event might have occurred to kick-start the Little Ice Age. Tree rings indicate higher solar irradiance before the Little Ice Age, which may be associated with the initial strengthening of the AMOC.

The Little Ice Ages also affected China and may have contributed to crop failure in 1644, when the Ming Dynasty fell. An Arctic hurricane in 1588 helped destroy the Spanish Armada. The Great Fire of London in 1666 was preceded by a very dry summer

following an exceptionally cold winter. Food production was severely disrupted, potentially leading to significant social change in Europe and elsewhere as the Plague shattered societal and cultural norms.

The 1816 eruption of Mount Tambora in present-day Indonesia greatly exacerbated the effects of cooling. The ash and SO_2 aerosols blocked solar irradiance. Droughts, floods, cholera epidemics, famine, and migration from Europe to the US and East to West partly arose from this event.

One of the worst times to be alive: 536

Historians report that in 536 AD, parts of Europe, the Middle East, and Asia experienced 24 hours of darkness for up to 18 months. Summer temperatures plummeted. Famines occurred for a few years after. It snowed in China in the summer. The worst effects were in the Northern Hemisphere, but they were worldwide. It was probably the most pronounced cooling in the last 2000 years. To make matters worse, a pandemic erupted around 541, spreading from southern Asia to northern Europe. It had a huge effect on the Byzantine Empire and is known as the Justinian (bubonic) Plague after the Byzantine emperor. Crop failures, trade expansion, and an influx of rodents driven by the cold temperatures could have led to and exacerbated the plague.

This second, more severe example of cooling was shorter-lived on a geological timescale. Temperatures fell in the summer by about 1.5-2.5^{0}C. A "smoking gun" has been linked to this cooling: a volcanic explosion in Iceland. In addition, another eruption occurred in 540, which lowered the temperature by 1.5-2.50C, and another in 547. The combined effects of climate change and the plague led to a significant economic decline in Europe. Signs of airborne lead in the ice at 640, originating from silver mining, suggest a recovery in economic growth. You should ask yourself how the modern world copes with such an occurrence.

What the science shows

The Little Ice Ages and the climate changes preceding and following the Justinian plague had multiple causes, including volcanic eruptions, small changes in solar irradiance, and shifts in North Atlantic Ocean currents and associated weather patterns. These short-term climate changes had disastrous effects on people's lives and the economic health of societies. Predicted future warming arising from CO_2 emitted from fossil fuel use (and other greenhouse gas causes) would bring far worse immediate and potentially irreversible consequences. As people who know the causes of climate change, we must act with due diligence and speed to avert the worst climate future.

Solar Activity and Climate Change

The Skeptic's Corner: Climate Change Misinformation

It's not CO_2 levels that cause any observed increases in temperature. The sun's activity is changing. It always has and always will. There's nothing we can do about it.

We have discussed how the orbital forcing of the climate kick-started each of the recurring ice ages in the Pleistocene. Some effects of the change in solar activity independent of the sun's orbit have been noted above. Specifically, we have shown that it cannot account for present warming. We present a series of graphs from the NOAA (National Oceanic and Atmospheric Administration) in the collective Figure 9.5.2.7 below to show the actual change in solar activity over recent times. Comments are shown at the bottom of each graph.

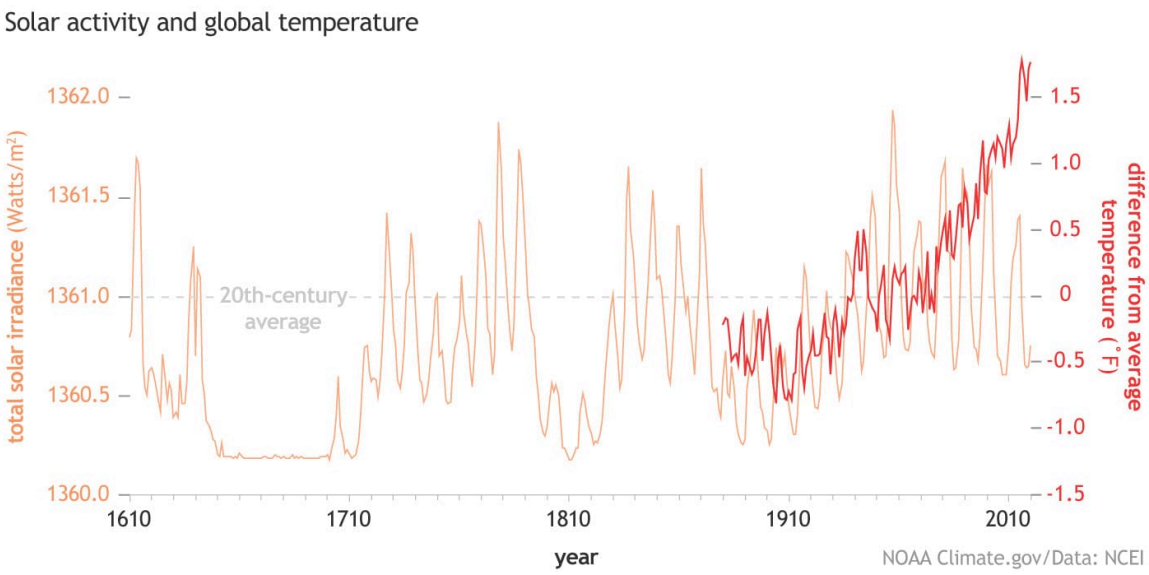


Figure $9.5.2.7a$: Actual change in solar activity over recent times. Dark red to the right are actual temperature differences

The maximum % spread between the lowest and highest is very small. Such a small change shouldn't have such dramatic effects on climate unless sustained, as it was from around 1630-1700. Hence, this decline in solar activity likely contributed to the Little Ice Age. The regular rise and fall (spikes) are associated with the 11-year sunspot cycle activity. Note that the rise in average temperature since 1910 (shown in red) cannot be accounted for by a change in solar activity. Figure $9.5.2.7b$ below shows the irradiance over time with the Maunder and Dalton minimums labeled.

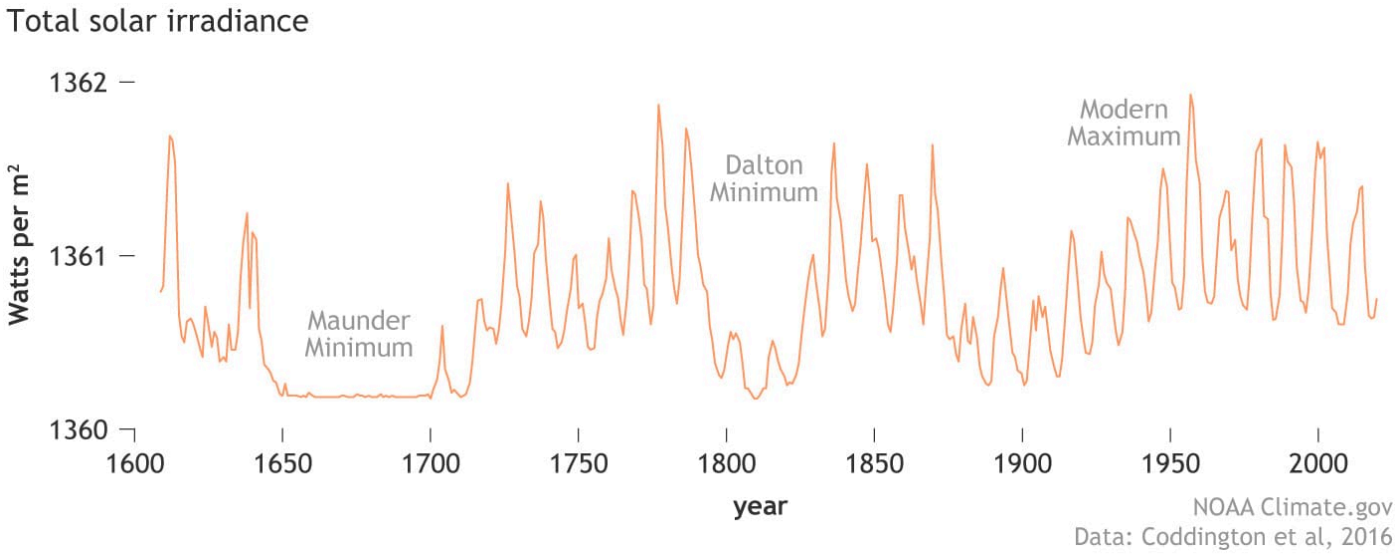


Figure $9.5.2.7b$: Irradiance over time with the Maunder and Dalton minimums

The above graph shows that the irradiance decreased by about 0.06% (although other values have been reported as high as 0.22%) during the Maunder Minimum, which occurred in the Little Ice Age. The average decrease in terrestrial temperatures was 1.0-2 ^{0}C.

Figure $9.5.2.7c$ below shows a best-fit average temperature difference (dark red line) compared to the 1800-1960 average.

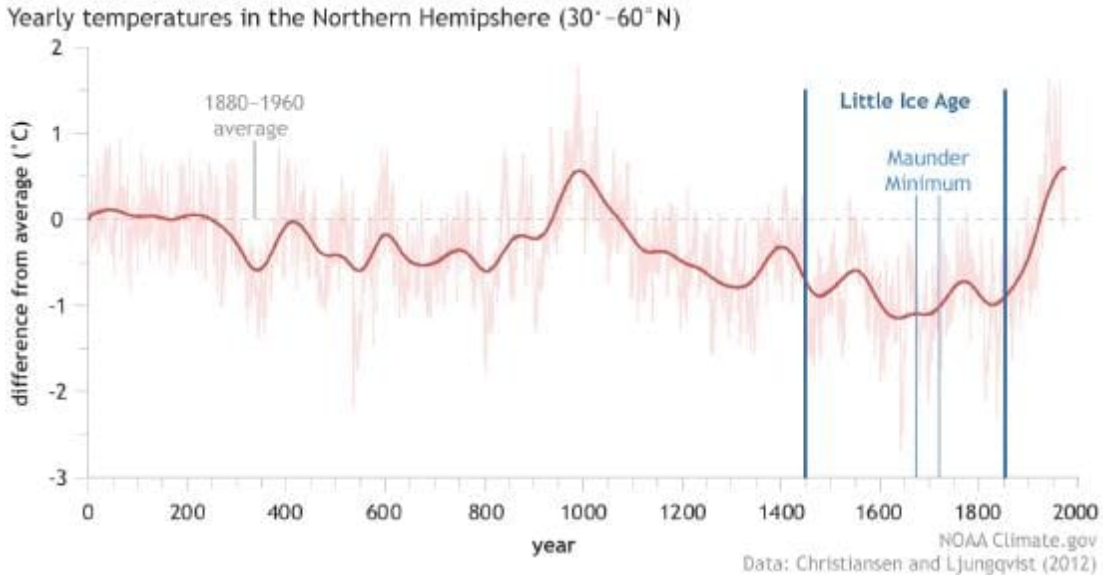


Figure $9.5.2.7c$: best fit average temperature difference (dark red line) compared to the 1800-1960 average.

Note that the averages are lower during the Little Ice Age, with the lowest values and the lowest spike temperatures near and in the Maunder Minimum. A lowering of just 1 ^{0}C had profound effects on Europe's climate.

Figure $9.5.2.7d$ below shows irradiance change from 1980 to 2020 through 4 solar cycles.

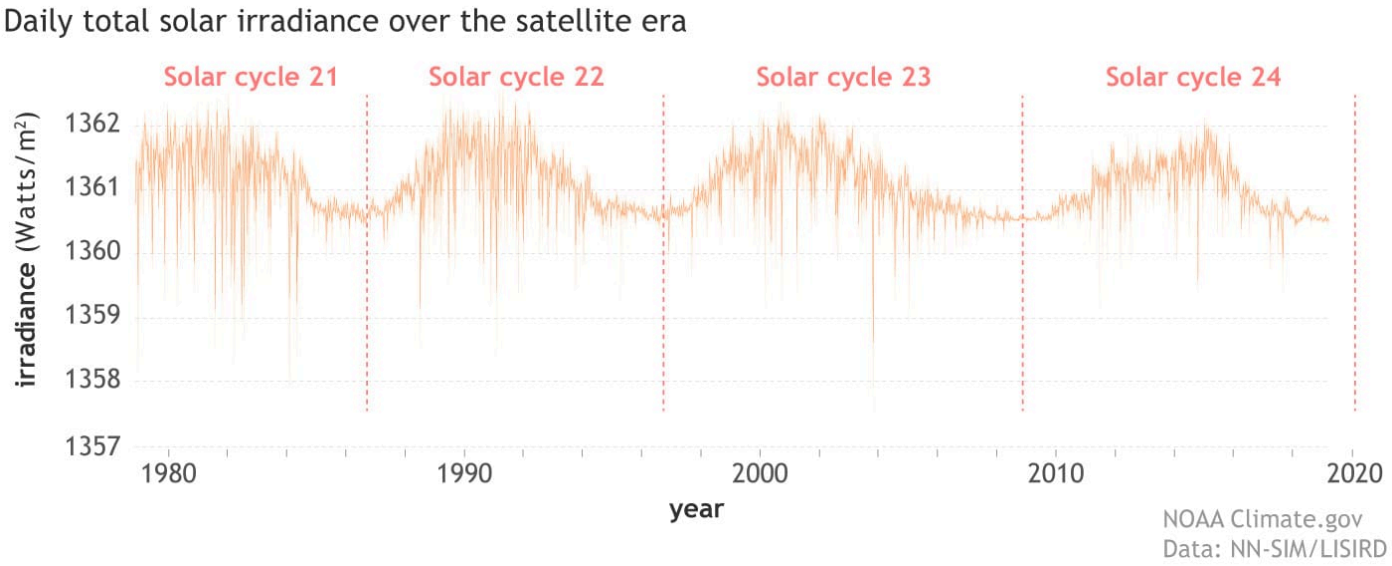


Figure $9.5.2.7d$: Irradiance change from 1980 to 2020 through 4 solar cycles.

The graph shows the 11-year repeat of sunspot activity and resulting solar irradiance. Although activity dropped in 2020 (not shown in the figure), it was the **second-warmest year** on record since 1880.

Finally, Figure $9.5.2.7e$ below shows irradiance over the last 10,000 years (from the end of the last Ice Age) until 0 CE.

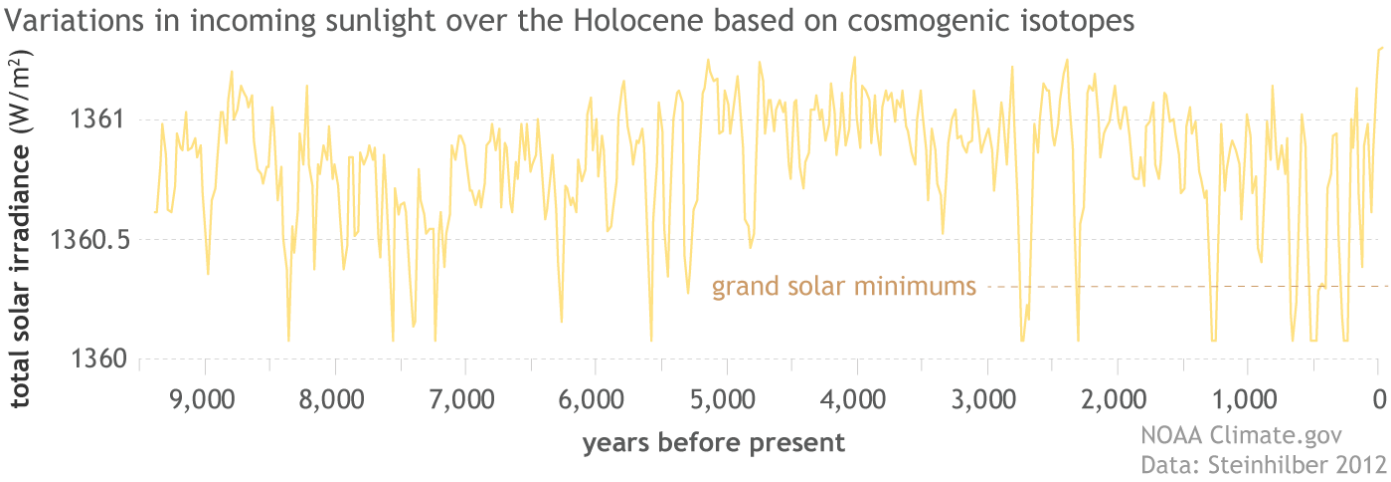


Figure $9.5.2.7e$: Irradiance over the last 10,000 years

This graph does not show the effects of orbital climate forcing. Rather, it shows that solar activity did not change significantly for the 10,000 years before 0 CE.

So the climate warming we see now can't be attributed to changes in solar irradiance. We have injected a massive amount of CO_2, approximately 1.5 trillion tons, into the atmosphere since the Industrial Revolution from using fossil fuels. Not all of that is still in the atmosphere, but enough to raise CO_2 to levels not seen for 3 million years. Based on the relationship between CO_2 and temperature across the ice ages, science can predict when conditions might exist to initiate and propagate the next ice age. The data arising from these models, illustrated in Figure $9.5.2.7f$, show how much incoming solar radiation (insolation) must arrive at the Earth (watts/m^2) to trigger the next ice age.

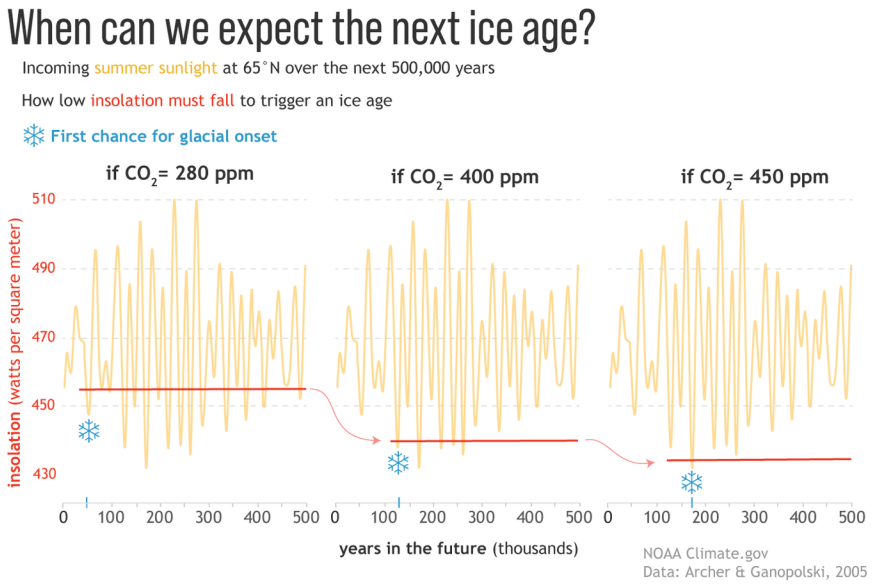


Figure $9.5.2.7f$: Incoming solar radiation required to trigger the next ice age.

As shown on the left side of the figure, if CO_2 were 280 ppm (typical of peaks in past interglacial periods), it would require repeated drops in insolation below the threshold of about 455 watts/m^2 (red line) to initiate glaciation. As of June, 2026, we are at 430 ppm and rising. If it rises to 450 ppm, as it surely will in the absence of carbon capture, it would require much less insolation to produce an ice age, since the greenhouse effect of higher CO_2 would warm the atmosphere. The right graph shows there is little chance of another ice age in the absence of large and sustained volcanic activity or an asteroid impact that would block solar radiation.

What science says

Changes in solar irradiance (not changes in Earth's orbital dynamics) **cannot** account for warming since the Industrial Revolution. They have contributed to short-term (geological time-scale) cooling during the Little Ice Ages.

Summary of Climate Change Causes and Effects Since 900 AC

Figure 9.5.2.8 summarizes possible contributions to temperature change over the last 1000 years. Note again that our current warming (1950 onward on the right side of the panels) is attributable solely to greenhouse gases (GHGs). One panel shows changes in land use. This has caused a decline in temperature since 1800. That effect is caused by deforestation and other land-cover changes, which lead to greater reflection of incident solar radiation back into space. This effect is greater in winter if the altered land is snow-covered. Deforestation would also reduce CO_2 uptake (via photosynthesis) by plants, thereby raising atmospheric temperature. That component has been added to the GHG panel.

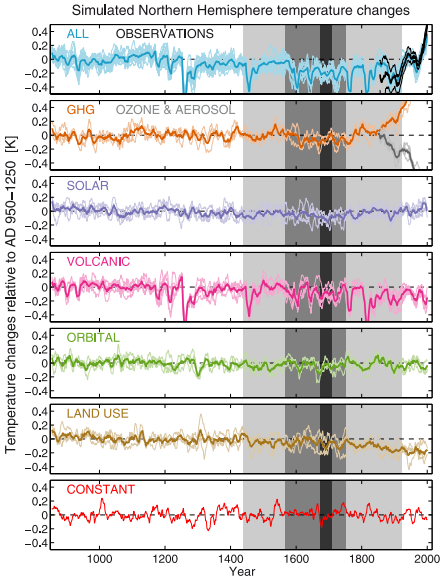


Figure 9.5.2.8: Simulated northern hemisphere temperature changes, smoothed with an 11-year running mean, relative to AD 950–1250. Owens et al. J. Space Weather Space Clim. 2017, 7, https://doi.org/10.1051/swsc/2017034. Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0).

The black line in the top panel shows the observed instrumental northern hemisphere temperature variations with their associated uncertainties (Morice et al., 2012), which match the simulations well. The bottom panel shows a simulation with no changes in radiative forcing. This quantifies the magnitude of natural internal variability in the simulations in the absence of changes in forcings. Note periodic but short-term dips in temperature due to volcanic activity. Grey-shaded regions represent the three Little Ice Age (LIA) periods, with the darkest interval (LIA3) most closely matching the Maunder Minimum (MM), a period of extremely low solar activity from 1650 to 1715. Warming since the Industrial Revolution (far right) is due to emissions from burning fossil fuels.

Climate Justice: The Emitters and the Affected

The Skeptic's Corner: Climate Change Misinformation

Why should we make changes to reduce fossil fuel emissions when China is the biggest emitter of CO_2?

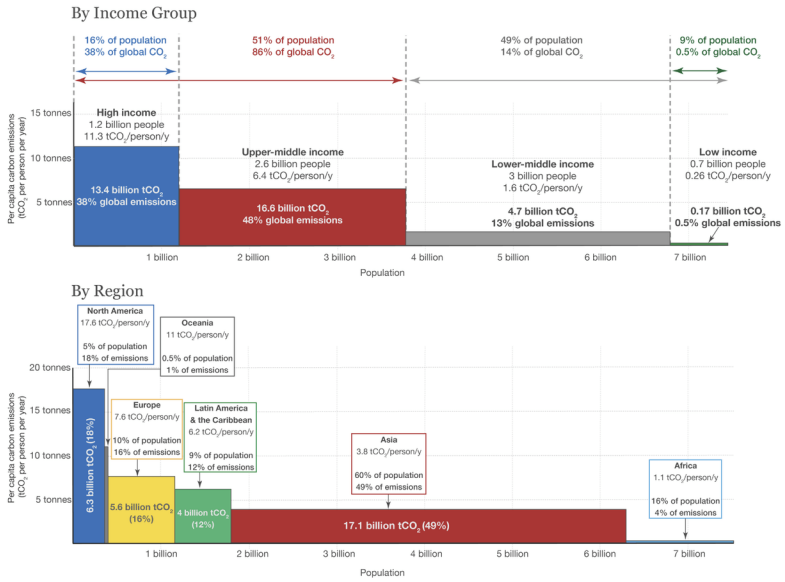
We present a series of graphs in Figure 9.5.2.9 below, taken from CO_2 Emissions - Our World in Data, to show which countries have emitted the most CO_2 in the past and now. In a just world, those countries that have emitted the most should move swiftly and forcefully not only to reduce emissions but also to support other countries' transitions to clean fuels and to help them with

climate change mitigation and adaptation. We don't wish to demonize the fossil fuel industry and those who work in it. The use of fossil fuels, which are high-energy, high-density, and cheap fuel (because of historically massive subsidies), has lifted billions out of poverty over time. We had no alternative to fossil fuels until recently. Most did not realize how significantly fossil fuel use would affect our present and future climate, human health, and the entire biosphere. Yet, we can't just stop using fossil fuels without inflicting great economic pain on those who can least afford it. To help those currently suffering and those who will suffer most in the future, and to help ourselves, our children, and our grandchildren, we must move away from using fossil fuels as soon as possible through a planned drawdown of their use.

Above: The dip in total world emissions in 2020 was due to the COVID-19 pandemic. Unfortunately, the rise has resumed. China is now the largest net emitter, but emissions in the US and EU are declining. India is on the rise, and if it follows a similar economic path as China, which it needs to lift many out of poverty, it will come with a huge cost in CO_2 emissions unless it can jumpstart their conversion to clean fuels. The world needs to help.

Above: Although China is the largest net emitter, **the US and Australia are the largest emitters per capita**, though that is declining.

The US still leads the world in total CO_2 emitted since the Industrial Revolution. We also have the greatest GDP. In 2022, Pakistan suffered tragic flooding exacerbated by climate change. Up to a third of the country was underwater. In a just world, the biggest emitters would aid the rest of the world.



Above: Inequality is evident in this graph as the wealthiest people (high and upper-middle income) collectively contribute 86% of CO_2 emissions

Figure 9.5.2.9: CO_2 emissions by country and income since the Industrial Revolution. Our World in Data. Creative Commons BY license.

What science says

Since the beginning of the Industrial Revolution, the United States has emitted the most CO_2 per capita. China is not even close.

Future Projections

We know the science and the consequences if we choose not to act or act in ways insufficient to meet the challenges of climate change. It is one of the most difficult challenges we have faced as a species. It requires sacrifice and united action for the common good. The benefits of our choice are mostly in the future and for future generations. We have models that predict

future warming. As climate models become more sophisticated, as we have more data, and as policies evolve, future scenarios for likely warming change as well. There are 3 main types of models important to this chapter. The newest one (June 2026) is most plausible given present trends. The first two (RCP and SSP) are shown in blue inset boxes with a clickable link for more background.

1. Representative Concentration Pathway from the IPCC

See link below

Link available at the end of this section.

We mentioned in 31.1A that a new value for climate sensitivity, which gave rise to a **rise of 4.8 °C (8.6 °F) for a doubling of CO_2** was determined by Hansen et al. (2023). This value has startling implications. If this new value holds, the IPCC/UN call to keep warming to 1.5°C above the pre-industrial revolution average is now **impossible**. We are already there or will be there in a few years. We are unlikely to make the changes required to keep warming below 2°C before 2050. The reasons for our inaction are politicians who continue to support the fossil fuel industry and who block significant legislation to act now, religious institutions and leaders who don't make climate action a sacred duty, and the fossil fuel industry that continues to expand fossil fuel exploration and mislead the public as to the causes of climate change and action to address it. Those who say we can't afford to act never mention the much greater cost of inaction!

The IPCC shifted away from the RCP label around 2020 to the **Shared Socioeconomic Pathways (SSPs)** model.

2. Shared Socioeconomic Pathways (SSPs)

The scenarios in this model are labeled as SSP#-##, where the second number ## still corresponds to the RCP forcing (W/m^2). The SSPs reflect possible social and economic developments that would pose different challenges to reducing future temperature increases and, hence, different strategies for mitigation and adaptation. The SSP scenarios are consistent with the RCP scenarios but use a more enhanced socio-economic and political framework for their construction. The mitigation strategies are based on the RCP forcing levels. The SSP scenarios are described below. They start with SSP1, which leads to a world that has adapted well and moved away from fossil fuels, and end with SSP5, which assumes continued and high reliance on fossil fuels:

Link available at the end of this section.

Both of these scenario types rely on the energy imbalance (W/m^2). We discussed in Chapter 32.1: A that Earth's Energy Imbalance (EEI) rose from about +0.6 Watts/m^2 in 2000 to +0.9 W/m^2 from 2005 to 2019, and to +1.0 W/m^2 in 2021. The trend is, unfortunately, upward, as shown in Figure 9.5.2.13.

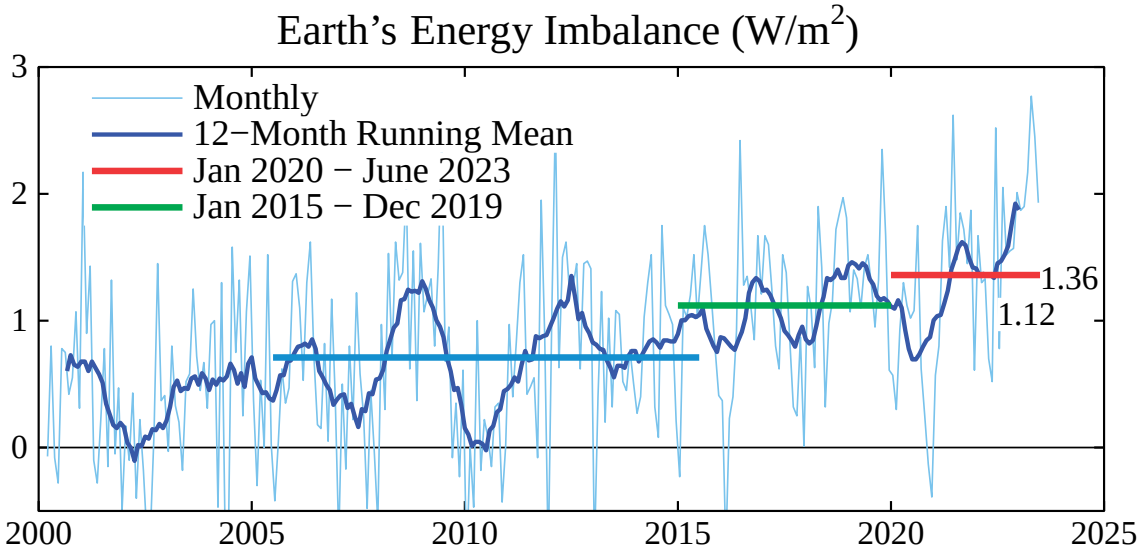


Figure 9.5.2.13: Earth's Energy Imbalance since 2000. 12-month running-mean of Earth's energy imbalance from CERES satellite data normalized to 0.71W/m2 mean for July 2005–June 2015 (blue bar). James E Hansen, Makiko Sato, Leon Simons, Larissa S Nazarenko, Isabelle Sangha, Pushker Kharecha, James C Zachos, Karina von Schuckmann, Norman G Loeb, Matthew B Osman, Qinjian Jin, George Tselioudis, Eunbi Jeong, Andrew Lacis, Reto Ruedy, Gary Russell, Junji Cao, Jing Li, Global warming in the pipeline, *Oxford Open Climate Change*, Volume 3, Issue 1, 2023, kgad008, https://doi.org/10.1093/oxfclm/kgad008. Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/)

The projected value of 1.36 (red bar) for the 2020s bodes poorly for our ability to reverse the effects of climate change. The large change that began around 2015 likely stems from decreased atmospheric sulfate emissions (required by legislation) from ships in the northern Atlantic and Pacific oceans and from coal burning in China. These decreases in atmospheric aerosols, which cause cardiovascular, pulmonary, and cancer diseases, paradoxically increase global warming. Sulfate aerosols reflect solar radiation. They also form clouds, which do the same. Both cool the planet. Aerosols that contribute to some of the worst pollution in the world in South Asian cities have helped keep temperatures from rising to dangerous levels.

Recent Updates: May, 2026

3. Coupled Model Intercomparison Project Phase 7: CMIP7

Van Vuuren, D. P. et al.: The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7), Geosci. Model Dev., 19, 2627–2656, https://doi.org/10.5194/gmd-19-2627-2026, 2026.

As our climate models improve and the world adopts more green energy, there is a need to revisit the RCP and SSP models described above. The analyses by Van Vuuren et al. suggest that the most dire 8.5 model is no longer needed as a possible worst-case scenario. This shows the progress the world has made toward fighting climate change. Some in the media suggest that the 8.5 model was developed to scare the public and policymakers into climate action. Its actual use was to place an upper limit on theoretical impacts of climate drivers and conditions, a feature that any predictive model would use. For example, financial planners use mathematical analyses called Monte Carlo simulations to model uncertainty. 1000s to millions of simulations are used in calculations, with different random input values, to generate a distribution of outcomes to determine the most and least likely scenarios.

The latest model is the **CMIP7** (Coupled Model Intercomparison Project, Phase 7), organized under the World Climate Research Program (WCRP). In the CMIP system, modelers run their own models (based on physics, chemistry, and biology of the entire biosphere), using the same protocols, climate forcings, and data sets, to develop scenarios that are compared and tested. It's like running different experiments around the world, studying the same data with their own models. An astonishing amount of data is analyzed.

The CMIP7 models use newly defined scenarios, named after **emission trends**, not climate forcing (W/m^2) or socio-economic-political drivers:

- *High emission scenario*: A scenario with emissions as high as judged to be plausible, based on assuming developments that include a rollback of current mitigation policies. This scenario is expected to result in forcings below SSP5-8.5.
- *High-to-Low emission scenario*: A scenario that follows approximately the same emissions pathway as the High, but changes course in the second half of the century, applying strong mitigation measures to reach net zero CO_2 emissions by 2100.
- *Medium emission scenario:* A middle scenario exploring the consequences of extending current policies and trends into the future.
- *Medium-to-Low emission scenario:* A scenario exploring a delayed increase in mitigation efforts, short of the Paris temperature goal but achieving net-zero CO_2 emissions by the end of the century, with a period of net negative CO_2 emissions thereafter to achieve 1.5 °C on a multi-century timescale.
- *Low-emission scenario:* The low-emission scenario is designed to be consistent with the goal of keeping warming below 2 °C, without returning to 1.5 °C before the end of the century. The scenario extends beyond 2100 under an emissions trajectory that leads to a gradual decrease in warming afterward.
- *Very Low emission scenario*: The Very Low emission scenario is designed to keep the temperature level as low as plausible given feasibility constraints. This scenario is thus relevant for the low end of the Paris range (staying as close as plausible to 1.5 °C at the time of peak warming and limiting warming to 1.5 °C by the end of the century).
- *Low-to-Negative emission scenario*: The last trajectory shows a higher overshoot of the 1.5 °C goal, followed by stringent climate policies that result in net-negative greenhouse gas emissions, returning to lower warming levels and thus supporting research into the reversibility of climate outcomes and their impacts.

Figure 9.5.2.14 below shows the CMIP7 model color-coded emission trends (a, left) and the resulting warming (b, right)

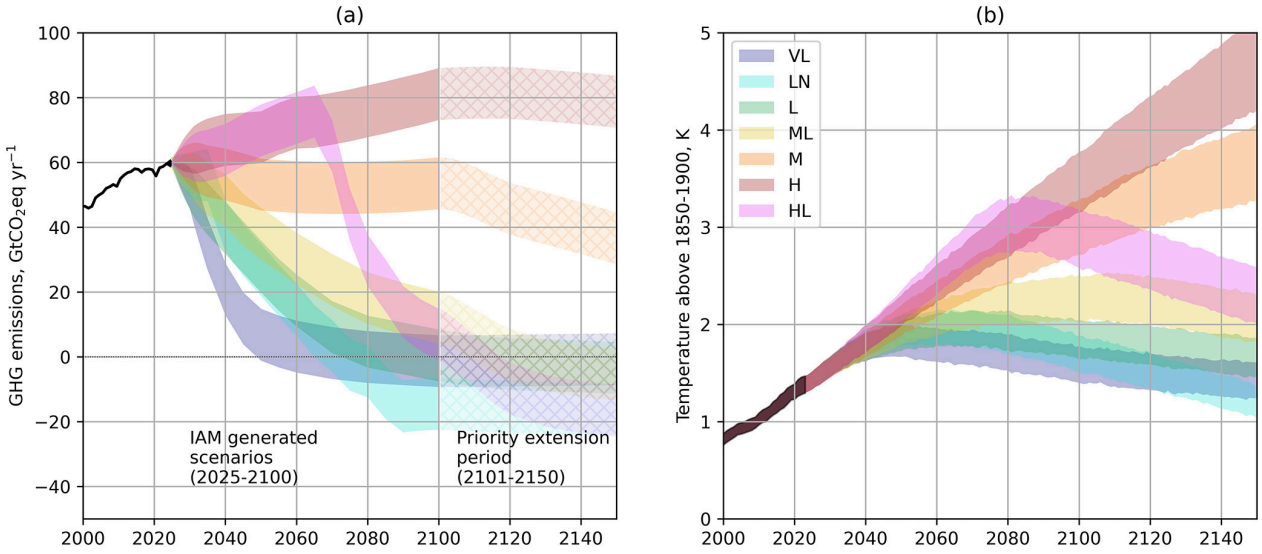


Figure 9.5.2.14: Proposed scenarios for CMIP7 ScenarioMIP, showing

(a) GHG emissions pathways as a function of time for each of the proposed scenarios (based on GWP-100) and

(b) The associated global average temperature outcomes using the probabilistic FaIR ensemble used in IPCC AR6 (Smith, 2025; Smith et al., 2024).

The shaded area for emissions shows ±8 $GtCO_2$ around the expected marker scenario value, while for temperature outcomes, it shows the 33–67 percentile range of the distribution for the same expected marker scenario. Data for the historical period can be found in Nicholls et al. (2025a). Scenarios are (H) High, (HL) High-to-Low, (M) Medium, (ML) Medium-to-Low, (L) Low, (LN) Low-to-Negative, and (VL) Very Low. The final emission trajectories will depend on the finalized IAM runs but are expected to be roughly consistent with the illustrations provided here. The final temperature outcomes will be known only upon completion

of Earth system model experiments and, for this phase of ScenarioMIP, will also include the effects of carbon cycle feedbacks. Models are requested to run the scenarios for the period 2025–2150; the textured regions for the 2100–2150 period (AD) indicate that these emissions and forcings are defined in the extension protocol.

It's not just about carbon: The Sulfur Cycle

We have discussed the carbon and nitrogen cycles. The sulfur cycle also plays a role in the Earth's climate. As described above, sulfur aerosols (such as those produced by SO_2) can locally lower atmospheric temperatures by reflecting incoming solar radiation. Of course, they also harm the environment and human health by contributing to acid rain. Reduced sulfur-containing compounds, such as H_2S (hydrogen sulfide), **$(CH_3)_2S$ (dimethyl sulfide)**, and **DMSP (dimethylsulfoniopropionate)**, are also part of the cycle. A simplified version of the sulfur cycle is shown in Figure 9.5.2.15 below.

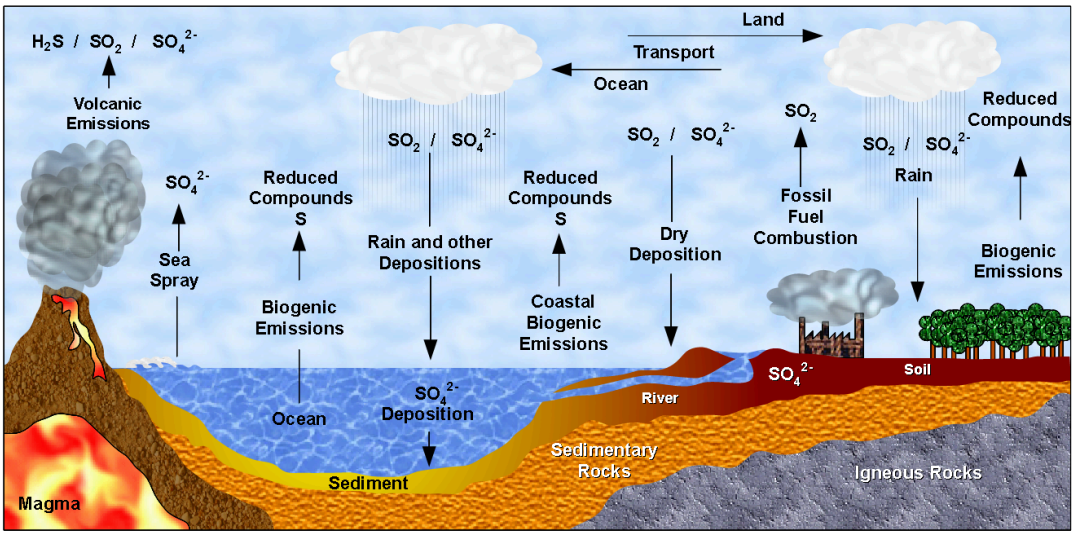


Figure 9.5.2.15: The sulfur cycle. Elmer Robinson and Robert C. Robbins. Bantle, CC0, via Wikimedia Commons. https://commons.wikimedia.org/wiki/F...o_Enxofre).png. Creative Commons CC0 1.0 Universal Public Domain Dedication

DMS is released into the atmosphere by ocean phytoplankton, other microorganisms, and some plants. These can form aerosols that help cool the climate and transfer sulfur to the land. The structures of DMS and DMSP, along with the enzymes involved in their formation, are shown below in Figure 9.5.2.16.

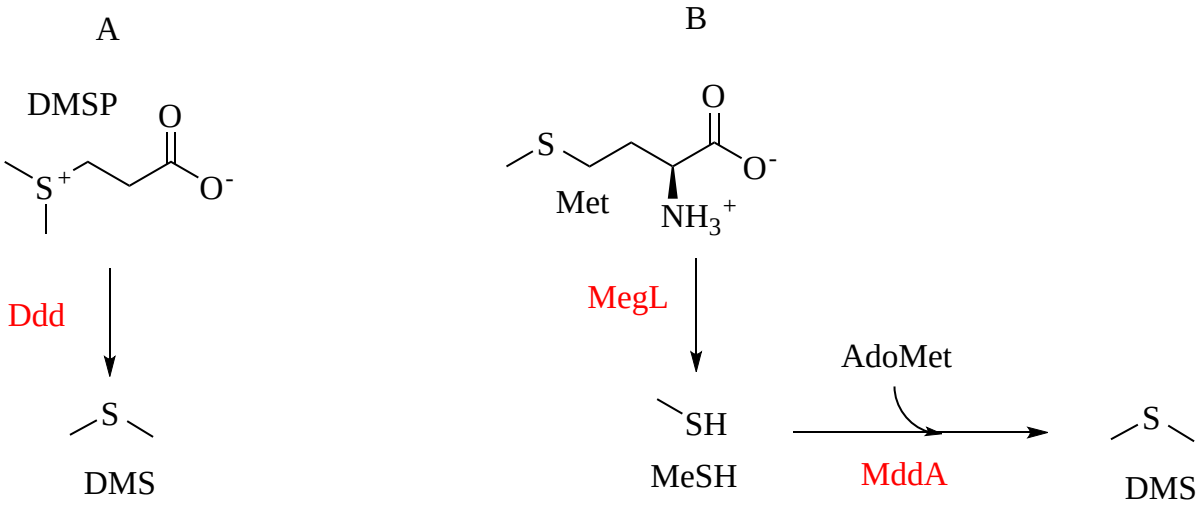


Figure 9.5.2.16: **Formation of Methylsulfide.** After Carrión, O., Curson, A., Kumaresan, D. *et al.* A novel pathway producing dimethylsulphide in bacteria is widespread in soil environments. *Nat Commun* **6**, 6579 (2015). https://doi.org/10.1038/ncomms7579.

Panel A shows the DMSP cleavage pathway, catalyzed by DMSP lyase enzymes (Ddd) found in some bacteria. Panel B shows the pathway in *Pseudomonas deceptionensis* M1^T. Methionine (Met) is converted to MeSH using Met gamma lyase enzyme (MegL) in *P. deceptionensis* M1^T. MeSH is methylated to DMS by the enzyme MddA (a membrane protein methanethiol S-methyltransferase) using Ado-Met as the methyl donor.

DMSP can be synthesized from methionine via a variety of pathways, as shown in Figure 9.5.2.17.

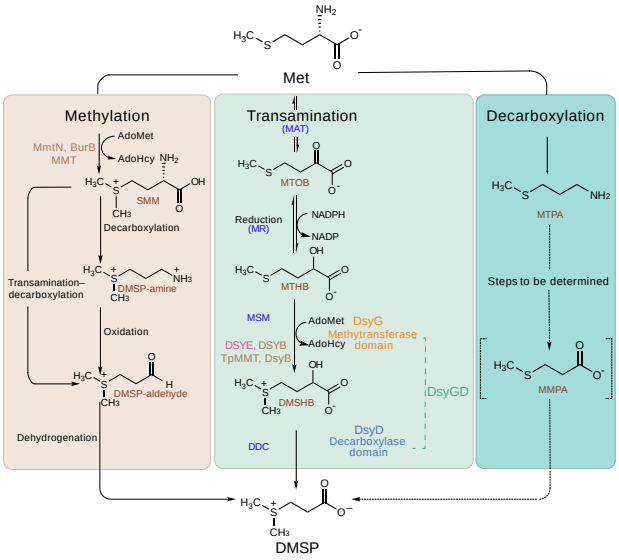


Figure 9.5.2.17: **DMSP biosynthesis genes, enzymes, and pathways.** Wang, J., Curson, A.R.J., Zhou, S. *et al.* Alternative dimethylsulfoniopropionate biosynthesis enzymes in diverse and abundant microorganisms. *Nat Microbiol* **9**, 1979–1992 (2024). https://doi.org/10.1038/s41564-024-01715-9. Creative Commons Attribution 4.0 International License. http://creativecommons.org/licenses/by/4.0/.

The 'methylation' pathway in some higher plants with the methionine (Met) S-methyltransferase (MMT) and bacteria containing MmtN or another methyltransferase (BurB) (left); the 'transamination' pathway in algae, bacteria, and corals with DSYB/DsyB, DsyGD/DsyG, DSYE and/or TpMMT (middle); and the 'decarboxylation' pathway in *Crypthecodinium cohnii* (right). The pathways are named after their first reaction step (in larger font). AdoMet, S-adenosylmethionine; AdoHcy, S-adenosylhomocysteine; NADP, nicotine adenine dinucleotide phosphate; MAT, methionine aminotransferase; MR, MTOB reductase; MSM, MTHB S-methyltransferase; DDC, DMSHB decarboxylase; SMM, S-methylmethionine; MTOB, 4-methylthio-2-oxybutyrate; MTHB, 4-methylthio-2-hydroxybutyrate; DMSHB, 4-dimethylsulfonio-2-hydroxybutyrate; MTPA, 3-methylthiopropylamine; MMPA, 3-methylmercaptopropionate.

DMSP is not a minor microbial product. Petagrams (10^{15}) are made in surface water and more in other ocean regions. Intracellular DMSP (often at millimolar concentrations) is an osmolyte that helps cells cope with the osmotic stress of living in saltwater. It also provides carbon and sulfur to marine organisms. DMS is released into the atmosphere and cycles diurnally, giving the oceans their characteristic smell. It and DMSP are signaling molecules in fish and whales.

These last two chapters clearly show that humans have been engaged in large-scale geoengineering of the planet and its biosphere. We must develop new methods and technologies to lower the Earth's temperature. One might be the large-scale production of salt aerosols over the oceans, which would reflect incident sunlight and increase cloud formation.

This chapter shows how our climate fate will depend on our individual and collective choices as societies.

Summary

(Summary written by Claude, Anthropic)

Human activities—primarily the combustion of fossil fuels beginning with the Industrial Revolution around 1760—have injected approximately 1.5 trillion tons of CO_2 into the atmosphere, raising atmospheric CO_2 to levels not seen in at least 3 million years. NASA climate models demonstrate unambiguously that only anthropogenic greenhouse gas forcing reproduces the observed global temperature rise since 1880; natural factors, including changes in solar irradiance, volcanic activity, orbital mechanics, and land use, cannot explain the magnitude or rate of current warming. The characteristic seasonal zig-zag in the CO_2 record reflects active Northern Hemisphere photosynthesis temporarily drawing down atmospheric CO_2 each summer. Methane, the second most important anthropogenic greenhouse gas, now accounts for up to ~20% of observed warming, and along with other greenhouse gases has risen sharply since 1975. Earth's Energy Imbalance (EEI) has risen from ~+0.6 W/m^2 in 2000 to ~+1.0 W/m^2 in 2021 and continues to trend upward, reflecting the growing thermal imbalance driving ongoing warming. A revised 2023 climate sensitivity estimate by Hansen et al. of 4.8°C per CO_2 doubling suggests that the IPCC's 1.5°C warming target may no longer be achievable and that staying below 2°C before 2050 will require immediate and dramatic action.

Historical climate fluctuations—including the Little Ice Ages (most severe 1450–1850) and the catastrophic 536 AD cooling—provide important context. The 536 AD event, caused by Icelandic volcanic eruptions (and compounded by additional eruptions in 540 and 547), dropped summer temperatures by 1.5–2.5°C, triggered widespread famines, and preceded the Justinian Plague around 541. The Little Ice Ages involved decreased solar irradiance (Maunder Minimum, ~0.06% decrease), multiple volcanic eruptions (most dramatically Tambora in 1815), and changes in Atlantic Meridional Overturning Circulation (AMOC) dynamics—with initial Arctic ice loss in the late 1300s–1400s cooling and diluting North Atlantic waters and collapsing the AMOC heat transfer. These events illustrate the climate system's sensitivity to relatively small radiative perturbations, but also demonstrate that their mechanisms are fundamentally different from anthropogenic forcing—and that future human-caused warming, if unmitigated, would produce far more severe and potentially irreversible consequences. Critically, sufficient anthropogenic CO_2 has now been injected into the atmosphere that the orbital insolation minimum required to trigger the next ice age has been pushed far below any naturally occurring threshold.

Climate projections have evolved through successive IPCC frameworks. The original RCP scenarios (Representative Concentration Pathways) characterized futures by radiative forcing (W/m^2); the SSP (Shared Socioeconomic Pathways) framework added socioeconomic and political context. The newest CMIP7 framework replaces these with scenarios named by emission trajectories—from Very Low (consistent with ~1.5°C peak warming) through High (below the retired RCP 8.5 boundary)—and incorporates more current data on clean energy deployment progress. The retirement of RCP 8.5 as a plausible worst-case scenario reflects real-world clean energy progress, while it retains legitimate value as an upper boundary condition for impact modeling, analogous to Monte Carlo worst-case scenarios in financial planning.

Climate justice is inseparable from climate science. The United States leads all nations in cumulative per-capita CO_2 emissions since the Industrial Revolution; the wealthiest 20% of the global population collectively account for ~86% of total emissions; and nations with minimal historical contributions—such as Pakistan, which experienced catastrophic flooding in 2022—suffer disproportionate climate impacts. The largest historical emitters bear the greatest moral and practical responsibility for rapid emissions reductions, financing clean energy transitions in developing nations, and providing climate adaptation support.

The sulfur cycle adds biochemical complexity to climate feedbacks. Marine phytoplankton, algae, bacteria, and some plants synthesize DMSP (dimethylsulfoniopropionate) from methionine via three pathways (methylation, transamination, or decarboxylation). At millimolar intracellular concentrations, DMSP serves as an osmolyte in hyperosmotic marine environments and as a source of carbon and sulfur for marine organisms. DMSP lyase enzymes (Ddd) cleave DMSP to release DMS (dimethylsulfide), which is released into the atmosphere in petagrams annually, where it oxidizes to sulfate aerosols that reflect solar radiation and promote cloud formation, locally cooling the climate and transferring sulfur to terrestrial ecosystems. This creates an important climate feedback: reductions in anthropogenic SO_2 emissions required by clean air regulations paradoxically accelerate warming by reducing the reflective and cloud-seeding aerosol load—a phenomenon already observed following maritime shipping sulfur restrictions implemented around 2015, which contributed to the recent sharp rise in EEI.

Taken together, this chapter underscores that human activities have become the dominant force shaping Earth's climate, and that individual, institutional, and collective choices about energy use, emissions, and policy will determine which climate scenario future generations inherit.

Answers

1. **Representative Concentration Pathway from the IPCC**

The Intergovernmental Panel on Climate Change (IPCC), composed of leading climate scientists and experts, defined several **Representative Concentration Pathways (RCPs)** leading to different emissions and climate futures. Where we end up depends on economic, social, and political choices. The IPCC initially designated four pathways, RCP 2.6, 4.5, 6, and 8.5, with higher numbers associated with higher temperatures and CO_2 levels. Each assumes a starting value and estimated emissions (which depend on technology, politics, economics, etc). RCP 8.5 assumes extra radiative forcing (Joules of heat energy/(m^2s), which is also Watts/m^2) by 2100 equal to 8.5 J/(s m^2) or 8.5 watts/m^2. This worst-case scenario, developed as a boundary condition for modeling, assumes increasing reliance on coal and gas with *no interventions* to reduce our emissions, a totally unlikely scenario given present actions (including the rapid rise of clean energy). The RCP 2.6 scenario assumes that the peak radiative forcing would be 3 watts/m^2, declining through strong governmental and economic actions to 2.5 by 2030-2040. The RCP designation, introduced around 2010, is based on the climate forcing from greenhouse gas concentrations, which drives climate change, with the number representing the W/m^2 value reached. Nothing is stated about the socio-economic-political drivers of the change. The abbreviation RCP is being retired in the second scenario

Table 9.5.2.1 below shows the four RCP scenarios with projected ending CO_2 equivalents (which include other greenhouse gases) and temperature increases.

RCP (W/m^2)	Timeframe	$CO_{2\ atm}$ equivalents (ppm)	Temp increase ($^oC/^oF$)	Description
~~8.5 (unlikely)~~	~~in 2100~~	~~1370~~	~~4.9/8.8~~	~~rising~~
6.0	after 2100	850	3/5.4	stabilizing without overshoot
4.5	after 2100	650	2.4/4.3	stabilizing without overshoot
2.6	decline from 3 before 2100	490	1.5/2.7	peak and decline

Table 9.5.2.1 below shows the four RCP scenarios with projected ending CO_2 equivalents

2. **Shared Socioeconomic Pathways (SSPs)**

SSP1: **Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)**
The world is gradually but pervasively shifting toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2: **Middle of the Road (Medium challenges to mitigation and adaptation)**
The world follows a path in which social, economic, and technological trends do not deviate markedly from historical patterns. Development and income growth proceed unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work towards achieving sustainable development goals but make slow progress. Environmental systems experience degradation, although there are some improvements, and overall, the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves slowly, and challenges to reducing vulnerability to societal and environmental changes remain.

SSP3: **Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)**
A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time, becoming increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized countries and high in developing countries. A low international priority for addressing environmental concerns results in severe environmental degradation in some regions.

SSP4: **Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)**
Highly unequal investments in human capital, combined with widening disparities in economic opportunity and political power, lead to greater inequality and stratification across and within countries. Over time, a gap widens between an internationally connected society contributing to the global economy's knowledge- and capital-intensive sectors and a fragmented collection of lower-income, poorly educated societies working in a labor-intensive, low-tech economy. Social cohesion degrades, and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector is diversifying through investments in both carbon-intensive fuels such as coal and unconventional oil and low-carbon energy sources. Environmental policies focus on local issues in middle and high-income areas.

SSP5: **Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)**
(This scenario is effectively retired as very unlikely.) This world places increasing faith in competitive markets, innovation, and participatory societies to produce rapid technological progress and develop human capital as the path to sustainable development. Global markets are increasingly integrated. There are also significant investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource- and energy-intensive lifestyles worldwide. All these factors lead to rapid global economic growth as the global population peaks and then declines in the 21st century. Local environmental problems, such as air pollution, are successfully managed. There is faith in effectively managing social and ecological systems, including, if necessary, geo-engineering.

Translating projected CO_2 equivalents in the atmosphere into associated temperature increases requires a high-quality estimate of climate sensitivity (the temperature rise per unit increase in CO_2). Figure 9.5.2.10 shows the likely temperature increase for the four SSP scenarios (including the now eliminated 8.5 one).

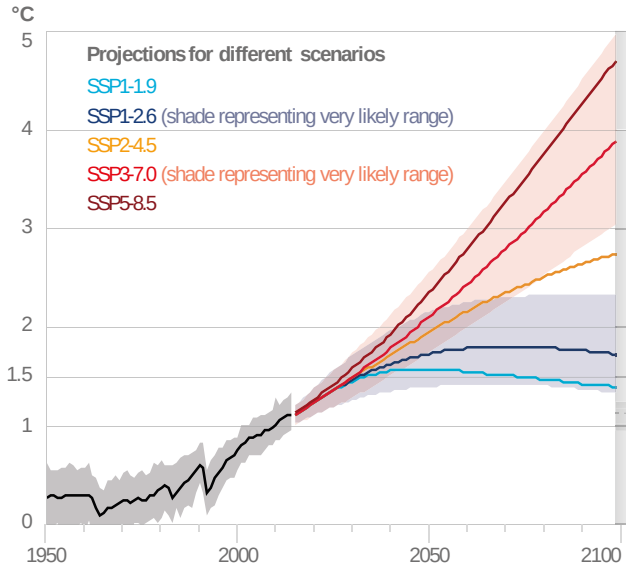


Figure 9.5.2.10: Projected temperature rises for 4 RCP scenarios. Pörtneret al. *Climate Change 2022: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. doi:10.1017/9781009325844.001.

The projected increases in emitted CO_2 (Gigatons/yr) and other greenhouse gases over the next 80 years for each SSP scenario are shown in Figure 9.5.2.11. The second number in the SSP label is the RCP scenario number, based on radiative forcing, as listed in Table 1 above. These all include the now eliminated 8.5 scenario.

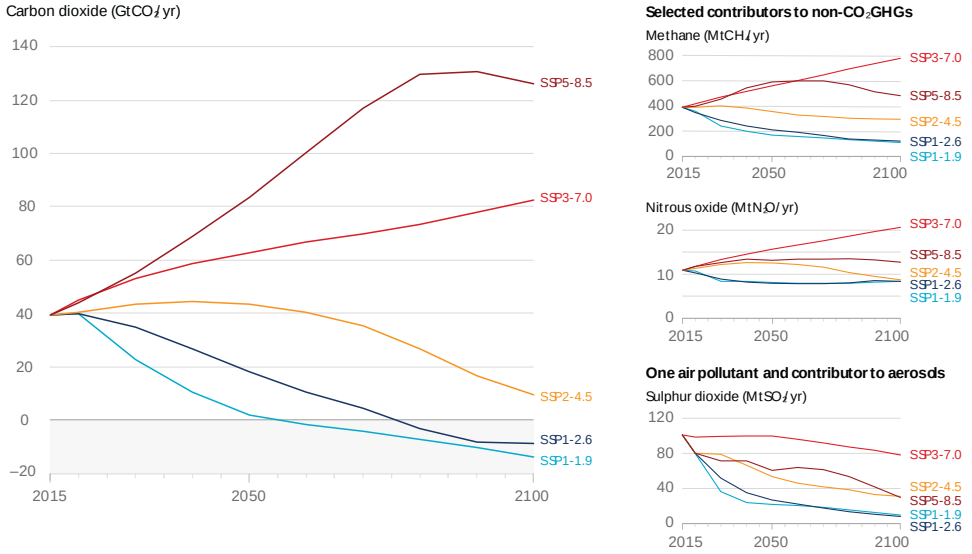


Figure 9.5.2.11: Projected increases in greenhouse gases under different SSP (RCP) scenarios. Masson-Delmotte et al. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32, doi:10.1017/9781009157896.001.

Note the welcome decline in SO_2, which causes acid rain and aerosols. This shows that across all SSP scenarios, we are working to clean up our air (in this case, reducing SO_2 emissions from burning sulfur-enriched coal or capturing SO_2 before it enters the atmosphere). Paradoxically and unfortunately, decreasing aerosols leads to higher temperatures because incident solar irradiance is less reflected.

Our final figure, Figure 9.5.2.12, shows how each greenhouse gas and SO_2 are projected to change in 2081-2100, compared to 1850-1900 levels, for each SSP scenario.

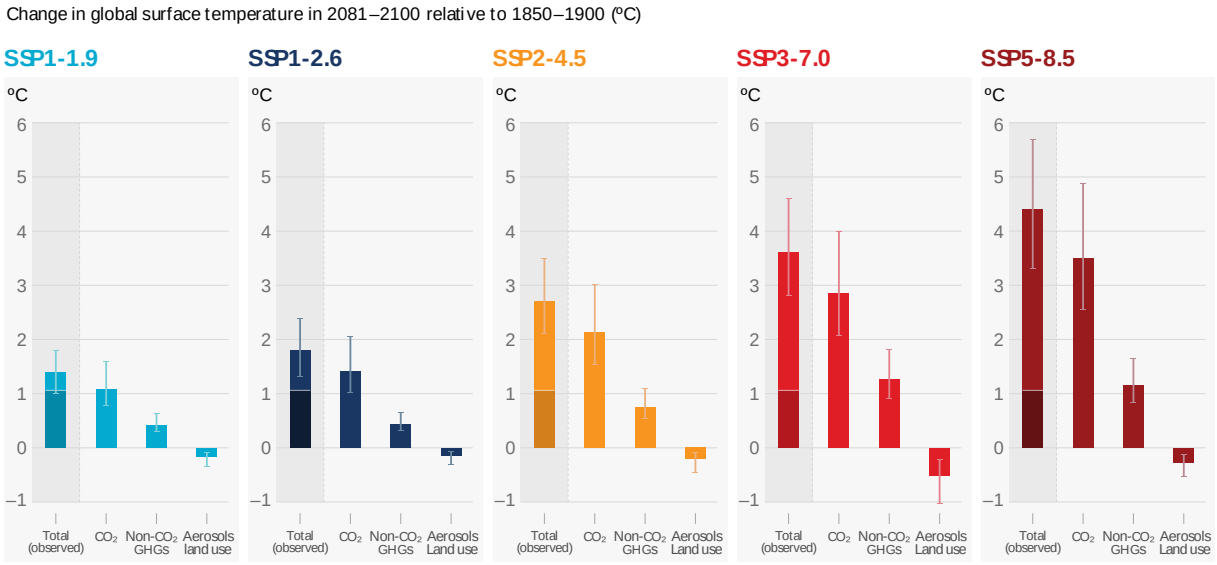


Figure 9.5.2.12: Projected changes in greenhouse gases and SO_2 in 2081-2100 compared to 1850-1900 levels for different SSP scenarios. Masson-Delmotte et al, ibid.

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10: FOOD AND AGRICULTURE

10.1: Food Security
10.2: Food and Nutrients
10.3: Soil Profiles and Processes
10.4: Soil-Plant Interactions
10.5: Industrial Agriculture
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10.1: Food Security

Food security is the state of having reliable access to a sufficient quantity of affordable, healthy food. 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. **Food insecurity** occurs when there is only limited or uncertain availability of suitable food. 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, gender, ethnicity, religion, and socioeconomic levels. Figure $10.1.1$ of food insecurity trends world-wide based on gender shows two distinct trends: Geographic disparity in food access, with the overall highest levels in Africa; A universal gender gap showing that women experience higher rates of both moderate and severe food insecurity than men across every surveyed macro-region.

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**.

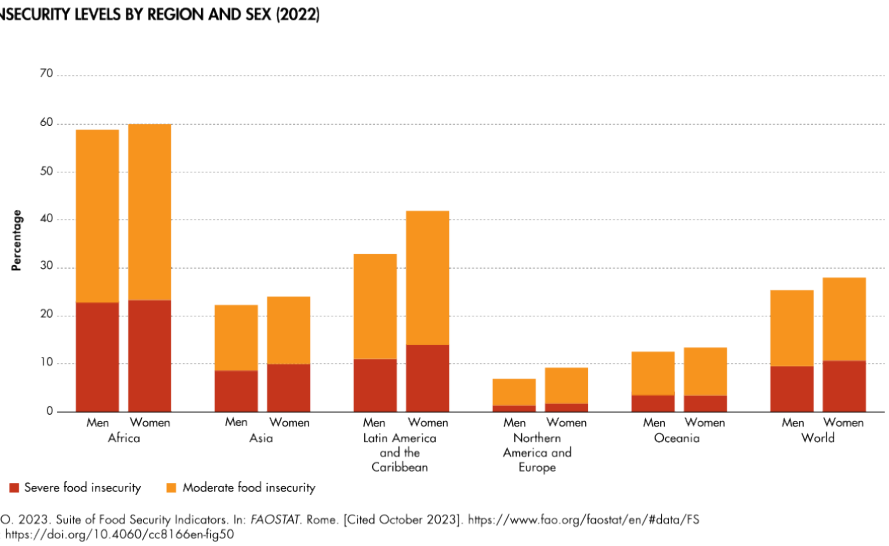
When food security is analyzed at the national level, an understanding not only of national production is important, but also of the country's **access** to food from the global market, its foreign exchange earnings, and its citizens' consumer choices. Food security analyzed at the household level is 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.

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 marketplace. However, it is only at the individual level that the analysis can be truly accurate because only through understanding who consumes what can we appreciate the impact of sociocultural and gender

inequalities on people's ability to meet their nutritional needs.

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.



Source: FAO. 2023. Suite of Food Security Indicators. In: *FAOSTAT*. Rome. [Cited October 2023]. https://www.fao.org/faostat/en/#data/FS
Download: https://doi.org/10.4060/cc8166en-fig50

Figure 10.1.1: Food Insecurity Levels by Region and Sex (2022). This chart illustrates the prevalence of moderate or severe food insecurity worldwide, broken down by geographic region and gender, based on the Food Insecurity Experience Scale (FIES). Source: FAO. 2023. *World Food and Agriculture – Statistical Yearbook 2023*. Rome. Licensed under CC BY 4.0.

Obesity

Obesity occurs when excess body fat accumulates to such an extent that it can have negative effects on health. It is not the same as being **overweight**, which means having more body fat than is considered healthy. Obesity has become a significant global health challenge, yet is preventable and reversible. Over the past 20 years, a global overweight/obesity epidemic has emerged, initially in industrial countries and now increasingly in low- and middle-income countries, particularly in urban settings, resulting in a triple burden of undernutrition, micronutrient deficiency, and overweight/obesity (Figure 10.1.2). 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.

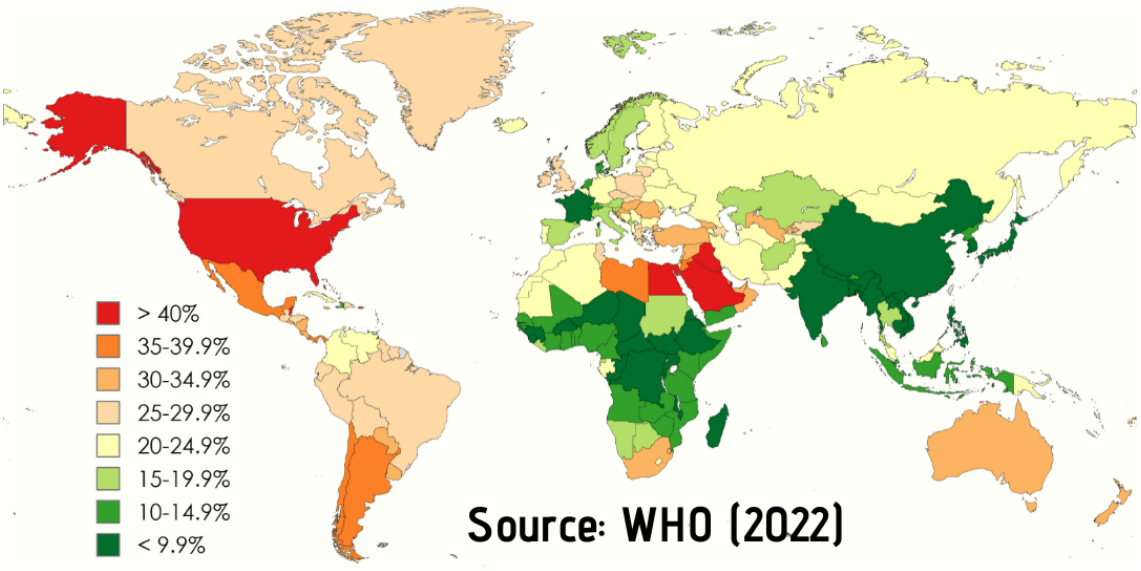


Figure 10.1.2: Global Prevalence of Adult Obesity (2022). World choropleth map illustrating age-standardized adult obesity rates ($\mathrm{BMI} \geq 30$) by country. Source: Map created by Ly.n0m on Wikimedia Commons based on data from the World Health Organization Global Health Observatory. Licensed under CC BY 4.0.

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

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

Suggested Supplementary Reading:

McMillan, T. 2018. How China Plans to Feed 1.4 Billion Growing Appetites(opens in new window). *National Geographic*. February. (Update 10/12/2025: This article requires paid access)

Contributors and Attributions

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10.2: Food and Nutrients

Eating a variety of healthful foods promotes good physical health and provides energy for growth and activity. Many common diseases and their symptoms can be prevented or helped with healthful eating. Knowing what your body needs can help you choose foods to meet those needs.

Nutrients, Energy, and Building Materials

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.

The exact amount of a macronutrient an individual needs depends on many factors, including gender and age. Recommended daily intakes of three macronutrients for young people of both genders are shown. *Includes water in foods as well as beverages.

Table 10.2.1*: Recommended Daily Intakes of Carbohydrates, Proteins, and Water*

Gender And Age	Carbohydrates(grams/day)	Proteins(grams/day)	Water*(liters/day)
Males 9–13 years	130	34	2.4
14–18 years	130	52	3.3
Females 9–13 years	130	34	2.1
14–18 years	130	46	2.3

Carbohydrates are classified as either simple or complex, based on the number of saccharides they contain.

Simple carbohydrates contain just one or two saccharides. They are all sugars. Examples of sugars in the diet include fructose, which is found in fruit, and lactose, which is found in milk. The main function of simple carbohydrates is to provide the body with energy. One gram of carbohydrate provides four kilocalories of energy. Glucose is the sugar that is used most easily by cells for energy. It circulates in the blood, providing energy to cells throughout the body. Glucose is the only source of energy used by the brain.

Complex carbohydrates, called polysaccharides, generally contain many saccharides. They include starches and fiber. Starches are found in plant foods such as vegetables and grains. They are broken down during digestion to form sugars that provide energy. Fiber consists of indigestible starches and other materials such as cellulose. It is present in all plant foods.

Fiber may be soluble or insoluble.

- **Soluble fiber** dissolves in water as it passes through the large intestine. It helps form substances that keep blood levels of glucose stable and blood levels of harmful lipids low (see below).

- **Insoluble fiber** does not dissolve but attracts water as it passes through the large intestine. This helps keep waste moist and moving easily through the intestine.

Proteins play many vital roles in the body, including:

- Making up the majority of muscle tissue.
- Regulating many body processes.
- Forming antibodies that destroy bacteria and other “foreign invaders.”
- Regulating the salt-water and acid-base balance in body fluids.
- Transporting nutrients and other vital substances in the blood.

Dietary proteins are broken down during digestion to provide the amino acids that cells need to make proteins for the body. Twenty different amino acids are needed for this purpose. Ten of these amino acids can be synthesized by cells from simple components. The other ten cannot be synthesized and must be obtained from foods. They are called essential amino acids because they are essential in the diet.

Proteins that contain all ten essential amino acids are referred to as complete proteins. They are found in animal foods such as milk and meat. Proteins that are missing one or more essential amino acids are referred to as incomplete proteins. They are found in plant foods such as legumes and rice. By eating a variety of different plant foods containing incomplete proteins, you can include all ten essential amino acids in your diet.

If you eat more protein than needed for the synthesis of new proteins by cells, the excess is used for energy or stored as fat. One gram of protein provides four kilocalories of energy. This is the same amount of energy that one gram of carbohydrate provides.

Lipids, or fatty acids, are organic compounds that consist of repeating units of carbon, hydrogen, and oxygen. They provide the body with energy. The heart and skeletal muscles rely mainly on lipids for fuel. One gram of lipids provides nine kilocalories of energy, more than twice the amount provided by carbohydrates or proteins. Lipids have several other functions as well. Lipids form an insulating sheath around nerve cells that helps nerve messages travel more quickly. Lipids also help form substances that regulate blood pressure, blood clotting, and blood lipid levels. In addition, lipids make up the membranes that surround cells.

The term fat is often used interchangeably with the term lipid, but fats are actually a particular type of lipid, called **triglycerides**, in which three fatty acids are bound to a compound called glycerol. Fats are important in the body. They are the main form in which the body stores energy. Stored body fat is called adipose tissue. Stored fat not only provides an energy reserve but also cushions and protects internal organs. In addition, stored fat insulates the body and helps prevent heat loss in cold weather.

Although lipids and fats are necessary for life, they may be harmful if they are present in the blood at high levels. Both triglycerides and the lipid called cholesterol are known to damage blood vessels if their concentrations in the blood are too high. By damaging blood vessels, triglycerides and cholesterol also increase the risk of heart disease.

Lipids are classified as either saturated fatty acids or unsaturated fatty acids. This classification is based on the number of chemical bonds between carbon atoms in lipid molecules.

- **Saturated fatty acids** have only single bonds between carbon atoms. This gives them properties that make them unhealthful. Their amount in the diet should be kept as low as possible. If consumed in excess, they contribute to high blood levels of cholesterol and triglycerides. Saturated fatty acids are found in animal foods, such as meat, whole milk, and eggs.
- **Unsaturated fatty acids** have at least one double bond between carbon atoms. This gives them properties that make them more healthful. Eaten in appropriate amounts, they may help lower blood levels of cholesterol and triglycerides and decrease the risk of cardiovascular disease. They are found mainly in plant foods.

The human body can synthesize all but two of the fatty acids it needs: omega-3 fatty acids and omega-6 fatty acids. Both are unsaturated fatty acids. They are called essential fatty acids because they must be present in the diet. They are found in salmon, vegetable oil, flaxseed, eggs, and whole grains. Small amounts of these two fatty acids may help lower blood pressure as well as blood levels of harmful lipids.

Unsaturated fatty acids known as trans fatty acids (or trans fats), are manufactured from plant oils and do not occur naturally. They are added to foods to extend their shelf life. Trans fats have properties like saturated fats and may increase risk of cardiovascular disease. They should be avoided in balanced eating. Many manufacturers no longer add trans fats to food products, and their use in restaurants has been banned in some cities.

Water

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.

Balanced Eating

Balanced eating is a way of eating that promotes good health. It includes eating several medium-sized meals regularly throughout the day. It also includes eating the right balance of different foods to provide the body with all the nutrients it needs. How much of these foods should you eat to get the right balance of nutrients? Two tools for choosing foods that provide balanced nutrition are the U.S. Department of Agriculture (USDA) recommendations, and food package nutrition labels.

The U.S. Department of Agriculture (USDA) Recommendations

The USDA has a long history of recommending dietary guidelines starting in 1894 with "Principles of Nutrition and Nutritive Value of Food". These recommendations have sought to translate technical nutrient requirements into understandable instructions for healthy eating. In 1992 the USDA formally adopted a Food Pyramid graphic to communicate this complex information in an easy understandable way. Food pyramids represent the optimal number of servings to each each day from each of the food groups, and the first pyramid was published in Sweden in 1974. The USDA's first pyramid in 1992 was motivated by a 1977 report of U.S. Dietary Goals that linked American diets directly to chronic illnesses. The US food pyramid is part of the Dietary Guidelines for Americans, which is published jointly by the US Department of Agriculture (USDA) and the US Health and Human Services (HHS) every five years, as mandated by the National Nutrition Monitoring and Related Research Act of 1990. The latest guidelines are known as the "New Pyramid" and were published in January, 2026, and replaced the "My Plate" graphic of recommendations that had been in place since 2011.

In general, the recommendations seek to provide guidance on how much of different dietary factors a person should eat, and portion sizes. The dietary factors include: whole grain foods; plant oils; vegetables; fruits; fish, poultry and eggs; dairy or calcium; red meat and butter; and processed grains and carbohydrates. The current "New Pyramid" prioritizes non-processed foods over processed items, and places proteins, vegetables and full-fat dairy at the top. The USDA's Food Pyramid has been a repeated source of controversy since the 1990's due to food industry efforts to modify the recommendations based on their own economic interests.

Food Labels

Packaged foods are required by law to carry a nutrition facts label that show the nutrient content and ingredients in the food, similar to the one in Figure 10.2.1.

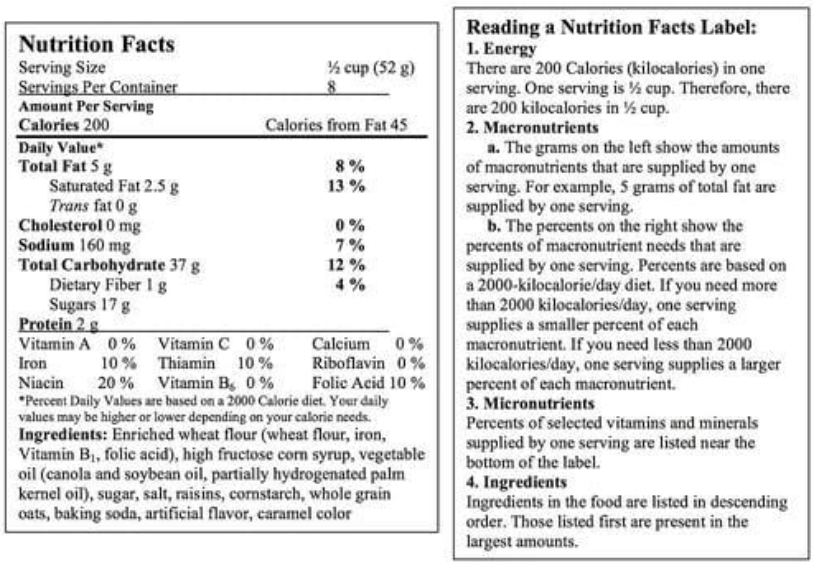


Figure 10.2.1: A sample food package graphic demonstrating how to break down energy, macronutrients, micronutrients, and listed ingredients on a traditional nutrition facts label. (Graphic courtesy of CK-12 Foundation; licensed under CC BY-NC 3.0).

Reading nutrition facts labels can help you choose foods that are high in nutrients such as protein and low in nutrients such as fat. Nutrition facts labels can also help you choose foods that are nutrient dense. Nutrient density is the ratio of nutrient content, measured in grams, to total energy content in kilocalories.

Consider the following two foods:

Two examples of food.

Food A	Food B
15g/300 kcal = 0.05 g/kcal	10g/120 kcal = 0.08 g/kcal
Nutrient Density:	Nutrient Density:
Energy: 300 kval	Energy: 120 kval
Protein: 15 g	Protein: 10 g

In terms of protein, Food B is more nutrient dense than Food A, because it provides more protein per kilocalorie. Eating nutrient-dense foods helps you to get enough of each nutrient without taking in too many kilocalories.

Reading the ingredients list on food labels can also help you choose healthful foods for balanced eating. At the top of the list, look for ingredients such as whole grains, vegetables, and fruits. These are foods you need the most of in a balanced diet. Avoid foods that contain processed ingredients, such as white flour or white rice. Processing removes nutrients. As a result, processed foods generally supply fewer nutrients than whole foods, even when they have been enriched or fortified with added nutrients.

Vitamins and Minerals

Unlike the major macronutrients, micronutrients—including vitamins and minerals—do not provide energy. Nonetheless, adequate amounts of micronutrients are essential for good health. The needed amounts generally can be met with balanced eating. However, many people do not eat enough of the right foods to meet their requirements. They may need vitamin or mineral supplements to increase their intake of micronutrients.

Vitamins

Vitamins are organic compounds that are needed by the body to function properly. There are 13 vitamins that humans need. They are described in **Table** below, which also includes recommended daily vitamin intakes for teens.

Vitamins play many roles in good health, ranging from helping maintain vision to helping form red blood cells. Many vitamins are components of enzymes. For example, vitamin K is a component of enzymes involved in blood clotting. Several vitamins, including vitamins C and E, act as antioxidants. An antioxidant is a compound that neutralizes chemicals called free radicals. Free radicals are produced naturally during cellular activities and may cause some types of cancer. Neutralizing free radicals makes them harmless.

Some vitamins, including vitamin B_6, are produced by bacteria that normally live in the intestines, where they help digest food. Vitamin D is synthesized in the skin when it is exposed to UV radiation in sunlight. Most other vitamins must be obtained from foods because the body is unable to synthesize them. Good food sources of vitamins are listed in the table below. They include whole grains, vegetables, fruits, milk, and nuts.

Consuming inadequate amounts of vitamins can cause deficiency diseases. For example, consuming inadequate amounts of vitamin D causes soft bones. In children this is called rickets. It can cause permanent bone deformities. Consuming inadequate amounts of vitamin A may lead to blindness and visual impairment.

Consuming too much of some vitamins can also be dangerous. Overdoses of vitamins can cause problems ranging from diarrhea to birth defects and even death.

Vitamins are either fat-soluble or water-soluble. This determines whether they can accumulate in the body and lead to overdoses.

- Vitamins A, D, E, and K are fat soluble. Excess intakes of these vitamins are stored in fatty tissues of the body. Because they are stored in the body, they can build up to toxic levels, especially if they are taken improperly in supplements.
- Vitamin C and all the B vitamins are water soluble. Excess amounts of these vitamins are excreted in the urine, so they are unlikely to reach toxic levels in the body.
- Recommended daily intakes not established; figures given are adequate daily intakes

Table 10.2.2*: Vitamins*

Vitamin (Chemical Name)	Functions in the Body	Good Food Sources
(Retinoids)Vitamin A	Needed for good vision, reproduction, and fetal development	Carrots, spinach, milk, eggs
(Thiamine)Vitamin B1	Helps break down macronutrients; essential for proper functioning of nerves	Whole wheat, peas, beans, fish, peanuts, meats
(Riboflavin)Vitamin B2	Helps the body process amino acids and fats; acts as antioxidant	Milk, liver, green leafy vegetables, almonds, soybeans
(Niacin)Vitamin B3	Helps release energy from macronutrients; needed for healthy skin and nerves	Beets, beef liver, pork, turkey, fish, sunflower seeds, peanuts
(Pantothenic Acid)Vitamin B5,	Helps form critical enzymes for synthesis of macronutrients	Whole grains, legumes, eggs, meat

Vitamin (Chemical Name)	Functions in the Body	Good Food Sources
(Pyridoxine) Vitamin B6	Forms enzymes needed for amino acid synthesis and energy storage	Cereals, yeast, liver, fish, avocadoes, nuts, green beans
(Biotin)Vitamin B7	Enables synthesis of fatty acids; helps store energy; keeps level of blood sugar stable	None
(Folate)Vitamin B9	Needed to make red blood cells	Liver, green leafy vegetables, dried beans and peas
(Cyanocobalamin)Vitamin B12	Needed for normal functioning of nervous system and formation of blood	Meat, liver, milk, shellfish, eggs
(Ascorbic Acid)Vitamin C	Needed to make many biological chemicals; acts as antioxidant	Citrus fruits such as oranges, red peppers, broccoli, kiwi
(Ergocalciferol and Cholecalciferol)Vitamin D	Helps maintain blood levels of calcium; needed for healthy bones and teeth	Salmon, tuna, eggs, mushrooms
(Tocopherol)Vitamin E	Acts as antioxidant; protects cell membranes from LDL cholesterol damage	Vegetable oils, nuts, green leafy vegetables, whole grains, fish
(Naphthoquinone)Vitamin K	Helps transport calcium; helps blood clot	Kale, spinach, Brussels sprouts, milk, eggs, soy products

Minerals

Dietary minerals are chemical elements that are essential for body processes. Minerals are inorganic, meaning they do not contain carbon. Minerals needed by humans in relatively large amounts (greater than 200 mg/day) are listed in Table 10.2.3 below. Minerals not listed in the table are called trace minerals because they are needed in very small amounts. Trace minerals include chromium, iodine, iron, molybdenum, selenium, and zinc.

Table 10.2.3: Minerals

Mineral Name (Symbol)	Functions in the Body	Good Food Sources
(Ca) Calcium	Needed for nerve and muscle action; builds bone and teeth; helps blood clot	Milk, soy milk, green leafy vegetables, sardines

Mineral Name (Symbol)	Functions in the Body	Good Food Sources
(Cl) Chloride	Helps maintain water and pH balance; helps form stomach acid	Table salt, most processed foods
(Mg) Magnesium	Needed to form several enzymes	Whole grains, green leafy vegetables, nuts, seeds
(P) Phosphorus	Component of bones, teeth, lipids, and other important molecules in the body	Meat, poultry, whole grains
(K) Potassium	Needed for muscle and nerve function; helps maintain salt-water balance in body fluids	Meats, grains, orange juice, potatoes, bananas
(Na) Sodium	Needed for muscle and nerve function; helps maintain salt-water balance in body fluids	Table salt, most processed foods
(S) Sulfur	Necessary component of many proteins	Whole grains, meats, seafood, eggs

Minerals play many important roles in the body. Most are found in the blood and cytoplasm of cells, where they control basic functions. For example, calcium and potassium regulate nerve and muscle activity. Several minerals, including zinc, are components of enzymes. Other minerals, including calcium, form the bulk of teeth and bones.Recommended daily intakes not established; figures given are adequate daily intakes.

Minerals cannot be synthesized by the body. Good food sources of minerals include dairy products, green leafy vegetables, and legumes. Mineral deficiencies are uncommon, but inadequate intakes of a few minerals may lead to health problems. For example, an inadequate intake of calcium may contribute to osteoporosis, a disease in which bones become brittle and break easily. A deficiency in iodine (necessary for the thyroid hormones that regulate growth) may lead to goiter. Iron deficiency is the primary cause of anemia.

Some minerals may be toxic in excess, but overdoses of most minerals are uncommon. Overdoses are more likely when mineral supplements are taken. Salt (sodium chloride) is added to many foods, so the intake of sodium may be too high in many people. Too much sodium in the diet can cause high blood pressure in some individuals.

Other Micronutrients

Recently, new micronutrients called phytochemicals have been found in plants. **Phytochemicals** are naturally occurring chemicals present in or extracted from plants. They occur primarily in colorful fruits and vegetables, like those shown in Figure 10.2.2. Thousands of phytochemicals have been discovered, and some have already been shown to lower the risk of certain diseases. For example, the phytochemical lutein helps reduce the risk of macular degeneration, an eye disease that leads to blindness. Lutein is found in many yellow and orange fruits and vegetables. Several phytochemicals, including some found in berries and cherries, have proven to be powerful antioxidants.



Figure 10.2.2: A vibrant retail display of fresh fruits and vegetables showcasing a diverse array of phytochemical sources. (Credit: Rootology, CC BY-SA 3.0, via Wikimedia Commons.)

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10.3: Soil Profiles and Processes

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 10.3.1). 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.

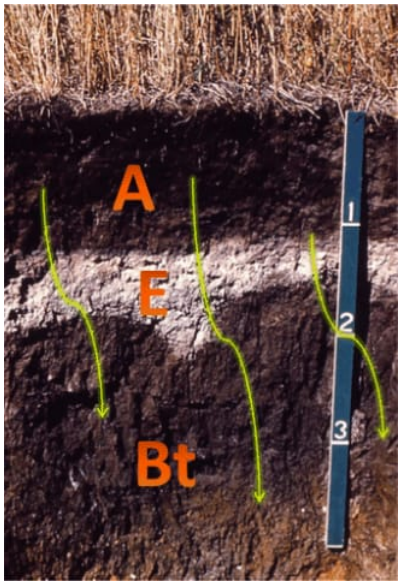


Figure 10.3.1. Soil Profile. Photograph shows a soil profile from South Dakota with A, E, and Bt horizons. The yellow arrows symbolize translocation of fine clays to the Bt horizon. The scale is in feet. Source: University of Idaho and modified by D. Grimley.

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 10.3.2) and reflect past climatic and environmental conditions.

Importance of Soil

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.

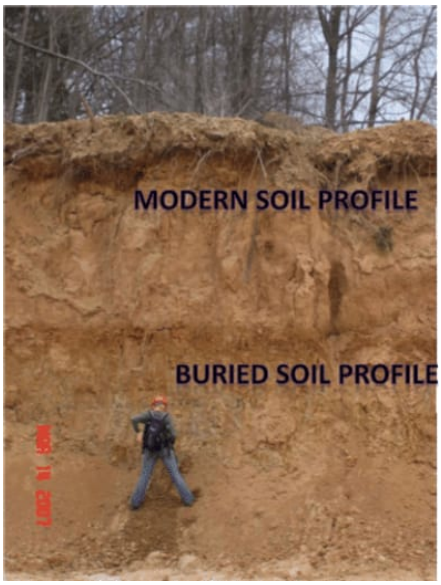


Figure 10.3.2. Modern versus Buried Soil Profiles. A buried soil profile, or paleosol (above geologist 's head), represents soil development during the last interglacial period. A modern soil profile (Alfisol) occurs near the land surface. Source: D. Grimley.

Soil 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, relief, parent material, and time. One could say that the relief, climate, and organisms dictate the local soil environment and act together to cause weathering and mixing of the soil parent material over time. As soil is formed it often has distinct layers, which are formally described as "horizons." Upper horizons (labeled as the A and O horizons) are richer in organic material and so are important in plant growth, while deeper layers (such as the B and C horizons) retain more of the original features of the bedrock below (Figure 10.3.3).

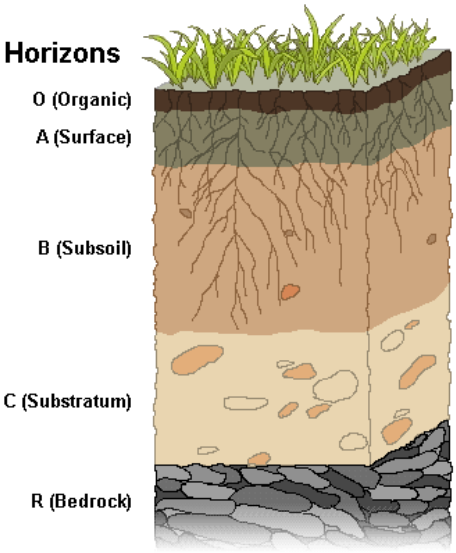


Figure 10.3.3. This images shows the different horizons, or layers, in soil. *This work by Wilsonbiggs is licensed under CC BY-SA 4.0*

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.

Relief (Topography and Drainage)

The local landscape can have a surprisingly strong effect on the soils that form on site. The local topography (**relief**) 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 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). Biological mixing can sometimes cause soil regression, a reversal or bump in the road for the normal path of increasing development over time.

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10.4: Soil-Plant Interactions

Soil plays a key role in plant growth. Beneficial aspects to plants include providing physical support, water, heat, nutrients, and oxygen (Figure 10.4.1). 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.

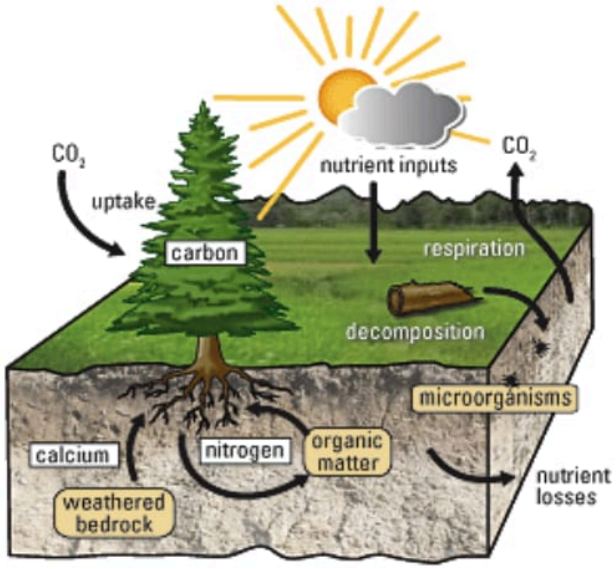


Figure 10.4.1. Soil-Plant Nutrient Cycle. This figure illustrates the uptake of nutrients by plants in the forest-soil ecosystem. Source: U.S. Geological Survey.

The 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.

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.

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10.5: Industrial Agriculture

Also known as conventional agriculture, **industrial agriculture** is a method of farming that involves use of synthetic fertilizer, synthetic pesticides, and machinery. Industrial agriculture is dependent on large investments in mechanized equipment powered mostly by fossil fuels. In the case of livestock, most production comes from systems where animals are highly concentrated and confined.

Synthetic Pesticides

Pests are organisms that occur where they are not wanted or that cause damage to crops, humans or other animals (figure $10.5.a$). 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** (weed killers), fungicides, and various other substances used to control pests. 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 (see Disadvantages of Industrial Agriculture). 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 $10.5.a$: The cotton boll weevil is considered a major pest because of the damage it does to cotton plants. Image by ARS USDA (public domain).

Monoculture Farming

Industrial agriculture employs **monoculture** farming, which involves growing only one species of crop in a large area (figure $10.5.b$). The plants in a monoculture are evenly spaced and have the same planting, irrigation, fertilizer, harvesting, etc. requirements, and this uniformity results in efficient use of farming machinery. Often, the crop is a **high yield variety** (high yielding variety; HYV), which is produced through selectively breeding individual plants with desirable characteristics. Compared to traditional crops, HYVs can produce more per unit area of land. Monoculture farming compromises genetic and species diversity in agriculture, however, promoting the spread of pests and risking that all the plants for hundreds of acres could be susceptible to the same disease (see Genetic Diversity).





Figure $10.5.b$: Monocultures like this potato farm (left) and cotton farm (right) make it easier to use farming equipment; however, this reduces genetic diversity and consumes fossil fuels. Left image by NightThree (CC-BY) and right image by Kimberly Vardeman (CC-BY).

Advantages of Industrial Agriculture

Industrial agriculture has delivered tremendous gains in productivity and efficiency. Food production worldwide has overall risen since the 1940s (figure $10.5.c$); the World Bank estimates that between 70 percent and 90 percent of the recent increases in food production are the result of industrial agriculture rather than greater acreage under cultivation (figure $10.5.d$). United States consumers have come to expect abundant and inexpensive food. Additionally, the use of synthetic pesticides ensures that produce is relatively free of blemishes (figure $10.5.e$).

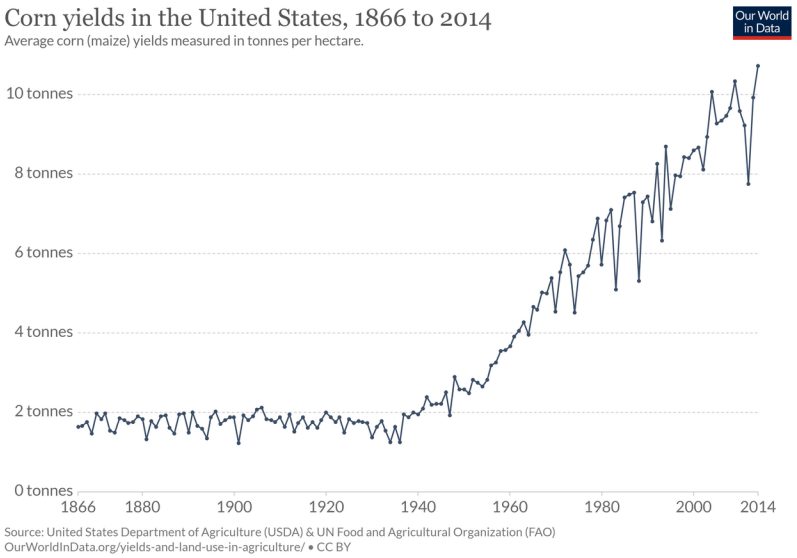


Figure $10.5.c$: Corn yields in metric tons (tonnes; 1000 kilograms) per hectare over time. While yields have fluctuated from year to year, they have overall increased since the 1940s. This improving agricultural efficiency is partly due to industrial agricultural practices. Image by Hannah Ritchie and Max Roser/ Our World in Data (CC-BY).

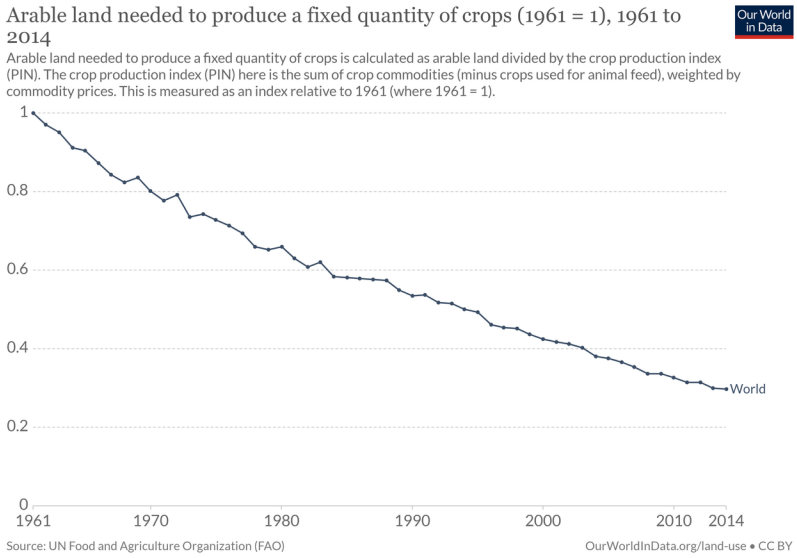


Figure $10.5.d$**:** The arable (farmable) land required to produce a fixed amount of a crop has decreased over time due to improved agricultural efficiency. Image by Hannah Ritchie and Max Roser/Our World in Data (CC-BY).



Figure $10.5.e$: Many of us carefully inspect produce at the grocery store and select those without blemishes. This visually appealing produce results from synthetic pesticides use. Image by Amanda Mills (public domain).

Industrial agriculture expands where crops can be cultivated. Applying synthetic fertilizers to poor soils can make them fertile. Additionally, irrigation systems promote high agricultural productivity in regions and during seasons that would otherwise only support the most drought-tolerant species. For example, about 25% of the food consumed in the United States is produced in California's Central Valley, which receives little rain in the summer months (figure $10.5.f$).



Figure $10.5.f$: The four regions of California's Central Valley from north to south are the Sacramento Valley, Delta and Eastside Streams, San Joaquin Basin, and Tulare Basin. Image by USGS (public domain).

Disadvantages of Industrial Agriculture

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. Farming equipment is expensive, and the industrial agricultural

system favors large corporate farms, which can more easily invest in this equipment. While this equipment promotes efficiency, it also reduces the number of jobs in agriculture (figure $10.5.g$).

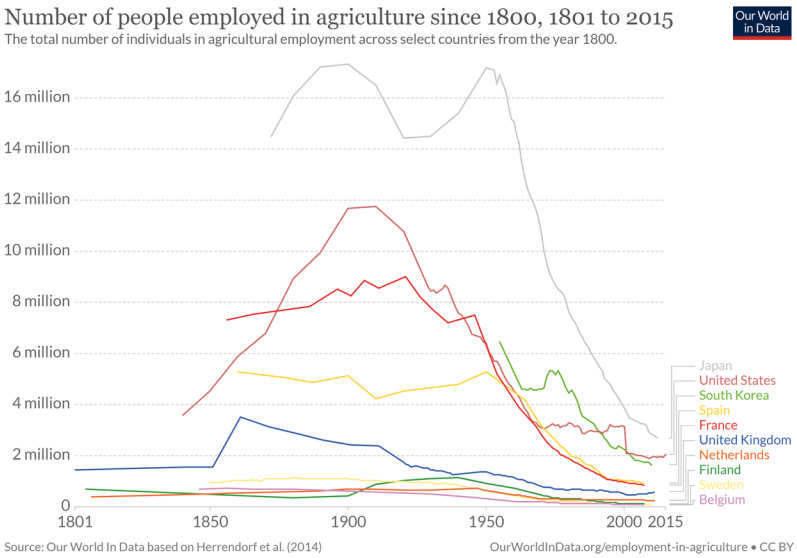


Figure $10.5.g$: The number of people working in agriculture in selected countries over time (from 1801-2015). Generally, the number of agricultural workers has declined as farming practices increased in efficiency and as farming machinery completed tasks that were once manual. This is both an advantage because people are free to pursue other careers and a disadvantage because of the reduction in jobs. In Japan, the number of agricultural workers peaked above 16 million around 1900 and again around 1960. In the United States, it peaked to nearly 12 million around 1900. France followed a similar pattern, peaking around 1925 at approximately 9 million workers. There were over 6 million agricultural workers in South Korea in 1950, and this has overall declined (although there was a spike around 1980). In Spain the number of workers was over 5 million in 1950 and has since decreased. In the United Kingdom, the number of agricultural workers peaked around 1960 at about 3.5 million. The other countries shown (Netherlands, Finland, Sweden, and Belgium) have consistently had under 1 million agricultural workers. Image by Max Roser/Our World in Data (CC-BY).

The mechanical farming equipment required for industrial agriculture relies on fossil fuels. Burning fossil fuels releases air pollution, including greenhouse gases, which cause climate change. Additionally, the synthetic fertilizers and pesticides used in industrial agriculture are produced from fossil fuels. Furthermore, agriculture areas rarely contain as much biomass (organic matter that comprises living things) as biodiverse, intact ecosystems. Biomass is an important carbon sink because its organic molecules store carbon that could otherwise be in the atmosphere as carbon dioxide or methane, both greenhouse gases. Soils with a substantial organic component are also carbon sinks. Industrial agricultural practices that deplete these soils (see below) contribute to climate change, but alternative practices can promote this benefit of healthy soils (see Sustainable Agriculture).

While synthetic fertilizers provide crops with the necessary nutrients for high productivity, excess nutrients from fertilizers can enter bodies of water through runoff. This can lead to a bloom of algae or photosynthetic bacteria in lakes, rivers, and bays in a process called **eutrophication**. These photosynthetic microorganisms sometimes produce toxins that kill aquatic animals and can even harm the humans who consume these animals. Furthermore, they block aquatic plants from accessing light. Eventual decomposition of algal blooms requires oxygen, which results in **hypoxia** (low levels of dissolved oxygen), further harming aquatic species. Additionally, industrial agriculture pollutes water with pesticides and sediments. Pesticides are not only widespread in surface waters, but pesticides from every chemical class have been detected in groundwater.

Industrial agricultural practices often deplete soil quality. For example, wind and water erosion of exposed topsoil removes particles and nutrients from the soil (which also contributes to eutrophication and sediment pollution). Tilling (mixing the soil) and overgrazing of livestock exacerbates erosion. When livestock remove too much vegetation from an area, plant roots no longer anchor the soil in place, and erosion ensues. Farming equipment compacts the soil. This limits infiltration of water into the soil (decreases soil permeability), makes it more difficult for roots to penetrate the soil, and hinders gas exchange in roots. In extreme cases, soil has eroded and lost its ability to retain water that once arable (farmable) land becomes a desert-like (**desertification**; see Soil Degradation; figure $10.5.h$).



Figure 10.5.*h*: Overgrazing depleted the soil in the Rukwa Plains of southwestern Tanzania. Image by Lichinga (CC-BY-SA).

Irrigation can lead to **salinization** (increased salinity). While the water itself eventually evaporates, is transpired, or drains from the soil, the minerals dissolved in the water may remain in the soil. Over time, these minerals can accumulate to levels that are toxic for most plants. As discussed in Water Usage, irrigation for agriculture accounts for 69% of global water usage. Withdrawal of sufficient water for irrigation contributes to water shortages and diverts water from ecosystems (see Aqueducts).

Repeated pesticide application exerts selective pressure on insects, fungi, and other crop pests to evolve pesticide resistance. By chance, some individuals in a pest population may carry gene versions that confer pesticide resistance. When these populations are exposed to pesticides, individuals with these gene versions are the most likely to survive and reproduce. They then pass these genes to their offspring, and pesticide resistance becomes more and more common in the population over time (figure 10.5.*i*). At this point, pesticides may need to be applied at greater concentrations or more frequently to achieve the same effect. If pesticide that was initially used is no longer effective at all, the farmer would be forced to find a different pesticide. Over 400 insects and mite pests and more than 70 fungal pathogens have become resistant to one or more pesticides.

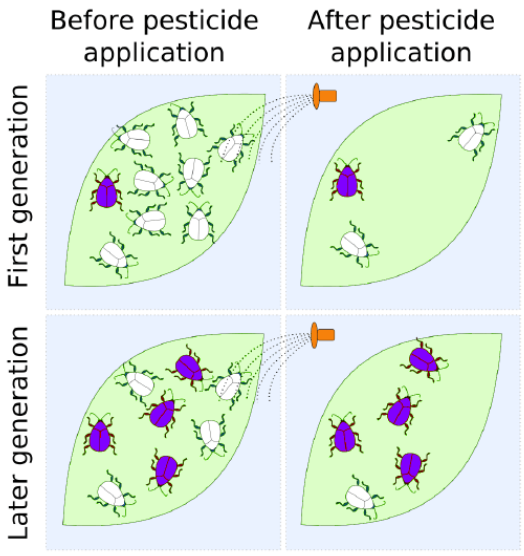


Figure 10.5.*i*: Pesticide application can exert selection for the evolution of pesticide resistance. In this hypothetical example, the purple beetle has a gene version that makes it resistant to pesticides (upper left). Pesticides are applied, killing most of the susceptible individuals (white beetles; upper right). In a later generation, purple, resistant beetles are more common because they had a better chance of surviving and reproducing (lower left). Upon another pesticide application, an even greater proportion of the population is resistant. Image modified from Delldot (CC-BY-SA).

The human health and environmental costs of pesticide use 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.

Pesticides have also placed stresses on pollinators and other beneficial insect species. They can lead to the destruction of natural enemies, which would regulate pest populations in an intact ecosystem. For example, once apple growers began controlling pests with the pesticide dichlorodiphenyltrichloroethane (DDT), which has since been banned, they quickly found their orchards being attacked by scale insects and mites. The reason: DDT had killed off their natural enemies. More generally, pollution from industrial agriculture along with habitat loss due to converting healthy ecosystems into agricultural fields is a major threat to biodiversity. As mentioned previously, monoculture farming limits biodiversity in crops.

With respect to animal agriculture, keeping livestock are kept in close quarters increases the risk of disease spread among them. For these reason, food animals are commonly given antibiotics, either preventatively or to treat existing infections. As discussed in the Infectious Diseases section, the overuse of antibiotics (whether in humans or farm animals) increases selection for the evolution of antibiotic-resistant strains of bacteria or other disease-causing organisms. Infections by antibiotic-resistant strains are more difficult to treat.

As with many industrial practices, potential health hazards are often tied to farming practices. Under research and investigation currently is the sub-therapeutic use of antibiotics in animal production, and pesticide and nitrate contamination of water and food. Farm worker health is also a consideration in all farming practices.

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10.6: Sustainable Agriculture

"**Sustainable agriculture**" was addressed by Congress in the 1990 "Farm Bill". Under that law, "the term sustainable agriculture means an integrated system of plant and animal production practices having a site-specific application that will, over the long term:

- satisfy human food and fiber needs;
- enhance environmental quality and the natural resource base upon which the agricultural economy depends;
- make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls;
- sustain the economic viability of farm operations; and
- enhance the quality of life for farmers and society as a whole."

Organic Farming is Good for Farmers, Consumers and the Environment

Organic agriculture is an ecological production management system that promotes and enhances biodiversity, biological cycles and soil biological activity. Organic food is produced by farmers who emphasize 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.

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 thuringenensis* to kill mosquito and moth larvae, and introduction of fungi, such as Trichoderma, to suppress fungal-caused plant diseases, leaf beetle (*Galerucella calmariensis*) to suppress purple loosestrife, a noxious weed (Figure 10.6.1). 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 10.6.1. 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 to as a biocontrol for invasive plants such as purple loosestrife.

Intercropping Promotes Plant Interactions

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 10.6.2). 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.



Figure 10.6.2. Intercropping alyssum (the flowering plants shown center left) with organic romaine lettuce for aphid control.

Organic Farming Practices Reduce Unnecessary Input Use

In modern agricultural practices, heavy machinery is used to prepare the seedbed for planting, to control weeds, and to harvest the crop. 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 10.6.3).



Figure 10.6.3. Farmers should consider no-till farming as the most important tool to prevent loss of soil moisture.

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.

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.

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.

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.

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10.7: Data Dive- Landslides and Ag Terraces

Overview

The beauty of terraced agriculture almost makes the observer forget that it is still a form of habitat destruction and landscape modification. A 2019 study investigated the risk to terraced landscapes with varying states of upkeep after severe rainfall events, which increase chances of serious damage due to landslide events. The authors compared three classes of upkeep:

- Succession on terrace: Which includes all terraced areas in which cultivation activities ceased, and is currently substituted by both wood and shrub cover.
- Cultivated terrace: Which includes all areas which are still under any kind of cultivation, from olive groves, to vineyards, to other crops
- Vegetated natural slopes: Which refer to those areas covered by spontaneous vegetation which have never been terraced.

Landslide mapping was used to estimate the size of damage after a landslide event took place. Below is a graph for some of the published results:

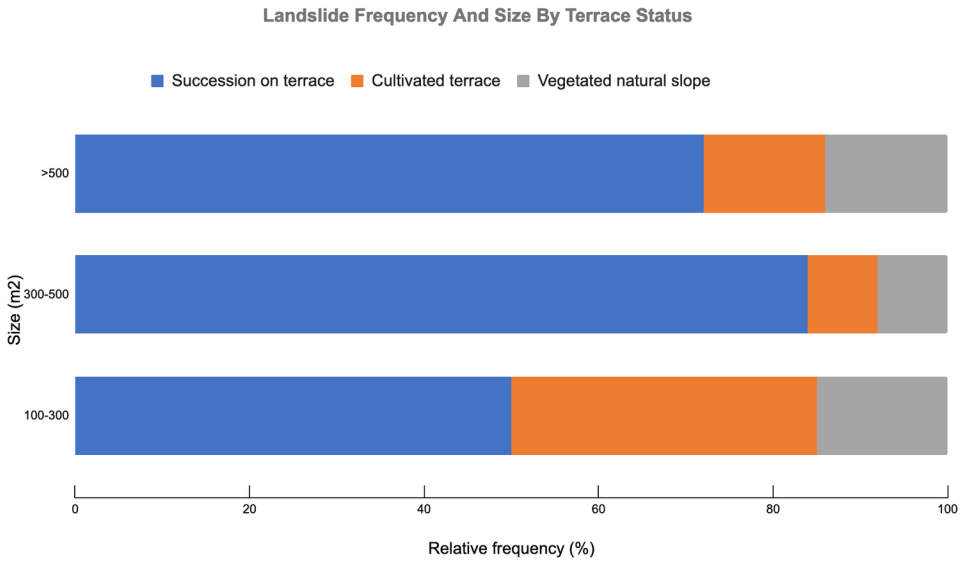


Figure $10.7.a$: Percent breakdown of landslide frequency and size by terrace status. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Agnoletti M, Errico A, Santoro A, Dani A, Preti F 2019.

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What question(s) are the authors trying to answer with this graph?
3. Do the authors use any control category/variable to help clarify the patterns observed? If so, what?
4. Which status has the most consistent increased landslide frequency?
5. What landslide frequency patterns can you observe across the three size?
6. How can the results of this graph to inform future projects/restoration efforts when a terrace is abandoned?

Raw Data For Above Graph(s)

Table $10.7.a$**:** Raw data for percent breakdown of landslide frequency and size by terrace status. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Agnoletti M, Errico A, Santoro A, Dani A, Preti F 2019.

Terrace Status	100-300	300-500	Over 500
Succession On Terrace	50	84	72
Cultivated Terrace	35	8	14
Vegetated Natural Slope	15	8	14

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11: ENERGY

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11.1: FOSSIL FUELS

11.1.1: Types of Fossil Fuels and Formation

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11.1.1: Types of Fossil Fuels and Formation

Fossil fuels are nonrenewable sources of energy formed from the organic matter of plants and microorganisms that lived millions of years ago. This energy was originally captured via photosynthesis by living organisms such as plants, algae, and photosynthetic bacteria. Sometimes this is known as fossil solar energy since the energy of the sun in the past has been converted into the chemical energy within a fossil fuel. As discussed in Food Chains and Food Webs and Matter, the organic molecules store chemical energy, which is released when the higher energy (less stable) bonds in these molecules are broken to form lower energy (more stable) bonds. Fossil fuels are nonrenewable because their formation took millions of years. Furthermore, higher productivity in the ancient environment allowed for more fossil fuel accumulation, meaning that the fossil fuel reserves available now could not necessarily be regenerated millions of years in the future.

Fossil fuels are composed primarily of **hydrocarbons** (molecules of just carbon and hydrogen), but they contain lesser amounts nitrogen, sulfur, oxygen, and other elements as well. The precise chemical structures vary depending on the type of fossil fuel (coal, oil, or natural gas). The molecules in coal tend to be larger than those in oil and natural gas. Coal is thus solid at room temperature, oil is liquid, and natural gas is in a gaseous phase. Specifically, **coal** is a black or dark brown solid fossil fuel found as coal seams in rock layers formed from ancient swamp vegetation. Both oil and natural gas are fossil fuels found underground that formed from marine microorganisms. **Oil** (petroleum) is a liquid fossil fuel and consists of a variety of hydrocarbons while **natural gas** is a gaseous fossil fuel that consists of mostly methane and other small hydrocarbons.

Coal

Coal is the product of fossilized swamps, although some older coal deposits that predate terrestrial plants are presumed to come from algal buildups. Coal was formed when plant material is buried, heated, and compressed in oxygen-poor conditions over a long period of time (figure 11.1.1.a). Millions of years ago, continents were in different locations with different climates, and swamp-like vegetation covered many regions. When the vegetation died, it could not fully decompose due to oxygen-poor conditions. Instead, it formed peat (a brown substance high in organic content). The peat was buried and formed coal after millions of years of high pressure and temperature. The pressure was from the weight of sediments as well as from continental collisions.

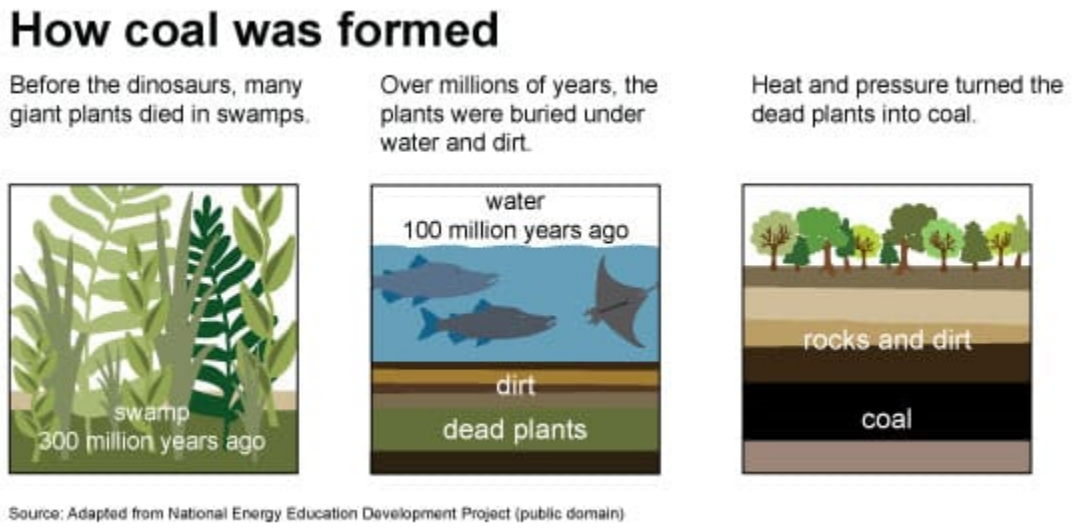


Figure 11.1.1.a: Coal was formed when large plants in swamps died 300 million years ago (before the dinosaurs). Over millions of years, this vegetation was buried under water and dirt (100 million years ago). Eventually, heat and pressure turned the dead plants into coal, which is found under layers of rock and dirt. Image from U.S. Energy Information Administration/National Energy Education Development Project (public domain).

There are several different types of coal ranging in quality (figure 11.1.1.b). The more heat and pressure that coal undergoes during formation, the greater is its fuel value and the more desirable is the coal. The general sequence of a swamp turning into the various stages of coal are as follows:

Swamp → Peat → Lignite → Subbituminous coal → Bituminous coal → Anthracitic coal → Graphite

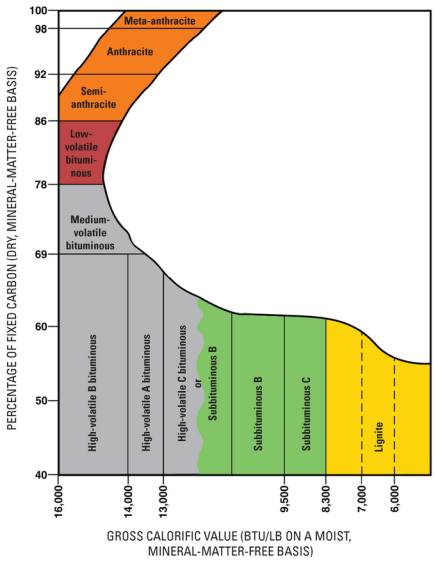


Figure 11.1.1.*b*: Coal rankings depend on energy content, measured as gross calorific value (how much energy is released from combustion) and carbon content that can be burned (percentage of fixed carbon). Anthracitic coal (orange) is the highest quality coal, with high energy and carbon content. Next in quality is bituminous coal (gray), subbituminous coal (green), and lignite (yellow). All three have less carbon content than anthracitic coal. Bituminous coal retains high energy content, but subbituminous coal and lignite have lower energy content. Image by USGS (public domain).

Specifically, peat compacts to form solid rock through a process called **lithification**, producing **lignite** (brown coal, a low-quality form of coal). With increasing heat and pressure, lignite turns to **subbituminous coal** and **bituminous coal**. Lignite, subbituminous coal, and bituminous coal are considered sedimentary rocks because they from from compacted sediments. At very high heat and pressure, bituminous coal is transformed to **anthracite**, a high-grade coal that is the most desirable coal since it provides the highest energy output (figure 11.1.1.*c*). Anthracite is considered a metamorphic rock because it has been compacted and transformed to the extent that it is denser than the other forms of coal and no longer contains sheet-like layers of sediments. With even more heat and pressure driving out all the components that evaporate easily and leaving pure carbon, anthracite can turn to **graphite**.



Figure 11.1.1.*c*: Anthracitic coal, the highest grade of coal.

Oil and Gas

Oil and natural gas formed from ancient marine microorganism (**plankton**). When plankton died, they were buried in sediments.

As with coal, oxygen-poor conditions limited decomposition. As sediments continued to accumulate, the dead organisms were further buried. High temperature and pressure over millions of years ultimately produced oil and natural gas from these dead organisms.

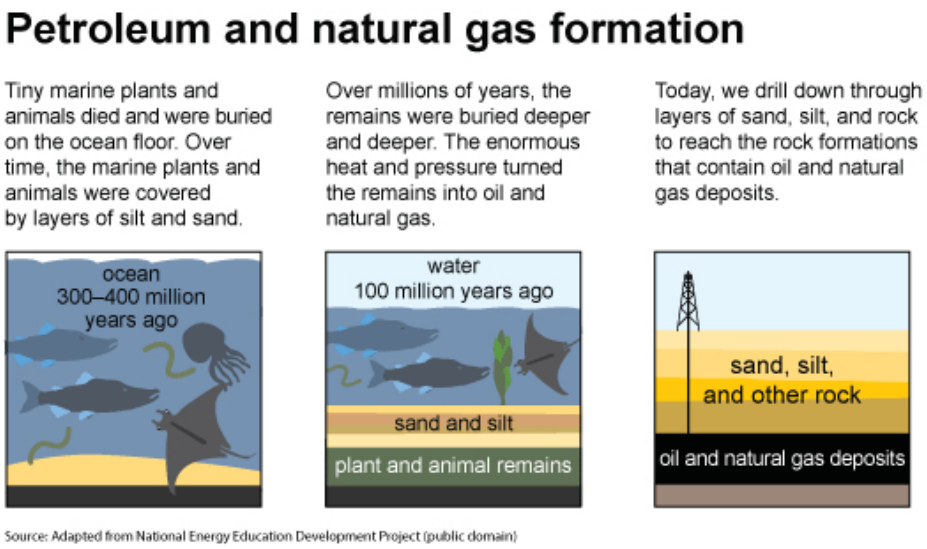


Figure 11.1.1.*d*: Petroleum (oil) and natural gas were formed from marine microorganisms. (The image text mentions tiny marine plants, but they were primarily algae and photosynthetic bacteria rather than plants.) These were covered by layers of silt and sand 300-400 million years ago. Over millions of years, the remains were buried deeper and deeper. They are pictured 100 million years ago. The enormous heat and pressure turned the remains into oil and natural gas. Now, oil and natural gas deposits are found underground and can be extracted via drilling through the layers of sand, silt, and rock. Image from U.S. Energy Information Administration/National Energy Education Development Project (public domain).

As the rock forms from the sediments that originally trapped the plankton, the oil and gas leak out of the **source rock** due to the increased pressure and temperature, and migrate to a different rock unit higher in the rock column. If the rock is porous and permeable rock, then that rock can act as a **reservoir** for the oil and gas. Petroleum is usually found one to two miles (1.6 – 3.2 km) below the Earth's surface, whether that is on land or ocean.

A **trap** is a combination of a subsurface geologic structure and an impervious layer that helps block the movement of oil and gas and concentrates it for later human extraction. Traps pool the fluid fossil fuels into a configuration in which extraction is more likely to be profitable, and such fossil fuels are called **conventional oil and natural gas** (figure 11.1.1.*e*). Extraction of oil or gas outside of a trap (**unconventional oil and natural gas**) is less efficient and more expensive; sometimes it is not economically viable at all (does not produce a profit). Examples of unconventional fossil fuels include oil shale, tight oil and gas, tar sands (oil sands), and coalbed methane.

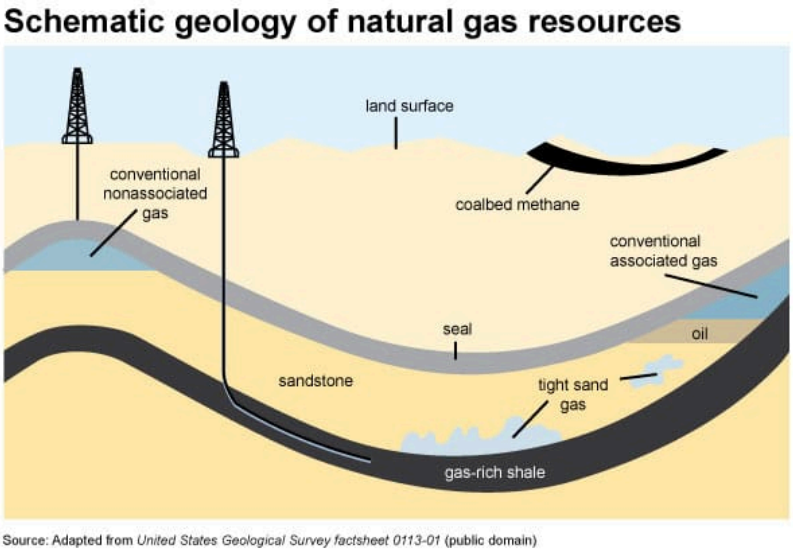


Figure 11.1.1.*e*: Conventional oil and natural gas deposits are trapped beneath impervious rock (gray). Conventional natural gas may be associated with oil or nonassociated. Coalbed methane and tight gas found in shale and sandstone are examples of unconventional fossil fuels. Image from USGS/EIA (public domain)

Oil Shale

Oil shale is a fine-grained sedimentary rock that sometimes contains **kerogen**, a solid material from which petroleum products can ultimately be manufactured. In order extract the fossil fuels, the material has to be mined and heated, which is expensive and typically has a negative impact on the environment.

Tight Oil and Natural Gas

Tight oil and natural gas are also trapped in shale rock, fine-grained sedimentary rocks with relatively high porosity and low permeability. They differ from oil shale in that they can be extracted through a process called hydraulic fracturing (fracking).

Similarly, fracking can be used to extract natural gas from tight sands, which are gas-bearing, fine-grained sandstones or carbonates (rocks made of minerals containing carbonate, CO_3^{2-}) with a low permeability.

Tar Sands

Tar sands, or oil sands, are sandstones that contain petroleum products that are highly viscous (like tar), and thus, can not be drilled and pumped out of the ground, unlike conventional oil (figure 11.1.1.*f*). The fossil fuel in question is bitumen, which can be pumped as a fluid only at very low rates of recovery and only when heated or mixed with solvents. Thus, injections of steam and solvent or mining of the tar sands for later processing can be used to extract the tar from the sands. (See related information about strip mining with respect to coal in Mining, Processing, and Generating Electricity.) Alberta, Canada is known to have the largest reserves of tar sands in the world.



Figure 11.1.1.*f*: Tar sandstone from the Miocene Monterrey Formation of California.

Coalbed Methane

Some natural gas is also found associated with coal deposits (**coalbed methane**), consisting of methane produced during coal formation.

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- Shale Gas 101. Office of Fossil Energy. U.S. Department of Energy. Accessed 01-12-2021. (public domain)
- The Process of Unconventional Natural Gas Production. 2021. United States Environmental Protection Agency. Accessed 01-12-2021. (public domain)

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11.1.2: Mining, Processing, and Generating Electricity

Fossil fuels must be extracted or mined before use, and the specific method depends on the type of fossil fuel. Coal and natural gas and primarily used for electricity generation, while petroleum is refined to produce fuel for vehicles, planes, and heating as well as other products.

Coal

Mining

Coal is extracted by two principal methods, of which there are many variants: surface mining or subsurface mining. **Surface mining** uses large machines to remove the soil and layers of rock known as **overburden** to expose coal seams that are close to the Earth's surface (figure $11.1.2.a$). **Strip mining** is a type of surface mining in which overburden is sequentially removed from each stretch (strip) of land. Once overburden is removed from the first strip, coal is removed. Overburden from the second strip is then deposited into the first strip, and coal is removed from the second strip. Overburden from the third strip is then placed in the first strip, and so on. **Mountaintop removal** is a more destructive type of surface mining in which all of the overburden is removed with explosives, revealing the entire coal seam at once (figure $11.1.2.b$). The large mass of overburden (the mountaintop) is dumped into a nearby valley, and the coal is them removed.



Figure $11.1.2.a$: Surface mining of coal in Wyoming. Image by Bureau of Land Management (public domain).

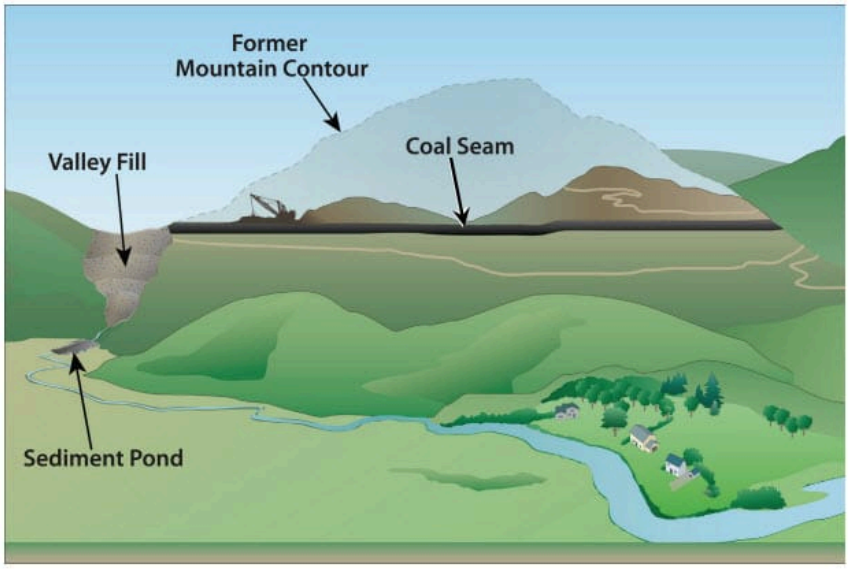




Figure 11.1.2.*b*: Left: Mountaintop removal uses explosives to loosen overburden at the top of a mountain, which is then displaced into a nearby valley (valley fill). The underlying coal seam is then extracted. A sediment pond collects soil that erodes from the valley fill. Image by EPA (public domain). Right: A mountaintop removal site. Image by JW Randolph (public domain)

Subsurface mining (deep mining) employs underground tunnels to access deeper deposits (figure 11.1.2.*c*). Some underground mines are thousands of feet deep, and extend for miles. Miners ride elevators down deep mine shafts and travel on small trains in long tunnels to get to the coal. The miners use large machines that dig out the coal. In **drift mines**, a tunnel is dug horizontally into the side of a mountain. In **slope mines**, this tunnel is diagonal. In **shaft mines**, elevators are used to move coal through vertical tunnels.

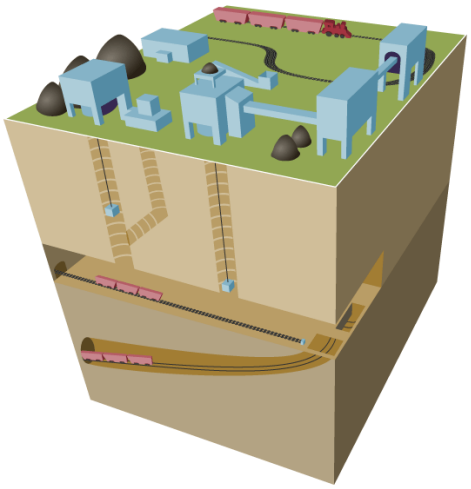


Figure 11.1.2.*c*: Subsurface mining involves digging tunnels to access coal deposits that are deep underground. Image by National Energy Education Development Project/EIA (public domain)

Processing of Coal

Once mined, coal may go to a preparation plant located near the mining site where it is cleaned and processed to remove impurities such as rocks and dirt, ash, sulfur, and other unwanted materials. This process increases the amount of energy that can be obtained from a unit of coal, known as its heating value.

Transport of Coal

Finally, the mined and processed coal must be transported. Transportation can be more expensive than mining the coal. Nearly 70% of coal delivered in the United States is transported, for at least part of its trip, by train (figure 11.1.2.*e*). Coal can also be transported by barge, ship, or truck. Coal can also be crushed, mixed with water, and sent through a slurry pipeline. Sometimes, coal-fired electric power plants are built near coal mines to lower transportation costs.



Figure 11.1.2.*e*: A freight train loaded with coal briquettes, formed from compressed coal dust, in Morwell, Victoria, Australia. Image and caption (modified) by CSIRO (CC-BY).

Generating Electricity from Coal

Once at the power plant, coal is first pulverized into a fine powder and then mixed with hot air and blown into a furnace (figure 11.1.2.f). This allows for the most complete combustion (burning) and maximum heat release. Purified water, pumped through pipes inside a boiler, is turned into steam by the heat from the combustion of coal. The high pressure of the steam pushing against a series of giant turbine blades turns the turbine shaft. The turbine shaft is connected to the shaft of the generator, where magnets spin within wire coils to produce electricity. After doing its work in the turbine, the steam is drawn into a condenser, a large chamber in the basement of the power plant. In this important step, millions of gallons of cool water from a nearby source (such as a river or lake) are pumped through a network of tubes running through the condenser. The cool water in the tubes converts the steam back into water that can be used over and over again in the plant. The cooling water is returned to its source without any contamination except at a higher temperature than when first extracted from the river or lake.

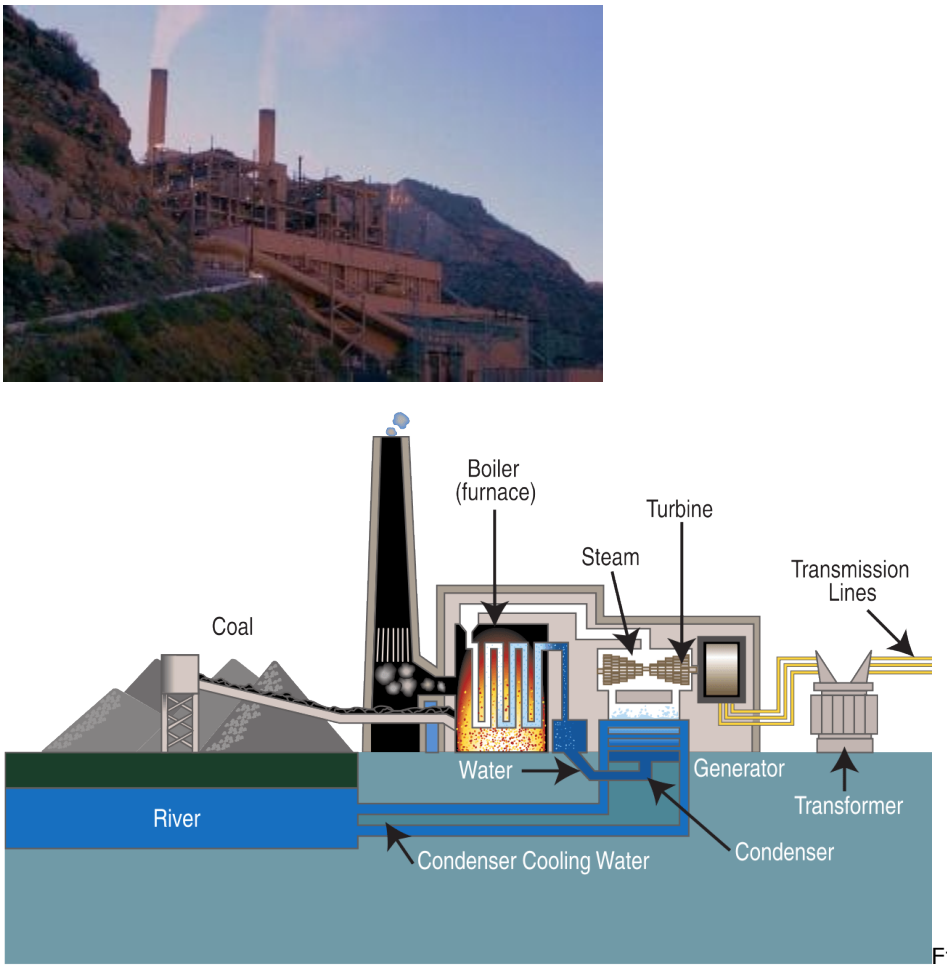


Figure 11.1.2.f: Left: Coal power plant in Helper, Utah. Right: Diagram of a typical steam-cycle coal power plant (proceeding from left to right). Coal enters the boiler (furnace), where it is burned. This boils water, producing steam. The steam turns a turbine, powering a generator. The resultant electricity is passed through a transformer (which changes the voltage) and is then sent through transmission lines. The steam cools and condenses back to liquid water in the condenser. This is facilitator by cooling water from a nearby river. Right image by Tennessee Valley Authority (public domain).

This video shows how heat energy can be used to generate electricity.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Oil and Natural Gas

Extraction of Conventional Oil and Natural Gas

Conventional oil and natural gas are contained under a trap (cap rock). Because natural gas consists of lighter molecules that are in a gaseous form at moderate temperatures, it is found on top of the oil, which may be floating on groundwater. To access conventional oil and natural gas, the trap is first pierced. Initially, they are under high enough pressure, and this drives them out of the well (**primary recovery**). Next, water (or gas) is injected to force more fossil fuels out (**secondary recovery**). Finally, enhanced oil recovery (**tertiary recovery**) may be used to extract further oil by applying heat (injecting steam) or injecting carbon dioxide, other gases, or larger molecules. For example, carbon dioxide causes the oil to thin and expand, making it easier to remove from the rocks. Note that secondary recovery simply increases pressure inside the reservoir whereas tertiary recovery changes the properties of the oil, making it easier to extract (figure $11.1.2.g$). Each stage of recovery is increasingly expensive, and extraction from a well continues as long as it remains profitable.

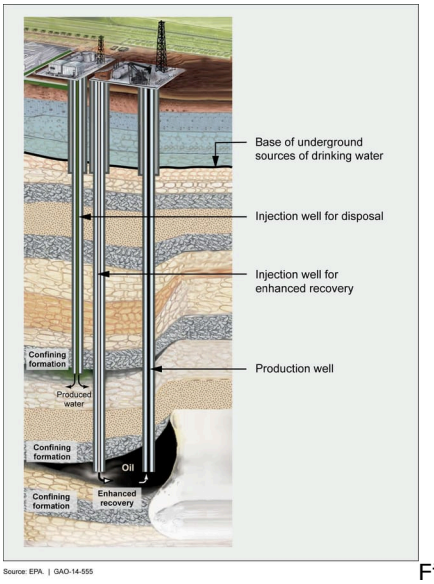


Figure $11.1.2.g$: Injection wells transfer water, carbon dioxide, or other substances to an oil deposit increase pressure or change the oil's properties, facilitating extraction. On the right is the production well, through which extracted oil flows. This is facilitated by an injection well for enhanced recovery. On the left is an injection well for disposal through with waste water (produced water) is stored underground. Several confining formations trap substances underground. Closer to the top is the base of underground sources of drinking water, meaning that all drinking water is extracted from above this point. Image by Government Accountability Office (public domain).

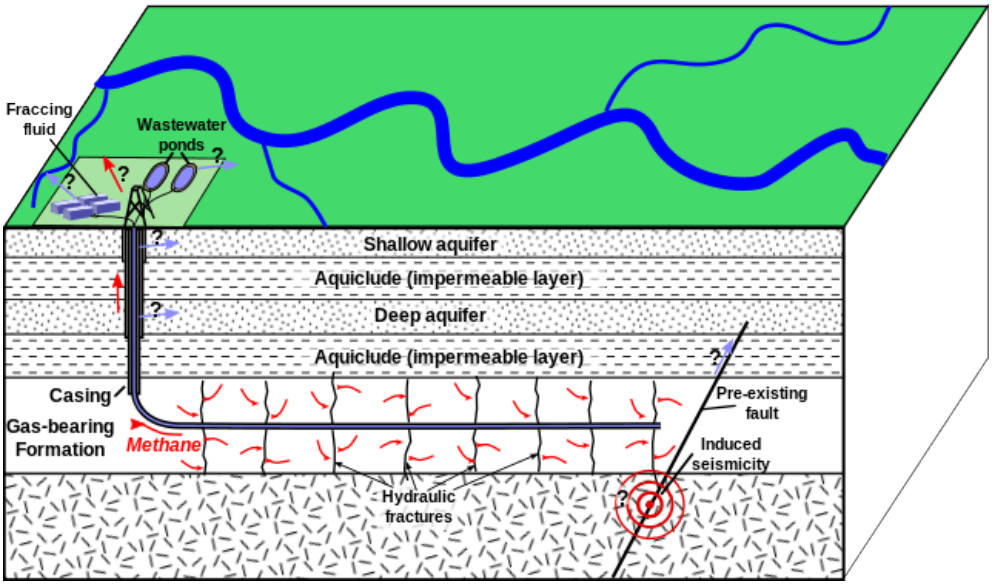
Oil is mainly obtained by drilling either on land (onshore) or in the ocean (offshore). Early offshore drilling was generally limited to areas where the water was less than 300 feet deep. Oil and natural gas drilling rigs now operate in water as deep as two miles. Floating platforms are used for drilling in deeper waters (figure $11.1.2.h$). These self-propelled vessels are attached to the ocean floor using large cables and anchors. Wells are drilled from these platforms which are also used to lower production equipment to the ocean floor. Some drilling platforms stand on stilt-like legs that are embedded in the ocean floor. These platforms hold all required drilling equipment as well as housing and storage areas for the work crews. Offshore production is much more expensive than land-based production.



Figure 11.1.2.*h*: A platform for offshore oil drilling. Image by Pixabay/keridjackson (Pixabay license).

Extraction of Unconventional Oil and Natural Gas

Tight oil and natural gas trapped in shale as well as natural gas in tight sands are extracted via **hydraulic fracturing**, informally referred to as "fracking". This process uses explosives to create new fractures in these low-permeability rocks as well as increase the size, extent, and connectivity of existing fractures and then applies high-pressure fluid. First, a drill permeates the rock layers and then proceeds horizontally. Explosives then fracture rocks, freeing oil and natural gas. Finally, water, sand, and chemicals and injected, which flush out oil and natural gas (figure 11.1.2.*i*).



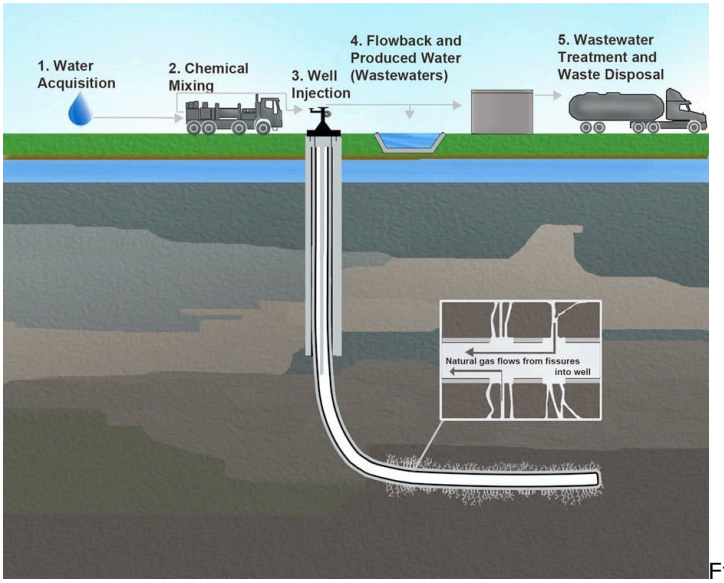


Figure 11.1.2.*i*: Two diagrams of fracking. Water is mixed with sand and chemicals and then injected into shale trapping tight oil and natural gas or tight sand. This flushes fossil fuels from the fissures that were previously created by explosives. Top: This section shows four underground layers. From top to bottom, they are the shallow aquifer, aquiclude (impermeable layer), deep aquifer, and another aquiclude. Fracking fluid is injected underground through a well surrounded by casing into the gas-bearing formation. Methane (red arrows) might escape from hydraulic fractures in this formation. Additionally, when the fractures intersect with a pre-existing fault, induced seismicity (earthquakes) is possible. Aboveground, fracking fluid is stored in wastewater ponds. Blue arrows and question marks indicate places where toxic wastewater may escape and contaminate groundwater such as from storage containers, wastewater ponds, casing, or faults. Bottom: Proper treatment and disposal of the wastewater is needed to limit environmental impact. 1: Water is acquired. 2: Chemicals are mixed. 3: Fracking fluid is injected into the well. Here, natural gas flows from fissures into the well. 4: Fracking results in flowback and produced water (wastewater). 5: Wastewater undergoes treatment and disposal. Bottom image by USGS (public domain).

As mentioned previously, bitumen in tar sands can be extracted by injecting steam, or they may be mined for later processing. Tar sands can mined through strip mining or **open-pit mining**, a type of surface mining that involves forming a progressively deeper hole. The walls of the pit are as steep as can safely be managed. A steep wall means there is less waste overburden to remove and is an engineering balance between efficient mining and mass wasting. Oil shale is extracted by strip mining, creating subsurface mines, or open-pit mining. Oil shale can be burned directly like coal or baked in the presence of hydrogen to extract liquid petroleum (figure 11.1.2.*j*).



Figure 11.1.2.*j*: Underground mining of oil shale in Estonia.

Refining Crude Oil

The result of oil recovery is crude oil (petroleum), which contains many types of hydrocarbons as well as some unwanted substances such as sulfur, nitrogen, oxygen, dissolved metals, and water all mixed together. Unprocessed crude oil is therefore, not generally useful in industrial applications and must first be separated into different useable products (**petrochemicals**) at a refinery. Gasoline (petrol), diesel, tar, and asphalt are examples of petrochemicals.

Fractional distillation is the key process used in oil refineries to separate the components of crude oil. During fractional distillation, crude oil is heated and then allowed to cool. The heaviest compounds sink to the bottom as residues. Components of vaporized crude oil condense at different levels in the distillation column depending on their boiling points, which is primarily due to their molecular sizes. The heaviest compounds (condense near the bottom of the column, where the temperature is still high. Lighter compounds condense at cooler temperatures higher up in the column. Some compounds remain as gases at the top of the column (figure $11.1.2.k$).

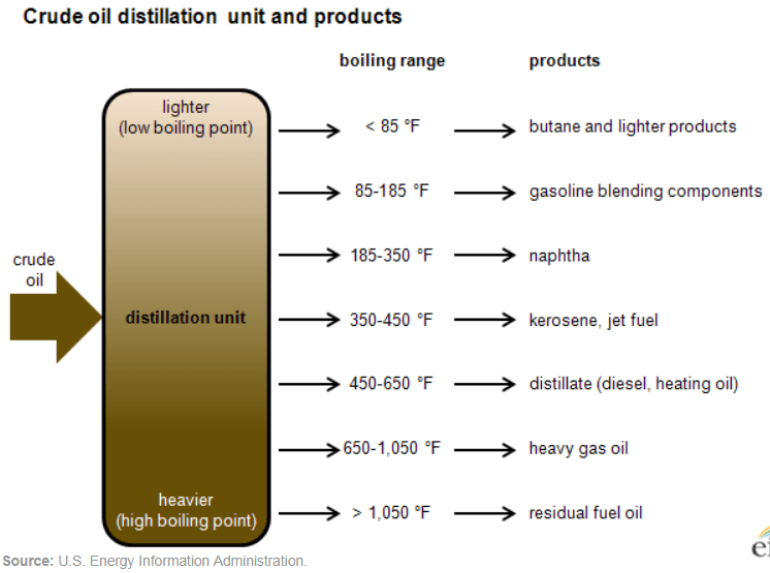


Figure $11.1.2.k$: The process of fractional distillation involves heating crude oil and allowing the components to cool. As they move up the distillation column, they condense at different levels based on their boiling points. The heaviest compounds have the highest boiling points and condense at the bottom of the column while lighter compounds (low boiling point) condense at the top. From lowest to highest boiling point the petrochemicals produced are residual fuel oil (1050 °F), heavy gas oil (650-1050 °F), diesel and heating oil (450-650 °F), kerosene and jet fuel (350-450 °F), naphtha (used to make gasoline, solvents, cleaning solutions, etc.; 185-350 °F), gasoline blending components (85-185 °F), and butane and lighter products (< 85 °F). Image by U.S. Energy Information Administration (public domain).

The video below explains the process of fractional distillation. The labeled distillation column at 3:00 shows heated crude oil (400 °C) separating into various petrochemicals. From bottom to top, they are bitumen (> 350 °C), diesel (250-350 °C), kerosene (160-250 °C), naphtha (70-160 °C), petrol (20-70 °C), and gas (< 20 °C).

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Conversion is the chemical processing in which some of the fractions (produced from fractional distillation) are transformed in to other products. For example, a refinery can turn diesel fuel into gasoline depending on the demand for gasoline. Conversion can

involve breaking larger hydrocarbon chains into smaller ones (cracking), combining smaller chains into larger ones (unification), or rearranging the molecules to created desired products (alteration).

Treatment is done to the fractions to remove impurities such as sulfur, nitrogen and water among others. Refineries also combine the various fractions (processed and unprocessed) into mixtures to make desired products. For example, different mixtures of hydrocarbon chains can create gasolines with different octane ratings, with and without additives, lubricating oils of various weights and grades (WD-40, 10W-40, 5W-30, etc.), heating oil, and many others. The products are stored onsite until they can be delivered to various markets such as gas stations, airports and chemical plants.

A 42 U.S. gallon barrel of crude oil yields about 45 gallons of petroleum products because of refinery processing gain (figure $11.1.2.l$). This increase in volume is similar to what happens to popcorn when it is popped. Gasoline makes up the largest fraction of all petroleum products obtained. Other products include diesel fuel and heating oil, jet fuel, petrochemical feedstocks (to manufacture plastics, synthetic rubber, or other chemicals), waxes, lubricating oils, and asphalt.

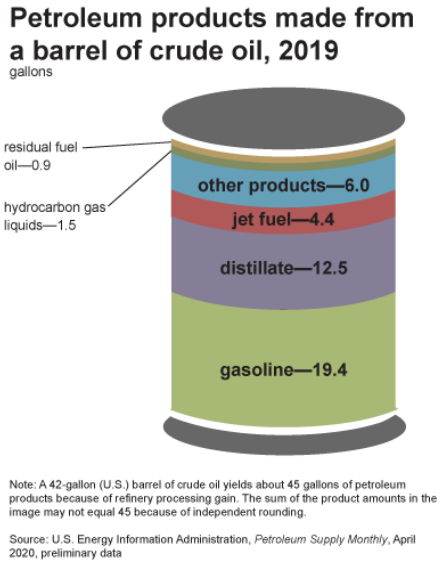


Figure $11.1.2.l$: Main products (measured in gallons) made from a barrel of crude oil in 2019. These include residual fuel oil (0.9 gallons), hydrocarbon gas (1.5), other products (6.0), jet fuel (4.4), distillate (12.5), and gasoline (19.4). Note: A 42-gallon (U.S.) barrel of crude oil yields about 45 gallons of petroleum products because of refinery processing gain. The sum of the product amounts in the image may not equal 45 because of independent rounding. Image by EIA (public domain).

Transporting Oil and Natural Gas

After the refinery, the gasoline and other fuels created are ready to be distributed for use. A system of pipelines runs throughout the United States to transport oil and fuels from one location to another. There are pipelines that transport crude oil from the oil well to the refinery. At the refinery, there are additional pipelines that transport the finished product to various storage terminals where it can then be loaded onto trucks for delivery, such as to a gas station.

Once natural gas is produced from underground rock formations, it is sent by pipelines to storage facilities and then on to the end user. The United States has a vast pipeline network that transports gas to and from nearly any location in the lower 48 states. There are more than 210 natural gas pipeline systems, using more than 300,000 miles of interstate and intrastate transmission pipelines (figure $11.1.2.m$). Compressor stations that maintain pressure on the natural gas to keep it moving through the system. There are more than 400 underground natural gas storage facilities that can hold the gas until it is needed back in the system for delivery.



Figure $11.1.2.m$: Construction of the controversial Dakota Access Pipeline, which stretches from North Dakota to Illinois. The pictured portion of the pipeline is in Central Iowa. You can learn more about the 2016 protests against this pipeline here. Image by Dakota Access Pipe Line (CC-BY).

Generating Electricity from Oil or Natural Gas

Natural gas is burned to produce electricity following the same general process used in a coal power plant (figure $11.1.2.n$). Oil is occasionally used to generate electricity as well.

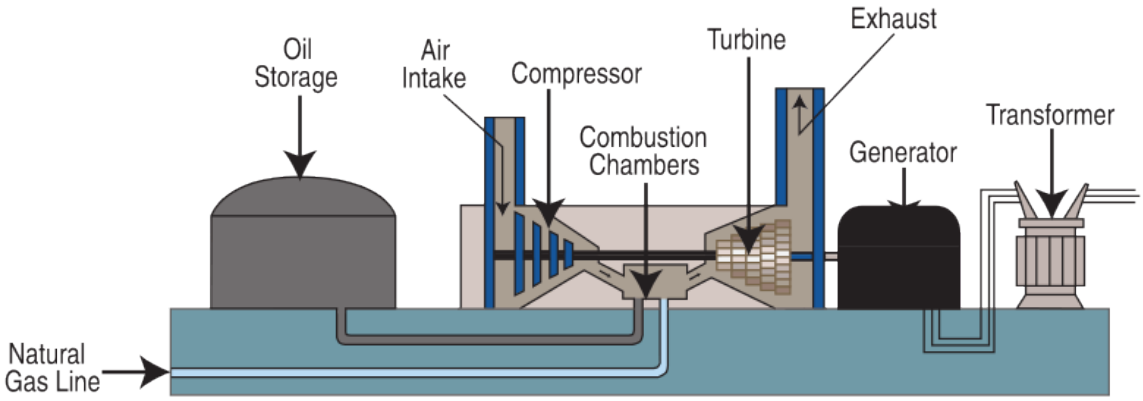


Figure $11.1.2.n$: This combustion chamber burns either natural gas or oil. Fuel flows through a natural gas line or from oil storage into the combustion chamber. Air passes through the air intake and is compressed in the compressor. Natural gas and compressed air are mixed with compressed air in the combustion chamber and burned. High-pressure combustion gases spin the turbine, which drives the generator. The resultant electric current is then passed through a transformer, which alters voltage. Image and caption (modified) by Tennessee Valley Authority (public domain).

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- Chapter 4: Non-Renewable Energy from *Introduction to Environmental Science: 2nd Edition* (2018) Biological Sciences Open Textbooks by Zehnder, Caralyn; Manoylov, Kalina; Mutiti, Samuel; Mutiti, Christine; VandeVoort, Allison; and Bennett, Donna (licensed under CC-BY-NC-SA).
- Fossil Energy Study Guide: Natural Gas. 2014. U.S. Department of Energy. Accessed 01-12-2021.
- Fossil Energy Study Guide: Oil. 2013. U.S. Department of Energy. Accessed 01-12-2021.

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11.1.3: Fossil Fuel Consumption

The U.S. and the world overall heavily depend on fossil fuels. In 2019, fossil fuels contributed to 62.6% of electricity generation in the U.S. with coal contributing 23.4% and natural gas contributing 38.4% (table $11.1.3.a$). Note that oil (petroleum) is primary used for transportation and thus only contributes a fraction of a percentage to electricity generation. With respect to total energy consumption, the world continues to rely on crude oil more than any other energy source (33.1%) followed by coal (27%) and natural gas (24.3%; figure$11.1.3.a$).

Table $11.1.3.a$***:*** *Contribution of Each Energy Source to Electricity Generation in the U.S. in 2019*

Energy source	Contribution to Electricity Generation (%)
Fossil fuels (total)	**62.6%**
Natural gas	38.4%
Coal	23.4%
Petroleum (total)	0.4%
Other gases	0.3%
Nuclear	**19.6%**
Renewables (total)	**17.6%**
Hydropower	7.0%
Wind	7.1%
Biomass (total)	1.4%
Solar (total)	1.7%
Geothermal	0.4%

Table modified from U.S. Energy Information Administration (public domain).

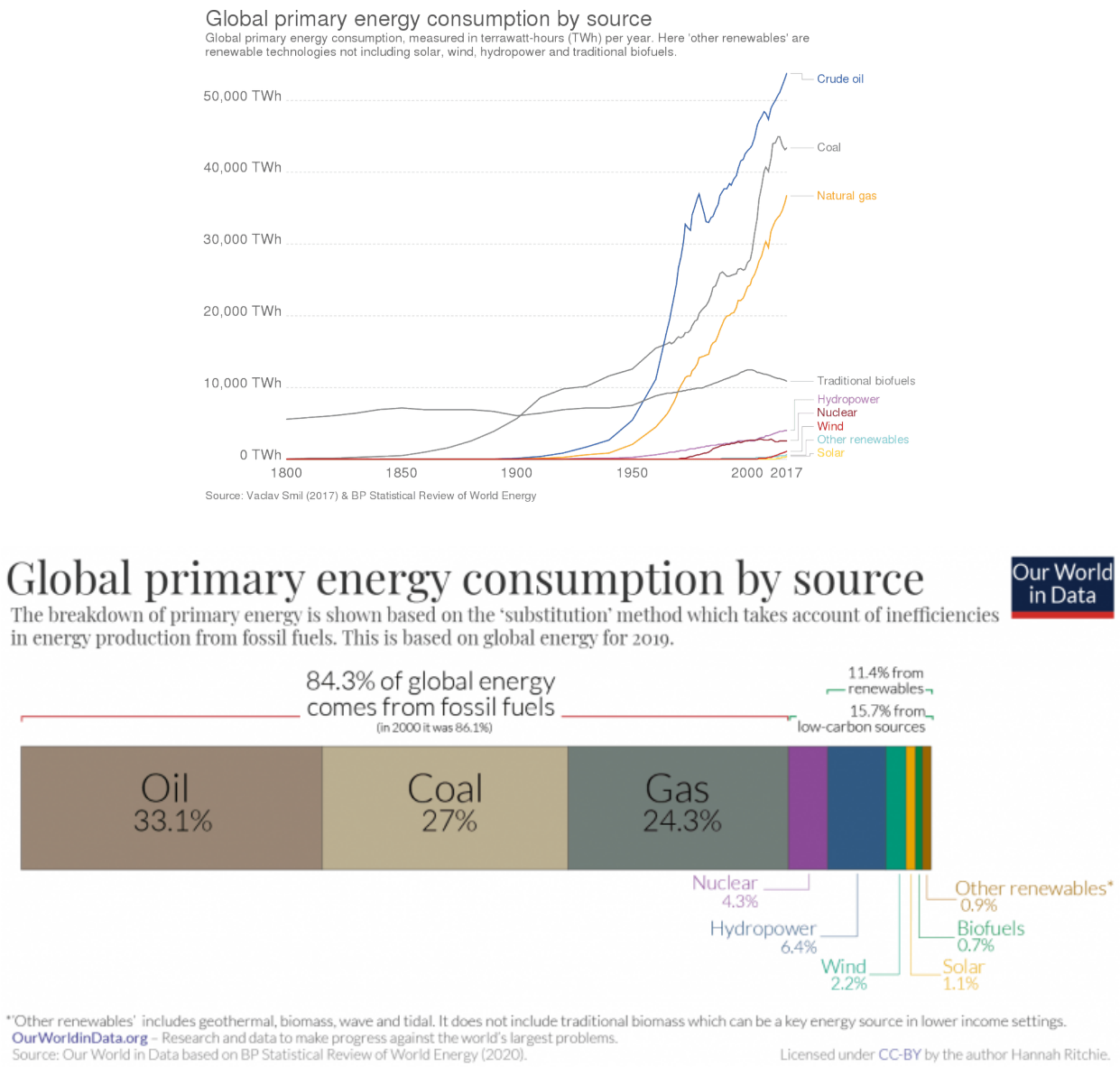


Figure 11.1.3.*a*: The top graph shows global energy consumption by source shows energy consumption in terrawatt-hours (TWh) on the y-axis and time in years (1800-2017) on the X-axis. The bottom graph shows the percentage that each energy source contributes to global energy consumption in 2019. Global consumption of most energy sources has increased over time. Consumption of crude oil is the highest (33.1% of global energy consumption in 2019), and it increased rapidly in the 1950s, surpassing coal consumption in the early 1960s. Coal is now the second most-consumed energy source (27%), but its global consumption has declined in recent years. Natural gas is the third most-consumed energy source (24.3%) and has also been increasing. Coal and natural gas consumption surpassed that of traditional biofuels in the early 1900s and 1970, respectively. Nuclear energy consumption has decreased recently, accounting for 4.3% of global energy consumption in 2019. Consumption of renewable energy overall (11.4%) is low compared to fossil fuels (84.3% combined), but it has generally increased in recent years. Images by Our World in Data (CC-BY).

Coal has been used by humans for at least 6000 years, mainly as a fuel source. Coal resources in Wales are often cited as a primary reason for the rise of Britain (and later, the United States) in the Industrial Revolution. 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. Coal is the largest domestically produced source of energy. At the end of 2018, BP estimated at 734,903 million tonnes, with nearly 23.7% of that in the United States. It is a major fuel resource that the United States controls domestically.

Proven oil reserves (or natural gas reserves) refers to the amount of oil or natural gas that can be extracted economically with

current methods (such as conventional wells or fracking). The U.S. Energy Administration estimates that there are enough liquid fuels to last through 2050 (and they include biofuels in this projection). In 2016, BP projected that proven reserves of oil and natural gas can support global demands for another 50 years. Additionally, they estimate that coal reserves can last another 115 years.

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 was initially predicted that global peak oil would be reached in 2000, but oil production and consumption continue to rise. The United States, however, already passed peak oil production in 1970.

The concentration of oil reserves in a few regions of the world makes much of the world dependent on imported energy for transportation (figure11.1.3.*b*). 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 spent $304.9 billion on oil imports in 2019. The United States has become more and more dependent on foreign oil since 1970 when our own oil production peaked.

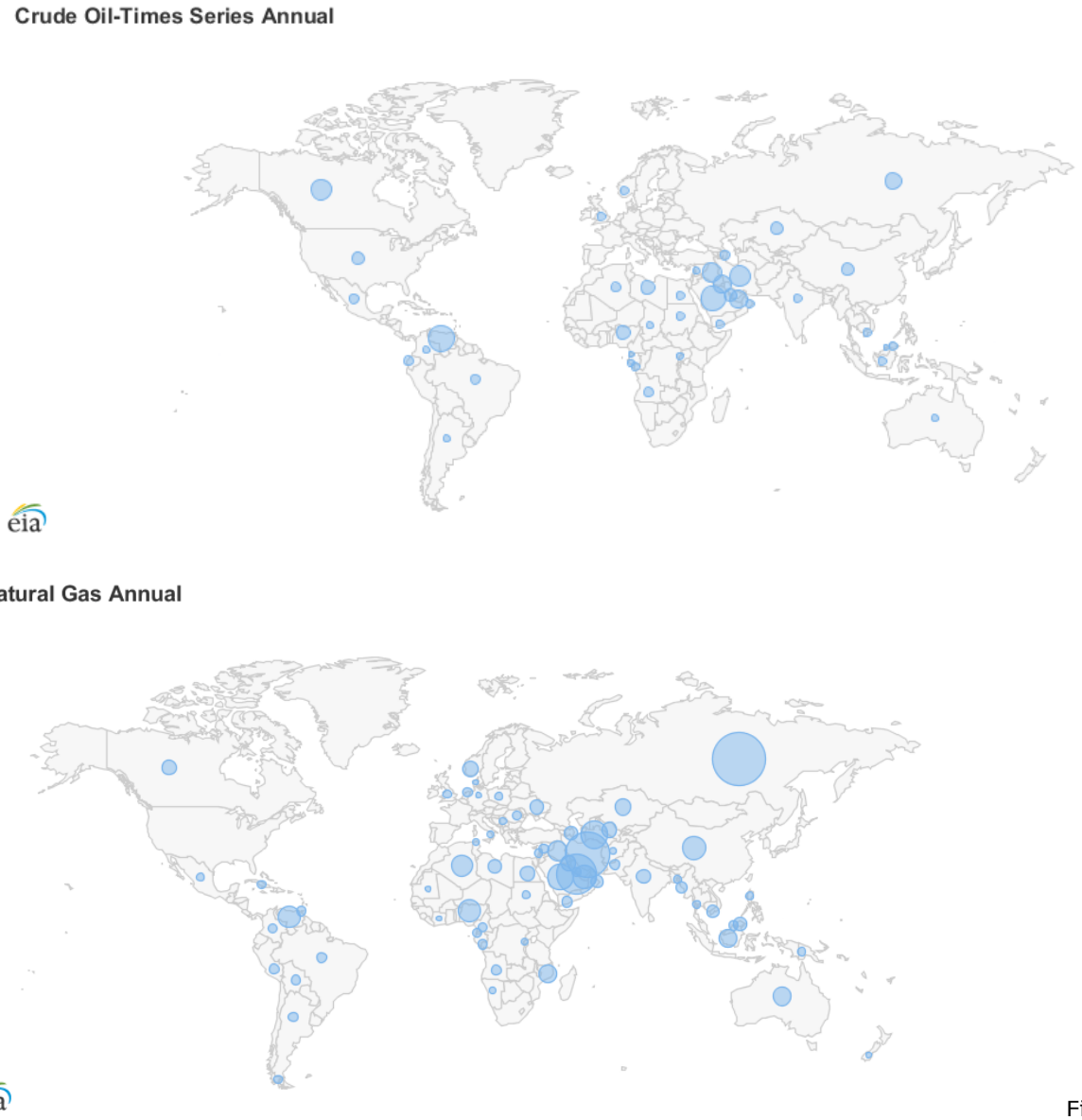


Figure11.1.3.*b*: Global reserves of oil (top) and natural gas (bottom) by country in 2017 and 2020, respectively. The blue circle in each country is scaled to the size of the reserve. Both fossil fuels are abundant in the Middle East. Russia also has a rich supply of natural gas. Images from EIA (public domain).

The major holder of oil reserves is the **Organization of Petroleum Exporting Countries,** (OPEC). As of 2024, there were 12 member countries in OPEC: Algeria, Congo, Equatorial Guinea, Gabon, Iran, Iraq, Kuwait, Libya, Nigeria, 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.

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.

Attribution

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11.1.4: Consequences of Fossil Fuels

Benefits of Using Fossil Fuels

The world is heavily dependent on fossil fuels, and existing infrastructure and technologies facilitate their continued use. An advantage of using coal for electricity is that it plentiful and inexpensive, especially in the United States, which has larger coal reserves than any other country. Furthermore, coal mining is a source of jobs and tax income. Coal's economic advantage is dwindling, however, as technologies associated with renewable sources of energy, such as solar and wind, become more efficient and inexpensive. The U.S. Energy Information Administration compared the levelized cost of electricity (LCOE) for technologies that will begin use in 2023, and the cost of coal-generated electricity exceeded that of many renewable sources (figure 11.1.4.a). The LCOE accounts for the building and operation costs of power plants, solar panels, wind turbines, etc.

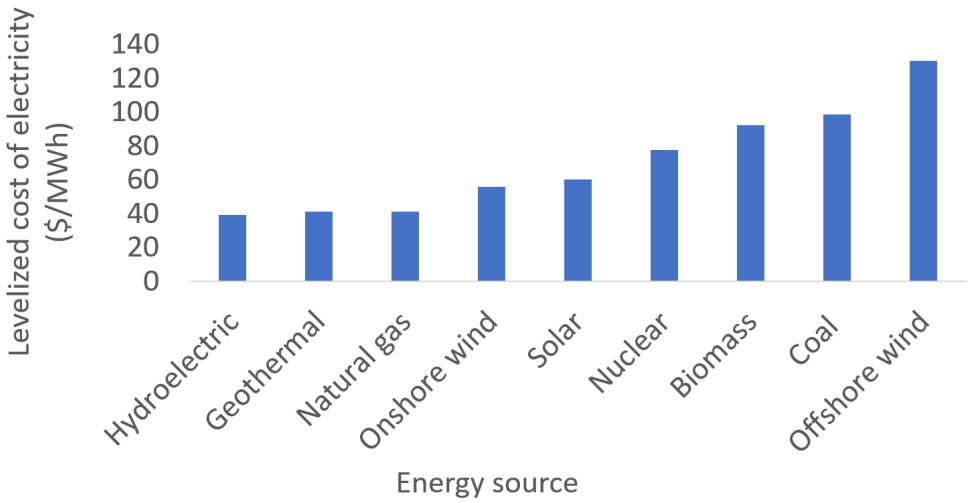


Figure 11.1.4.a: The **levelized cost of electricity** (**LCOE**) for various energy sources. Of these, hydroelectric, geothermal, natural gas, onshore/offshore wind, solar, and biomass are considered renewable. Nuclear and coal are nonrenewable energy sources. Values are in 2018 dollars per **megawatt hour** ($/MWh). As a reference, the average U.S. household, uses about 0.909 MWh of electricity per month. These values are for the newest technologies that will being use in 2023. Hydroelectric energy is the least expensive, at about $39/MWh. Hydroelectric energy is the least expensive, at about $39/MWh. Next is geothermal ($41/MWh), natural gas ($41/MWh), onshore wind ($56/MWh), solar ($60/MWh), nuclear ($78/MWh), biomass ($92/MWh), coal ($99/MWh), and offshore wind ($130/MWh). Graph by Melissa Ha (CC-BY-NC) using data U.S. Energy Information Administration, Annual Energy Outlook 2019 (public domain).

Oil and natural gas continue to meet global energy needs. Despite expansions in renewable energy use, no alternative energy source is currently sufficient to replace oil and natural gas. (A combination of different renewable sources could be possible in the future.) While the United States does rely on imported oil, it continues to produce some oil and natural gas (mostly through fracking), bolstering U.S. energy independence. Local and state economics in regions rich in oil and natural reserves depend on continued extraction of these fossil fuels.

While all fossil fuels harm cause some degree of environmental harm, natural gas is a preferred fossil fuel for electricity generation when considering its environmental impacts. When burned, coal emits nearly double the carbon dioxide that natural gas does. Additionally, much less nitrogen oxides and sulfur dioxide (both air pollutants) are emitted from burning natural gas. It also does not produce ash as coal does (see below).

Health and Environmental Impacts

The negative impacts of fossil fuel use begin with the extraction of the resource. Fossils 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. Additional negative impacts are associated with processing, electricity generation, and disposal of the waste generated.

Coal Mining and Usage

Surface mining of coal disrupts local ecosystems above coal deposits as overburden is removed to access them (figure 11.1.4.*b*). In mountaintop removal, a large volume of overburden is dumped over nearby habitats, causing further destruction (figure 11.1.4.*c*). Mountaintop removal has affected large areas of the Appalachian Mountains in West Virginia and Kentucky. Habitat loss from coal mining decreases biodiversity, resulting in a loss of ecosystem services. Both surface and subsurface mining expose rocks that can contain contaminants, such as heavy metals or sulfates, which them leach into streams or other bodies of water. This not only harms aquatic life, but it also disrupts nutrient cycling. One of the largest environmental impacts of subsurface mining may be the methane gas that must be vented out of mines to make the mines a safe place to work. Methane gas is a potent greenhouse gas and contributes to climate change. Finally, the process of mining ultimately compacts soil. This combined with the loss of trees, which slow the flow of run-off and promote infiltration, increases the risk of flooding.



Figure 11.1.4.*b*: Peak Downs and Saraji Coal Mine in Queensland, Australia. To access the coal, vegetation was removed, destroying habitat for native organisms. Image by Lock the Gate Alliance (CC-BY).



Figure 11.1.4.*c*: Mountaintop Removal Coal Mining in Martin County, Kentucky Photograph shows mountaintop coal removal mining in Martin County, Kentucky. Source: Flashdark.

Coal miners face health hazards such as explosions, mine collapse, and exposure to toxic fumes. **Black lung disease** is a respiratory condition characterized by coughing and shortness of breath that occurs in miners exposed to too much coal dust. Residents near mines also risk exposure to coal dust and underground toxins following explosions. As a result of exposure to toxins, birth defects and other health problems are common in residents near mines.

Coal is considered the "dirtiest" source of energy because its combustion results in the most air pollution. Coal power plants emits a variety of air pollutants including sulfur dioxide, nitrogen oxide, and heavy metals. Sulfur dioxide and nitrogen oxide are sources of acid rain (acid deposition), smog, and health issues. Heavy metals cause neurological and developmental problems in humans and other animals. Burning of coal emits particulate matter and higher amounts of carbon dioxide per unit of energy than the use of oil or natural gas. Carbon dioxide is the most frequently emitted greenhouse gas and causes climate change. In 2018, electricity generation was responsible 27% of greenhouse gas emissions in the United States, and much of this was emitted from coal power plants. The transportation of coal usually relies on fossil fuels, releasing further pollution.

Ash (including fly ash and bottom ash) is a residue created when coal is burned at power plants. In the past, fly ash was released into the air through the smokestack, where it would contribute to particulate matter air pollution. Laws now require that much of the fly ash now must be be captured by pollution control devices, like scrubbers. In the United States, fly ash is generally stored at coal power plants or placed in landfills. Ash from storage or landfills can spill or leach into groundwater, resulting in water pollution.

Conventional Extraction Oil and Natural Gas

Exploring and drilling for oil degrades land and ocean habitats. On land, extensive infrastructure such as road networks, transport pipelines and housing for workers are needed to support a full-scale drilling operation. These can pollute soil and water, fragment habitats, and disturb wildlife. Extraction of oil and natural gas is also hazardous for workers, who have a high incidence of cancer and heart disease.

Human-caused oil spills in rivers and oceans harm ecosystems. From an economic perspective, oil spills disrupt the fishing industry and tourism. Oil spills at sea are generally much more damaging than those on land, since they can spread for hundreds of nautical miles in a thin oil slick which can cover beaches with a thin coating of oil. This can kill sea birds, mammals, shellfish and other organisms it coats. Oil spills on land are more readily containable if a makeshift earth dam can be rapidly bulldozed around the spill site before most of the oil escapes, and land animals can avoid the oil more easily.

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 began in April 2010 when a natural gas explosion at an oil well 65 km offshore of Louisiana occurred on Deepwater Horizon Oil Rig. It killed 11 employees and flowed for 3 months in 2010, releasing an estimated 200 million gallons of oil (figure $11.1.4.d$). 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 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 11.1.4.*d*: Platform supply vessels battle the blazing remnants of the off shore oil rig Deepwater Horizon. A Coast Guard MH-65C dolphin rescue helicopter and crew document the fire aboard the mobile offshore drilling unit Deepwater Horizon, while searching for survivors. Multiple Coast Guard helicopters, planes and cutters responded to rescue the Deepwater Horizon's 126 person crew. Image and caption (modified) from US Coast Guard (public domain).

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 a variety of components, but each has its procs and cons. Skimmer ships that vacuum oil from the water surface, but these are effective only for small spills. Controlled burning works only in early stages before the light, ignitable part evaporates, but this also pollutes the air. **Dispersants** are detergents that break up oil to accelerate its decomposition, but some dispersants may be toxic to the ecosystem. **Bioremediation** refers to adding microorganisms that specialize in quickly decomposing oil, but this can disrupt the natural ecosystem.

Unconventional Extraction of Oil and Natural Gas

Fracking causes more environmental damage than conventional extraction. The considerable use of water (figure 11.1.4.*e*) may affect the availability of water for other uses in some regions, and this can affect aquatic habitats. In fact, fracking consumes more water than the use of nuclear energy, coal, or conventional oil and natural gas. If mismanaged, hydraulic fracturing fluid can be released by spills, leaks, or various other exposure pathways that contaminate land and groundwater (figure 11.1.4.*f*). Fracking fluid flowback – the fluid pumped out of the well and separated from oil and gas – not only contains the chemical additives used in the drilling process but also contains heavy metals, radioactive materials (which release radiation), volatile organic compounds, benzene (a carcinogen), toluene, ethylbenze, xylene, and other toxic air pollutants. Volatile organic compounds (VOCs) can react with the atmosphere to form ground-level ozone, which is associated with respiratory disease. Toulene can cause dizziness, confusion, headaches, and miscarriages. Ethylbenzene is a possible carcinogen that also causes dizziness, eye irritation, and hearing loss. Xylene also causes dizziness and headaches and furthermore can be fatal at high concentrations. In some cases, this contaminated water is sent to water treatment plants that are not equipped to deal with some of these classes of contamination. Finally, injecting wastewater for disposal can even induce earthquakes.

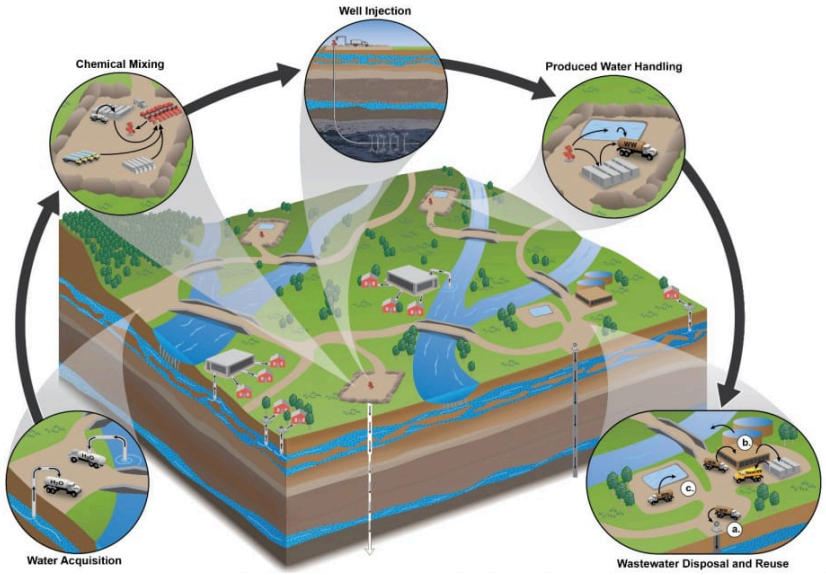


Figure 11.1.4.*e*: Fracking influences the water cycle. Water acquisition is the withdrawal of groundwater or surface water to make hydraulic fracturing fluids. Chemical mixing involves combining a base fluid, sand, and additives at the well site to create hydraulic fracturing fluids. During well injection, hydraulic fracturing fluids move through the oil and gas production well and in the targeted rock formation. Produced water handling refers to the onsite collection and handling of water that returns to the surface after hydraulic fracturing and the transportation of that water for disposal or reuse. Finally, the disposal and reuse of wastewater occurs. If this is not done properly, wastewater can pollute surrounding areas. Image and caption (modified) by EPA (public domain).

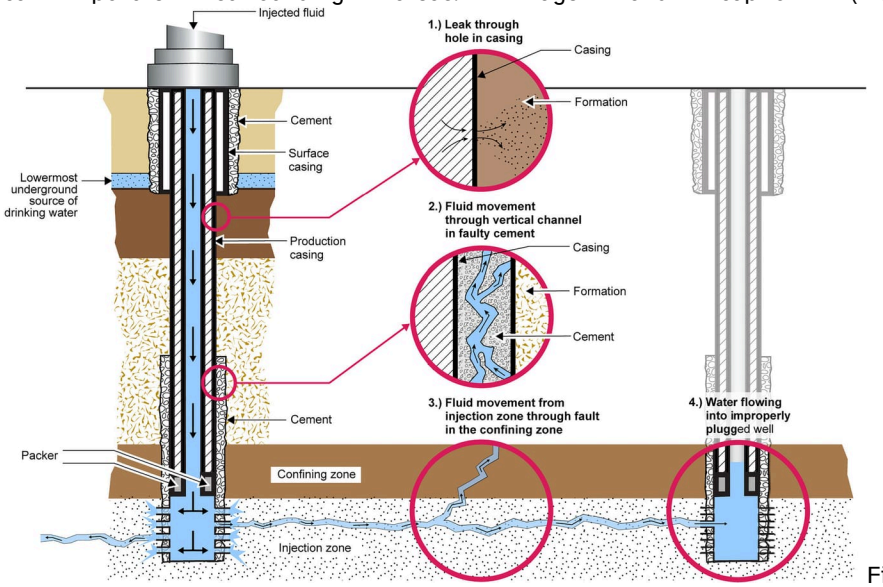


Figure 11.1.4.*f*: The toxic fluid injected during fracking can escape, contaminating groundwater. For example, it can leak through a hole in the casing, move through faulty cement, or move through a fault in the rock that confines the deposit. Image by Government Accountability Office (public domain).

Other unconventional sources of fossil fuels can also harm the environment. Surface mining of tar sands or oil shales requires the removal of all vegetation and leaves pollutants behind, causing habitat loss (figure 11.1.4.*g*).

 Figure 11.1.4.*g*: An open pit mine in the tar sands oil fields of Alberta, Canada. Conifer trees, which previously provided habitat to native animals, have been cleared to allow for mining. Image by Howl Arts Collective (CC-BY).

Transportation, Refineries, and Combustion

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, contributing to climate change. When natural gas is produced but cannot be captured and transported economically, it is "flared," or burned at well sites, which converts it to carbon dioxide. This is considered to be safer and better than releasing methane into the atmosphere because carbon dioxide is a less potent greenhouse gas than methane. However, when natural gas with high concentrations of the toxic gas hydrogen sulfide is flared, it produces carbon dioxide, carbon monoxide, sulfur dioxide, nitrogen oxides, and many other compounds (see Air Pollution for more details).

Leaks also happen when we use petrochemicals on land. For example, gasoline sometimes drips onto the ground when people are filling their gas tanks, when motor oil gets thrown away after an oil change, or when fuel escapes from a leaky storage tank. When it rains, the spilled petrochemicals get washed into the gutter and eventually flow to rivers and into the ocean. Another way that oil sometimes gets into water is when fuel is leaked from motorboats and jet skis. When a leak in a storage tank or pipeline occurs, petrochemicals can also get into the ground, and the ground must be cleaned up. To prevent leaks from underground storage tanks, all buried tanks are supposed to be replaced by tanks with a double lining.

Oil refining emits a variety of toxins and is the single largest source of benzene (figure 11.1.4.*g*). As a result, residents living near oil refineries have a high incidence of cancer, asthma, and birth defects. When petrochemicals such as gasoline or diesel are burned, they release a variety of air pollutants, including carbon dioxide (a cause of climate change), sulfur dioxide, nitrous oxides, volatile organic compounds (VOCs), particulate matter, and lead (see Air Pollution for more details). The transport of oil by ship or trunk also requires energy in the form of fossil fuels, generating more pollutants. Compared to oil and coal, burning natural gas releases the fewest pollutants and greenhouse gases.



Figure 11.1.4.*g*: Pollutants are emitted from the Pine Bend oil refinery in Rosemount, Minnesota. Image by Tony Webster (CC-BY).

Solutions

Reclamation can mitigate the habitat damage that results from mining or extracting fossil fuels. It involves restoring the land to an extent after mining or extraction is complete. This can entail returning displaced land and covering with top soil, which protects organisms from heavy metals, radioactive materials, and other underground toxins. Additionally, acids, which often form from the leaching of sulfates from underground rocks, may be neutralized. Vegetation is then planted, and water flow if disrupted is somewhat restored. Of course, the intricate topography, network of streams, and mature vegetation (such as large trees in forest) that may have been present prior to mining cannot be recreated, but reclamation makes it easier for native species to begin recolonizing the area.

Clean coal technologies can limit the air pollution released when burning coal. Some of these technologies remove toxins from coal before burning it while others capture toxins that are released while burning coal. For example, **smokestack scrubbers** in power plants clean sulfur dioxide, nitrous oxide, particulate matter, and mercury from the smoke before it is released. **Carbon capture and sequestration** involves capturing carbon dioxide released and storing it, but it requires 25-40% more energy, reducing the efficiency of coal (figure 11.1.4.*h*). In this process, smoke from a coal power plant is passed through a solvent to trap carbon dioxide, but other waste gases are still released in the smoke. Carbon dioxide is then separated from the solvent. Some can be used in industry (such as for carbonated beverages or to tertiary recovery of oil), and the rest is sequestered (stored) underground. Note that clean coal technologies can reduce coal's contribution to climate change and reduce the amount of toxins that are released, but it does not fully prevent coal-generated air pollution (figure 11.1.4.*i*).

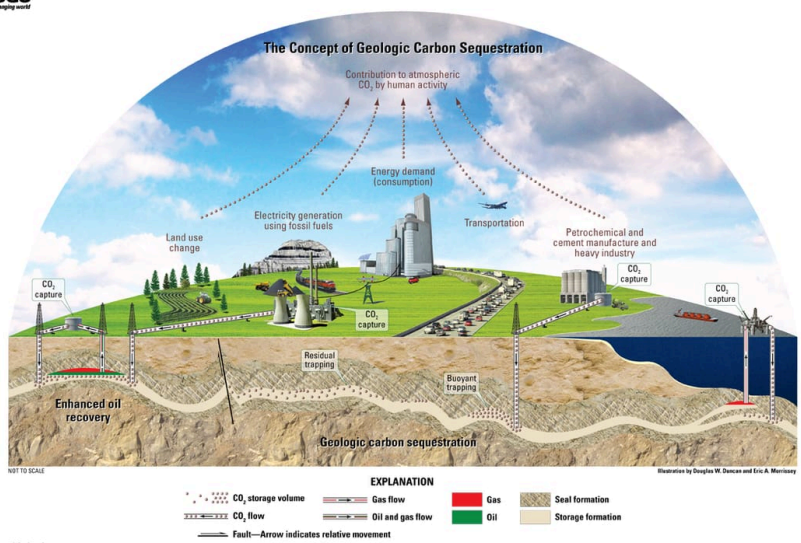


Figure $11.1.4.h$: Burning fossil fuels releases carbon dioxide into the atmosphere, but there are also opportunities to sequester (store) carbon dioxide, offsetting some fo this damage. Some of the carbon dioxide injected during tertiary recovery (enhanced oil recovery) remains underground. Additionally, carbon dioxide may be captured from smoke released by power plants and other industries and stored under ground. Image by USGS (public domain).



Figure $11.1.4.i$: A protest against clean coal at the United Nations Climate Change Conference (COP19) in 2013. Image by 350.org (CC-BY-NC-SA).

Because fossil fuels are nonrenewable, reserves will eventually be depleted, and the world will need to fully rely on other energy sources. Those concerned about the environmental and health consequences of fossil fuels advocate for making this transition as soon as possible. This is because the technologies and practices discussed above do not fully prevent fossil fuels from causing environmental damage and causing health hazards for workers and the general public. The next two chapters discuss nuclear energy and renewable energy, which are alternatives to fossil fuels. As even these alternatives have their disadvantages, **energy conservation** (using energy more efficiently and limiting unnecessary energy use) is also critical.

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- Chapter 4: Non-Renewable Energy from *Introduction to Environmental Science: 2nd Edition* (2018) Biological Sciences Open Textbooks by Zehnder, Caralyn; Manoylov, Kalina; Mutiti, Samuel; Mutiti, Christine; VandeVoort, Allison; and Bennett, Donna (licensed under CC-BY-NC-SA).

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11.1.5: Data Dive- Global Fossil Fuel Consumption

Overview

Our World in Data (OWID) is a scientific online publication that focuses on using research and data to help tackle global concerns such as poverty, disease, hunger, climate change, war, and inequitable treatment of our world's most vulnerable and unstable communities. Their website is particularly known for publishing a variety of graphs, some even interactive, to present the research that helps explain causes and consequences of global concerns to the public. One example graph, seen below, illustrates global fossil fuel consumption:

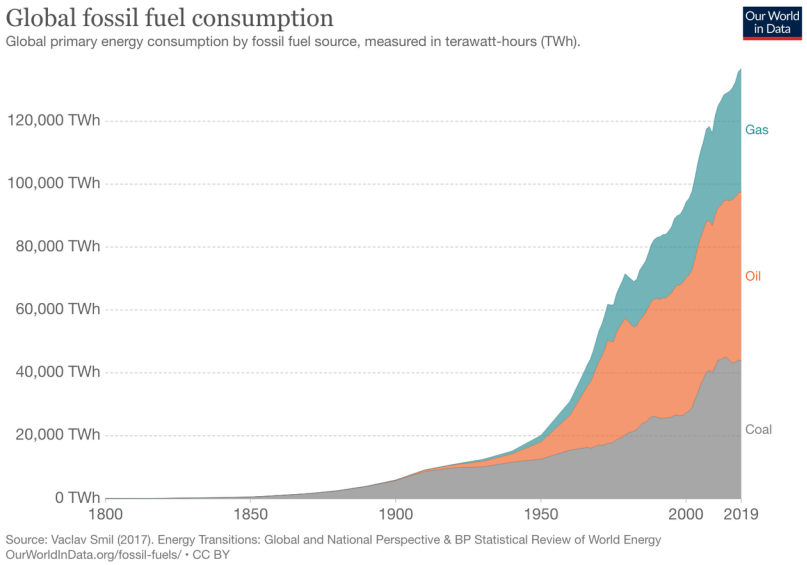


Figure 11.1.5.*a*: Global consumption of gas, oil, and coal. Graph by Our World in Data (CC-BY)

Questions

1. What kind of graph is this?
2. What question(s) are the authors trying to answer with this graph?
3. What are the observed patterns of fossil fuel use (gas, oil, and coal) in this graph?
4. Make a prediction for each fossil fuel use pattern for the next 50 years. For each prediction, state why you think that pattern will occur.
5. How do you think climate scientists are using a graph like this to predict climate into the future?

Raw Data For Above Graph(s)

Raw data table link to Our World in Data graph above. (CC-BY)

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11.1.6: Review

Summary

After completing this chapter you should be able to...

- Distinguish among coal, oil, and natural gas and explain how each is formed.
- Describe the processes of mining, processing, transporting, and burning coal to produce electricity.
- Compare the processes of conventional oil and natural gas extraction and fracking.
- Identify the relative contributions of coal, oil, and natural gas to electricity generation in the U.S. and total energy consumption globally.
- Detail the advantages and disadvantages of fossil fuel use.
- Describe strategies to mitigate harm caused by fossil fuel use.

Fossil fuels are nonrenewable energy sources that were formed from ancient organisms. **Coal** is a solid fossil fuel formed from ancient swamp vegetation. **Oil** (petroleum) and natural gas both formed from marine microorganisms and are often found together; however, oil is a liquid fossil fuel, and natural gas is in gaseous form.

Coal is produced through **surface** and **subsurface mining**. Some oil and natural gas reserves can be recovered through **conventional extraction**, but unconventional reserves are recovered through **hydraulic fracturing** (tight oil and natural gas; tight sands) or mining (oil shale and tar sands). To produce electricity from coal or natural gas, the fuel is combusted (burned). The heat is used to produce steam, and the pressure from the steam turns a turbine, which powers a generator. **Crude oil** must be refined to separate it into a variety of **petrochemicals**, each with a different use.

Nationally and globally, fossil fuel consumption remains high. **Proven reserves** of oil and natural gas are projected to last another 50 years while coal reserves are projected to last another 115 years. The U.S. has a large supply of the world's coal but relies largely on imports to meet its oil demands. The world's oil supply is concentrated in OPEC countries, which have great influence over global rates of production.

While existing technologies facilitate continued fossil fuel use, which support local and national economies, fossil fuels cause a variety of health and environmental consequences. Workers and those living near mines or oil refineries are at the greatest risk of health consequences, but combustion of fossil fuels releases air pollutants that harm the general public and native organisms. Furthermore, mining, drilling, and fracking, destroy habitats and release pollutants. **Clean coal technologies** and **reclamation** reduces but does not eliminate these negative consequences.

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11.2: RENEWABLE ENERGY

11.2.1: Renewable Energy History and Consumption

11.2.2: Wind Energy

11.2.3: Solar Energy

11.2.4: Geothermal Energy

11.2.5: Hydropower

11.2.6: Biofuels (Biomass Energy)

11.2.7: Energy Conservation

11.2.8: Data Dive- Global Renewable Energy Generation

11.2.9: Review

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11.2.1: Renewable Energy History and Consumption

Renewable energy sources can be replenished within human lifespans. Although renewable energy is often classified as **wind**, **solar**, **geothermal**, **hydropower** (hydroelectric energy/hydroelectricity), and **biofuels** (**biomass energy**), all forms of renewable energy arise from only three sources: the light of the sun (wind, solar, hydropower, and biofuels), the heat of the earth's crust (geothermal), and the gravitational attraction of the moon and sun (**tidal energy**; figure $11.2.1.a$). 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. 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.



Figure $11.2.1.a$: A tidal current energy generator at Race Rocks in British Columbia, Canada. Image by Garry Fletcher (CC-BY-SA).

Most renewable energy sources have a relatively **small carbon footprint**, meaning that they do not significantly contribute to climate change. However, building dams for hydropower (hydroelectric energy) does release methane, a potent greenhouse gas. Renewable energy sources are pollution free (except biofuels), and they typically have minimal environmental impact (except habitat loss from dams). Up to this point, however, no single source of renewable energy is sufficient. They generally are paired with other energy sources.

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. Other renewables, such as hydropower and biomass, continued to experience growth. As climate change worstens, the solar and wind energy has expanded globally in recent years.

Renewable energy accounted for 11.4% of total global energy consumption and 26.3% of global electricity generation in 2019 (figure $11.2.1.b$). In the United States, renewable energy also accounted for about 11% of total energy consumption but only 17.6% of electricity generation. Nearly half (43%) of total renewable energy use in the U.S. is from biofuels. For electricity generation in

the U.S., wind was the greatest contributor (7.1%) followed by hydropower (7.0%), solar (1.7%), biomass (1.4%), and geothermal (0.4%).

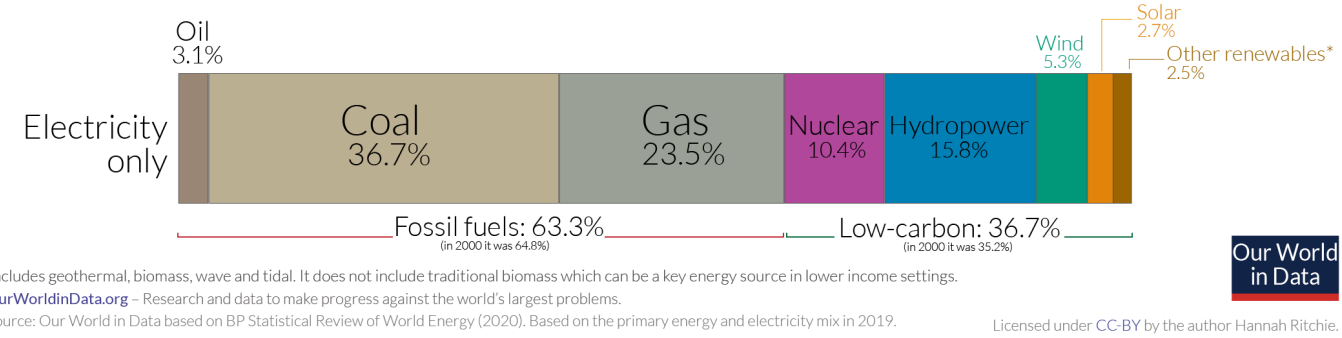


Figure 11.2.1.*b*: The global electricity breakdown in 2019. Renewables accounted for 26.3% of global electricity generation, with hydropower accounting for 15.8% followed by wind (5.3%), solar (2.7%), and other renewables (2.5%; geothermal, biomass, wave, and tidal). Fossil fuels accounted for 63.3% of global electricity generation, including oil (3.1%), coal (36.7%), and gas (23.5%). For comparison, fossil fuels accounted for 64.8% of global electricity generation in 2000. Nuclear accounted for 10.4% of global electricity generation. Nuclear and renewables combined are considered low-carbon electricity sources, together accounting for 36.7% of electricity generation. For comparison, low-carbon sources accounted for 35.2% of electricity generation in 2000. Image modified from Hannah Ritchie/Our World in Data (CC-BY).

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11.2.2: Wind Energy

Wind energy arises from the motion of the air. It is driven by solar energy (differences in air temperature causes air currents). The wind turns a turbine, which powers a generator (figure $11.2.2.a$). The rotor blades of a wind turbine work like an airplane wing or helicopter rotor blade. When wind flows across the blade, the air pressure on one side of the blade decreases, and this causes the rotor to spin. The rotor connects to the generator, either directly or through a series of gears that speed up the rotation and allow for a physically smaller generator. Similar to the electricity generation from coal, natural gas, or nuclear energy, the rotating motion causes magnets spin within wire coils to produce electricity. According to the American Wind Energy Association, 39% of all new electrical generating capacity in the United States in 2019 was due to wind.

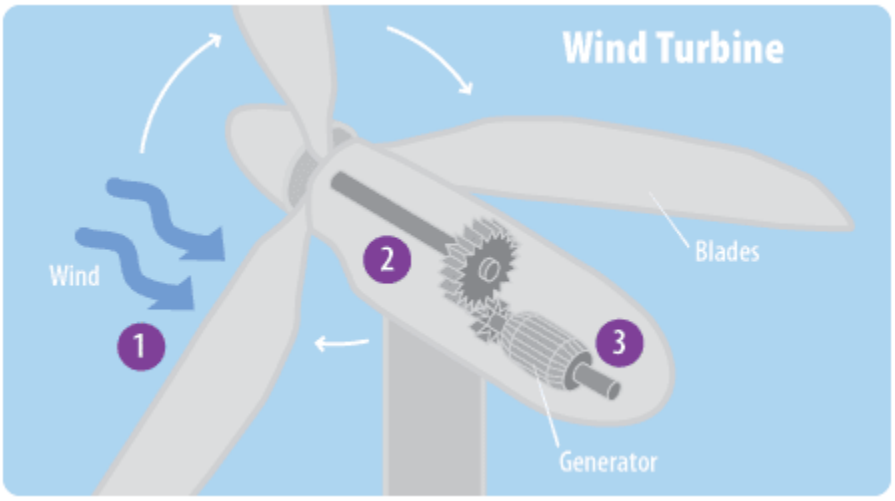


Figure $11.2.2.a$: (1) As the wind blows over the blades of a wind turbine, it causes the blades to lift and rotate. (2) The rotating blades turn a shaft that is connected to a generator. (3) The generator creates electricity as it turns. Image and caption (modified) from EPA (public domain).

Interactive Element

Click here for an interactive animation illustrating how wind turbines work.

Advantages of Wind Energy

Wind is among the lowest-cost sources of renewable energy, and its expansion creates jobs (figure $11.2.2.b$). Like many renewable energy sources, wind turbines do not release air pollutants or contribute to climate change, and they do not require water for cooling. 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, and winds are up to 50% stronger and steadier offshore than on land (figure $11.2.2.c$).

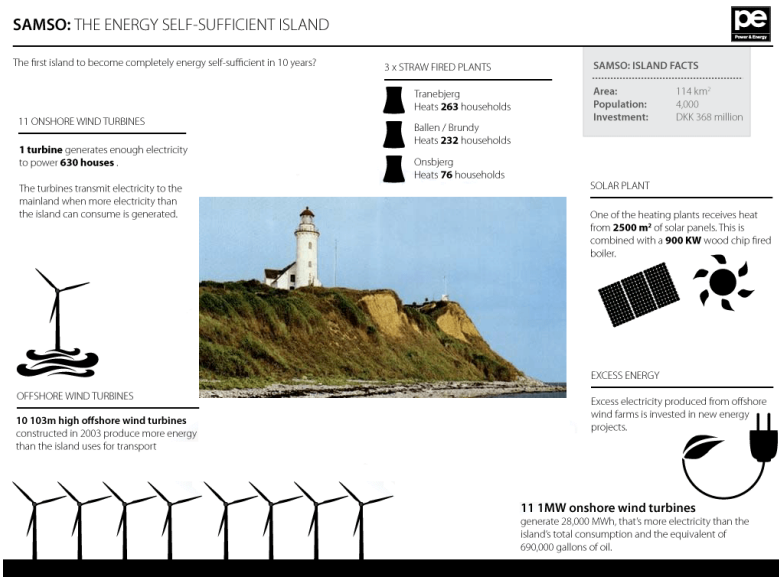


Figure 11.2.2.*b*: The Danish island of Samsø was the first region in the country to transition to 100% renewable energy, relying on offshore wind, onshore wind, straw (a biofuel), and solar. The text in the image is, "Samsø : The Energy Self-sufficient Island. The first island to become complete energy self-sufficient in 10 years. Samsø: Island Facts— Area: 114 km^2, Population: 4,000, Investment: DKK 368 million. 11 Onshore Wind Turbines— 1 turbine generates enough electricity to power 630 houses. The turbines transmit electricity to the mainland when more electricity than the island can consume is generated. Offshore Wind Turbines- 10 103-m-high offshore wind turbines constructed in 2003 produce more energy than the island uses for transport. 11 1-MW Onshore Wind Turbines generate 28,000 MWh. That's more electricity than the island's total consumption and the equivalent of 690,000 gallons of oil. 3X Straw-fired Plants— Traneberg- heats 263 households, Ballen/Brundy- heats 232 households, Onsbjerg- heats 76 households. Solar Plant- One of the heating plants receives heat from 2500 m^2 of solar panels. This is combined with a 900 KW wood chip-fired boiler. Excess Energy- Excess electricity produced from offshore wind farms is invested in new energy projects. Images by GDS Infographics (CC-BY) and National Geospatial-Intelligence Agency (public domain).



 Figure 11.2.2.*b*: Wind turbines may be on land (onshore, left) or in the ocean (offshore, right). Left image by Joshua Winchell/USFWS (public domain). Right image by CGP Grey (CC-BY).

Disadvantages of Wind Energy

Wind energy does have a few challenges. Wind turbines are only effective in regions with strong enough winds to generate sufficient electricity. Even in regions with strong winds, wind availability is intermittent. This can be mitigated by the use batteries to store energy, but battery capacity, despite continuous technological advances, is still limited. There are aesthetic concerns to some people when they see them on the landscape, and some people do not like the sound that wind turbine blades make. A few wind turbines have caught on fire, and some have leaked lubricating fluids, though this is relatively rare. Turbines have been found to cause bird and bat deaths particularly if they are located along their migratory path, although communication towers and domestic cats are bigger threats. 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.

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11.2.3: Solar Energy

Solar energy refers to heat or light energy from the sun. Solar energy is by far the most plentiful type of renewable energy, delivered to the surface of the Earth at a rate of 120,000 Terawatts (TW) per hour, compared to the global human use of 19.8 TW in the entire year of 2019. To put this in perspective, covering 1.2% of the Sahara desert with solar panels could meet Earths energy needs. Of course, this does not consider limitations on storage capacity and the ability to distribute that energy.

Technologies to harness solar energy may be passive or active. **Passive solar technologies** do not require complex equipment and can be as simple as using natural light from a window or skylight to illuminate a room (figure $11.2.3.a$). Similarly, solar tubes are lined with reflective material and can concentrate light energy to better illuminate a room (figure $11.2.3.a$). These are embedded in the ceiling as regular light fixtures would be.



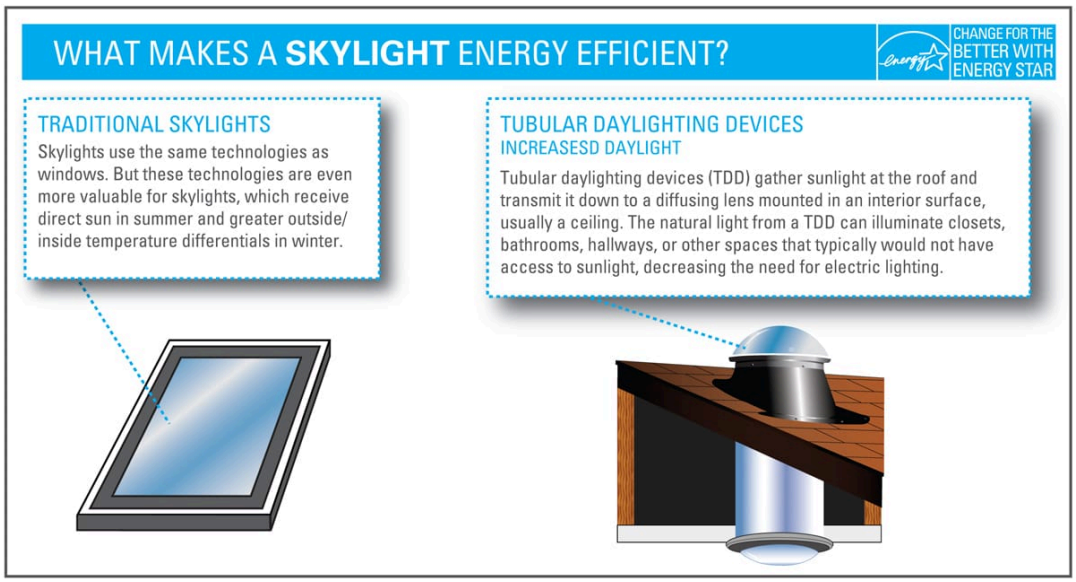


Figure $11.2.3.a$: Skylights and solar tubes (tubular daylighting devices, TDD). While skylights resemble windows that are installed in the ceiling, solar tubes use lenses and a reflective lining to concentrate sunlight, providing bright illumination for darker parts of the home. What makes a skylight energy efficient? Traditional skylights are skylights that use the same technologies as windows, but these technologies are even more valuable for skylights, which receive direct sun in summer and greater outside/inside temperature differentials in winter. Tubular daylighting devices gather sunlight at the roof and transmit it down to a diffusing lens mounted in an interior surface, usually a ceiling. The natural light from a TDD can illuminate closets, bathrooms, hallways, or other spaces that typically

would not have access to sunlight, decreasing the need for electric lighting. Left image by U.S. Department of Energy (public domain), and right image by Energy Star (public domain).

Solar energy can also be used as heat, which can be maximized through careful architecture (figure $11.2.3.b$). Firstly, the building requires south-facing windows (or glass doors). As sunlight passes through these areas, the energy is stored in the thermal mass of the building. This refers to heat trapping materials such as rock or tiles. The building is also designed such that heat is then distributed throughout the building. Finally, roof eaves or similar structures block sunlight from entering the home during the summer.

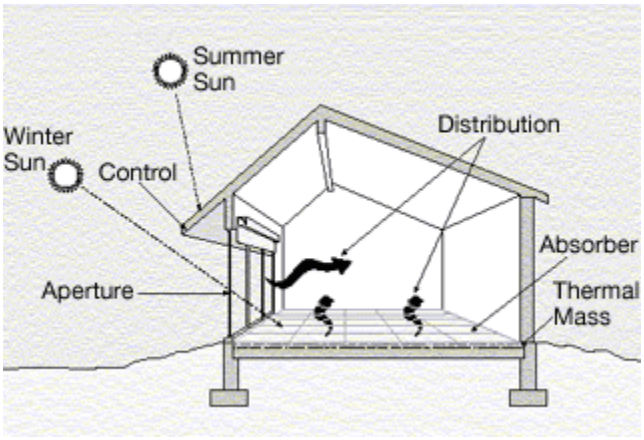


Figure $11.2.3.b$: This building design uses the sun for heating during the winter and is thus a passive solar technology. The roof overhang serves as a control, blocking the higher summer sun while allowing the lower winter sunlight to pass through the window (aperture). Heat energy from the sun is then distributed in the building. Thermal mass (such as a tile or stone floor) absorbs and later releases heat energy. Image by U.S. Department of Energy (public domain).

A simple solar water heater is a passive technology consisting of a network of tubes that are heated by the sun (figure $11.2.3.c$). The hot water is then transferred through the plumping of a home. (Some solar water heaters are more complex, using pumps, and are thus considered active solar technologies.)



Figure $11.2.3.c$: A solar water heater. Image by Vijayanarasimha/Pixabay (public domain).

Active solar technologies are more complex. For example, solar panels use light energy to generate electricity (figure$11.2.3.d$). This occurs in the units of the solar panel, which are called **photovoltaic cells** (PV cells; figure$11.2.3.e$). Each photovoltaic cell consists of two layers of **semiconductors**, substances that only conduct electricity under certain circumstances. (In contrast, conductors always conduct electricity, and insulators do not.) One semiconductor has extra electrons, but the other has extra spaces for electrons. When light shines on the photovoltaic cell, it causes electrons to move from between semiconductor layers

through the conductor that connects them (such as metal wires or plates). This movement results in an electric current.



Figure 11.2.3.d: 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

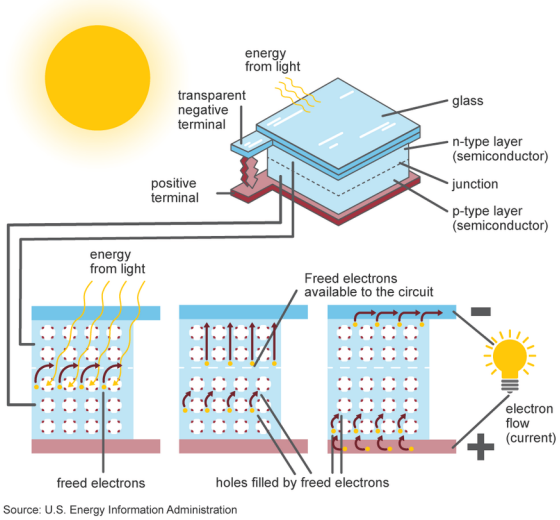


Figure 11.2.3.e: Diagram of a **photovoltaic cell** consisting of two layers of semiconductors. The top (n-type) semiconductor has extra electrons and the bottom (p-type) semiconductor has extra spots (holes) for electrons. A junction divides these two layers. Light frees the electrons and allows them to move through a wire from the n-type to fill "electron holes" in the p-type semiconductor. The movement of electrons through the wire results in an electrical current. Image by U.S. Energy Information Administration (public domain).

This video explains how the photovoltaic cells within solar panels generate electricity.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

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Another example of active solar technology is **solar thermal technology**. This involves using a series of mirror to concentrate solar energy, ultimately generating steam. From there, the steam turns a turbine and powers a generator (figure$11.2.3.f$).

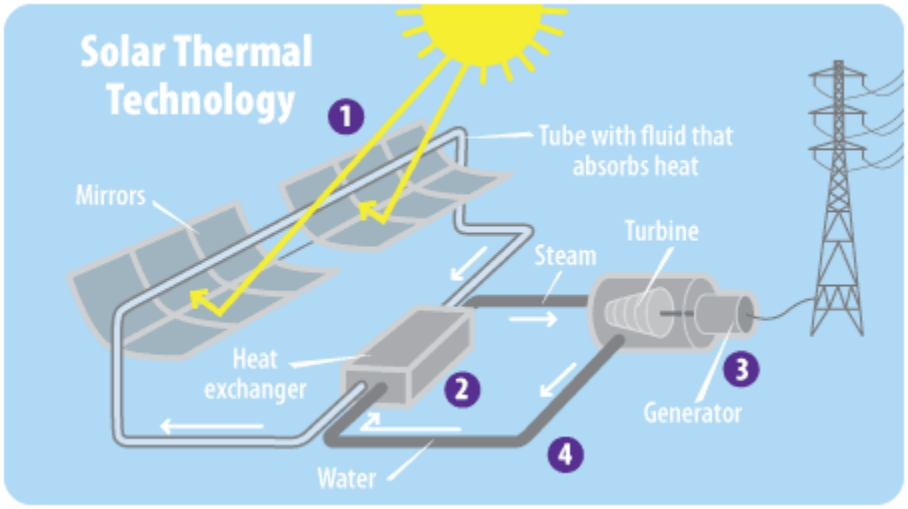


Figure $11.2.3.f$: In solar thermal technology, (1) mirrors or reflectors concentrate the sun's rays to heat a special kind of liquid, which absorbs heat. (2) The heat from this liquid boils water to create steam, facilitated by the heat exchanger. (3) Steam spins a turbine that is connected to a generator, which creates electricity. (4) The steam cools and condenses back to water, which is recycled, reheated, and converted into steam again. Image and caption (modified) from EPA (public domain).

Not only is solar energy abundant, but the use of solar panels for electricity does not generate air pollution or contribute to climate change. (The manufacture of solar panels can generate some pollution, including greenhouse gas emissions, but this is minimal compared to that of fossil fuels.) Like wind energy, expansions on solar energy can create jobs and boost economies. Also like wind, sunlight is intermittent and storage of solar energy is limited by battery capacity. Some locations do not receive consistently direct sunlight and are ill-suited for solar panels. While solar energy has historically been the most expensive form of renewable energy, new technologies have lowered its cost.

The placement of solar panels determines how their environmental impact. Solar arrays are often 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. Additionally, solar farms can compete for agricultural space.

Other downsides of solar energy are water consumption (for some uses) and generation of hazardous wastes. Large networks of mirrors and lenses that concentrate solar energy for electricity generation in thermal solar systems or for heating may need to be cleaned regularly with water. Water is also needed for cooling the turbine-generator. Using water from underground wells may affect the ecosystem in some arid locations. The manufacturing of photovoltaic cells generates some hazardous waste from the chemicals and solvents used in processing. Some solar thermal systems use potentially hazardous fluids (to transfer heat) that require proper handling and disposal. Nuclear power exceeds solar energy in water consumption and hazardous waste generation, however.

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11.2.4: Geothermal Energy

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. **Geothermal power plants** harness this heat energy to produce electricity much in the same way that heat from burning coal generates energy (figure $11.2.4.a-c$). Water is injected underground and heated. The steam that emerges can be used directly, the heat can be transferred to closed system of another fluid, which then boils (figure $11.2.4.c$). Either way, the steam (or other high-pressure gas) ultimately turns a turbine and powers a generator.



Figure $11.2.4.a$: Steam is released from a geothermal power plant. Image by Open Access Government (CC-BY).

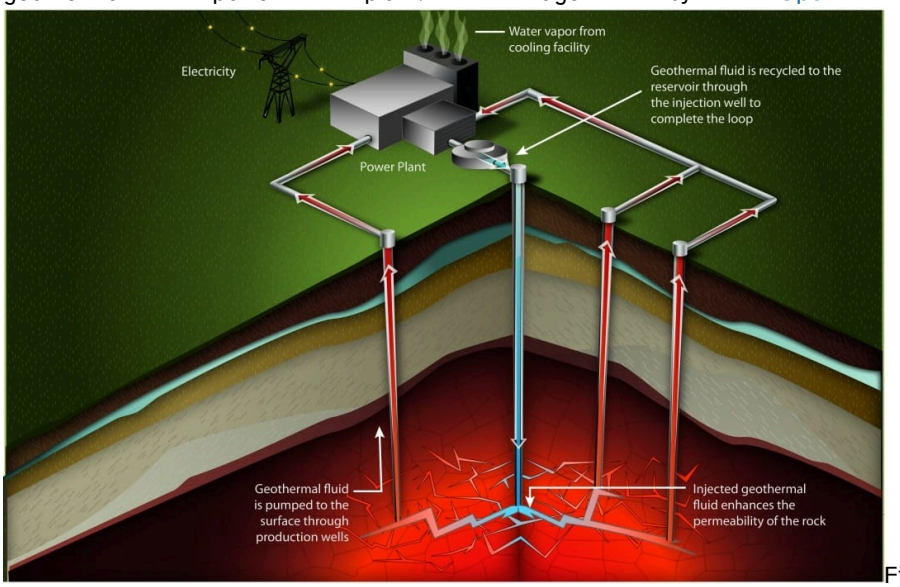


Figure $11.2.4.b$: In a geothermal power plant, geothermal fluid is injected underground. (Geothermal water refers to the hot water/steam used in this process.) It enhances the permeability of the rocks and is heated underground. It exits to the surface through production wells, where it is used to generate electricity in the geothermal power plant. Water vapor is released from the cooling facility of the power plant. To recycle the geothermal fluid, it is returned to the reservoir and injected back into the ground. Image from Office of Energy Efficiency and Renewable Energy/U.S. Department of Energy (public domain).

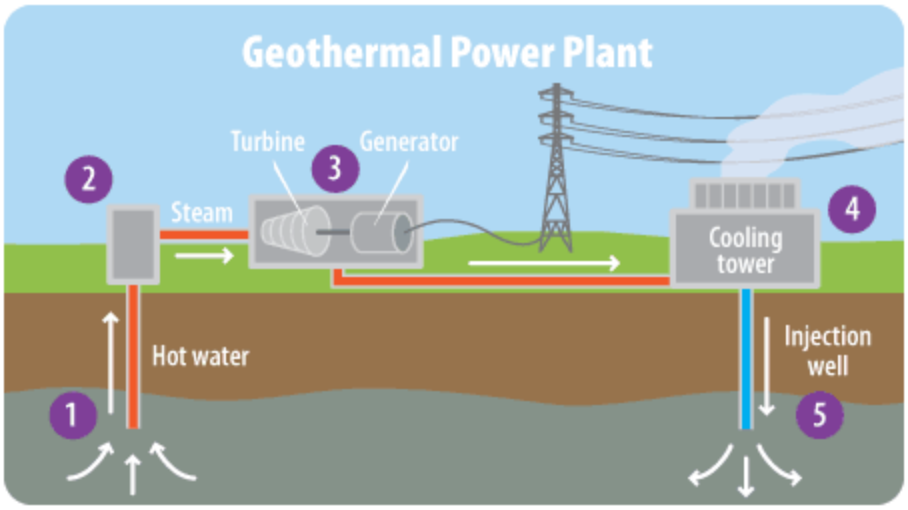


Figure 11.2.4.*c*: (1) In a geothermal power plant, hot water is pumped from deep underground through a well under high pressure. (2) When the water reaches the surface, the pressure is dropped, which causes the water to turn into steam. (3) The steam spins a turbine, which is connected to a generator that produces electricity. (4) The steam cools off in a cooling tower and condenses back to water. (5) The cooled water is pumped back into the Earth to begin the process again. Image and caption (modified) from EPA (public domain).

Geothermal heat pumps (**ground-source heat pumps**) rely on cool temperatures underground to cool or heat homes (figure 11.2.4.*d*). They are sometimes considered a second type of geothermal energy, but they are also a means of energy conservation. Geothermal heat pumps use a heat-exchange system that runs in the subsurface about 20 feet (5 meters) below the surface, which is consistently cool (around 55°F, or 12.5° C). Fluid is pumped underground and then along ducts in the home. This cools the house during the summer, acting as a heat sink. During a cold winter, it warms the house to 55° F (acting as a heat source), and traditional heating systems do the rest. This reduces the energy consumption required to generate heat from gas, steam, hot water, and conventional electric air-conditioning systems.

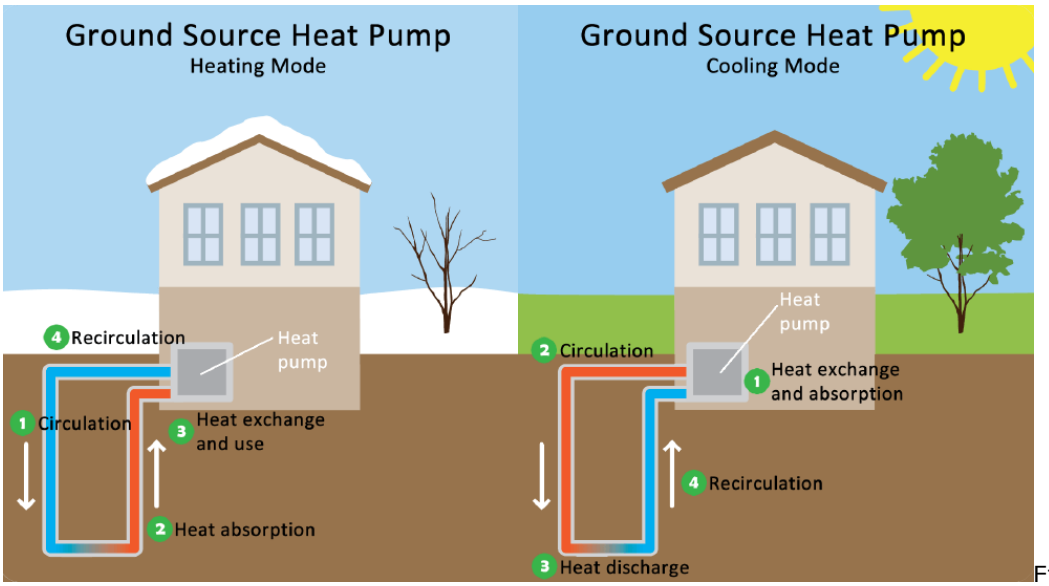


Figure 11.2.4.*d*: A ground source heat pump (geothermal heat pump) in heating mode (during the winter; left) and in cooling mode (during the summer; right). There are four steps for heating mode (left). (1) Circulation: The above-ground heat pump moves water or another fluid through a series of buried pipes or ground loops. (2) Heat absorption: As the fluid passes through the ground loop, it absorbs heat from the warmer soil, rock, or ground water around it. (3) Heat exchange and use: The heated fluid returns to the building where it used for space or water heating. The system uses a heat exchanger to transfer heat into the building's existing air handling, distribution, and ventilation system. (4) Recirculation: Once the fluid transfers its heat to the building, it returns at a lower temperature to the ground loop to be heated again. This process is repeated, moving heat from one point to another. The four steps for cooling mode (right) are similar: (1) heat exchange and absorption, (2) circulation, (3) heat discharge, and (4) recirculation. Images and caption (modified) from EPA (public domain).

This video explains the construction and mechanism of geothermal heat pumps.

YouTube Video

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Not only does geothermal energy have multiple applications (generating electricity, heating, and cooling), but it is reliable. While solar and wind energy are intermittent, heat is consistently radiated from deep underground. Additionally, the cool temperatures closer to the surface needed for geothermal heat pumps are present year round and at all locations. Geothermal power plants for electricity generation, however, can only be built in specific locations where hot magma is close enough to the Earth's surface. These locations are typically associated with geysers, hot springs, or volcanoes (figure $11.2.4.e$). Additionally, geothermal power plants are costly to build.



Figure $11.2.4.e$: Locations of the world's volcanoes. They are concentrated along the west coasts of North American and South America as well as just east of Asia and Australia. These regions, which wrap around the Pacific Ocean, form what is known as the Ring of Fire. Image by Salazar, S.S., Muñoz, Y. & Ospino, A. Analysis of geothermal energy as an alternative source for electricity in Colombia. *Geotherm Energy* **5,** 27 (2017). (CC-BY)

The environmental impact of geothermal energy depends on how it is being used. The use of geothermal heat pumps has almost no negative impact on the environment. Geothermal power plants do not burn fuel to generate electricity, so they generate minimal air pollution. They release less than 1% of the carbon dioxide emissions of a fossil fuel plant. Geothermal plants 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 sulfur compounds (one cause of acid deposition/acid rain) 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. One environmental concern associated with geothermal power plants is geothermal drilling during their construction has caused earthquakes, similar to the effects of injection wells for fracking.

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11.2.5: Hydropower

Hydropower (hydroelectric energy) refers to the energy in moving water, which can be used to generate electricity. It is ultimately driven by solar energy. Water at high elevations is replenished through evaporation (induced by solar heat), condensation, and precipitation. The moving water turns a turbine (figure $11.2.5.a$) and this moves magnets within a wire coil, causing the movement of electrons in a generator. The result is an electric current (electricity). Combustion of fossil fuels or biofuels, nuclear energy, wind energy, and thermal solar systems all follow this same general mechanism; the difference is what causes the turbine to spin.

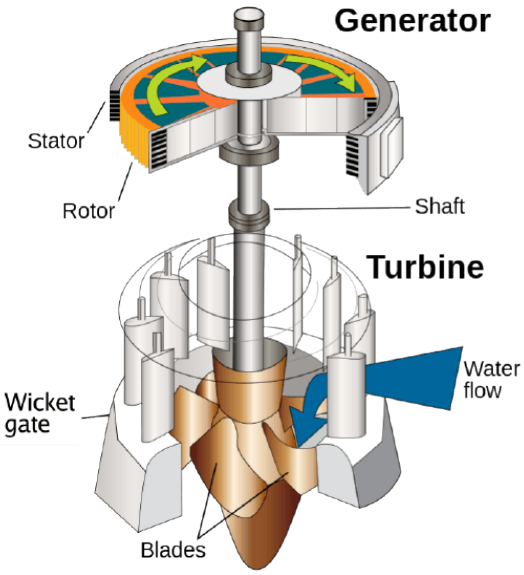


Figure $11.2.5.a$: A water turbine. Moving water turns the blades of the turbine. The wicket gate controls the water flow. The moving water causes magnets in the rotor to spin and move electrons within the loops of wire in the stator, generating an electric current. Image by U.S. Army Corps of Engineers (public domain).

There are several types of hydropower, but each generates electricity through the same general mechanism described above. The most well-known use of hydropower involves dams. **Dams** block the flow of rivers, producing an artificial lake (reservoir) upstream. The release of water is then controlled. Some of this water moves through a channel (penstock), and this kinetic energy (energy of motion) is harnessed into electricity (figure $11.2.5.b$). In **run-of-the-river hydroelectricity**, the turbine is placed directly into a river, and the natural flow of water through the river spins the turbine. **Tidal energy** and **energy from ocean waves** (figure $11.2.5.c$) are also considered forms of hydropower. However, 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. In other words, most forms of hydropower are indirect forms of solar energy, with the exception of tidal energy.

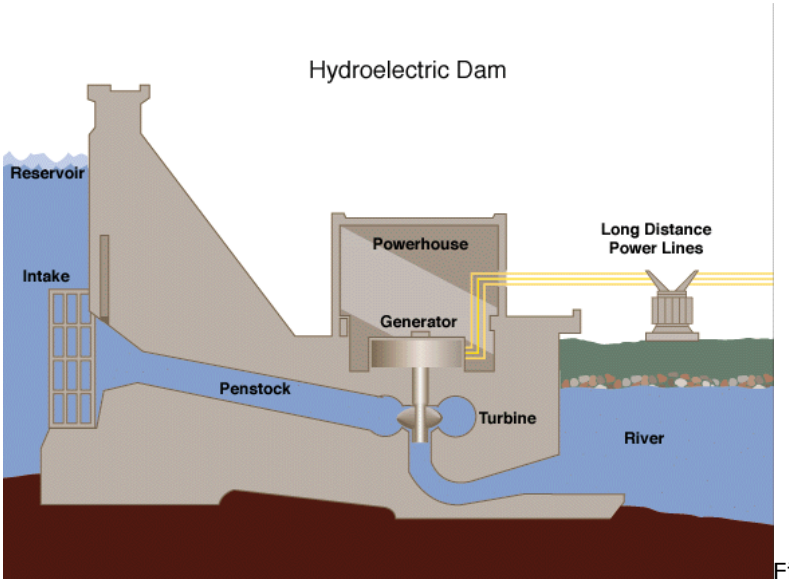


Figure 11.2.5.*b*: A section of a hydroelectric dam. Water in the reservoir passes through the intake into the penstock, which is a narrow channel. The moving water turns a turbine. This powers the generator in the powerhouse. The water continues down the river. Meanwhile electricity is distributed through long distance power lines. Image by Tennessee Valley Authority (public domain).

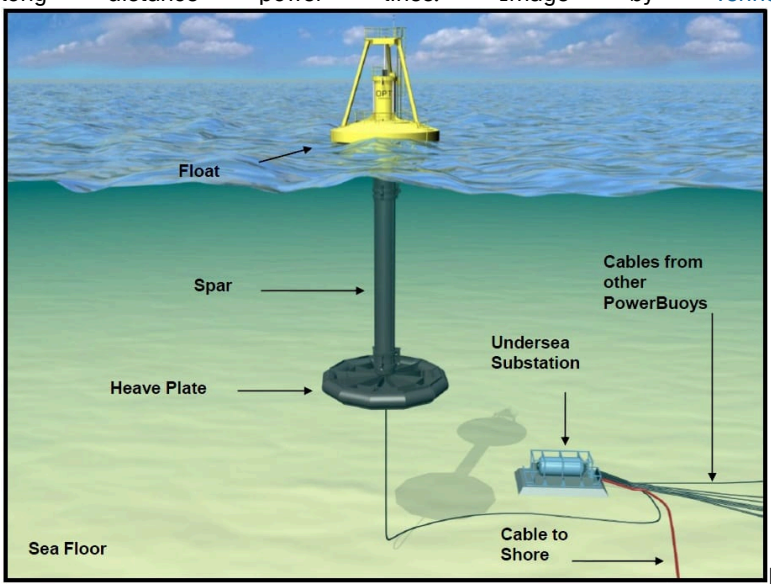


Figure 11.2.5.*c*: One way to harness wave energy is with an absorber. Abosorbers extract energy from the rise and fall of the waves with a buoy. The buoy consists of the float, which is above the water and a heavy plate. The narrow spar connects the two. A cable connects the heavy plate of each buoy to an undersea substation, and another cable runs from the substation to the shore. Image and caption (modified) by OpenEI (public domain).

Small hydropower projects offer 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 have a capacity between 0.01 to 30 megawatt (MW) of power. For reference, a 1-MW generator operating for an hour (producing 1 MWh) generates enough electricity to powers the average home in the U.S. for a little over a month. Small hydropower systems that generate less than 0.1 MW are more specifically called **microhydropower** systems (figure 11.2.5.*d*). 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.

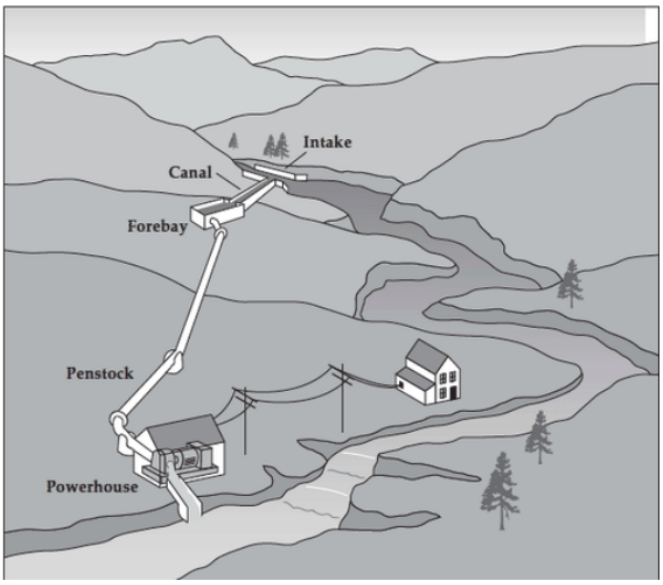


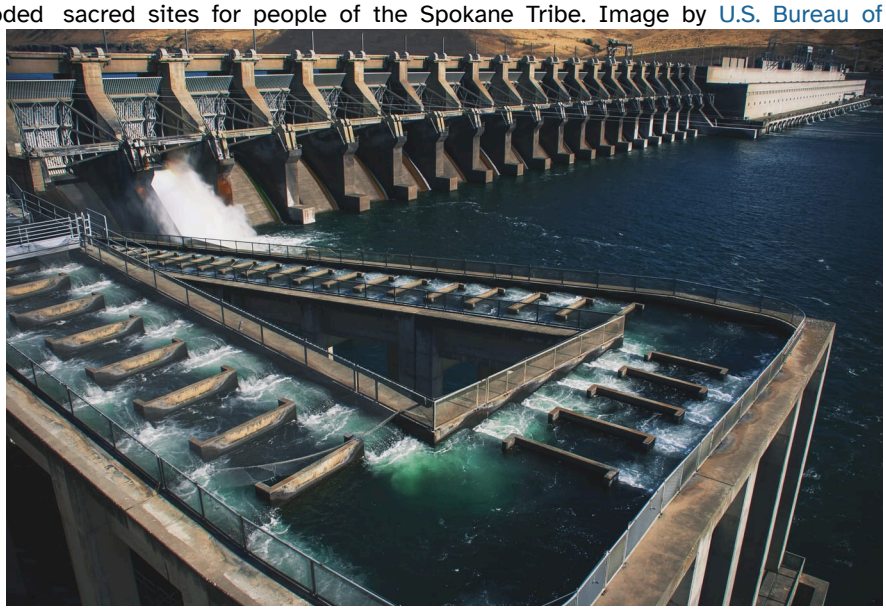
Figure 11.2.5.*d*: A microhydropower system. Although there are several ways to harness the moving water to produce energy, run-of-the-river systems, which do not require large storage reservoirs, are often used for microhydropower projects. For run-of-the-river hydro projects, a portion of a river's water is diverted to a channel, pipeline, or pressurized pipeline (penstock) that delivers it to a waterwheel or turbine. In this image, water from the river moves through the intake then to the canal, forebay, penstock, and powerhouse, which contains the 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 produce electricity. In this image, electrical lines connect the powerhouse to a nearby house.

One benefit of using hydropower is that dams and reservoirs can additionally be used for recreation, flood control, and storing freshwater (see Water Scarcity and Solutions). While we will never run out of moving water, the potential to use hydropower fluctuates based on precipitation. For example, during a drought, water levels in a reservoir decreases, and there is less water released to generate electricity. As with most sources of renewable energy, hydropower is not practical everywhere, and it is most effective in mountainous regions with high rainfall and snowmelt.

Hydropower dams and the reservoirs they create degrades habitat and negatively impacts native species. 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 (figure 11.2.5.*e*). This problem can be partially alleviated by using "fish ladders" that help salmon get around the dams (figure 11.2.5.*f*). 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. When reservoirs first fill with water, they inundate terrestrial (land) habitats, farms, cities, and archeological and cultural sites, sometimes forcing populations to relocate. The terrestrial vegetation slowly decomposes in oxygen-poor conditions, releasing methane into the atmosphere, a potent greenhouse gas. In this sense, hydropower generates few air pollutants during operation, but construction does contribute to climate change.



Figure 11.2.5.e: The Grand Coulee Dam on the Columbia River in Washington state created Lake Roosevelt, which provides outdoor recreation such as fishing and swimming. However, it compromised salmon populations and flooded sacred sites for people of the Spokane Tribe. Image by U.S. Bureau of Reclamation (public domain).



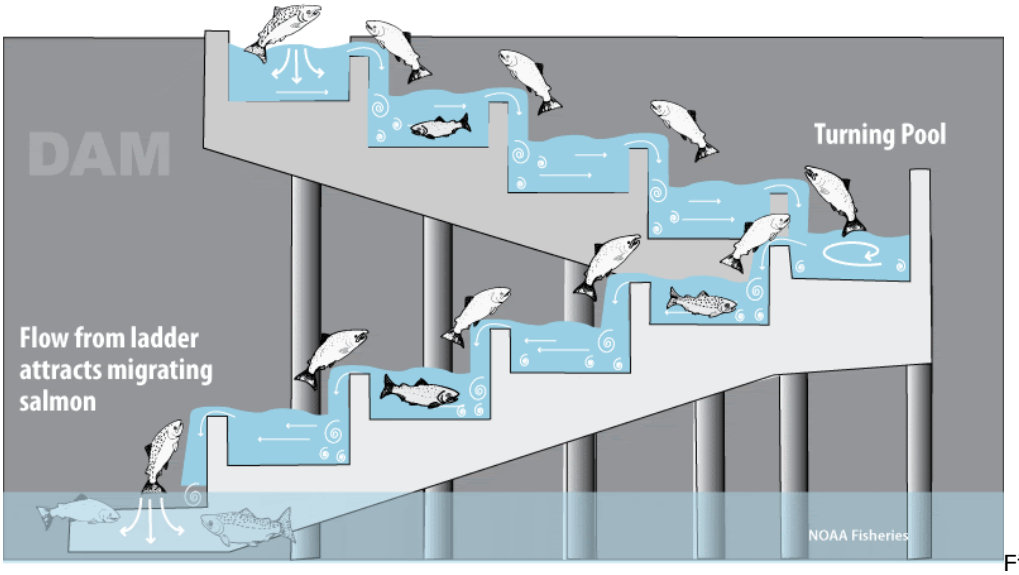


Figure 11.2.5.f: Left: The fish ladder at John Day Lock and Dam along the Columbia River in Oregon allows adult fish to migrate upstream of the dam on their own. Right: Diagram of a fish ladder, which allows the passage of salmon over a dam. Salmon swim upstream to spawn (reproduce) and are able to swim up the steps of the ladder. The flow from the ladder attracts migrating salmon. At the turning pool, they rotate and then proceed up the next flight of the ladder until they are over the dam. Left image and caption (modified) from U.S. Army Corps of Engineers, and right image by NOAA Fisheries (public domain).

While large-scale dam hydropower projects are often criticized for their impacts on wildlife habitat, fish migration, and water flow and quality, small run-of- the-river projects are free from many of these environmental problems. Because they use the natural flow of the river, they hardly alter the stream channel and flow. Thus, effects such as oxygen depletion, increased temperature, decreased flow, and impeded upstream migration are not problems for many run-of-the-river projects.

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11.2.6: Biofuels (Biomass Energy)

Biofuels (biomass energy) contain energy produced from organisms, such as animal waste, plants, or algae. It is another indirect form of solar energy. Biofuels have many uses. They be burned directly or first converted to ethanol (often with the help of bacteria and fungi) to generate electricity. The heat from combustion produces steam and turns a turbine to power a generator. Biodiesel offers an alternative to petrochemicals for fueling vehicles. Biofuels have even been used to power small planes (figure $11.2.6.a$). Furthermore, burning wood or straw provides heating.



Figure $11.2.6.a$: Test flight of the "Green Hornet", a Navy fighter jet partially powered by biofuels. Image by U.S. Navy (public domain).

Unlike fossil fuels, biofuels are **carbon neutral** (figure $11.2.6.b$). Fossil fuels store carbon that was captured by organisms millions of years ago. When we burn them, carbon dioxide is released much more rapidly than it was removed. Biofuels removed carbon dioxide from the atmosphere more recently, and they form over shorter time spans. When biofuels are burned, this carbon dioxide that was recently removed is released back into the atmosphere.

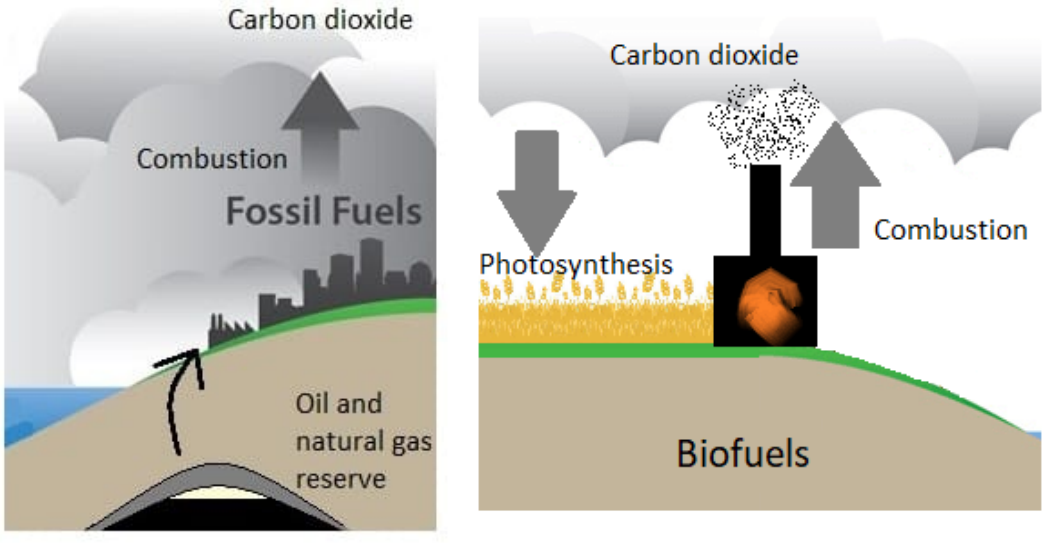


Figure $11.2.6.b$: Fossil fuels, such as oil and natural gas, contain carbon that has been stored underground for millions of years. Combustion (burning) of these fossil fuels releases carbon dioxide into the atmosphere, contributing to climate change. When biofuels are grown, they capture carbon dioxide through photosynthesis. Burning them or their products for heat, transportation, or electricity generation release

this carbon dioxide, which was only recently captured. For this reason, biofuels are considered carbon neutral. Images created by Melissa Ha from NETL/DOE (public domain) and publicdomainvectors.org (public domain).

Another advantage of biofuels is that they can be produced locally and can be cultivated in many different locations. On the other hand, they occupy space that could otherwise be used for food production. To further complicate matters, the characteristics that make a plant species ideal for biofuel (such as being resistant to pests and fast-growing) are also characteristics that help invasive species thrive. Care must taken to contain these species if grown outside of their native ranges.

Combustion of solid municipal waste (see below) or animal wastes as biofuels, reduces waste and generates electricity simultaneously. Unlike most forms of renewable energy, however, combustion of biofuels pollutes the air. (The carbon dioxide released is not an issue since biofuels are carbon neutral, but other air pollutants are also released.) In fact, indoor air pollution from fires used for cooking inside the home is a major cause of death in developing countries.

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. 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, livestock manure, or trash. These materials would otherwise just accumulate or decompose. Several examples of biofuel use are discussed below in more detail, including the specific advantages and disadvantages of type of use.

Burning Wood

Using wood, and charcoal made from wood, for heating and cooking can replace fossil fuels and may result in lower carbon dioxide 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 (see Air Pollution).

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 developing countries, the wood may be harvested faster than trees can grow resulting in deforestation (figure $11.2.6.c$). The largest share of biofuel use comes from traditional biomass, mostly fuel wood gathered for household cooking and heating, often without regard for sustainable replacement.



Figure $11.2.6.c$: Charcoal production in Uganda. (A) Trees cut down for charcoal. (B) Pieces of firewood. (C) Wood logs read for charcoal burning. (D) Charcoal packed and ready for market. Image and caption (modified) from Bamwesigye et al. *Sustainability* **2020**, 12(20), 8337. (CC-BY)

Biomass can be used in small power plants. For instance, Colgate College has had a wood-burning boiler since the mid-1980s (figure $11.2.6.d$). 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.



Figure $11.2.6.d$: Wood chips are one example of a biofuel that can be burned to generate electricity. Source: Ulrichulrich

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 Environmental Protection Agency in the U.S. 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 blocks, and artificial reefs (similar to coral reefs, but built by humans).

Landfill Gas (Biogas)

Landfill gas (**biogas**) is a sort of human-made "biogenic" gas as discussed above (figure $11.2.6.e$). 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, reducing carbon dioxide emissions. The only environmental impacts are from the construction of the plant itself, similar to that of a natural gas plant.

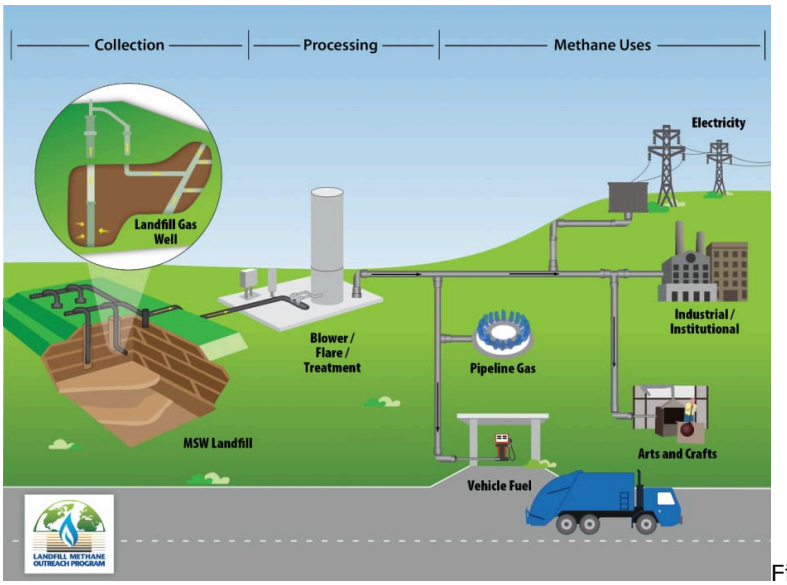


Figure 11.2.6.*e*: The collection and processing of landfill gas to produce methane for multiple uses. First, landfill gas is collected from the landfill gas well. A system of vertical and horizontal piping buried in an municipal solid waste landfill. The landfill gas is then processed and treated for use (blower/flare/treatment). Potential end uses include industrial/institutional uses, arts and crafts, pipeline gas, and vehicle fuel. Image and caption (modified) from Landfill Methane Outreach Program/EPA (public domain).

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. Additionally, it can 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 versus 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. Derived biofuels from parts of plants not used for food, such as stalks, reduces their environmental impact. Biodiesel can be made from used vegetable oil and has been produced on a very local basis. Compared to diesel, a petrochemical derived from crude oil, biodiesel combustion produces less sulfur oxides, particulate matter, carbon monoxide, and unburned and other hydrocarbons, but it produces more nitrogen oxide (see Air Pollution).

Liquid biofuels typically replace petroleum and are used to power vehicles (figure 11.2.6.*f*). 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 (see Air Pollution). Gasoline requires extra processing to reduce evaporative emissions before it is blended with ethanol.



Figure 11.2.6.f: A bus running on soybean biodiesel. Image and caption (modified) from U.S Department of Energy (public domain).

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11.2.7: Energy Conservation

Energy conservation refers to reducing energy waste and increasing efficiency. Energy conservation can involve behavior changes as well as technologies. Some examples of energy conservation have no financial impact. These include turn off and unplugging electronics when not in use, turning down the water heater, and driving efficiently (figure $11.2.7.a$). Additionally, opening blinds on south-facing windows in the morning during the winter takes advantage of a passive solar technology. Relying on the sun for heating and lighting reduces the use of electricity.



Figure $11.2.7.a$: A plant on the dashboard of this Ford Fusion (right) indicates if the driver's behavior promotes fuel efficiency. In this picture, there is only one leaf on the plant, indicating low efficiency. Some ways to drive efficiently include following the speed limit and adjusting your speed gradually. Image by ogilvyprworldwide (CC-BY).

Other examples of energy conservation require some financial investment, but they quickly pay for themselves with savings on an energy bill. An **energy audit** is a first step to investigate inefficiencies in one's home. This helps homeowners identify where their home is losing energy, and which problem areas and fixes they should prioritize to save energy and money. For example, an energy audit may reveal places in the home where hot escaping in the winter or entering in the summer. An energy auditor might recommend installing insulation to better seal the home as well as to insulate the hot water heater and pipes. Investing in most high-efficiency appliances also pays for itself relatively quickly (figure $11.2.7.b$).



Figure $11.2.7.b$: Energy Star appliances use

energy efficiently. Image by MoneyBlogNewz (CC-BY)

This video provides a walkthrough of an energy audit.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Finally, some strategies for energy conservation require sizeable financial investment. They can eventually pay for themselves over extended periods of time. Once example are double-paned, low emissivity (low e) windows (figure 11.2.7.c). The two layers of glass trap air between them, which serves as insulation. Additionally, the glass is coated with very small metal dots that allow light to pass through, but infrared (heat) energy is reflected back. If it is hotter outside, heat is emitted back outside; if warmer inside, heat will be emitted back inside. Energy-efficient air conditioners, geothermal heat pumps, and on-demand (tankless) water heaters (figure 11.2.7.d) are also examples of energy-conserving technologies that require sizeable investment.

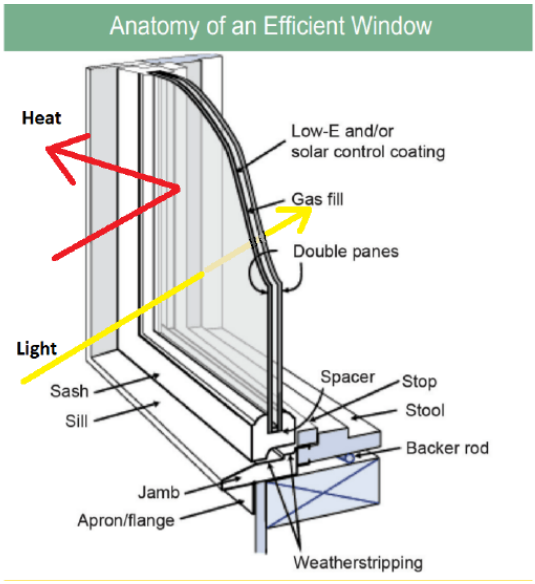


Figure 11.2.7.c: Anatomy of an efficient window. A double-paned, low emissivity window allows light from the sun to pass through, but tiny metal dots (not visible) reflect heat (labeled "Low-E and/or solar control coating"). The double panes trap air between them, an insulator (labeled "gas fill"). Spacers are between the glass and the sash, which surrounds the glass. The sash can move out of the frame when the window is open, and weatherstipping prevents air from leaking between the sash and the frame. The stop on the outside prevents the sash swinging outward, and the stool extends perpendicular to the wall outside of the stop. Under it is a backer rod, filling the space between the stool and the wall beneath it. The frame consists of the horizontal sill and vertical jamb. The apron/flange is the trim just below the frame.

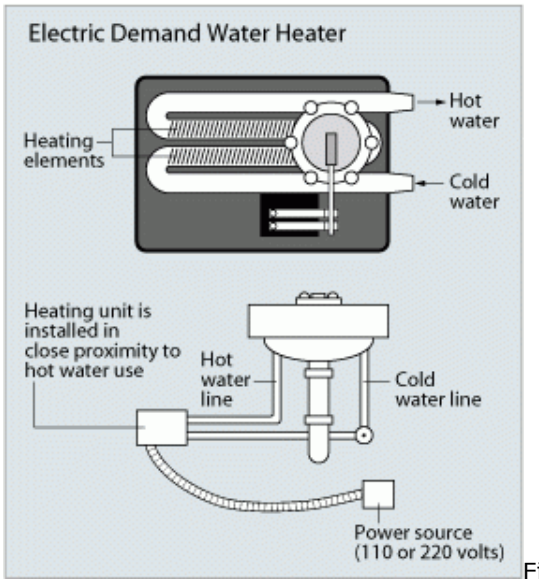


Image modified from U.S. Department of Energy (public domain). Figure $11.2.7.d$: An tankless water heater (electric demand water heater). Because hot water is not stored, there is no opportunity for it to cool and need to be reheated. This conserves energy. The heating unit is installed in close proximity to hot water use. It is suppled by a power source (110 or 220 volts). Hot and cold water lines run from the heating unit (which contains heating elements) to the sink. Image by U.S. Department of Energy (public domain).

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11.2.8: Data Dive- Global Renewable Energy Generation

Overview

Our World in Data (OWID) is a scientific online publication that focuses on using research and data to help tackle global concerns such as poverty, disease, hunger, climate change, war, and inequitable treatment of our world's most vulnerable and unstable communities. Their website is particularly known for publishing a variety of graphs, some even interactive, to present the research that helps explain causes and consequences of global concerns to the public. One example graph, seen below, illustrates renewable energy generation:

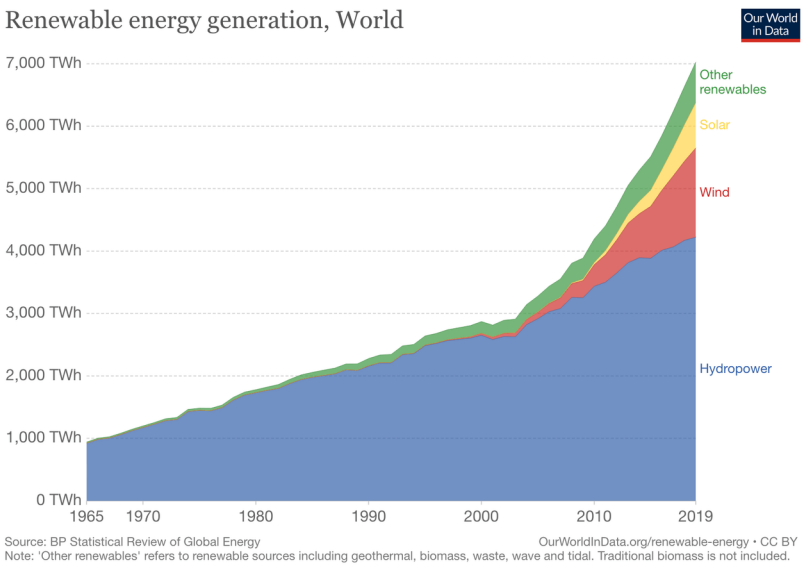


Figure 11.2.8.a: Global renewable energy generation. Graph by Our World in Data (CC-BY).

Questions

1. What renewable energy source has had the most consistent use globally?
2. Based on what you have learned in the chapter, what sources do you think are in the "other" category? Don't peek on the website!
3. Describe the pattern you see for the "other" category for 1965 to 2019.
4. Moving into the future, which renewable energy source do you think will grow the most in the next 50 years? Why?

Raw Data For Above Graph(s)

Raw data table link for Our World In Data graph above. (CC-BY)

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11.2.9: Review

Summary

After completing this chapter you should be able to...

- Detail the percentage that renewable energy contributes to electricity generation and total energy consumption globally and in the United States.
- Distinguish among the five main types of renewable energy, explain the mechanisms by which they are used, and discuss their advantages and disadvantages.
- Distinguish between passive and active solar technologies and provide examples of each.
- Explain how solar panels generate electricity.
- Distinguish between geothermal power plants and geothermal (ground source) heat pumps.
- Identify the main types of hydropower.
- Explain how environmental damage associated with hydropower can be mitigated.
- Explain why combustion of biofuels is carbon neutral.
- Provide examples of biofuel use and evaluate their sustainability.
- Define energy conservation and provide examples of behaviors and technologies that conserve energy.

Renewable energy sources can be replenished within a short timeframe. This includes **wind**, **solar**, **geothermal**, **hydropower**, and **biofuels**. Each is a direct or indirect form of solar energy with the exception of geothermal energy, which comes from deep underground, and tidal energy, a type of hydropower. Most forms of renewable energy generate electricity by turning a turbine, which powers a generator. For wind energy and hydropower, the motion of air or water, respectively, turns the turbine. For geothermal energy and biofuels, heat from the Earth or from burning organisms, respectively, produce steam, which turns a turbine. Solar panels generate electricity when light energy displaces electrons in semiconductors.

Generally, renewable energy sources generate little air pollution and are not major causes of climate change, but there are exceptions. A downside of renewables is that wind and solar can only be efficiently harnessed in certain locations and are intermittently available. Geothermal energy is more reliable, but geothermal power plants can typically only be built near geysers, volcanoes, or hot springs. Hydropower that involves **dams** and **reservoirs** destroys terrestrial habitats and disrupts aquatic species, but **run-of-the-river hydroelectricity** causes minimal damage. Biofuels are **carbon neutral**, capturing as much carbon dioxide as they release. Biofuels are most sustainable when they are made from materials that would otherwise be wasted.

Energy conservation involves reducing energy use or using it more efficiently. Examples of energy conservation include turning off lights and electronics when they are not in use, driving efficiently, and purchasing energy-efficient applicances.

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12: WATER RESOURCES AND POLLUTION

12.1: Water Cycle and Fresh Water Supply
12.2: Water Supply Problems and Solutions
12.3: Water Scarcity and Storage
12.4: Water Pollution
12.5: Water Treatment
12.6: Water Management
12.7: Chapter Resources

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12.1: Water Cycle and Fresh Water Supply

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 (km3) (330 million cubic miles) or about 53 billion gallons per person on Earth. All of Earth's water could cover the United States to a depth of 145 km (90 mi). From a human perspective, the problem is that over 97% of it is seawater, which is too salty to drink or use for irrigation. The most commonly used water sources are rivers and lakes, which contain less than 0.01% of the world's water!

One of the most important environmental goals is to provide 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 12.1.1). 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.

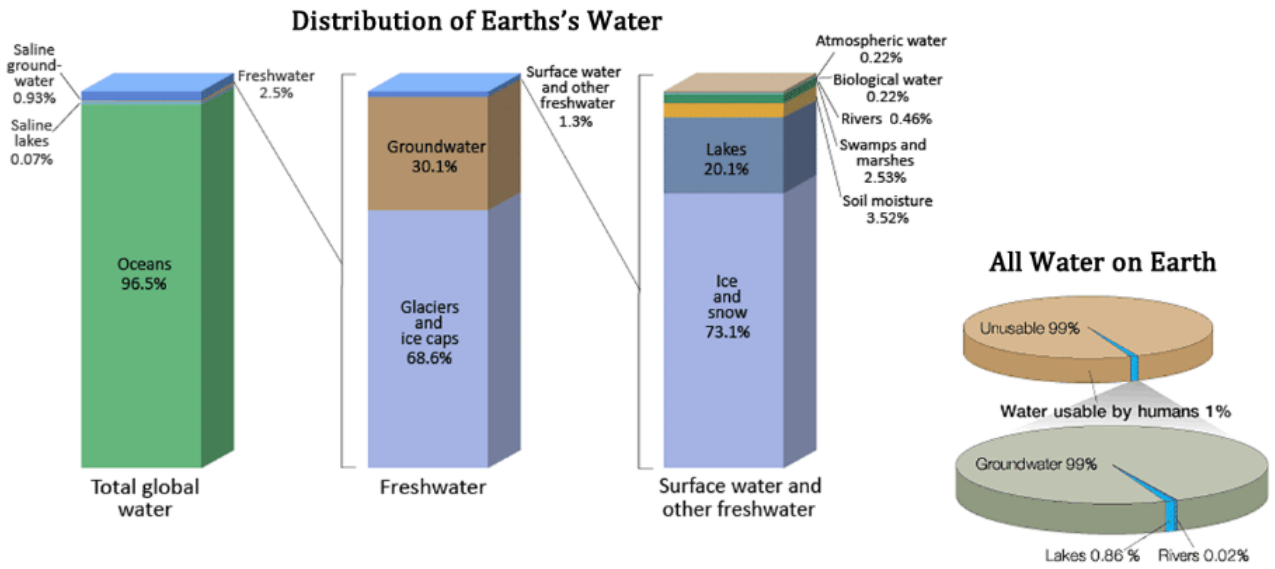


Figure 12.1.1. Earth's Water Reservoirs. Bar chart Distribution of Earth's water including total global water, fresh water, and surface water and other fresh water and Pie chart Water usable by humans and sources of usable water. Source: United States Geographical Survey Igor Skiklomanov's chapter "World 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 Chapter 3.2) shows the movement of water through different reservoirs, which include oceans, atmosphere, glaciers, groundwater, lakes, rivers, and biosphere. Solar energy and gravity drive the motion of water in the water cycle. Simply put, the water cycle involves water moving from oceans, rivers, and lakes to the atmosphere by evaporation, forming clouds. From clouds, it falls as precipitation (rain and snow) on both water and land. The water on land can either return to the ocean by surface runoff, rivers, glaciers, and subsurface groundwater flow, or return to the atmosphere by evaporation or **transpiration** (loss of water by plants to the atmosphere).

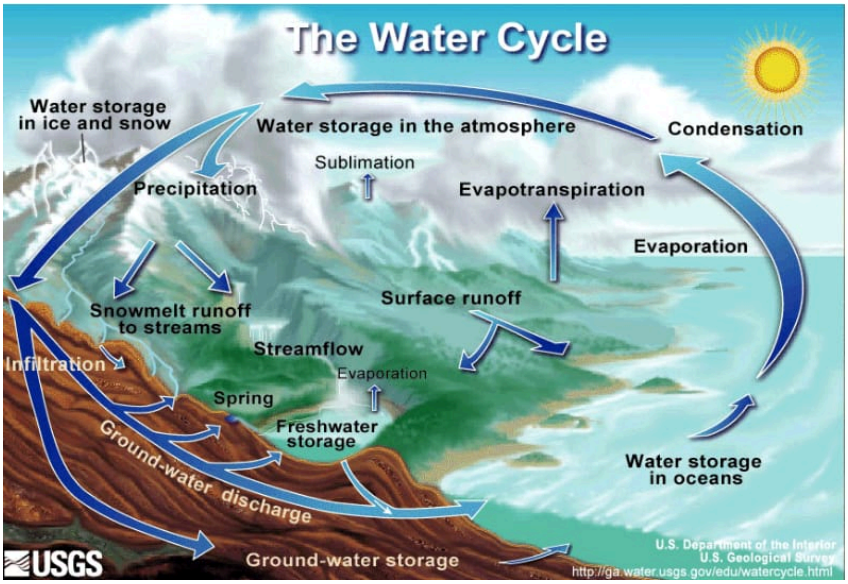


Figure 12.1.2. The Water Cycle. Arrows depict movement of water to different reservoirs located above, at, and below Earth's surface. Source: United States Geological Survey

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** (where water changes from liquid to gas at ambient temperatures) is a distillation process that produces nearly pure water with almost no dissolved ions. As water vaporizes, it leaves the dissolved ions in the original liquid phase. Eventually, **condensation** (where water changes from gas to liquid) forms clouds and sometimes precipitation (rain and snow). After rainwater falls onto land, it dissolves minerals in rock and soil, which increases its salinity. Most lakes, rivers, and near-surface groundwater have a relatively low salinity and are

called freshwater. The next several sections discuss important parts of the water cycle relative to fresh water resources.

Primary Fresh Water Resources: Precipitation

Precipitation levels are unevenly distributed around the globe, affecting fresh water availability (Figure 12.1.3). More precipitation falls near the equator, whereas less precipitation tends to fall near 30 degrees north and south latitude, where the world's largest deserts are located. These rainfall and climate patterns are related to global wind circulation cells. The intense sunlight at the equator heats air, causing it to rise and cool, which decreases the ability of the air mass to hold water vapor and results in frequent rainstorms. Around 30 degrees north and south latitude, descending air conditions produce warmer air, which increases its ability to hold water vapor and results in dry conditions. Both the dry air conditions and the warm temperatures of these latitude belts favor evaporation. Global precipitation and climate patterns are also affected by the size of continents, major ocean currents, and mountains.

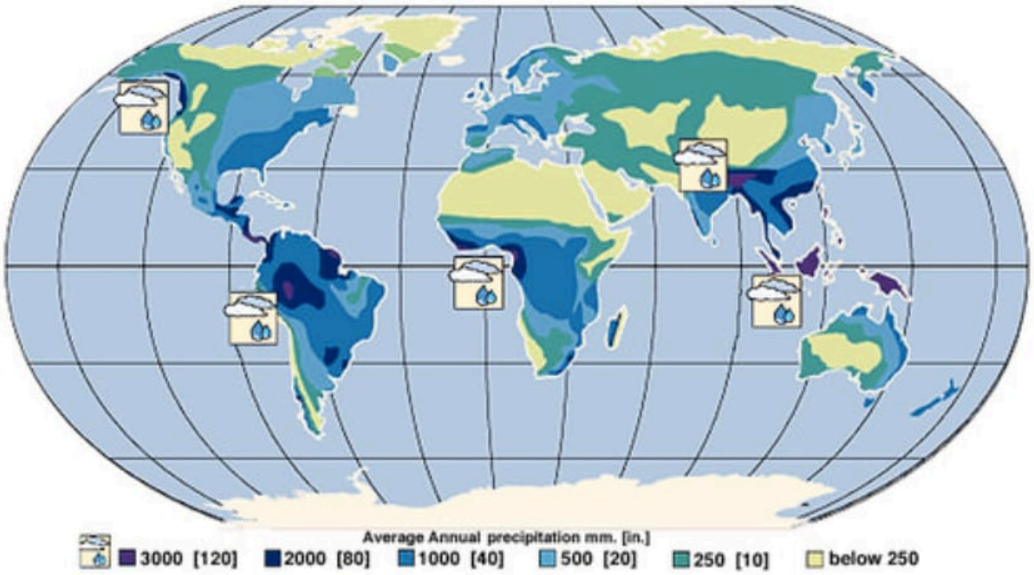


Figure 12.1.3. World Rainfall Map. The false-color map above shows the amount of rain that falls around the world. Areas of high rainfall include Central and South America, western Africa, and Southeast Asia. Since these areas receive so much rainfall, they are where most of the world's rainforests grow. 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 12.1.4. Surface Runoff Surface runoff, part of overland flow in the water cycle Source: James M. Pease at Wikimedia Commons

Flowing water from rain and melted snow on land enters river channels by surface runoff (Figure 12.1.4) and groundwater seepage (Figure 12.1.5). **River discharge** describes the volume of water moving through a river channel over time (Figure 12.1.6). The relative contributions of surface runoff vs. groundwater seepage to river discharge depend on precipitation patterns, vegetation, topography, land use, and soil characteristics. Soon after a heavy rainstorm, river discharge increases due to surface runoff. The steady normal flow of river water is mainly from groundwater that discharges into the river. Gravity pulls river water downhill toward the ocean. Along the way the moving water of a river can erode soil particles and dissolve minerals. Groundwater also contributes a large amount of the dissolved minerals in river water. The geographic area drained by a river and its tributaries is called a **drainage basin** or **watershed**. The Mississippi River drainage basin includes approximately 40% of the U.S., a measure that includes the smaller drainage basins, such as the Ohio River and Missouri River that help to comprise it. Rivers are an important water resource for 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).



Figure 12.1.5. 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 called Lake Bonneville.



Figure 12.1.6. River Discharge Colorado River, U.S.. Rivers are part of overland flow in the water cycle and an important surface water resource. Source: Gonzo fan2007 at Wikimedia Commons.



Figure 12.1.7. 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

Groundwater Resources

Although most people in the world use surface water, groundwater is a much larger reservoir of usable fresh water, containing more than 30 times more water than rivers and lakes combined. Groundwater is a particularly important resource in arid climates, where surface water may be scarce. In addition, groundwater is the primary water source for rural homeowners, providing 98% of that water demand in the U.S.. **Groundwater** is water located in small spaces, called **pore space**, between mineral grains and fractures in subsurface earth materials (rock or sediment). Most groundwater originates from rain or snowmelt, 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. A large area of sub-surface, porous rock that holds water is an aquifer. Aquifers are commonly drilled, and wells installed, to provide water for agriculture and personal use.

Water Use in the U.S. and World

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.

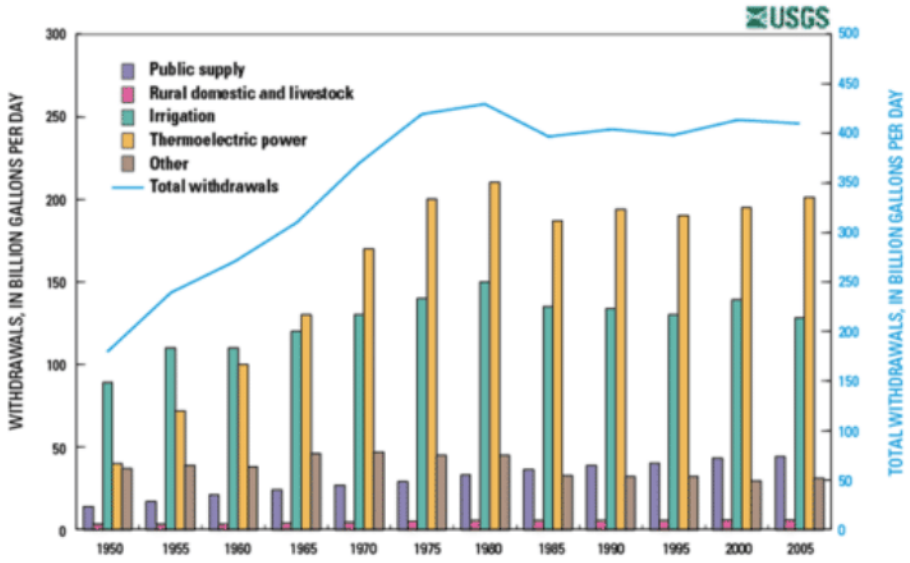


Figure 12.1.8. Trends in Total Water Withdrawals by Water-use Category, 1950-2005 Trends in total water withdrawals in the U.S. from 1950 to 2005 by water use category, including bars for thermoelectric power, irrigation, public water supply, and rural domestic and livestock. Thin blue line represents total water withdrawals using vertical scale on right. Source: United States Geological Survey

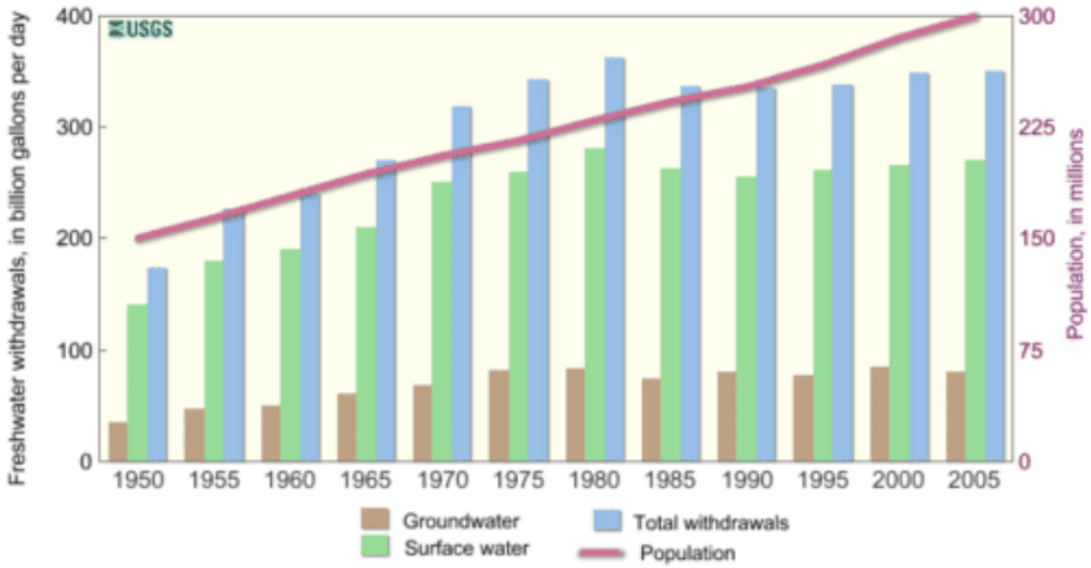


Figure 12.1.9. Trends in Source of Fresh Water Withdrawals in the U.S. from 1950 to 2005 Trends in source of fresh water withdrawals in the U.S. from 1950 to 2005, including bars for surface water, groundwater, and total water. Red line gives U.S. population using vertical scale on right. Source: United States Geological Survey

Global total water use is steadily increasing at a rate greater than world population growth (Figure 12.1.10). During the 20th century global population tripled and water demand grew by a factor of six. The increase in global water demand beyond the rate of population growth is due to improved standard of living without an offset by water conservation. Increased production of goods and energy entails a large increase in water demand. The major global water uses are irrigation (68%), public supply (21%), and industry (11%).

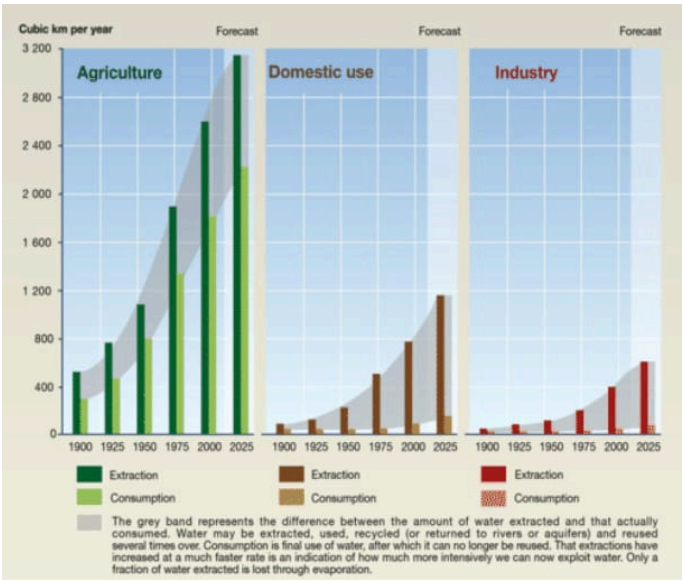


Figure 12.1.10. Trends in World Water Use from 1900 to 2000 and Projected to 2025 For each water major use category, including trends for agriculture, domestic use, and industry. Darker colored bar represents total water extracted for that use category and lighter colored bar represents water consumed (i.e., water that is not quickly returned to surface water or groundwater system) for that use category. Source: Igor A. Shiklomanow, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999

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12.2: Water Supply Problems and Solutions

Water Supply Problems: Resource Depletion

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

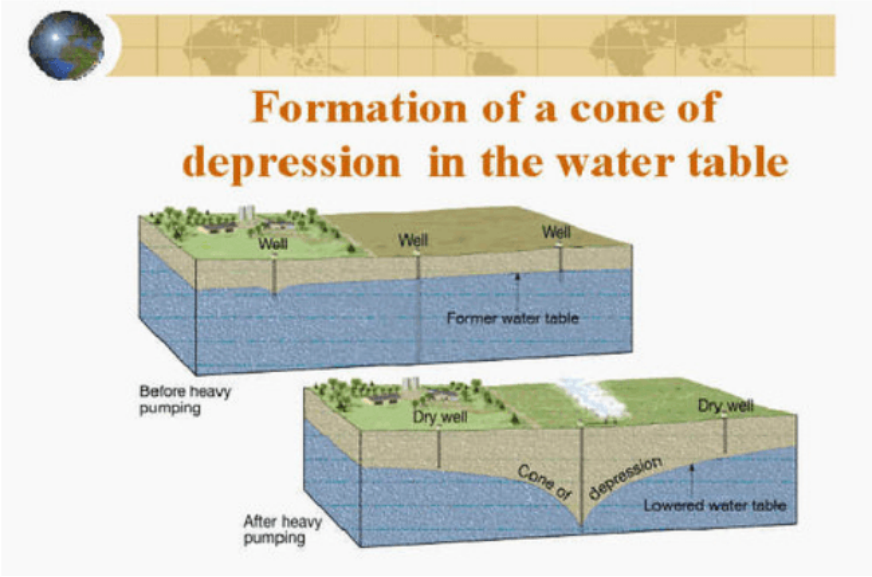


Figure 12.2.1. Formation of a cone of depression around a pumping water well source. The upper block diagram shows a stable system before heavy pumping, where the water table remains level across three active wells. The lower block diagram demonstrates the system after heavy pumping; intensive drawdown from the deeper middle well lowers the local water table into a distinct, V-shaped "cone of depression," dropping the water level below the reaching depth of the two shallower outer wells and causing them to go dry. (Diagram adapted from standard geological textbook schematics, originally published by Pearson Prentice Hall/Tarbuck & Lutgens).

Another water resource problem associated with groundwater mining is saltwater intrusion, where overpumping of fresh water aquifers near ocean coastlines causes saltwater to enter fresh water zones. The drop of the water table around a **cone of depression** in an unconfined aquifer can change the direction of regional groundwater flow, which could send nearby pollution toward the pumping well instead of away from it Figure 12.2.1.. 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.

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.

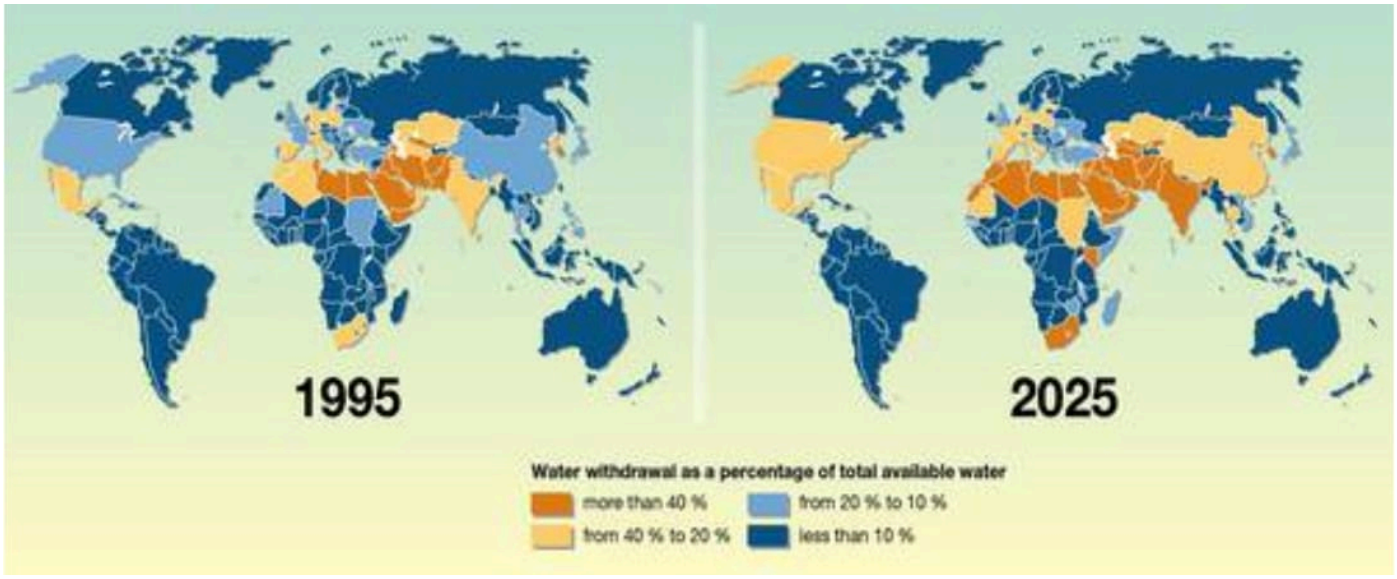


Figure 12.2.2. Countries Facing Water Stress in 1995 and Projected in 2025. Water stress is defined as having a high percentage of water withdrawal compared to total available water in the area. Source: Philippe Rekacewicz (Le Monde diplomatique), February 2006

According to a 2006 report by the United Nations Development Programme, 700 million people (11% of the world's population) lived with water stress. Most of them live in the Middle East and North Africa (Figure 12.2.2). By 2025, the report projects that more than 3 billion people (about 40% of the world's population) will live in water-stressed areas with the large increase coming mainly from China and India. The water crisis will also impact food production and our ability to feed the ever-growing population. We can expect future global tension and even conflict associated with water shortages and pollution. 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).

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 reservoirs and aqueducts.

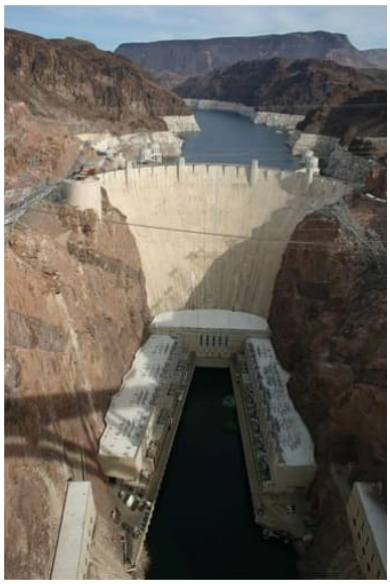


Figure 12.2.3. Hoover Dam, Nevada, U.S. Hoover Dam, Nevada, U.S.. Behind the dam is Lake Mead, the largest reservoir in U.S.. White band reflects the lowered water levels in the reservoir due to drought conditions from 2000 – 2010. Source: Cygnusloop99 at Wikimedia Commons

Reservoirs that form behind dams in rivers can collect water during wet times and store it for use during dry spells. They also can be used for urban water supplies. Other benefits of dams and reservoirs are hydroelectricity, flood control, and recreation. Some of the drawbacks are evaporative loss of water in arid climates, downstream river channel erosion, and impact on the ecosystem including a change from a river to lake habitat and interference with migration and spawning of fish. The Hoover Dam in Nevada forms the largest capacity reservoir in the U.S., Lake Mead (Figure 12.2.3). Lake Mead is located in the states of Nevada and Arizona, and supplies nearly 20 million people and large areas of farmland in Arizona, California, and Nevada as well as some of Mexico. At maximum capacity, Lake Mead is 112 miles (180 km) long, 532 feet (162 m) at its greatest depth, hand has a surface area of 247 square miles (640 km^2). The lake has remained below full capacity since 1983 owing to drought and increased water demand.

Aqueducts can move water from where it is plentiful to where it is needed. Aqueducts can be controversial and politically difficult especially if the water transfer distances are large. One drawback is the 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 12.2.4). 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.

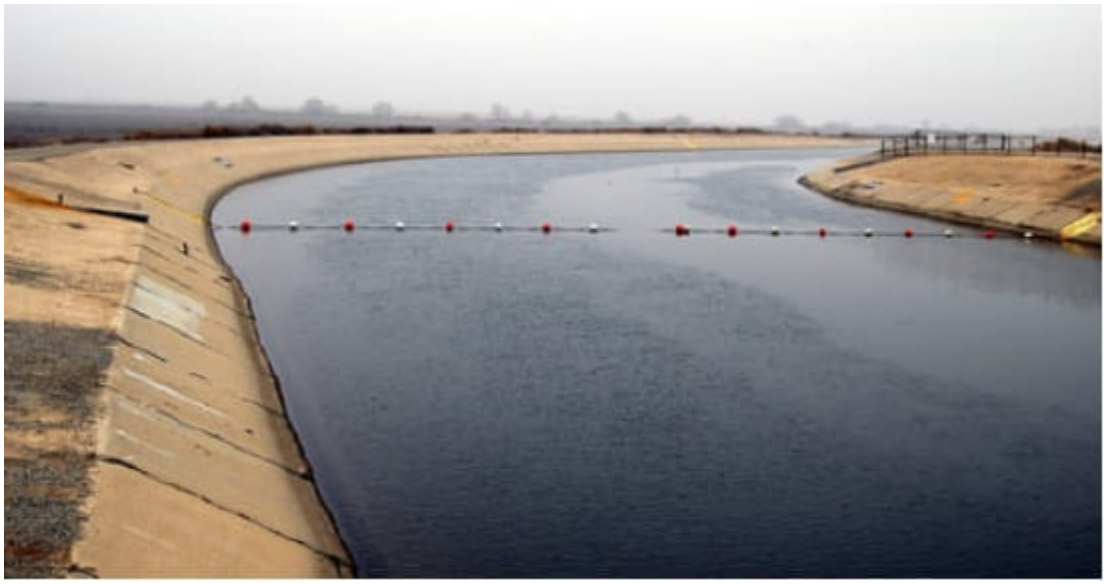


Figure 12.2.4. The California aqueduct, a concrete-lined section of the canal system near Tupman, California. A safety buoy line stretches across the channel to prevent debris or watercraft entry. This open infrastructure model is built to move massive volumes of fresh water across long distances, though it remains vulnerable to high evaporative losses. *(Image in the Public Domain, available via Wikimedia Commons.)*

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.

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

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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12.3: Water Scarcity and Storage

Water has been identified as one of the major environmental crisis facing the world today. More than one billion people in the world lack access to clean drinking water. The demand for water has grown at a very fast pace in response to the rate of global population growth. Figures 12.3.1, and 12.3.2 illustrate this change in water use over time. It is predicted that over the next two decades, the average supply of water per person will drop by a third.

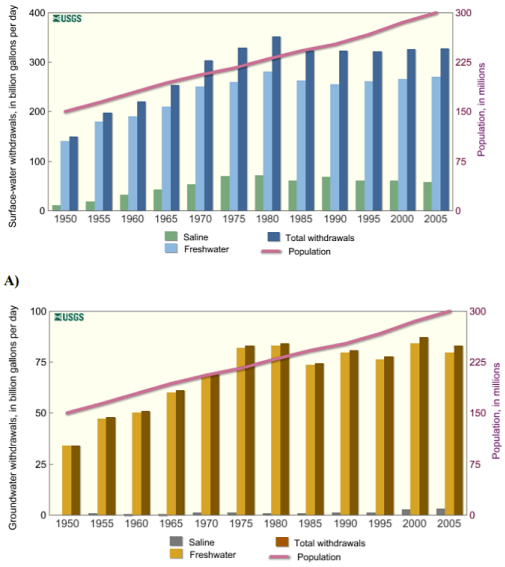


Figure 12.3.1: Trends in fresh and saline water withdrawals in response to population growth (A) surface water withdrawals (B) Groundwater withdrawal trends: water.usgs.gov/edu/wugw.html

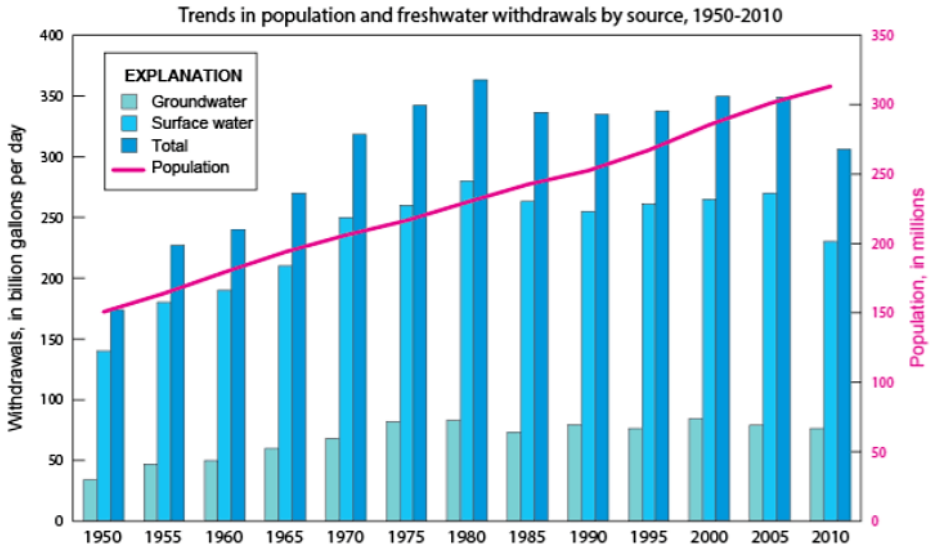


Figure 12.3.2: Both groundwater and surface water withdrawals had increased over time until 1980 when the withdrawals peaked and stabilized.

Water Scarcity and Availability

There is enough fresh water on Earth to supply every human being with enough drinking water. The main problem we face with regards to water is that it is unevenly distributed, polluted, mismanaged and wasted. Tony Allan, the author of Virtual Water, asserts that water follows money. This refers to the fact that rich countries and societies with money and affluence have more access to safe drinking water even when they live in regions without much water. It also means that areas with large supplies of water can still have water scarcity if they lack the financial resources to build the infrastructure to supply people with safe clean

drinking water. Water scarcity is caused by the demand for water being greater than the supply. Scarcity can be defined as either **physical scarcity** or **economic scarcity**.

Physical water scarcity is a situation where there is an actual shortage of water, regardless of quality or infrastructure. It is estimated that about 1.2 million people around the world are experiencing physical water scarcity. Economic scarcity is a condition where countries lack the financial resources and/or infrastructure to supply their citizens with reliable safe drinking water. About 1.6 billion people are experiencing economic water shortage; most of them live in less industrialized countries. For a lot of places in the world, scarcity is a transient condition that can be reduced or eliminated by installing the right infrastructure. The major problem in less industrialized countries is the lack of political, financial, and physical structures to provide water to everyone. A few rich people in these countries get the clean water while the majority of the people who cannot afford to pay for it are left out. Examples of such communities include many villages in Africa, Asia, and South America. Figure 12.3.3 shows communities in southeast Kenya that are experiencing severe water shortages primarily due to lack of infrastructure. Women in these communities must walk long distances to get untreated and contaminated water for drinking and other household needs.



Figure 12.3.3: Communities in southeast Kenya without ready access to safe drinking water. (A) Groundwater in the area is too salty for consumption. B) Maasai women in Amboseli National Park collecting water from a wetland. (C) Women in Magwede village in SE Kenya walking long distances to get water from a Kiosk. D) Children collecting water in Bungule Village from a water kiosk that is only open for about an hour every day. Photo credit: Jonathan Levy, Sam Mutiti and Christine Mutiti

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- 15.4C: Respiratory Syncytial Virus Infection is licensed CC BY-SA 4.0.

12.4: Water Pollution

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 12.4.1). Compounding the water crisis is the issue of social justice; poor people more commonly lack clean water and sanitation than wealthy people in similar areas. Globally, improving water safety, sanitation, and hygiene could prevent up to 9% of all disease and 6% of all deaths.

In addition to the global waterborne disease crisis, chemical pollution from agriculture, industry, cities, and mining threatens global water quality. Some chemical pollutants have serious and well-known health effects, whereas many others 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.

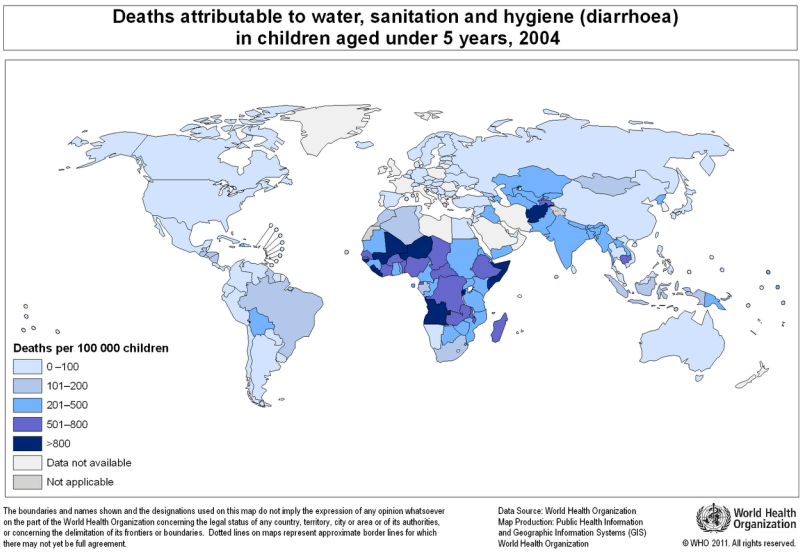


Figure 12.4.1. Deaths attributable to water, sanitation and hygiene (diarrhea) in children aged under 5 years, 2004. The highest mortality concentrations remain localized across Sub-Saharan Africa and South Asia. (Image courtesy of the World Health Organization Public Health Information and Geographic Information Systems, © WHO 2011; reproduced under educational open-access terms.)

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.

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. The level of water pollution depends on the abundance of the pollutant, the ecological impact of the pollutant, and the use of the water. Pollutants are derived from biological, chemical, or physical processes. Although natural processes such

as volcanic eruptions or evaporation sometimes can cause water pollution, most pollution is derived from human, land-based activities. Water pollutants can move through different water reservoirs, as the water carrying them progresses through stages of the water cycle (Figure 12.4.2). **Water residence time** (the average time that a water molecule spends in a water reservoir) is very important to pollution problems because it affects pollution potential. Water in rivers has a relatively short residence time, so pollution usually is there only briefly. Of course, pollution in rivers may simply move to another reservoir, such as the ocean, where it can cause further problems. Groundwater is typically characterized by slow flow and longer residence time, which can make groundwater pollution particularly problematic. Finally, **pollution residence time** can be much greater than the water residence time because a pollutant may be taken up for a long time within the ecosystem or absorbed onto sediment.

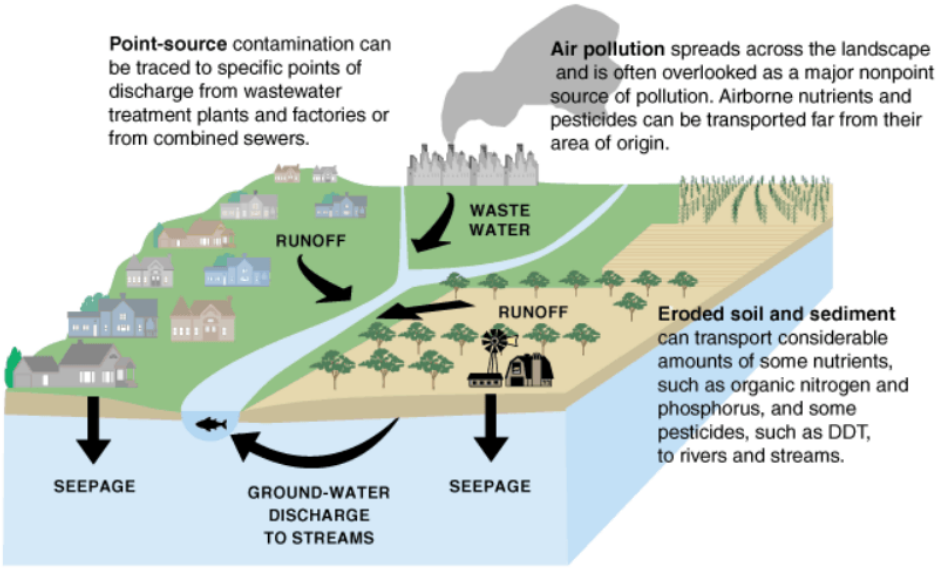


Figure 12.4.2. Sources of Water Contamination. Sources of some water pollutants and movement of pollutants into different water reservoirs of the water cycle. (Source: U.S. Geological Survey)

Pollutants enter water supplies from **point sources** (any single, identifiable, and localized origin from which pollutants are discharged directly into the environment.), or **nonpoint sources**, which are large and more diffuse areas. Point sources of pollution include animal factory farms (Figure 12.4.3) that raise a large number and high density of livestock such as cows, pigs, and chickens. Also, pipes included are pipes from a factories or 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 12.4.4).



Figure 12.4.3. A concentrated animal feeding operation (CAFOs) for hogs showing dense group-penning configurations over slotted concrete flooring. These farms are considered potential point sources of pollution because untreated animal waste may enter nearby water bodies as untreated sewage. (Image in the Public Domain, sourced from the U.S. Environmental Protection Agency via Wikimedia Commons).

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.

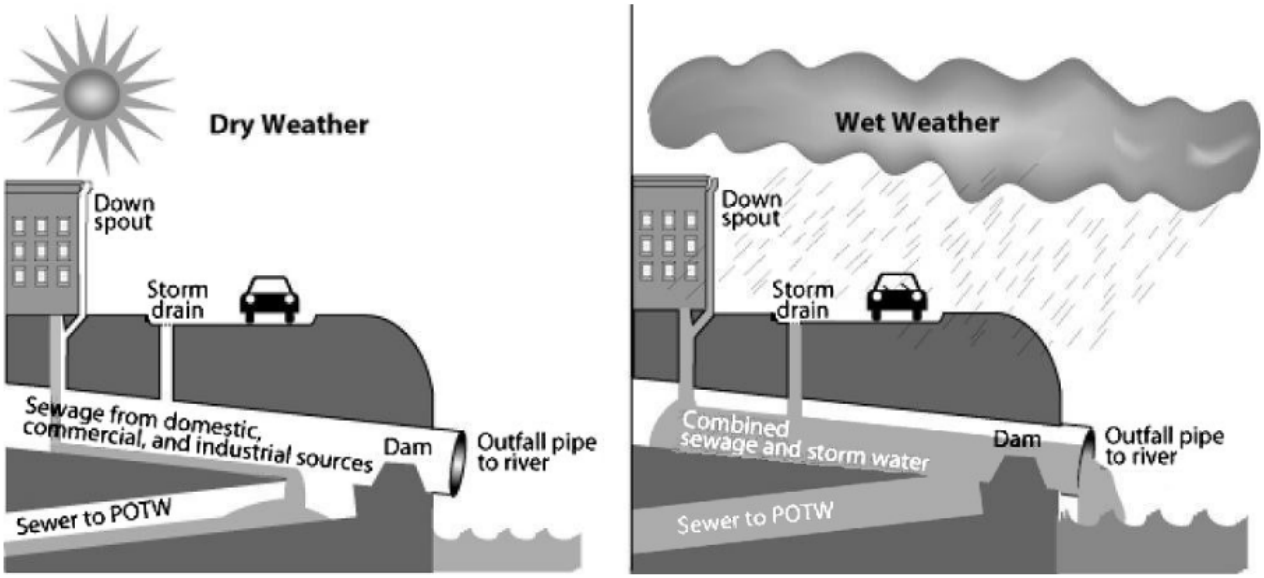


Figure 12.4.4. Combined Sewer System A combined sewer system is a possible major point source of water pollution during heavy rain due to overflow of untreated sewage. During dry weather (and small storms), all flows are handled by the publicly owned treatment works (POTW). During large storms, the relief structure allows some of the combined stormwater and sewage to be discharged untreated to an adjacent water body. Source: U.S. Environmental Protection Agency at Wikimedia Commons

Types of Water Pollutants

Oxygen-demanding waste is an extremely important pollutant to ecosystems. Most surface water in contact with the atmosphere has a small amount of dissolved oxygen, which is needed by aquatic organisms for cellular respiration. Bacteria decompose dead

organic matter and remove dissolved oxygen (O_2) according to the following reaction:

$$\text{organic matter} + O_2 \rightarrow CO_2 + H_2O \tag{12.4.1}$$

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** (requiring 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; grass and leaves are smaller sources. An unpolluted water body with respect to BOD is a turbulent river that flows through a natural forest. Turbulence continually brings water in contact with the atmosphere where the O_2 content is restored. The dissolved oxygen content in such a river ranges from 10 to 14 ppm O_2, BOD is low, and clean-water fish such as trout. A polluted water body with respect to oxygen is a stagnant deep lake in an urban setting with a combined sewer system. This system favors a high input of dead organic carbon from sewage overflows and limited chance for water circulation and contact with the atmosphere. In such a lake, the dissolved O_2 content is ≤5 ppm O_2, BOD is high, and low O_2-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 O_2 concentrations in the water (< 2 ppm O_2), a condition called **hypoxia.** This results in a **dead zone** because it causes death from asphyxiation to organisms that 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 12.4.5) 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 12.4.5. 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 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.

Water with high mineral content is called **hard water.** It 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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12.5: Water Treatment

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 12.5.1).

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.

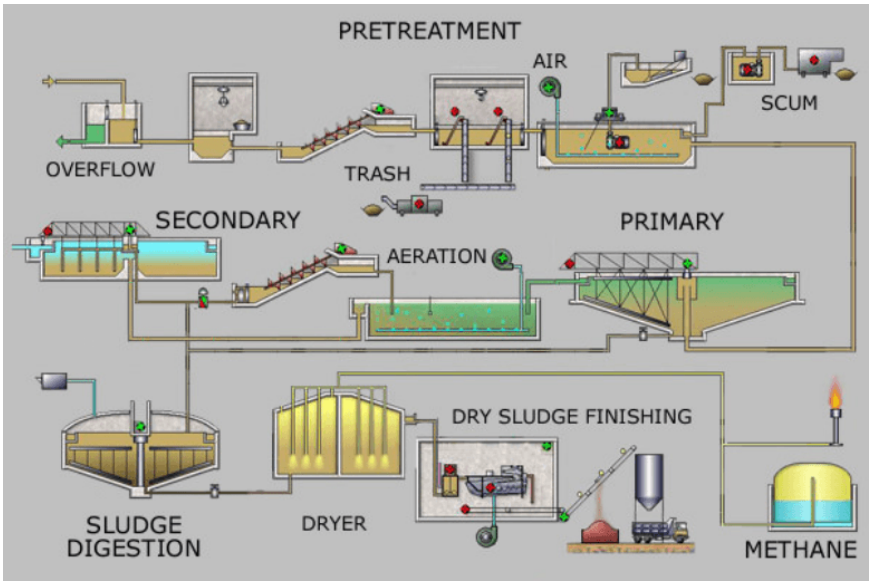


Figure 12.5.1. Steps at a Sewage Treatment Plant The numerous processing steps at a conventional sewage treatment plant include pretreatment (screening and removal of sand and gravel), primary treatment (settling or floatation to remove organic solids, fat, and grease), secondary treatment (aerobic bacterial decomposition of organic solids), tertiary treatment (bacterial decomposition of nutrients and filtration), disinfection (treatment with chlorine, ozone, ultraviolet light, or bleach), and either discharge to surface waters (usually a local river) or reuse for some other purpose, such as irrigation, habitat preservation, and artificial groundwater recharge. Source: Leonard G.via Wikipedia

A **septic tank system** is an individual sewage treatment system for homes in typically rural settings. The basic components of a septic tank system (Figure 12.5.2) 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.

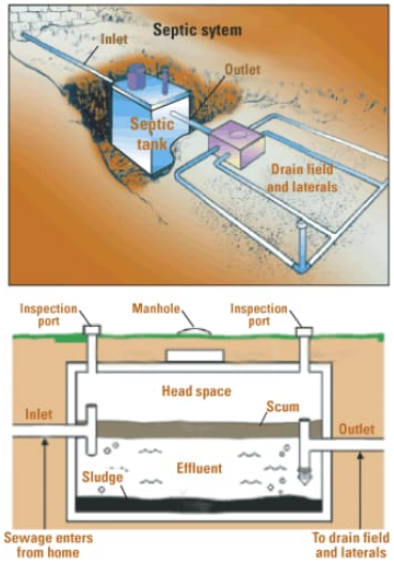


Figure 12.5.2. Septic System Septic tank system for sewage treatment. Source: United States Geological Survey

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!

CLEAN WATER ACT



Figure 12.5.3. 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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12.6: Water Management

Pollution control begins with testing and monitoring of water quality. Water quality is usually monitored using easy to measure indicators such as pH, specific conductance (commonly referred to as conductivity), temperature, fecal and total coliform bacteria, dissolved oxygen, macroinvertebrates, and algae. Polluted sites typically have reduced DO levels, lower pH (more acidic), higher nutrient levels, more bacteria, and higher temperatures compared to less impacted or pristine sites.

Non-point source control relates mostly to land management practices in the fields of agriculture, mining and urban design and sanitation. Agricultural practices leading to the greatest improvement of sediment control include: contour grading, avoidance of bare soils in rainy and windy conditions, polyculture farming resulting in greater vegetative cover, and increasing fallow periods. Minimization of fertilizer, pesticide and herbicide runoff is best accomplished by reducing the quantities of these materials, as well as applying fertilizers during periods of low precipitation. Other techniques include avoiding of highly water soluble pesticides and herbicides, and use of materials that have the most rapid decay times to benign substances.

The main water pollutants associated with mines and quarries are aqueous slurries of minute rock particles, which result from rainfall scouring exposed soils and also from rock washing and grading activities. Runoff from metal mines and ore recovery plants is typically contaminated by the minerals present in the native rock formations. Control of this runoff is chiefly achieved by preventing rapid runoff and designing mining operations that avoid tailings either on steep slopes or near streams.

In the case of urban stormwater control, good urban planning and design can minimize stormwater runoff. By reducing impermeable surfaces (pavement that doesn't allow water through), then cities can reduce the amount of surface water runoff the carries pollutants into surface water and causes flooding. Additionally, the use of native plant and xeriscape techniques reduces water use and water runoff, and minimizes the need for pesticides and nutrients. Regarding street maintenance, a periodic use of street sweeping can reduce the sediment, chemical and rubbish load into the storm sewer system.

The two common approaches to water management fall under either voluntary programs or the regulatory program. The regulatory approach has been very successful in controlling and reducing point source pollution, which was the focus of regulations when they were first introduced. Voluntary programs, together with new amendments to regulations, have had great success in increasing conservation and reducing diffuse nonpoint source pollution. One of the most widely used voluntary programs is **Watershed Management** while the regulatory approach is centered on the Clean Water Act (CWA).

Watershed Management

The watershed management approach recognizes that water contamination problems are complex and not localized to a section of a river. Water pollution problems are caused by multiple activities within the watershed and, therefore, require holistic approaches in the entire watershed. A **watershed** (drainage basin or catchment) is an area of land that drains to a single outlet and is separated from other watersheds by a drainage divide. Rainfall that falls in a watershed will generate runoff (if not trapped or infiltrated into groundwater) to that watershed's outlet. Topographic elevation is used to define a watershed boundary. A focal point of water management plans is the Best Management Practices (BMPs) section. BMPs are designed to consider all of the various uses of water, maximize conservation and minimize pollution.

The regulatory approach

Water management through policy and laws seeks to clean up polluted water, prevent further pollution and apply punitive measures for polluters. In the US water-related regulations go as far back as 1899 with the Rivers and Harbors Act, also known as the Refuse Act that prohibited the dumping of solid waste and obstruction of waterways. This regulation, however, did not include waste flowing from streets and sewers. In 1948 another regulation, the Federal Water Pollution Act (which is the basis of the Clean Water Act) was enacted. This regulation covered contamination from sewage outfalls. It was created to reduce contamination of both interstate groundwater and surface waters. Through this regulation funding was made available to states and local governments for water quality management.

One of the major water-related regulations in the US is the Clean Water Act (CWA) of 1972. The regulation was very comprehensive with lots of programs and empowered the Environmental Protection Agency (EPA) to create goals, and objective laws for its implementation. The legislation has programs for both point and nonpoint source pollution. One other major piece of regulation governing water was the 1974 Safe Drinking Water Act (SDWA).

In 1974, amended in 1986, the SDWA was enacted to establish standards for many chemical constituents for public water supplied by public water agencies. In the regulations, maximum contaminant level goals (MCLG), which are non-enforceable and maximum contaminant levels (MCLs) that are enforceable where created. MCLG are what would be ideal and desirable while MCL are what should be attained in any drinking water supplied by a public municipal agency. For any carcinogen, the MCLG is 0 even though many contaminants have MCLs and detection limits in the parts per billion (ppb) range. Some of them (e.g. dioxin) have MCLs in the parts per trillion (ppt). To give you a sense of how small this ppt is, it is the same as 0.4 mm divided by the distance to the moon.

A Closer Look at the Clean Water Act

The 1972 Clean Water Acts was an overhaul of the 1948 Federal Pollution Control Act. The current regulation includes numerous programs for water quality improvement and protection. The EPA works with its federal, state and tribal regulatory partners to monitor and ensure compliance with clean water laws and regulations in order to protect human health and the environment. The Clean Water Act is the primary federal law governing water pollution. One of the objectives of the CWA was to restore and maintain the integrity of the nation's physical, chemical, and biological waters quality. The ultimate goals of the act are to establish zero pollutant discharge, as well as fishable & swimmable waters in the country. One main component of the CWA is regulations on industrial and municipal discharges into navigable US waters. The act is designed to be a partnership between states and the federal government. The federal government sets the agenda and standards while the state carries out the implementation of the law. States also have the power to set standards that are more stringent than the federal standards if needed. Under the CWA, discharge into US waters is only legal if authorized by a permit. Perpetrators of the law can be punished using administrative, civil, or criminal charges. The second component of the act is providing funding for constructing municipal waste water treatment plants and other projects to improve water quality (Title II and Title VI).

The act covers both point sources (discharge from sources such as pipes) and nonpoint sources (pollution from diffuse sources such as stormwater runoff). Point sources are explicitly covered under section 402, National Pollutant Discharge Elimination System (NPDES). This section requires industries and municipalities to get permits from the EPA before discharging into US waters. The permits require the use of control technology to reduce and prevent pollution.

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12.7: 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 within the subtropical latitudes 20° - 30° North and South of the equator, 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 or clean water, or both. To solve 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 by 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

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13: ECONOMICS AND URBANIZATION

13.1: Urbanization and Cities
13.2: Urbanization Around the World
13.3: The Impacts of Urban Sprawl
13.4: The Sustainable City
13.5: Environmental Economics

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13.1: Urbanization and Cities

Urbanization is the study of the social, political, and economic relationships in cities, and someone specializing in **urban sociology** would study those relationships. In some ways, cities can be microcosms of universal human behaviour, while in others they provide a unique environment that yields their own brand of human behaviour. There is no strict dividing line between rural and urban; rather, there is a continuum where one bleeds into the other. However, once a geographically concentrated population has reached approximately 100,000 people, it typically behaves like a city regardless of what its designation might be.

There are three prerequisites for the development of a city. First, **good environment** with fresh water and a favourable climate; second, **advanced technology**, which will produce a food surplus to support non-farmers; and third, **strong social organization** to ensure social stability and a stable economy. Most scholars agree that the first cities were developed somewhere in ancient Mesopotamia, though there are disagreements about exactly where. Most early cities were small by today's standards, and the largest city around 100 CE was most likely Rome, with about 650,000 inhabitants. The factors limiting the size of ancient cities included lack of adequate sewage control, limited food supply, and immigration restrictions. For example, serfs were tied to the land, and transportation was limited and inefficient. Today, the primary influence on cities' growth is economic forces.

Growth of Urban Populations

Urbanization levels are affected by two things – migration and natural increase. **Migration** is the movement of population from one area to another. Some migrations are forced, voluntary, permanent and temporary, international and regional. Rural to urban migration, is the movement of people from countryside to city areas. This type of migration happened in developed countries from the *18th century onwards* on a large scale, and has gradually slowed down. However, many developing countries are experiencing massive rural to urban migration, mainly of young males, into the major cities.

The major reasons for migration can be classified into push and pull factors. A **push factor** is something that can force or encourage people to move away from a country. Push factors can include famine (as in Ethiopia in the 1980s), drought, flooding, a lack of employment opportunities, population growth, over population, and civil war. A **pull factor** is one in which encourages people to move to a city. Pull factors include the chance of a better job, better access to education and services, a higher standard of living. These factors have contributed to millions of people in developing countries moving to cities, creating mass urbanization. **Natural increase** (a population increase due to more births and fewer deaths) also has a major effect on rates of urbanization. Natural increase is stimulated by better access to medical care, improved water supplies, sanitary conditions and wealth.

Suburbs and Exurbs

As cities grew and became more crowded (and often more impoverished and costly) more and more people began to migrate back out of them. But instead of returning to rural small towns (like they had resided in before moving to the city), these people needed close access to the cities for their jobs. In the 1850s, as the urban population greatly expanded and transportation options improved, suburbs developed. **Suburbs** are the communities surrounding cities, typically close enough for a daily commute in, but far enough away to allow for more space than city living affords. The bucolic suburban landscape of the early 20th century has largely disappeared due to sprawl.

Urban sprawl contributes to *traffic congestion*, which in turn contributes to commuting time. Commuting times and distances have continued to increase as new suburbs developed farther and farther from city centers. Simultaneously, this dynamic contributed to an exponential increase in natural resource use, like petroleum, which sequentially increased *pollution* in the form of carbon emissions (negative aspects of urban sprawl will be explored further in the following section).

As the suburbs became more crowded and lost their charm, those who could afford it turned to the **exurbs**, communities that exist outside the ring of suburbs and are typically populated by even wealthier families who want more space and have the resources to lengthen their commute. It is interesting to note that unlike U.S. cities, Canadian cities have always retained a fairly large elite residential presence in enclaves around the city centres, a pattern that has been augmented in recent decades by patterns of inner-city resettlement by elites (Caulfield 1994; Keil and Kipfer 2003). As cities evolve from industrial to postindustrial, this practice of **gentrification** becomes more common. Gentrification refers to members of the middle and upper classes entering city areas that have been historically less affluent and renovating properties while the poor urban underclass are forced

by resulting price pressures to leave those neighbourhoods. This practice is widespread and the lower class is pushed into increasingly decaying portions of the city.

Together, the city centres, suburbs, exurbs, and metropolitan areas all combine to form a **metropolis**. New York was the first North American **megalopolis**, a huge urban corridor encompassing multiple cities and their surrounding suburbs. The Toronto-Hamilton-Oshawa and Calgary-Edmonton corridors are similar megalopolis formations. These metropolises use vast quantities of natural resources and are a growing part of the North American landscape.

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13.2: Urbanization Around the World

As was the case in North America, other urban centers experienced a growth spurt during the Industrial Era. In 1800, the only city in the world with a population over 1 million was Beijing, but by 1900, there were 16 cities with a population over 1 million. The development of factories brought people from rural to urban areas, and new technology increased the efficiency of transportation, food production, and food preservation. For example, from the mid-1670s to the early 1900s, London increased its population from 550,000 to 7 million.

The growth in global urbanization in the 20th and 21st centuries is following the blueprint of North American cities, but is occurring much more quickly and at larger scales, especially in peripheral and semi-peripheral countries. Shanghai almost tripled its population from 7.8 million to 20.2 million between 1990 and 2011, adding the equivalent of the population of New York City in 20 years. It is projected to reach 28.4 million by 2025, third in size behind Tokyo (38.7 million) and New Delhi (32.9 million).

Urban Environmental Problems of the Developing World

Global urbanization reached the 50 percent mark in 2008, meaning that more than half of the global population was living in cities compared to only 30 percent 50 years ago. The access to basic services— clean water, sanitation, electricity, and roads—are some of the main urbanization challenges facing the developing world.

Municipal **waste** management is a crucial service provided by cities around the world, but is often inefficient and underperforming in developing countries. Low income countries face the most acute challenges with solid waste management. In low income countries, cities collect less than half the waste stream. Of this, only about half is processed to minimum acceptable standards. Improper waste management, especially open dumping and open burning, has significant adverse effects on water bodies, air and land resources. People who live near or work with solid waste have increased disease burdens. Unmanaged waste also frequently blocks drainage systems and worsens flooding. Even when collected and transported, waste in dumpsites and landfills contributes to greenhouse gas emissions.

Roughly 2.6 billion people in the developing world are without adequate **sanitation**, and facilities are often overloaded, in disrepair, or unused. Even though the sanitation gap is twice as large as that of water supply, investments in sanitation and hygiene have lagged far behind those in water and other "social" sectors, such as health and education. The main costs of urban sanitation services are those of sewers and sewage treatment. Whereas sewers contribute to public health through reducing everyday contact with sewage (especially by children), wastewater treatment is designed largely to meet ecological objectives and not those of public health. Urban utilities, by and large, are not well designed or staffed to address off-network solutions for water supply or sanitation, yet those solutions are likely to be the most important first steps of progress in environmental health for many of the urban poor.

Experience suggests that demand for car ownership increases dramatically at annual household incomes of $6,000–$8,000. If history repeats itself, an additional 2.3 billion cars will be added by 2050, mostly in developing countries, given expected economic growth and past patterns of motorization. For instance, in the six largest cities in India, the population doubled between 1981 and 2001, but the number of motor vehicles increased eight times over the same period. Between 2000 and 2013, car ownership in China increased more than six times. Similar trends are seen in other fast growing economies. Increased income levels and the availability of cheaper personal vehicles, coupled with increased travel distances and inadequate public transport systems, have made the personal motorcar an increasingly attractive travel option. The associated health costs are high—in Beijing, the health costs from local **air pollution** are estimated at $3.5 billion annually. In Pakistan, more than 22,600 adult deaths were attributable to urban ambient air pollution in 2005 where air pollution alone causes more than 80,000 hospital admissions per year, nearly 8,000 cases of chronic bronchitis, and almost 5 million cases of lower respiratory cases among children under five.

Slum cities refer to the development on the outskirts of cities of unplanned shantytowns or squats with no access to clean water, sanitation, or other municipal services. These slums exist largely outside the rule of law and have become centres for child labour, prostitution, criminal activities, and struggles between gangs and paramilitary forces for control. Mike Davis (2006) estimates that there are 200,000 slum cities worldwide including Quarantina in Beirut, the Favéla in Rio de Janeiro, the "City of the Dead" in Cairo, and Santa Cruz Meyehualco in Mexico City. He notes that while slum residents constitute only 6 percent of the urban population in developed countries, they constitute 78.2 percent of city dwellers in semi-peripheral countries. In Davis's analysis, neoliberal restructuring and the Structural Adjustment Programs of the World Bank and the International Monetary Fund (IMF)

are largely responsible for the creation of the informal economy and the withdrawal of the state from urban planning and the provision of services. As a result, slum cities have become the blueprint for urban development in the developing world.

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13.3: The Impacts of Urban Sprawl

Urban sprawl is the extension of low-density residential, commercial, and industrial development into areas beyond a city's boundaries that occurs in an unplanned or uncoordinated manner. It is generally characterized by:

- low-density development that is dispersed and situated on large lots (greater than one acre)
- geographic separation of essential places such as work, home, school, and shopping
- high dependence on automobiles for travel
- increased impervious surface area in watersheds
- habitat fragmentation and degradation

Urban sprawl combines low density and urban area fragmentation, such as in Atlanta, GA (Figure 13.3.1). It also increases the average travel distances for daily trips, and hinders a shift toward less energy-intensive transportation modes.

The sprawling nature of cities is critically important because of the major impacts that are evident in increased energy, land and soil consumption. These impacts threaten both the natural and rural environments, raising greenhouse gas emissions that cause climate change, and elevated air and noise pollution levels which often exceed the agreed human safety limits. Thus, urban sprawl produces many adverse impacts that have direct effects on the quality of life.

	Sprawling City	Compact City
		
Location	Atlanta	Barcelona
Urban Population (million inhabitants)	2.5	2.8
Urban Area (km^2)	4,280	162
Urban Density (pph)	6	173
Energy Consumption Per Capita for Private Transportation (MJoules)	80	9

Figure 13.3.1: A comparison of built-up urban footprints and transportation energy use between a sprawling city (Atlanta, USA) and a compact city (Barcelona, Spain). Despite having similar population sizes, Atlanta's vast geographic area results in a significantly lower urban density and nearly nine times higher per capita transport energy consumption. (Graphic adapted from the World Bank; licensed under CC BY 3.0 IGO).

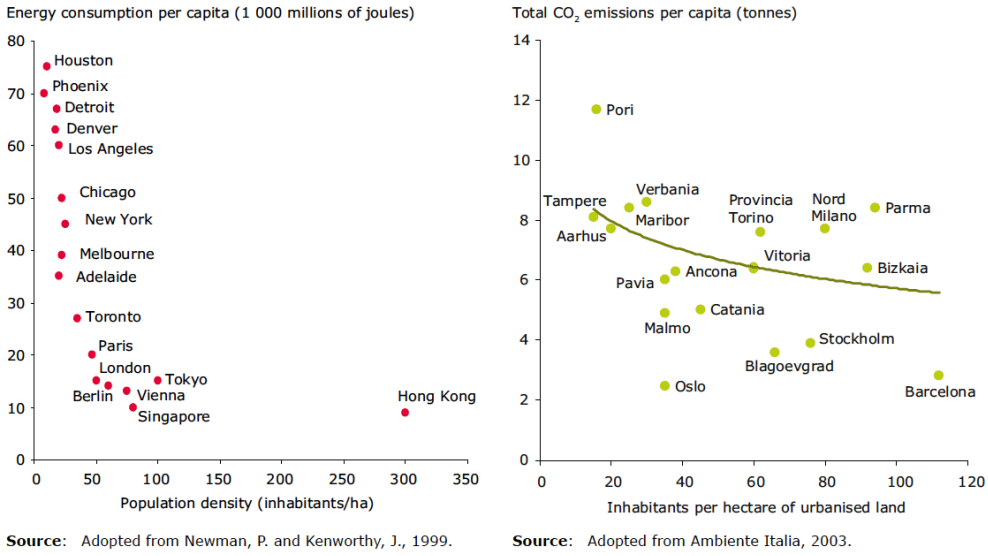
Health

If communities are not walkable or bikeable, people need to drive everywhere, such as to schools, shops, parks, entertainment, and play dates. As a result, we become more sedentary. Residents of sprawling counties are likely to walk less during leisure time and weigh more than residents of compact counties. A sedentary lifestyle increases the risk of overall mortality, cardiovascular disease, and some types of cancer. The effect of low physical fitness is comparable to that of hypertension, high cholesterol and diabetes.

Consumption of Energy

A consequence of the increasing consumption of land and reductions in population densities as cities sprawl is the growing consumption of energy. Generally, compact urban developments with higher population densities are more energy efficient.

Evidence from 17 cities around the world shows a consistent link between population density and energy consumption (Figure 13.3.2). In particular, spread-out low-density cities waste significantly more energy than compact, tightly packed cities.



Source: Adopted from Newman, P. and Kenworthy, J., 1999.

Source: Adopted from Ambiente Italia, 2003.

Figure 13.3.2: The inverse relationship between urban layout and environmental impact. The left panel shows per capita energy consumption against population density for select global cities, while the right panel tracks per capita carbon dioxide (CO_2) emissions relative to localized inhabitants per hectare. (Graphic courtesy of Lumen Learning; data adapted from Newman & Kenworthy, 1999, and Ambiente Italia, 2003; CC BY 4.0).

Transport related energy consumption in cities depends on a variety of factors including the nature of the rail and road networks, the extent of the development of mass transportation systems, and the modal split between public and private transport. Evidence shows that there is a significant increase in travel related energy consumption in cities as densities fall. Essentially, the sprawling city is dominated by relatively energy inefficient car use, as the car is frequently the only practical alternative to more energy efficient, but typically inadequate, relatively and increasingly expensive public transportation systems. Increased transport related energy consumption is in turn leading to an increase in the emission of CO_2 to the atmosphere. Urban sprawl therefore poses significant threats to the commitments to reduce GHG gas emissions.

Air pollution

Using fossil fuels also results in the emission of other gases and particulates that degrade air quality (note that commuters generate emissions of air pollution, which lowers the ambient quality of the air in areas they pass through and causes health problems for other people). Longer transportation distances intensify traffic congestion, resulting in lost productivity, and increase the need for more extensive infrastructure (such as more highways) that negatively impact the environment by increasing the amount of impervious cover and by requiring more natural resources. Finally, traffic congestion and air pollution from driving contribute to an estimated 900,000 fatalities per year worldwide.

Natural and Protected areas

The impacts of sprawl on natural areas are significant. The considerable impact of urban sprawl on natural and protected areas is exacerbated by the increased proximity and accessibility of urban activities to natural areas, imposing stress on ecosystems and species through noise and air pollution. Immediate impacts such as the loss of agricultural and natural land or the fragmentation of forests (Figure 13.3.4), wetlands and other habitats are well known direct and irreversible impacts. Urban land fragmentation, with the disruption of migration corridors for wildlife species, isolates these populations and can reduce natural habitats to such an extent that the minimum area required for the viability of species populations is no longer maintained.



Figure 13.3.4: An aerial perspective of low-density exurban housing, illustrating forest fragmentation as residential tracts and cul-de-sacs are built. (Graphic courtesy of the University of West Florida Pressbooks; CC BY 4.0).

The environmental impacts of sprawl are evident in a number of ecologically sensitive areas located in coastal zones and mountain areas. The Mediterranean coast, one of the world's 34 biodiversity hotspots, is particularly affected, and the increased demand for water for urban use, competes with irrigation water for agricultural land. This problem has been exacerbated by the increased development of golf courses in Spain, where the over-extraction of groundwater has led to salt water intrusion into the groundwater. Increased transit and tourist traffic, particularly day tourism from the big cities, also adds to the exploitation of the mountain areas as a natural resource for 'urban consumption' by the lowland populations.

Rural Environments

The growth of European cities in recent years has primarily occurred on former agricultural land. Typically, urban development and agriculture are competing for the same land, as agricultural lands adjacent to existing urban areas are also ideal for urban expansion. The loss of agricultural land has major impacts on biodiversity with the loss of valuable biotopes for many animals, and particularly birds. Sprawling cities also threaten to consume the best agricultural lands, displacing agricultural activity to both less productive areas (requiring higher inputs of water and fertilisers) and more remote upland locations (with increased risk of soil erosion).

Soil

Urban sprawl and the development of urban land dramatically transform the properties of soil, reducing its capacity to perform its essential functions. These impacts are evident in the extent of compaction of soil leading to impairment of soil functions; loss of water permeability (soil sealing) which dramatically decreases; loss of soil biodiversity, and reductions of the capacity for the soil to act as a carbon sink. In Germany, for example, it is estimated that 52 % of the soil in built-up areas is sealed (or the equivalent of 15 m2 per second over a decade). In addition, rainwater which falls on sealed areas is heavily polluted by tire abrasion, dust and high concentrations of heavy metals, which when washed into rivers degrade the hydrological system.

Water Quality

Increasing numbers of roads and parking lots are needed to support an automobile transportation system, which lead to increased non-point source water pollution and contamination of water supplies (road runoff of oil/gas, metals, nutrients, organic waste, to name a few) with possible impacts on human health. Increased erosion and stream siltation causes environmental damage and may affect water treatment plants and thus affect water quality.

Socio-economic Impacts

From a social perspective urban sprawl generates greater segregation of residential development according to income. Consequently, it can exacerbate urban social and economic divisions. The socio-economic character of suburban and peripheral areas is typified by middle and upper income families with children, who have the necessary mobility and lifestyle to enable them to function effectively in these localities. However, the suburban experience for other groups, including the young and old, who lack mobility and resources can be very different and can reduce social interaction. Furthermore, large segments of urban society are excluded from living in such areas.

From an economic perspective urban sprawl is at the very least a more costly form of urban development due to:

- increased household spending on commuting from home to work over longer and longer distances;
- the cost to business of the congestion in sprawled urban areas with inefficient transportation systems;
- the additional costs of the extension of urban infrastructures including utilities and related services, across the urban region.

Urban sprawl inhibits the development of public transport and solutions based on the development of mass transportation systems, and the provision of alternative choices in transportation that are essential to ensure the efficient working of urban environments. These conclusions are reinforced by experience from both Munich and Stockholm where the efficient control of urban sprawl and resulting increase in population densities fosters the use of public transport and reduces the growth of car use.

Social Capital

On the social sustainability side, we can look at social capital otherwise defined as the “connectedness” of a group built through behaviors such as *social networking* and *civic engagement*, along with attitudes such as trust and reciprocity. Greater social capital has been associated with healthier behaviors, better self-rated health, and less negative results such as heart disease. However, social capital has been diminishing over time. Proposed causes include long commute times, observed in sprawling metropolitan areas. As of 2011, according to an article in the Chicago Tribune, Chicago commuting times are some of the worst – with Chicagoans spending 70 hours per year more on the road than they would if there was no congestion – up from 18 hours in 1982. They have an average commute time of 34 minutes each way. These drivers also use 52 more gallons per year per commuter.

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13.4: The Sustainable City

Sustainability, from science to philosophy to lifestyle, finds expression in the way we shape our cities. Cities are not just a collection of structures, but rather groups of people living different lifestyles together. When we ask if a lifestyle is sustainable, we're asking if it can endure. Some archaeologists posit that environmental imbalance doomed many failed ancient civilizations. What could the sustainable city look like, how would it function, and how can we avoid an imbalance that will lead to the collapse of our material civilization? This module will make some educated guesses based upon the ideas and practices of some of today's bold innovators.

Throughout history settlement patterns have been set by technology and commerce. Civilizations have produced food, clothing and shelter, and accessed foreign markets to purchase and sell goods. Workers traditionally had to live near their place of occupation, although in modern industrial times advanced transportation systems have enabled us to live quite a distance from where we work. In hindsight we can see how reliance on water and horse-drawn transportation shaped historical civilizations and how this equation was radically altered with the rise of the automobile following World War II. While attempting to envision the "Sustainable City" we must discern what factors will influence its shape and form in the future.

Green Urbanism and Sustainable Cities

Green urbanism is a conceptual model that seeks to transform and re-engineer existing city districts and regenerate the post-industrial city centre. **Green urbanism** promotes the development of socially and environmentally sustainable city districts. Figure 13.4.1 offers practical steps in green urbanism on the path to sustainable cities, harmonizing growth and usage of resources.



Figure 13.4.1: The framework of Green Urbanism and the Eco-City concept. The top diagram illustrates the three pillars of Green Urbanism—Energy and Materials, Water and Biodiversity, and Urban Planning and Transport—and emphasizes their interconnected relationship. The bottom diagram maps the decentralized "Eco-City" landscape model, balancing urban areas with the surrounding countryside, farmland, forest, and water ecosystems. (Diagrams adapted from Steffen Lehmann, 2007/2008; ResearchGate).

Principle: Climate and Context

This principle means that sustainable design must be shaped by the local environment. Planners must study the site's unique climate, landscape, and surroundings right from the start. By optimizing building angles and compactness, cities can reduce energy loss and match the existing topography to minimize their environmental footprint. Every site or place has its own unique individual conditions in regard to orientation, solar radiation, rain, humidity, prevailing wind direction, topography, shading, lighting, noise, air pollution and so on. Maintaining complexity in the system is always desirable (be it biodiversity, eco-system or neighborhood layout), and a high degree of complexity is always beneficial for society. Enhancing the opportunities offered by topography and natural setting leads to a city well adapted to the local climate and its eco-system. We can use the buildings'

envelope to filter temperature, humidity, light, wind and noise. Due to the different characteristics of every location, each city district has to come up with its own methods and tailored strategies to reach sustainability and to capture the spirit of the place. Each site or city is different and the drivers for re-engineering existing districts will need to understand how to take full advantage of each location's potential, and how to fine-tune the design concept to take advantage of local circumstances. As an aim, all urban development must be in harmony with the specific characteristics, various site factors and advantages of each location and be appropriate to its societal setting and contexts (cultural, historical, social, geographical, economical, environmental and political). In future, all buildings should have climate-adapted envelope technologies, with facades that are fully climate-responsive.

Principle: Renewable Energy for Zero CO_2 Emissions

This principle focuses on cleaning up our energy supply and using it more efficiently. It requires immediately replacing heavy fossil fuels like coal and oil with renewable power, and using natural gas only as a temporary bridge. Ultimately, it aims to transform city neighborhoods from energy consumers into local green energy producers. In general, a well-balanced combination of energy sources will insure the future supply. As our oil supply will last shorter than the life-expectancy of most buildings, the first selection criteria for deciding on energy generation should look at the local availability of renewable energy sources. Another important goal is to be able to utilize local renewable energy sources via a decentralized distribution system. This will transform city districts into local power stations of renewable energy sources, which can include: solar photovoltaics (PV), solar thermal, wind (on- and off-shore), biomass, geothermal power, mini-hydro energy and other new technologies. Some of the most promising technologies are in building-integrated PV, urban wind turbines, micro combined-heat-and-power plants, and solar cooling. That is to say, there should be on-site electrical generation and energy storage in combination with a smart grid, which integrates local solar and wind generation and utilizes energy-efficiency in all its forms. Solar hot water systems would be compulsory. Co-generation technology utilizes waste heat through combined-heat-and-power plants.

Energy-efficiency programs are not enough. Too often we find that savings from energy-efficiency programs are absorbed by a rise in energy use. Genuine action on climate change means that coal-fired power stations cease to operate and are replaced by renewable energy sources. We will need to operate on renewable energy sources as close to 100 per cent as possible. As a minimum, at least 50 per cent of on-site renewable energy generation should be the aim of all urban planning, where the energy mix comes from decentralized energy generation and takes into account the resources that are locally available, as well as the cost and the availability of the technology. Optimizing the energy balance means arranging an urban area so that energy is shared between buildings (exchange), saved when there is a surplus (storage), and recycled through multiple levels of tasks from high-temperature electricity generation down to low-temperature space heating. This last mechanism for energy-efficiency is known as **exergy** or energy cascading, where the same energy can be reused multiple times as it naturally cools down, stepping it down through different tasks based on temperature requirements (Figure 13.4.2). This minimizes the need to import new, raw energy into the system, and makes it essential that the fossil-fuel powered transportation systems currently supporting our cities are rapidly turned into renewable energy based systems. In office buildings, energy can be conserved through the use of highly effective building insulation, high energy-efficiency standards and the use of smart metering technology. If a part of an office building is not in use, the intelligent building management system will shut down the associated lights and ventilation.

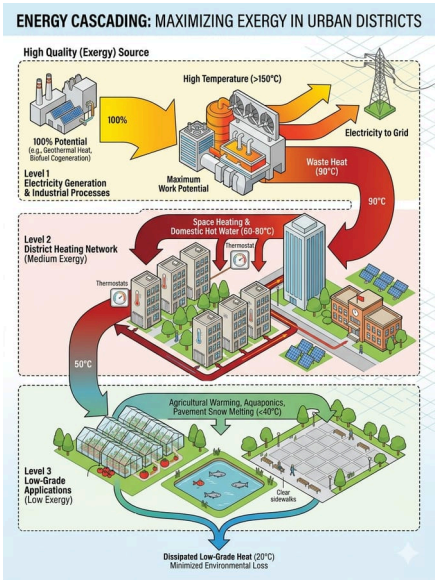


Figure 13.4.2: Exergy: the sequential recycling of energy. High-temperature energy ($> 150^{\circ}\mathrm{C}$) is utilized first for work-intensive processes like electricity generation. The remaining thermal energy is progressively stepped down to meet lower-temperature demands, passing from a residential district heating network (60--$80^{\circ}\mathrm{C}$) down to agricultural and community applications ($< 40^{\circ}\mathrm{C}$), minimizing overall environmental heat loss. (Image generated by using Google Gemini AI, 2026, licensed under CC BY 4.0)

Principle: Zero-Waste

Sustainable waste management means to turn waste into a resource. **Zero-waste urban planning** includes reducing, recycling, reusing and composting waste to produce energy. All material flows need to be examined and fully understood, and special attention needs to be given to industrial waste and e-waste treatment. To maximize this principle we would eliminate the concept of waste and land-fills, and enable recycling centers. **Eco-districts** would be formed from neighborhoods that reuse and recycle materials and significantly reduce the volume of solid waste and toxic chemical releases. All construction materials as well as the production of goods (and building components) would be healthy and fully-recyclable.

Waste prevention is always better than treating or cleaning-up waste. Additional systems can help with this. One system would focus on routine remanufacturing of metals, glass, plastics, and paper - without down-grading the product. Another is **waste-to-energy** strategies for residual waste. For all products, an `extended producer responsibility' clause would cause the waste-prevention and recycling obligations to be shared by both the manufacturer and consumer. A growing challenge for sustainable development is the ability to lessen agriculture's impact on the global nitrogen cycle. Efforts that work towards this include developing improved fertilization technologies, and technologies in capturing and recycling waste. Essentially, we need to again become a recycling society, and strive towards a goal of recycling and composting all of our waste.

Principle: Water Conservation

The various aspects of this principle include: reducing water consumption, finding more efficient uses for water resources, ensuring good water quality and the protection of aquatic habitats. The city can be used as a water catchment area by educating the population in water efficiency, promoting rainwater collection (Figure 13.4.3) and using wastewater recycling and storm water harvesting techniques. Storm water and flood management concepts that can be adopted as part of the urban design includes: storm water run-offs, improved drainage systems and the treatment of wastewater.

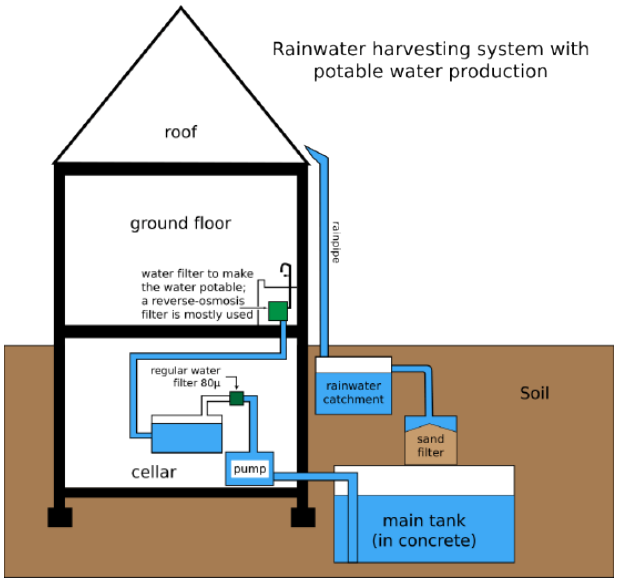
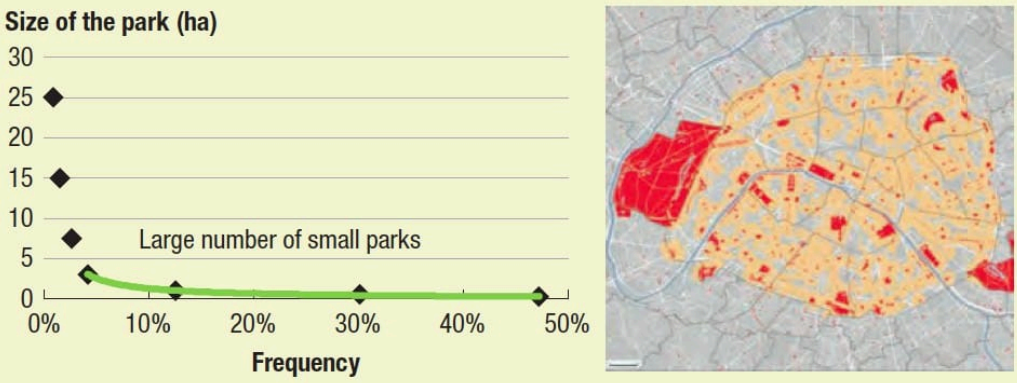


Figure 13.4.3: Residential rainwater harvesting system with potable purification, and domestic rainwater reclamation. Runoff travels from the roof catchment area down into a primary filtration sequence consisting of an external rainwater catchment box and an underground sand filter. The pre-filtered water is held in a secure concrete main tank before being pumped into the cellar for fine particle filtration (80μ) and a final reverse-osmosis stage on the ground floor to ensure portability. *(Image by Adityamail, available via Wikimedia Commons, licensed under CC BY 3.0).*

The eco-district's efforts in adequate and affordable health care provisions will need to ensure the supply of safe water and sanitation. This includes such things as algae and bio-filtration systems for recycling grey water. **Grey water** is domestic wastewater (households, office buildings) that lacks substantial fecal contamination; Sources include sinks, showers, baths, washing machines and dishwashers. Black water is domestic wastewater containing feces. An integrated urban water cycle planning and management system that includes a high-performance infrastructure for sewage recycling (grey and black water recycling), storm water retention and harvesting the substantial run-off through storage, must be a routine in all design projects. On a household level we need to collect rain water and use it sparingly for washing and install dual-water systems and low-flush toilets. On a food production level we need to investigate the development of crops that need less water and are more drought resistant.

Principle: Landscape Biodiversity, Urban Gardening and Agriculture

Green spaces are an essential feature of energy efficient and livable cities. A sustainable city takes pride in its many beautiful parks and public gardens. This pride is best formed through a strong focus on local biodiversity, habitat and ecology, wildlife rehabilitation, forest conservation and the protecting of regional characteristics. A city that plans its natural landscapes and increases its urban vegetation based on ecological principles will help in stopping the loss of biodiversity. Ready access to these green spaces are essential components of a healthy city, including: public parks, gardens, and opportunities for leisure and recreation. Although many urban green space policies are based on a predetermined percentage of green space, what really matters is access and proximity to these green spaces with diversified social activities. In Paris, France, they have approached this problem with policies and regulations that ensure that every citizen lives less than 400 m from a public park, square, or garden. This target has been reached whereas green spaces only represent 5 percent of the urban area (Figure 13.4.4). There are a few large parks that allow a wide range of activities for residents, and a large number of very successful pocket parks for daily family activities and intergenerational mix. In comparison, green spaces in Beijing, China, represent 30 percent of the urban area. However, most of the green spaces are very big parks. As a result, on average residents live more than 3 km away from public parks. A city that preserves and maximizes its open spaces, natural landscapes and recreational opportunities is a more healthy and resilient city.



Left: Long tail distribution of parks in Paris, with the long tail of small parks in green.
Right: Numerous small parks in Paris ensure 5 minute walk accessibility to parks (red) to 80% of the people.

Figure 13.4.4: Spatial distribution and walkability of parks in Paris, France. The urban landscape is dominated by a large frequency of small pocket parks under five hectares. The corresponding geographic mapping (right) visualizes 5-minute walking catchments in red, and shows how a dense, decentralized network of small green spaces ensures walk accessibility for 80% of the urban population. (Image adapted from standard urban planning open data; available for educational redistribution under LibreTexts open-access repository terms).

Sustainable cities will also have inner-city gardens, **urban farming** and **green roofs** in all its urban design projects (Figure 13.4.5). In this manner the urban plan will maximize the use of the city for the resident's food supply. This will maximize the resilience of the eco-system by using plants for air-purification and urban cooling, and will mitigate the increased heat of urban landscapes. The **urban heat island effect** (UHI) is a meteorological and climatological phenomenon in which urban areas experience significantly warmer temperatures than surrounding rural areas. The UHI can be lowered further by narrowing roads and using extra space for planting trees. Increasing the number of urban trees can help in lowering UHI through transpiration, and in mitigating the human impact of the global carbon cycle through CO_2 use in photosynthesis. A city's efforts in promoting natural resources for the health of its residents can be helped by increasing the percentage of green spaces on city land, and increasing the population density.



Figure 13.4.5: Urban Farming in Chicago, IL. Rows of crops grow in a dense urban neighborhood demonstrate how underutilized city spaces can be repurposed for sustainable food production. *(Image adapted from Linda N., available via Wikimedia Commons, licensed under CC BY 2.0).*

The local food and short supply chains that come about as a result of urban farming and agriculture will support green urbanism.

A sustainable city will support through its design: eat-local food initiatives, decreased petrol-based transport, composting kitchen scraps and garden clippings, re-using bags and glass containers, and paper recycling or disuse. Decreasing our meat and animal product consumption will also: decrease our dependence on oil-based fertilizers, decrease our production of greenhouse gasses and electrical needs. A sustainable city will bridge the urban-rural disconnect and move cities towards models that deal in natural eco-systems and healthy food systems.

Principle: Public Transport and the Sustainable Commute

Access to basic public transport services and reducing the need to travel both help to reduce automobile dependency and are critical to green urbanism. It is a fact that more and wider roads result in increased fossil-fuel based traffic and CO_2 emissions. A sustainable city will integrate non-motorized transport such as cycling and walking. It can build pedestrian and bicycle friendly environments by providing safe bicycle ways, free rental bike schemes, and compelling public spaces and routes. A sustainable city would also optimize transportation that makes inter-connections of public transport and the integration of private and public transport systems. Some ways to do this include: eco-mobility concepts and smart infrastructure (electric vehicles); integrated transport systems (bus transit, light railway, bike stations); improved public space networks and connectivity, and a focus on transport-oriented development.

Principle: Density and Retrofitting of Existing Districts

The various aspects of this principle include: encouraging the densification of the city centre through mixed-use urban infill, centre regeneration and green transit-oriented development (TOD); increasing sustainability through density and compactness; promoting business opportunities around green transit-oriented developments; optimizing the relationship between urban planning and transport systems; retrofitting inefficient building stock and systematically reducing the city district's carbon footprint.

Consideration will need to be given to better land-use planning to reduce the impact of urban areas on agricultural land and landscape; to increasing urban resilience by transforming city districts into more compact communities and designing flexible typologies for inner-city living and working. Special strategies for large metropolitan areas and fast-growing cities are required. Strategies specific to smaller areas will also benefit small and medium-sized towns, coastal cities, and small island states. Adaptive reuse of existing buildings can also help in urban renewal efforts to bring people back to the city. To bring about diverse and vibrant communities in existing city centers requires people to move back into downtown areas. This can be achieved through mixed-use urban infill projects, by converting low density districts into higher density communities; and by revitalizing underutilized land for community benefit and affordable housing.

Principle: Green Buildings and Districts Using Passive Solar Design Principles.

The various aspects of this principle include: low-energy, zero-emission designs, applying best practice for **passive solar design principles** (Figure below), for all buildings and groups of buildings; dramatically reducing building energy use; introducing compact solar architecture; and renovating and retrofitting the entire building stock. New design typologies need to be developed at low cost, and we need to produce functionally neutral buildings that last longer.

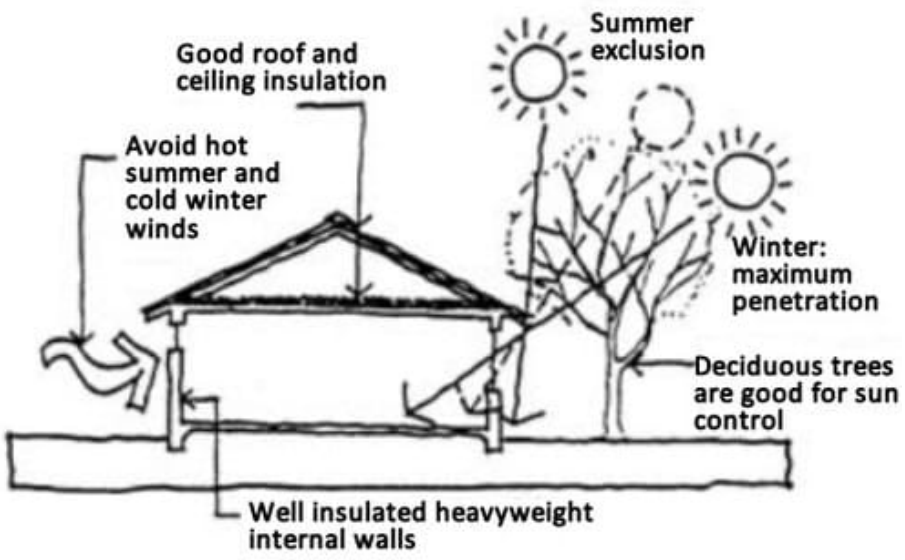


Figure 13.4.6: Passive Solar Design

We need to apply facade technology with responsive building skins for bio-climatic architecture, to take advantage of cooling breezes and natural cross-ventilation, maximizing cross-ventilation, day-lighting and opportunities for night-flush cooling; we need to focus on the low consumption of resources and materials, including the reuse of building elements and design for disassembly. Other ideas include: mixed-use concepts for compact housing typologies; adaptive reuse projects that rejuvenate mature estates; solar architecture that optimizes solar gain in winter and sun shading technology for summer, catching the low winter sun and avoiding too much heat gain in summer. It is important to renew the city with energy-efficient green architecture, creating more flexible buildings of long-term value and longevity. Flexibility in plan leads to a longer life for buildings. Technical systems and services have a shorter life-cycle. This means, first of all, applying technical aids sparingly and making the most of all passive means provided by the building fabric and natural conditions. Buildings that generate more energy than they consume, and collect and purify their own water, are totally achievable. We need to acknowledge that the city as a whole is more important than any individual building.

Principle: Local and Sustainable Materials with Lower Energy Production Needs

The various aspects of this principle include: advanced materials technologies, using opportunities for shorter supply chains, using local materials and technological know-how. Affordable housing can be achieved through modular prefabrication. **Prefabrication** (Figure below) has come and gone several times, but modern architecture has shifted more of its focus to sustainability. In 2010, a prototype AQUA house for low-income families was exhibited in São Paulo, measuring 40 m^2 and a construction cost of R$45,000 (11,000 USD). The design integrates several eco-efficiency strategies, including modular soil-cement bricks assembled without mortar, fiber-cellulose roofing shingles, a solar hot water heater, a localized rainwater catchment cistern, a sloped roof with skylights was designed to take advantage of natural light and ventilation, and a vertical bio-filter green wall. The interior of the house also includes environmentally friendly products such as cement board made from mineralized wood, which does not require finishing, and the use of recycled Tetra Pak packaging on some walls. The house has a dual-flush toilet, which reduces water usage, and fluorescent light bulbs. The construction of the Casa AQUA takes between 30-60 days to complete.

A successful sustainable city will benefit from: increased support for sustainable production and consumption, process-integrated technologies that lead to waste reduction, and the use of environmentally friendly lightweight structures that rely on local materials with lower energy production needs. It will also benefit from supporting research into: new materials and technological innovation; using fewer types of materials in a product to make it easier to recycle; and the possibility of reusing entire building components. Success in this area will increase the long-term durability of buildings, reduce waste and minimize packaging.



Figure 13.4.7: The Casa Aqua Sustainable Housing Prototype. Exhibited in São Paulo, this 40-square-meter low-income housing model showcases modular, low-impact urban architecture. The structure features a modern sloped roof made of corrugated fiber-cellulose shingles, supported by a warm wooden framing system. A lush green wall row of hanging plants lines the upper edge of the building's facade. The exterior walls are built from light-colored soil-cement bricks, with dark wooden planter pots housing tall leafy plants positioned along the entryway walkway. A prominent black solar water heating panel or integrated photovoltaic element is mounted vertically on the left exterior wall corner. (Image courtesy of the Fundação Vanzolini, via Lumen Learning)

Cultural Heritages, Identity and Sense of Place

All sustainable cities aim for air quality, health and pollution reduction, to foster resilient communities, to have strong public space networks and modern community facilities. This is the nature of sustainable cities. However, each city has its own distinct environment, whether it be by the sea, a river, in a dessert, a mountain; whether its climate is tropical, arid, temperate, etc, each situation is unique. The design of the city will take all these factors into consideration, including materials, history and population desires. The essence of place is the up-swelling of grassroots strategies, the protection of its built heritage and the maintenance of a distinct cultural identity, e.g. by promoting locally owned businesses, supporting creativity and cultural development. New ideas require affordable and flexible studio space in historic buildings and warehouses. Cities will grow according to the details and unique qualities of localities, demographic qualities of the populace and the creativity of the authorities and citizens. The aim of a city is to support the health, the activities and the safety of its residents. It is, therefore, incumbent on city councils to protect the city by developing a master plan that balances heritage with conservation and development; fostering distinctive places with a strong sense of place, where densities are high enough to support basic public transit and walk-to retail services.

Principle: Urban Governance, Leadership and Best Practice

Good urban governance is extremely important if we want to transform existing cities into sustainable compact communities. It has to provide efficient public transport, good public space and affordable housing, high standards of urban management, and without political support change will not happen. City councils need strong management and political support for their urban visions to be realized. They need strong support for a strategic direction in order to manage sustainability through coherent combined management and governance approaches, which include evolutionary and adaptive policies linked to a balanced process of review, and to public authorities overcoming their own unsustainable consumption practices and changing their methods of urban decision-making. A city that leads and designs holistically, that implements change harmoniously, and where decision-making and responsibility is shared with the empowered citizenry, is a city that is on the road to sustainable practices. In balancing community needs with development, public consultation exercises and grassroots participation are essential to ensuring people-sensitive urban design and to encouraging community participation. Citizens need to participate in community actions aimed at governments and big corporations, by writing letters and attending city-council hearings. Empowering and enabling people to be actively involved in shaping their community and urban environment is one of the hallmarks of a democracy. Cities are a collective responsibility. As far as bureaucratic urban governance and best practice is concerned, authorities could consider many of the following: updating building code and regulations; creating a database of best practice and worldwide policies for eco-cities; revising contracts for construction projects and integrated public management; raising public awareness; improving planning participation and policy-making; creating sustainable subdivisions, implementing anti-sprawl land-use and growth boundary policies; legislating for controls in density and supporting high-quality densification; arriving at a political decision to adopt the Principles of Green Urbanism, based on an integrated Action Plan; measures to finance a low-to-no-carbon pathway; implementing environmental emergency management; introducing a program of incentives, subsidies and tax exemptions for sustainable projects that foster green jobs; eliminating fossil-fuel subsidies; developing mechanisms for incentives to accelerate renewable energy take-up; implementing integrated land-use planning; having a sustainability assessment and certification of urban development projects.

Principle: Education, Research and Knowledge

The various aspects of this principle include: technical training and up-skilling, communication and knowledge dissemination, and research into ecological city theory and sustainable design. These efforts would be aided through the development of primary and secondary programs in waste recycling, water efficiency and sustainable behavior, and increased avenues to obtaining green jobs.

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13.5: Environmental Economics

Environmental and natural resource economists study the tradeoffs associated with one of the most important scarce resources we have—nature. Economists mean something very specific when they use the word **efficient**. In general, an allocation is efficient if it maximizes social well-being, or **welfare**. Traditional economics defines welfare as total net benefits—the difference between the total benefits all people in society get from market goods and services and the total costs of producing those things. Environmental economists enhance the definition of welfare. The values of environmental goods like wildlife count on the "benefit" side of net benefits and damages to environmental quality from production and consumptive processes count as costs.

Under ideal circumstances, market outcomes are efficient. In perfect markets for regular goods, goods are produced at the point where the cost to society of producing the last unit, **the marginal cost**, is just equal to the amount a consumer is willing to pay for that last unit, the **marginal benefit**, which means that the net benefits in the market are maximized. Regular goods are supplied by industry such that supply is equivalent to the marginal production costs to the firms, and they are demanded by consumers in such a way that we can read the marginal benefit to consumers off the demand curve; when the market equilibrates at a price that causes quantity demanded to equal quantity supplied at that price, it is also true that marginal benefit equals marginal cost.

Even non-renewable resources such as oil would be used efficiently by a well-functioning market. It is socially efficient to use a non-renewable resource over time such that the price rises at the same rate as the rate of interest. Increasing scarcity pushes the price up, which stimulates efforts to use less of the resource and to invest in research to make "backstop" alternatives more cost-effective. Eventually, the cost of the resource rises to the point where the backstop technology is competitive, and the market switches from the non-renewable resource to the backstop. We see this with copper; high prices of non-renewable copper trigger substitution to other materials, like fiber optics for telephone cables and plastics for pipes. We would surely see the same thing happen with fossil fuels; if prices are allowed to rise with scarcity, firms have more incentives to engage in research that lowers the cost of backstop technologies like solar and wind power, and we will eventually just switch. Unfortunately, many conditions can lead to **market failure** such that the market outcome does not maximize social welfare. The extent to which net benefits fall short of their potential is called **deadweight loss**. Deadweight loss can exist when not enough of a good is produced, or too much of a good is produced, or production is not done in the most cost-effective (least expensive) way possible, where costs include environmental damages. Some types of market failures (and thus deadweight loss) are extremely common in environmental settings.

Externalities

In a market economy, people and companies make choices to balance the costs and benefits that accrue to them. These side effects can be seen as ways in which the actions of a producer impact the well being of a bystander. The market fails to allocate adequate resources to address such side effects because it is only concerned with buyers and sellers, not with the well-being of the environment. When this is true economists say there are externalities, and individual actions do not typically yield efficient outcomes. A **negative externality** is a cost associated with an action that is not borne by the person who chooses to take that action.

When external costs occur, a company's private production cost and the social cost of production are at odds. The firm does not consider the cost of pollution cleanup to be relevant, while society does. The social costs of production include the negative effects of pollution and the cost of treatment. As a result, the social costs end up exceeding the private production costs. When external pollution and treatment costs are included in the production cost of the product, the supply curve intersects the demand curve at a higher price point. As a result of the higher price there will be less demand for the product and less pollution produced.

For example, exhaust pollutants from automobiles adversely affect the health and welfare of the human population. However, oil companies consider their cost of producing gasoline to include only their exploration and production costs. Therefore, any measures to reduce exhaust pollutants represent an external cost. The government tries to help reduce the problem of exhaust pollutants by setting emissions and fuel-efficiency standards for automobiles. It also collects a gasoline tax that increases the final price of gasoline, which may encourage people to drive less. Sometimes, pollution results from the production process because no property rights are involved. For example, if a paper manufacturer dumps waste in a privately owned pond, the landowner generally takes legal action against the paper firm, claiming compensation for a specific loss in property value caused by the industrial pollution. In contrast, the air and most waterways are not owned by individuals or businesses, but instead are considered to be public goods. Because no property rights are involved the generation of pollution does not affect supply and demand.

Firms have an incentive to use public goods in the production process because doing so does not cost anything. If the paper manufacturer can minimize production costs by dumping wastes for free into the local river then it will do so. The consequences of this pollution include adverse impacts on the fish and animal populations that depend on the water, degradation of the surrounding environment, decrease in the quality of water used in recreation and business, human health problems and the need for extensive treatment of drinking water by downstream communities. An important role of the government is to protect public goods, especially those with multiple uses, from pollution by companies seeking to minimize company costs and to maximize profits. People desire clean water for recreation and drinking, and the government must act to protect the broad interests of society from the narrow profit-driven focus of companies.

Other example of negative externalities in environmental settings include:

- Companies that spill oil into the ocean do not bear the full costs of the resulting harm to the marine environment, which include everything from degraded commercial fisheries to reduced endangered sea turtle populations).
- Commuters generate emissions of air pollution, which lowers the ambient quality of the air in areas they pass through and causes health problems for other people.
- Developers who build houses in bucolic exurban settings cause habitat fragmentation and biodiversity loss, inflicting a cost on the public at large.

A **positive externality** is a benefit associated with an action that is not borne by the person who chooses to take that action. Positive externalities exist in the world of actions and products that affect the environment including:

- A homeowner who installs a rain barrel to collect unchlorinated rainwater for her garden also improves stream habitat in her watershed by reducing stormwater runoff.
- A delivery company that re-optimizes its routing system to cut fuel costs also improves local air quality by cutting its vehicle air pollution emissions.
- A farmer who plants winter cover crops to increase the productivity of his soil will also improve water quality in local streams by reducing erosion.

Public Goods and Common-Pool Resources

Market outcomes are almost never efficient in two broad kinds of cases: public goods and common-pool resources. The market failures in these settings are related to the problems we saw with externalities. A pure public good is defined as being nonexclusive and nonrival in consumption. If something is nonexclusive, people cannot be prevented from enjoying its benefits. A private house is exclusive because doors, windows, and an alarm system can be used to keep nonowners out. A lighthouse, on the other hand, is non-exclusive because ships at sea cannot be prevented from seeing its light. A good that is nonrival in consumption has a marginal benefit that does not decline with the number of people who consume it. A sandwich is completely rival in consumption: if I eat it, you cannot. On the other hand, the beauty of a fireworks display is completely unaffected by the number of people who look at it. Some elements of the environment are pure public goods: Clean air in a city provides health benefits to everyone, and people cannot be prevented from breathing.

The efficient amount of a public good is still where social marginal benefit equals the marginal cost of provision. However, the social marginal benefit of one unit of a public good is often very large because many people in society can benefit from that unit simultaneously. One lighthouse prevents all the ships in an area from running aground in a storm. In contrast, the social marginal benefit of a sandwich is just the marginal benefit gained by the one person who gets to eat it. Society could figure out the efficient amount of a public good to provide—say, how much to spend on cleaner cars that reduce air pollution in a city. Unfortunately, private individuals acting on their own are unlikely to provide the efficient amount of the public good because of the free rider problem. If my neighbors reduce pollution by buying clean electric cars or commuting via train, I can benefit from that cleaner air; thus, I might try to avoid doing anything costly myself in hopes that everyone else will clean the air for me. Evidence suggests that people do not behave entirely like free riders – they contribute voluntarily to environmental groups and public radio stations. However, the levels of public-good provision generated by a free market are lower than would be efficient. The ozone layer is too thin; the air is too dirty. Public goods have big multilateral positive externality problems.

In contrast, a common-pool resource (also sometimes called an open-access resource) suffers from big multilateral negative externality problems. This situation is sometimes called the "**tragedy of the commons**." Like public goods, common-pool resources are non-excludable. However, they are highly rival in use. Many natural resources have common-pool features: Water in a river can be removed by anyone near it for irrigation, drinking, or industrial use; the more water one set of users removes, the less water there is available for others. Swordfish in the ocean can be caught by anyone with the right boat and gear, and the more fish are caught by one fleet of boats, the fewer remain for other fishers to catch. Old growth timber in a developing country

can be cut down by many people, and slow re-growth means that the more timber one person cuts the less there is available for others. One person's use of a common-pool resource has negative effects on all the other users. Thus, these resources are prone to overexploitation. One person in Indonesia might want to try to harvest tropical hardwood timber slowly and sustainably, but the trees they forebear from cutting today might be cut down by someone else tomorrow. The difficulty of managing common-pool resources is evident around the world in rapid rates of tropical deforestation, dangerous over-harvesting of fisheries, and battles fought over mighty rivers that have been reduced to dirty trickles. The tragedy of the commons occurs most often when the value of the resource is great, the number of users is large, and the users do not have social ties to one another, but common-pool resources are not always abused.

Incentive Policies

Incentive policies try to make use of market forces for what they do best—allocating resources cost-effectively within an economy—while correcting the market failures associated with externalities, public goods, and common pool resources.

Taxing Pollution

One way to "internalize" some of the external costs of pollution is for the government to tax pollution. A pollution tax would require that polluting firms pay a tax based on the air, water and land pollution that they generate. This tax would raise the private production cost of a company to include to the social cost of production. In addition, the generated tax revenues could be used by the government to help mitigate the effects of pollution. Thus, if we think the social cost of ton of carbon dioxide (because of its contribution to climate change) is $20, then we could charge a tax of $20 per ton of carbon dioxide emitted. The easiest way to do this would be to have a tax on fossil fuels according to the amount of carbon dioxide that will be emitted when they are burned.

If a price is placed on carbon dioxide, all agents would have an incentive to reduce their carbon dioxide emissions to the point where the cost to them of reducing one more unit (their marginal abatement cost) is equal to the per unit tax. Therefore, several good things happen. All carbon dioxide sources are abating to the same marginal abatement cost, so the total abatement is accomplished in the most cost-effective way possible. Furthermore, total emissions in the economy overall will go down to the socially efficient level. Firms and individuals have very broad incentives to change things to reduce carbon dioxide emissions—reduce output and consumption, increase energy efficiency, switch to low carbon fuels—and strong incentives to figure out how to innovate so those changes are less costly. Finally, the government could use the revenue it collects from the tax to correct any inequities in the distribution of the program's cost among people in the economy or to reduce other taxes on things like income.

While taxes on externality-generating activities have many good features, they also have several drawbacks and limitations. First, while an externality tax can yield the efficient outcome (where costs and benefits are balanced for the economy as a whole), that only happens if policy makers know enough about the value of the externality to set the tax at the right level. If the tax is too low, we will have too much of the harmful activity; if the tax is too high, the activity will be excessively suppressed. Second, even if we are able to design a perfect externality tax in theory, such a policy can be difficult to enforce. The enforcement agency needs to be able to measure the total quantity of the thing being taxed. In some cases that is easy—in the case of carbon dioxide for example, the particular fixed link between carbon dioxide emissions and quantities of fossil fuels burned means that through the easy task of measuring fossil fuel consumption we can measure the vast majority of carbon dioxide emissions. However, many externality-causing activities or materials are difficult to measure in total. Nitrogen pollution flows into streams as a result of fertilizer applications on suburban lawns, but it is impossible actually to measure the total flow of nitrogen from a single lawn over the course of a year so that one could tax the homeowner for that flow. Third, externality taxes face strong political opposition from companies and individuals who don't want to pay the tax. Even if the government uses the tax revenues to do good things or to reduce other tax rates, the group that disproportionately pays the tax has an incentive to lobby heavily against such a policy. This phenomenon is at least partly responsible for the fact that there are no examples of pollution taxes in the U.S. Instead, U.S. policy makers have implemented mirror-image subsidy policies, giving subsidies for activities that reduce negative externalities rather than taxing activities that cause those externalities.

Tradable Permits

Another major type of incentive policy is a tradable permits scheme. Tradable permits are actually very similar to externality taxes, but they can have important differences. These policies are colloquially known as "cap and trade". If we know the efficient amount of the activity to have (e.g., number of tons of pollution, amount of timber to be logged) the policy maker can set a cap

on the total amount of the activity equal to the efficient amount. Permits are created such that each permit grants the holder permission for one unit of the activity. The government distributes these permits to the affected individuals or firms, and gives them permission to sell (trade) them to one another. In order to be in compliance with the policy (and avoid punishment, such as heavy fines) all agents must hold enough permits to cover their total activity for the time period. The government doesn't set a price for the activity in question, but the permit market yields a price for the permits that gives all the market participants strong incentives to reduce their externality-generating activities, to make cost-effective trades with other participants, and to innovate to find cheaper ways to be in compliance. Tradable permit policies have been used in several environmental and natural resource policies. The European Union used a tradable permit market as part of its policy to reduce carbon dioxide emissions under the Kyoto protocol. Individual tradable quotas for fish in fisheries of Alaska and New Zealand have been used to rationalize fishing activity and keep total catches down to efficient and sustainable levels. Economists do think differently about costs than engineers or other physical scientists, and several key insights about the economics of cost evaluation are important for policy analysis. Viewed through an inverse lens, all these ideas are important for benefit estimation as well.

Discounting and Cost Benefit Analysis

Economists have developed a tool for comparing net benefits at different points in time called **discounting**. Discounting converts a quantity of money received at some point in the future into a quantity that can be directly compared to money received today, controlling for the time preference. A particular cost or benefit is worth less in present value terms the farther into the future it accrues and the higher the value of the discount rate. These fundamental features of discounting create controversy over the use of discounting because they make projects to deal with long-term environmental problems seem unappealing. The most pressing example of such controversy swirls around analysis of climate-change policy. Climate-change mitigation policies typically incur immediate economic costs (e.g. switching from fossil fuels to more expensive forms of energy) to prevent environmental damages from climate change several decades in the future. Discounting lowers the present value of the future improved environment while leaving the present value of current costs largely unchanged. **Cost-benefit analysis** is just that: analysis of the costs and benefits of a proposed policy or project. To carry out a cost-benefit analysis, one carefully specifies the change to be evaluated, measures the costs and benefits of that change for all years that will be affected by the change, finds the totals of the presented discounted values of those costs and benefits, and compares them. Some studies look at the difference between the benefits and the costs (the net present value), while others look at the ratio of benefits to costs. A “good” project is one with a net present value greater than zero and a benefit/cost ratio greater than one. The result of a cost-benefit analysis depends on a large number of choices and assumptions. What discount rate is assumed? What is the status quo counterfactual against which the policy is evaluated? How are the physical effects of the policy being modeled? Which costs and benefits are included in the analysis—are non-use benefits left out? Good cost-benefit analyses should make all their assumptions clear and transparent.

Cost-benefit analysis gives us a rough sense of whether or not a project is a good idea. However, it has many limitations. Here we discuss several other measures of whether a project is desirable. Economists use all these criteria and more when evaluating whether a policy is the right approach for solving a problem with externalities, public goods, and common-pool resources.

Efficiency

A policy is efficient if it maximizes the net benefits society could get from an action of that kind. Such efficiency will occur when the marginal benefits of the policy are equal to its marginal costs. Sometimes a cost-benefit analysis will try to estimate the total costs and benefits for several policies with different degrees of stringency to try to see if one is better than the others. However, only information about the marginal benefit and marginal cost curves will ensure that the analyst has found the efficient policy. Unfortunately, such information is often very hard to find or estimate.

Cost Effectiveness

It can be particularly difficult to estimate the benefits of environmental policy, and benefit estimates are necessary for finding efficient policies. Sometimes policy goals are just set through political processes—reducing sulfur dioxide emissions by 10 million tons below 1980 levels in the Clean Air Act acid rain provisions, cutting carbon dioxide emissions by 5% from 1990 levels in the Kyoto protocol—without being able to know whether those targets are efficient. However, we can still evaluate whether a policy will be cost effective and achieve its goal in the least expensive way possible. For example, for total pollution reduction to be distributed cost-effectively between all the sources that contribute pollution to an area (e.g. a lake or an urban airshed), it must be true that each of the sources is cleaning up such that they all face the same marginal costs of further abatement. If one source had a high marginal cost and another’s marginal cost was very low, total cost could be reduced by switching some of the cleanup from the first source to the second.

Incentives to Innovate

At any one point in time, the cost of pollution control or resource recovery depends on the current state of technology and knowledge. For example, the cost of reducing carbon dioxide emissions from fossil fuels depends in part on how expensive solar and wind power are, and the cost of wetland restoration depends on how quickly ecologists are able to get new wetland plants to be established. Everyone in society benefits if those technologies improve and the marginal cost of any given level of environmental stewardship declines. Thus, economists think a lot about which kinds of policies do the best job of giving people incentives to develop cheaper ways to clean and steward the environment.

Fairness

A project can have very high aggregate net benefits, but distribute the costs and benefits very unevenly within society. We may have both ethical and practical reasons not to want a policy that is highly unfair. Some people have strong moral or philosophical preferences for policies that are equitable. In addition, if the costs of a policy are borne disproportionately by a single group of people or firms, that group is likely to fight against it in the political process. Simple cost-benefit analyses do not speak to issues of equity. However, it is common for policy analyses to break total costs and benefits down among subgroups to see if uneven patterns exist in their distribution. Studies can break down policy effects by income category to see if a policy helps or hurts people disproportionately depending on whether they are wealthy or poor. Other analyses carry out regional analyses of policy effects. For example, climate-change mitigation policy increases costs disproportionately for poor households because of patterns in energy consumption across income groups. Furthermore, the benefits and costs of such policy are not uniform across space in the U.S. The benefits of reducing the severity of climate change will accrue largely to those areas that would be hurt most by global warming (coastal states hit by sea level rise and more hurricanes, Western states hit by severe water shortages) while the costs will fall most heavily on regions of the country with economies dependent on sales of oil and coal.

Some of our evaluative criteria are closely related to each other; a policy cannot be efficient if it is not cost-effective. However, other criteria have nothing to do with each other; a policy can be efficient but not equitable, and vice versa. Cost-benefit analyses provide crude litmus tests—we surely do not want to adopt policies that have costs exceeding their benefits. However, good policy development and evaluation considers a broader array of criteria.

Gross National Product and Its Alternatives

Most countries strive to increase their capacities to produce goods and services and consider doing so as a positive sign of development. Economic growth is stimulated by population growth, which in turn increases the consumption of natural resources and increases the per capita consumption of goods and services. Various indicators are used to measure economic growth. One of them is the Gross National Product (GNP), which represents the total market value of final goods and services produced by a country during a given period (usually one year). Unfortunately, GNP does not take into account the global nature of many companies. If a company produces goods in a foreign country, then the "home" country does not really benefit from that production. Thus, if Pepsi bottles and sells soda in Japan, those revenues should not be included in the GNP of the United States. The GDP (Gross Domestic Product) provides a better indicator of the health of a country's economy. This measure refers to the value of the goods and services produced within the boundaries of an economy during a given period of time.

Both the GNP and Gross Domestic Product (GDP) are economic measures and indicate nothing about social or environmental conditions within a country. They are not measures of the quality of life. In fact, severe environmental problems can actually raise the GNP and GDP, because the funds used to clean up environmental contamination (such as hazardous waste sites) help to create new jobs and increase the consumption of natural resources. Alternative systems to GDP have been suggested that are based on genuine wellbeing and progress. The UN Human Development Index is an estimate of the quality of life in a country based on three indicators: life expectancy, literacy rate and per capita GNP. The Genuine Progress Index (GPI) is based on measurements that include health care, safety, clean environment, pollution and crime. The Environmental Performance Index (EPI) is based on indicators tracked in two categories: protection of human health from environmental harm and protection of ecosystems.

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14: ENVIRONMENTAL LAW, POLICY AND SUSTAINABILITY - IN CONTEXT

14.1: Introduction to Sustainability

14.2: Environmental Policy in the United States

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14.1: Introduction to Sustainability

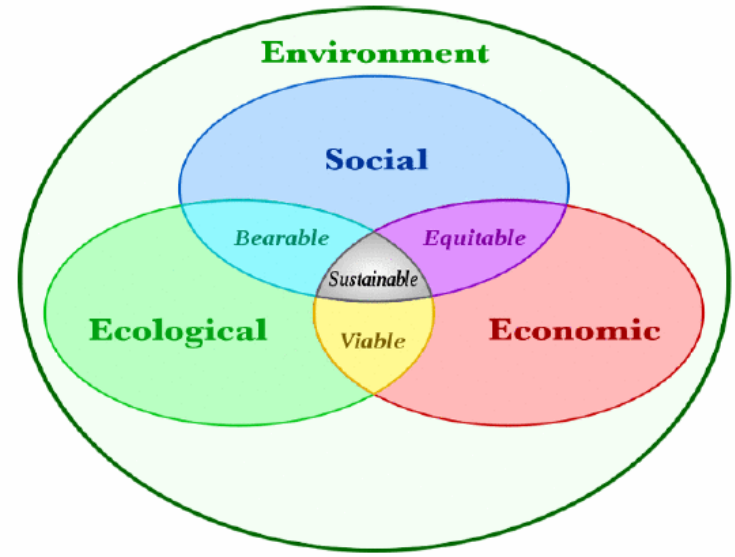
Introduction

Sustainability is derived from two Latin words: *sus* which means up, and *tenere* which means to hold. Thus, sustainability is essentially about holding up human existence by meeting the needs of the present without compromising the ability of future generations to meet their needs.

There are three dimensions that sustainability seeks to integrate: economic, environmental, and social (including sociopolitical).

- Economic interests define the framework for making decisions, the flow of financial capital, and the facilitation of commerce, including the knowledge, skills, competences and other attributes embodied in individuals that are relevant to economic activity.
- Environmental aspects recognize the diversity and interdependence within living systems, the goods and services produced by the world's ecosystems, and the impacts of human wastes.
- Social/Socio-political refers to interactions between institutions/firms and people, functions expressive of human values, aspirations and well-being, ethical issues, and decision-making that depends upon collective action.

The intersection of social and economic elements can form the basis of social "equitability". In the sense of enlightened management, "viability" is formed through consideration of economic and environmental interests. Between environment and social elements lies "bearability," the recognition that the functioning of societies is dependent on environmental resources and services. At the intersection of all three of these lies sustainability (Figure 14.1.1).



Figure

: Venn diagram of defining the components of sustainability. Image by Andrew, Sunray, based on "File:Sustainable development.svg" by Johann Dréo in Wikimedia Commons (CC-BY-SA4.0)

The three main elements of the sustainability paradigm are thought of as equally important, however, tradeoffs occur depending on the local/global objective. For example, in some instances it may be deemed necessary to degrade a particular ecosystem in order to facilitate commerce, or food production, or housing. In reality, the extent to which tradeoffs can be made before irreversible damage results is not always known, and in any case there are definite limits on how much substitution among the three elements is wise (to date, humans have treated economic development as the dominant one of the three). This has led to the notion of strong sustainability, where tradeoffs among natural, human, and social capital are not allowed or are very restricted, and weak sustainability, where tradeoffs are unrestricted or have few limits. Whether or not one follows the strong or weak form of sustainability, it is important to understand that while economic and social systems are human creations, the environment is not.

Rather, a functioning environment underpins both society and the economy.

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14.2: Environmental Policy in the United States

In its modern form, sustainability is a concept born out of the human desire to continue existing on planet Earth for a very long time, perhaps the indefinite future. Possibly, the most succinct articulation of the issue can be found in the 1987 Report of the World Commission on Environment and Development. The report entitled “Our Common Future” primarily addressed the closely related issue of Sustainable Development. The report, commonly know as the Brundtland Report after the Commission Chair Gro Harlem Brundtland, stated that “Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.” Following the concept of Sustainable Development, the commission went on to add ” Yet in the end, sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs. We do not pretend that the process is easy or straightforward. Painful choices have to be made. Thus, in the final analysis, sustainable development must rest on political will.” Sustainability and Sustainable Development are human constructs which seek to insure the very survival of humanity in a reasonably civilized mode of existence.

It is common to think of the sustainability paradigm as being a recent interpretation of environmental policy, one that was given credence by the United Nations report "Our Common Future". The final decade of the twentieth century was witness to significant growth in our understanding of the complexity and global reach of many environmental problems and issues, and the Brundtland report gave a clear voice to these concerns through its analysis of human dependency and quality of life on ecological systems, social networks, and economic viability — systems that are closely intertwined and that require more integrated approaches to solving humanity's many problems. It also was among the first widely disseminated writings to define and use the modern meaning of "sustainable" as "sustainable development." However, it would be a mistake to conclude that the concept of sustainability came into being suddenly and at a single moment in time. Most environmental historians of U.S. policy describe three periods through which the modern sustainability paradigm was built via advances in new concepts and ideas, scientific understandings, technological advances, political institutions, and laws and regulations. These were (1) the American conservation movement, (2) the rise of environmental risk management as a basis for policy, and (3) the integration of social and economic factors. This chapter examines the ways our environmental policies have changed through time as the norms, attitudes, and needs or each era are embodied in our modern concept of sustainability.

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14.3: Environmental Risk Management

General Definitions

For most people, the concept of risk is intuitive and, often, experiential; for instance most people are aware of the considerably greater likelihood of suffering an injury in an automobile accident (116/100 million vehicle miles) versus suffering an injury in a commercial airplane accident (0.304/100 million airplane miles). Environmental risk can be defined as the chance of harmful effects to human health or to ecological systems resulting from exposure to any physical, chemical, or biological entity in the environment that can induce an adverse response (see Module 9.5 for more detail on the science of risk assessment). Environmental risk assessment is a quantitative way of arriving at a statistical probability of an adverse action occurring. It has four main steps:

1. Identification of the nature and end point of the risk (e.g. death or disability from hazardous chemicals, loss of ecological diversity from habitat encroachment, impairment of ecosystem services, etc.)
2. Development of quantitative methods of analysis (perturbation-effect, dose-response)
3. Determination of the extent of exposure (i.e. fate, transport, and transformation of contaminants to an exposed population), and
4. Calculation of the risk, usually expressed as a statistical likelihood.

Risk management is distinct from risk assessment, and involves the integration of risk assessment with other considerations, such as economic, social, or legal concerns, to reach decisions regarding the need for and practicability of implementing various risk reduction activities. Finally, risk communication consists of the formal and informal processes of communication among various parties who are potentially at risk from or are otherwise interested in the threatening agent/action. It matters a great deal how a given risk is communicated and perceived: do we have a measure of control, or are we subject to powerful unengaged or arbitrary forces?

The Beginnings of Modern Risk Management

The beginnings of environmental risk management can be traced to the fields of public health, industrial hygiene, and sanitary engineering, which came into prominence in the latter decades of the 19th century and beginning of the 20th. The spread of disease was a particularly troublesome problem as the country continued to urbanize. For instance if you lived your life in, say, Chicago during the period 1850-1900 (a typical lifespan of the day), you had about a 1 in 100 chance of dying of cholera (and a 1 in 2000 chance of dying of typhoid), of which there were periodic epidemics spread by contaminated drinking water. Chicago's solution was to cease polluting its drinking water source (Lake Michigan) by reversing the flow of its watercourses so that they drained into the adjacent basin (the Mississippi). The widespread chlorination of municipal water after 1908 essentially eliminated waterborne outbreaks of disease in all major cities (with some notable exceptions—the outbreak of chlorine-resistant Cryptosporidium parvum in Milwaukee's drinking water in 1993 resulted in the infection of 403,000 people with 104 deaths).

Parallel work on the effects of chemical exposure on workers (and poor working conditions in general) were pioneered by Alice Hamilton (1869-1970), who published the first treatise on toxic chemical exposure "Industrial Poisons in the United States" in 1925. Hamilton is considered the founder of the field of occupational health. In 1897 she was appointed professor of pathology at the Women's Medical School of Northwestern University, and in 1902 she accepted the position of bacteriologist at the Memorial Institute for Infectious Diseases in Chicago. Dr. Hamilton joined Jane Addams's Hull House, in Chicago, where she interacted with progressive thinkers who often gravitated there, and to the needs of the poor for whom Hull House provided services.

Environmental Contamination and Risk

Events during the period 1920-1950 took an unfortunate turn. Global conflicts and economic uncertainty diverted attention from environmental issues, and much of what had been learned during the previous hundred years, for example about soil conservation and sustainable forestry, ceased to influence policy, with resultant mismanagement on a wide scale (see Figures 14.3.1 and 14.3.2).



Figure 14.3.1 Texas Dust Storm. Photograph shows a dust storm approaching Stratford, TX in 1935. *Source: NOAA via Wikimedia Commons*



Figure 14.3.2 Clear Cutting, Lousiana 1930. Typical cut-over longleaf pine area, on Kisatchie National Forest. Areas of this type were the first to be planted on this forest. Circa 1930s. *Source: Wait, J.M. for U.S. Forest Service. U.S. Forest Service photo courtesy of the Forest History Society, Durham, N.C.*

In the aftermath of the World War II, economic and industrial activity in the United States accelerated, and a consumer-starved populace sought and demanded large quantities of diverse goods and services. Major industrial sectors, primary metals, automotive, chemical, timber, and energy expanded considerably; however there were still few laws or regulations on waste management, and the ones that could and often were invoked (e.g. the Rivers and Harbors Act of 1899) were devised in earlier times for problems of a different nature. The Module 9.2 provides a more detailed accounting of the current framework for managing waste. Here we recount the circumstances that eventually resulted in the promulgation of environmental risk as a basis for public policy, with subsequent passage of major environmental legislation.



Figure 14.3.3 Zinc Smelter. Photograph shows a local smelter in a small valley town in Pennsylvania with, essentially, uncontrolled emissions. *Source: The Wire Mill, Donora, PA, taken by Bruce Dresbach in 1910. Retrieved from the Library of Congress*

If there were any doubts among American society that the capacity of the natural environment to absorb human-caused contamination with acceptably low risk was indeed infinite, these were dispelled by a series of well-publicized incidents that occurred during the period 1948-1978. Figure 14.3.3 shows a local smelter in a small valley town in Pennsylvania with, essentially, uncontrolled emissions. During periods of atmospheric stability (an inversion), contaminants became trapped, accumulated, and caused respiratory distress so extraordinary that fifty deaths were recorded. Figure 14.3.4 illustrates the dramatically poor air quality, in the form of reduced visibility, during this episode. Such incidents were not uncommon, nor were they limited to small American towns. A well-documented similar episode occurred in London, England in 1952 with at least 4000 deaths, and 100,000 illnesses resulting.



Figure 14.3.4 Noon in Donora. Photograph, dated October 29, 1948, illustrates the extremely poor air quality in the Pennsylvania town at the time. *Source: NOAA*

The generally poor state of air quality in the United States was initially tolerated as a necessary condition of an industrialized society. Although the risks of occupational exposure to chemicals was becoming more well known, the science of risk assessment as applied to the natural environment was in its infancy, and the notion that a polluted environment could actually cause harm was slow to be recognized, and even if true it was not clear what might be done about it. Nevertheless, people in the most contaminated areas could sense the effects of poor air quality: increased incidence of respiratory disease, watery eyes, odors, inability to enjoy being outside for more than a few minutes, and diminished visibility.



Figure 14.3.5 Cuyahoga River Fire, 1969. Photograph illustrates a 1969 fire on the Cuyahoga River, one of many fires during the time period. *Source:* NOAA.

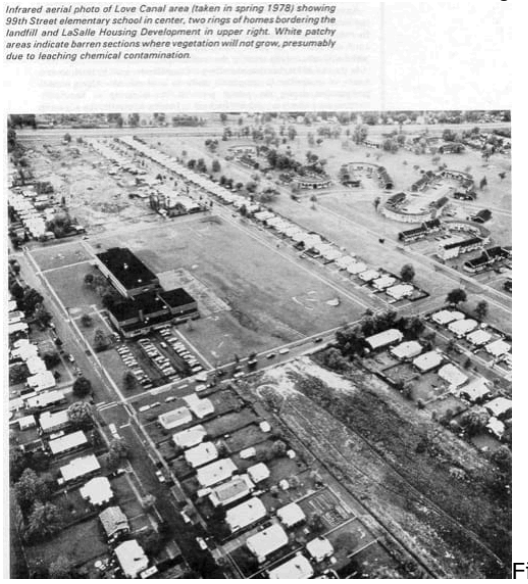


Figure 14.3.6 Love Canal. The Love Canal region of Niagara Falls, NY, 1978 showing the local grade school and neighboring houses. *Source: New York State Department of Health (1981, April). Love Canal: A special report to the Governor and Legislature, p. 5.*

Risk Management as a Basis for Environmental Policy

Environmental scientists of the day were also alarmed by the extent and degree of damage that they were documenting. The publication of *Silent Spring* in 1962 by Rachel Carson (1907-1964), about the impact of the widespread and indiscriminate use of pesticides, was a watershed moment, bringing environmental concerns before a large portion of the American, and global, public. Carson, a marine biologist and conservationist who initially worked for the U.S. Bureau of Fisheries, became a full time nature writer in the 1950s. She collected scientifically documented evidence on the effects of pesticides, particularly DDT, heptachlor, and dieldrin, on humans and mammals, and the systemic disruption they caused to ecosystems. *Silent Spring* is credited with bringing about a ban on the use of DDT in the United States, and setting in motion a chain of events that would ultimately result in the transformation of environmental public policy from one based on the problems and attitudes that brought about nineteenth century conservation, to one based on the management of risks from chemical toxins. The U.S. Environmental Protection Agency was established in 1970, just eight years after the publication of *Silent Spring*. The same year Earth Day was created.

As noted, the modules in the Chapter 9.1 contain a comprehensive treatment of the major laws and regulations that underpin the risk management approach to environmental policy. However it is worth considering one law in particular at this point, the National Environmental Policy Act of 1970 (NEPA), because it provides a legal basis for U.S. environmental policy, and lays out its terms clearly and unambiguously. NEPA established a national goal to create and maintain "conditions under which [humans] and nature can exist in productive harmony, *and fulfill the social, economic and other requirements of present and future generations of Americans*[emphasis added]" (NEPA, 1970). Further, NEPA saw the need for long term planning, to "fulfill the responsibilities of each generation as trustee of the environment for succeeding generations," for equity "to assure for all Americans safe, healthful, productive, and esthetically and culturally pleasing surroundings," and for economic prosperity as we "achieve a balance between population and resource use that will permit high standards of living and a wide sharing of life's amenities" (NEPA, 1970). Although the exact word "sustainable" does not appear, NEPA is in all major respects congruent with the goals of the Brundtland Report (written 17 years later, see Chapter 2), retains the character of American conservation, and anticipates the need to integrate environmental quality with social and economic needs.

Every four to six years the U.S. EPA releases its Report on the Environment, a collection of data and analysis of trends on environmental quality. It is quite comprehensive; reporting on an array of measures that chart progress, or lack thereof, on human impacts on the environment and, in turn, the effects of our actions on human health. It is difficult to summarize all the information available in a concise way, however most measures of human exposure to toxic chemicals, dating in many cases back to the late 1980s, show clear downward trends, in some cases dramatically so (for example DDT in human tissues, lead in blood serum, exposure to hazardous wastes from improper disposal, exposure to toxic compounds emitted to the air). In addition, many of other indicators of environmental quality such as visibility, drinking water quality, and the biodiversity of streams, show improvement. These are success stories of the risk management approach to environmental quality. On the other hand, other measures, such as hypoxia in coastal waters, quantities of hazardous wastes generated, and greenhouse gases released are either not improving or are getting worse.

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14.4: Sustainability and Public Policy

Complex Environmental Problems

NEPA, both in tone and purpose, was in sharp contrast to the many environmental laws that followed in the 1970s and 1980s that defined increasingly proscriptive methods for controlling risks from chemical exposure (this is sometimes termed the "command-and-control" approach to environmental management). In many ways these laws and regulations are ill-suited to the types of environmental problems that have emerged in the past twenty years. Whereas the focus of our environmental policy has been on mitigating risk from local problems that are chemical – and media – (land, water, or air) specific, the need has arisen to address problems that are far more complex, multi-media, and are of large geographic, sometimes global, extent.

An early example of this type of shift in the complexity of environmental problems is illustrated by the phenomenon of acidic rainfall, a regional problem that occurs in many areas across the globe. Although the chemical cause of acid rain is acidic gases (such as sulfur dioxide and nitrogen oxides) released into the atmosphere from combustion processes (such as coal burning), the problem was made considerably worse because of the approach to problem solving typical of the day for episodes such as the Donora disaster.

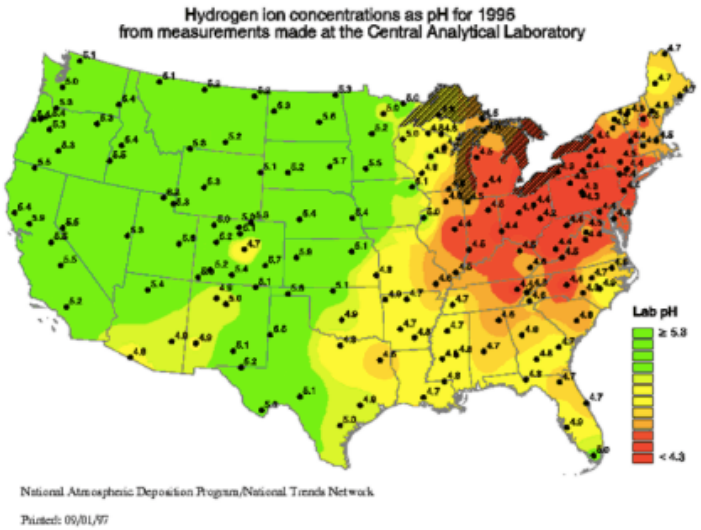


Figure 14.4.1 The pH of rainfall pH in the United States, 1996. *Source: National Atmospheric Deposition Program/National Trends Network via National Park Service.*

In order to prevent the local accumulation of contaminants, emission stacks were made much taller, effectively relying on the diluting power of the atmosphere to disperse offending pollutants. The result was a significant increase in the acidity of rainfall downwind of major sources, with associated impacts on aquatic and forest resources. Figure 14.4.1 shows this pattern for the eastern United States in 1996. A more comprehensive solution to this problem (short of replacing coal as a fuel source), has involved integrated activity on many fronts: science to understand the impacts of acid rain, technology to control the release of acidic gases, politics in the form of amendments to the Clean Air Act, social equity that defined the role of regional responsibilities in the face of such large geographic disparities, and economics to understand the total costs of acid rain and design markets to spread the costs of control. Although acidic rainfall is still an issue of concern, its impacts have been mitigated to a significant degree.

Sustainability as a Driver of Environmental Policy

The level of complexity illustrated by the acid rain problem can be found in a great many other environmental problems today, among them:

- Hypoxic conditions in coastal regions of the world caused by excessive release of nutrients, principally dissolved nitrogen and phosphorous from artificial fertilizer applied to crops (in addition to the Gulf of Mexico and Chesapeake Bay in the United States, there are over 400 such areas worldwide),
- Stratospheric ozone depletion caused by the release of certain classes of chlorofluorocarbon compounds used as propellants and refrigerants (with increases in the incident of skin cancers and cataracts),
- Urbanization and sprawl, whereby the population density in urban areas, with its attendant problems (degradation of air and water quality, stormwater management, habitat destruction, infrastructure renewal, health care needs, traffic congestion, loss of leisure time, issues of social equality), continues to grow (for example eighty percent of the population of the United States, about fifty percent of global, now lives in urban regions),
- Global climate change, and its resultant impacts (increases in temperature and storm and flooding frequency, ocean acidification, displacement of human populations, loss of biodiversity, sea-level rise), caused by the human-induced emission of greenhouse gases.

Problems such as these, which require highly integrated solutions that include input from many disciplines and stakeholders, have been termed "wicked" (Batie, 2008; Kreuter, DeRosa, Howze, & Baldwin, 2004). Wicked problems have certain key characteristics:

- There is not universal agreement on what the problem is – different stakeholders define it differently.
- There is no defined end solution, the end will be assessed as "better" or "worse."
- The problem may change over time.
- There is no clear stopping rule – stakeholders, political forces and resource availability will make that determination on the basis of "judgments."
- The problem is associated with high uncertainty of both components and outcomes.
- Values and societal goals are not necessarily shared by those defining the problem or those attempting to make the problem better.

Wicked problems are not confined to environmental issues, for example the same characteristics arise for problems such as food safety, health care disparities, and terrorism, but in the context of environmental policy they create the need to reassess policy approaches and goals, laws and regulations, as well as methods and models for integrated research.

Table 14.4.1 summarizes the major attributes of U.S. environmental policy as it has evolved over the past two centuries. To most observers it would seem to be true that advances in public policy, in any realm, are driven by problems, real and perceived, that require systemic solutions. Environmental policy is no exception. Early conservationists were alarmed at the inefficiencies of human resource management and the encroachment of humans on unspoiled lands. During the 20th century many groups: scientists, economists, politicians, and ordinary citizens, became alarmed and fearful of the consequences of toxic pollutant loads to the environment that included localized effects on human health and well-being. And now, as we proceed into the 21st century, an array of complex problems that have the potential to alter substantially the structure and well-being of large segments of human societies, calls for a renewal and reassessment of our approach to environmental policy. This has, thus far, proven to be a difficult transition. Many of these complex problems have multiple causes and impacts, affect some groups of people more than others, are economically demanding, and are often not as visibly apparent to casual observers as previous impacts, nor are the benefits perceived to be commensurate with costs. Devising a regulatory strategy for such problems requires an adaptive and flexible approach that current laws do not foster.

Table 14.4.1 Table summarizes the major attributes of U.S. environmental policy as it has evolved over the past two centuries. Source: T. Theis adapted from Fiksel, Graedel, Hecht, Rejeski, Saylor, Senge, et al. (2009).

	1850-1920	1960-1990	1990-present
Focus	Conservation/sanitation	Media/site/problem specific	Complex regional/ global problems
Outcome	Land preservation/efficiency/ control of disease	Manage anthropocentricand ecological risk	Global sustainable development
Principal Activity	Resource management reform/simple contaminant controls	Compliance/ remediation/ technological emphasis on problem solving	Integration of social, economic, and technological information for holistic problem solving
Economic Focus	Profit maximization/public health	Cost minimization	Strategic investments/long-term societal well-being
Regulatory Activity	Low	Heavy	Adaptive and Flexible

	1850-1920	1960-1990	1990-present
Conceptual Model	Expansion vs. preservation	Command-and-control	Systems/life cycle approach
Disciplinary Approach	Disciplinary and insular	Multidisciplinary	Interdisciplinary/Integrative

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14.5: Environmental Laws and Regulations

Although environmental laws are generally considered a 20th century phenomenon, attempts have been made to legislate environmental controls throughout history. In 2,700 B.C., the middle-eastern civilization in Ur passed laws protecting the few remaining forests in the region. In 80 A.D., the Roman Senate passed a law to protect water stored for dry periods so it could be used for street and sewer cleaning. During American colonial times, **Benjamin Franklin** argued for "public rights" laws to protect the citizens of Philadelphia against industrial pollution produced by animal hide tanners.

Significant environmental action began at the beginning of the 20th century. In 1906, Congress passed the “Antiquities Act,” which authorizes the president to protect areas of federal lands as national monuments. A few years later, **Alice Hamilton** pushed for government regulations concerning toxic industrial chemicals. She fought, unsuccessfully, to ban the use of lead in gasoline. She also supported the legal actions taken by women who were dying of cancer from their exposure to the radium then used in glow-in-the-dark watch dials. During the early 1960’s, biologist **Rachel Carson** pointed out the need to regulate pesticides such as DDT to protect the health of wildlife and humans.

With the establishment of the **Environmental Protection Agency (EPA)** in 1970, environmental law became a field substantial enough to occupy lawyers on a full-time basis. Since then, federal and state governments have passed numerous laws and created a vast network of complicated rules and regulations regarding environmental issues. Moreover, international organizations and agencies including the **United Nations**, the **World Bank**, and the **World Trade Organization** have also contributed environmental rules and regulations.

Because of the legal and technical complexities of the subjects covered by environmental laws, persons dealing with such laws must be knowledgeable in the areas of law, science and public policy. Environmental laws today encompass a wide range of subjects such as air and water quality, hazardous wastes and biodiversity. The purpose of these environmental laws is to prevent, minimize, remedy and punish actions that threaten or damage the environment and those that live in it. However, some people believe that these laws unreasonably limit the freedom of people, organizations, corporations and government agencies by placing controls on their actions.

Federal Laws

Early attempts by Congress to enact laws affecting the environment included the **Antiquities Act** in 1906, the **National Park Service Act** in 1916, the **Federal Insecticide**, **Fungicide and Rodenticide Act** in 1947 and the **Water Pollution Control Act** in 1956. The **Wilderness Act** of 1964, protected large areas of pristine federal lands from development and ushered in the new age of environmental activism that began in the 1960’s. However, it was the **National Environmental Policy Act (NEPA)** enacted in 1969 and the formation of the Environmental Protection Agency (EPA) in 1970 that started environmental legislation in earnest. The main objective of these two federal enactments was to assure that the environment would be protected from both public and private actions that failed to take into account the costs of damage inflicted on the environment.

Many consider NEPA to be the most far-reaching environmental legislation ever passed by Congress. The basic purpose of NEPA is to force governmental agencies to comprehensively consider the effects of their decisions on the environment. This is effected by requiring agencies to prepare detailed **Environmental Impact Statements** (EIS) for proposed projects. The EPA is the government's environmental watchdog. It is charged with monitoring and analyzing the state of the environment, conducting research, and working closely with state and local governments to devise pollution control policies. The EPA is also empowered to enforce those environmental policies. Unfortunately, the agency is sometimes caught up in conflicts between the public wanting more regulation for environmental reasons and businesses wanting less regulation for economic reasons. Consequently, the development of a new regulation can take many years.

Since 1970, Congress has enacted several important environmental laws, all of which include provisions to protect the environment and natural resources. Some of the more notable laws include:

- The **Federal Clean Air Act** (1970, 1977 & 1990) established national standards for regulating the emission of pollutants from stationary and mobile sources.
- The **Federal Water Pollution Control Act** (1972) amended by the **Clean Water Act** (1977, 1987), established water quality standards; provides for the regulation of the discharge of pollutants into navigable waters and for the protection of wetlands.
- The **Federal Safe Drinking Water Act** (1974, 1977 & 1986) set drinking water standards for levels of pollutants; authorizing

the regulation of the discharge of pollutants into underground drinking water sources.
- The **Toxic Substances Control Act** (1976) provided for the regulation of chemical substances by the EPA and the safety testing of new chemicals.
- The **Resource Conservation and Recovery Act** (1976) established cradle-to-grave regulations for the handling of hazardous wastes.
- The **Comprehensive Environmental Response**, **Compensation and Liability Act** (1980), also known as the **Superfund**program, provided for the cleanup of the worst toxic waste sites.
- The **Food Security Act** (1985, 1990) later amended by the **Federal Agriculture Improvement and Reform Act** (1996), discouraged cultivation of environmentally sensitive lands, especially wetlands, and authorized incentives for farmers to withdraw highly erodible lands from production.

The application, or enforcement, of an environmental law is not always straightforward, and problems can arise. Often, the biggest problem is that Congress fails to allocate the funds necessary for implementing or enforcing the laws. Administrative red tape may make it impossible to enforce a regulation in a timely manner. It also may be unclear as to which agency (or branch of an agency) is responsible for enforcing a particular regulation. Furthermore, agency personnel decline to enforce a regulation for political reasons.

State Laws

Most states, like California, have enacted their own environmental laws and established agencies to enforce them. California faced some of its first environmental challenges in the mid-1800's, with regard to debris from the hydraulic mining of gold. Water quality concerns, dangers of flooding, negative impact on agriculture and hazards to navigation prompted the state to act.

Some of California's environmental regulations preceded similar federal laws. For example, California established the nation's first air quality program in the 1950s. Much of the federal Clean Air Act amendments of 1990 were based upon the **California Clean Air Act of 1988**. California also pioneered advances in vehicle emission controls, control of toxic air pollutants and control of stationary pollution sources before federal efforts in those areas. The **Porter-Cologne Act of 1970**, upon which the state's water quality program is based, also served as the model for the federal Clean Water Act.

International Treaties and Conventions

Conventions, or treaties, generally set forth international environmental regulations. These conventions and treaties often result from efforts by international organizations such as the **United Nations (UN)** or the **World Bank**. However, it is often difficult, if not impossible, to enforce these regulations because of the sovereign rights of countries. In addition rules and regulations set forth in such agreements may be no more than non-binding recommendations, and often countries are exempted from regulations due to economic or cultural reasons. Despite these shortcomings, the international community has achieved some success via its environmental agreements. These include an international convention that placed a moratorium on whaling (1986) and a treaty that banned the ocean dumping of wastes (1991).

The UN often facilitates international environmental efforts. In 1991, the UN enacted an **Antarctica Treaty**, which prohibits mining of the region, limits pollution of the environment and protects its animal species. The United Nations Environment Program (UNEP) is a branch of the UN that specifically deals with worldwide environmental problems. It has helped with several key efforts at global environmental regulations:

- **The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer**. As a result of this global agreement, industrialized countries have ceased or reduced the production and consumption of ozone-depleting substances such as chlorofluorocarbons.
- **The Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade**. This agreement enhances the world's technical knowledge and expertise on hazardous chemicals management.
- **The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)**. This agreement protects over 30,000 of the world's endangered species.
- In 1995 **UNEP and the International Olympic Committee (IOC)** signed a partnership agreement to develop environmental guidelines for sports federations and countries bidding to host the Olympic games.
- **The Rotterdam Convention** (1998) addressed the growing trade in hazardous pesticides and chemicals. Importing countries must now give explicit informed consent before hazardous chemicals can cross their borders.
- **The International Declaration on Cleaner Production** (1998). The signatories commit their countries to implement cleaner industrial production and subsequent monitoring efforts.

In 1992, the UN member nations committed their resources to limiting greenhouse gas (e.g., carbon dioxide) emissions at or below 1990 levels, as put forth by the **UN Framework Convention on Climate Change**. Unfortunately, the agreement was non-binding and by the mid-1990's, it had had no effect on carbon emissions. The 1997 **Kyoto Protocol** was a binding resolution to reduce greenhouse gases. Although the United States initially supported the resolution, the Senate failed to ratify the treaty, and by 2001 the resolution was opposed by President Bush as threatening the United States economy.

California's state environmental regulations are sometimes more stringent than the federal laws (e.g., the California Clean Air Act and vehicle emissions standards). In other program areas, no comparable federal legislation exists. For example, the California **Integrated Waste Management Act** established a comprehensive, statewide system of permitting, inspections, enforcement and maintenance for solid waste facilities and sets minimum standards for solid waste handling and disposal to protect air, water and land from pollution. Also, **Proposition 65** (**Safe Drinking Water and Toxic Enforcement Act**) requires the Governor to publish a list of chemicals that are known to the State of California to cause cancer, birth defects or other reproductive harm.

Despite the state's leadership in environmental programs and laws, the creation of a cabinet-level environmental agency in California lagged more than two decades behind the establishment of the federal EPA. Originally, organization of California's environmental quality programs was highly fragmented. Each separate program handled a specific environmental problem (e.g., the **Air Resources Board**), with enforcement responsibility falling to both state and local governments. It was not until 1991 that a California EPA was finally established and united the separate programs under one agency.

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14.6: The Human Dimensions of Sustainability- History, Culture, Ethics

Sustainability in human terms is, first and foremost, a commonsense goal: to ensure that conditions on earth continue to support the project of human civilization, that widely diverse populations of the global community not slip into protracted crisis on account of deteriorating environmental conditions and depleted resources. This preventive dimension of sustainability discourse inevitably involves doom projections. Despite the popularity of apocalyptic, end-of-the-world scenarios in Hollywood movies, science fiction, and some corners of the blogosphere, the biological end of the human race remains scarcely imaginable—we will continue on, in some form. But in the emerging perfect storm of food stock declines, water scarcity, climate disruption, and energy shortfalls, there now exist measurable global-scale threats to social order and basic living standards that are the material bedrock of civic society as we recognize it.

The dramatic environmental changes underway on earth are already impacting human social systems. Droughts, floods, and rising sea levels are taking lives, damaging infrastructure, reducing crop yields and creating a new global underclass of environmental refugees. The question is how much more serious will these impacts become and how soon? There are no reassuring answers if we continue on a business-as-usual path. One thing about sustainability in the twenty-first century is certain: individual nations and the international community together will need to both mitigate the projected declines of the planet's ecosystems, and at the same time adapt to those that are irreversible. As one popular sustainability policy mantra has it: "we must strive to avoid the unmanageable, while managing the unavoidable."

The environmental historian Sing Chew sees in the cluster of environmental crises of the early 21st century the hallmarks of a potential new Dark Age, that is, a period of conflict, resource scarcity and cultural impoverishment such as has afflicted the global human community only a few times over the past five millennia. The goal of sustainability, in these terms, is clear and non-controversial: to avoid a new and scaled-up Dark Age in which the aspirations of billions of people, both living and yet unborn, face brutal constraints. The implications of sustainability, in this sense, extend well beyond what might ordinarily considered "green" issues, such as preserving rainforests or saving whales. Sustainability is a human and social issue as much as it is "environmental." Sustainability is about people, the habitats we depend on for services vital to us, and our ability to maintain culturally rich civic societies free from perennial crises in food, water, and energy supplies.

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GLOSSARY

A

Abiotic
|

Nonliving, inanimate, characterized by the absence of life; of inorganic matter.

Acid
|

A substance that provides hydrogen ions (H+) and lowers pH.

Adaptation
|

A heritable trait or behavior in an organism that aids in its survival in its present environment.

Adaptive Radiation
|

A speciation when one species radiates out to form several other species.

Adhesion
|

The ability of a substance to stick to an unlike substance.

Aerobic
|

Requiring oxygen.

Allopatric Speciation
|

A speciation that occurs via a geographic separation.

Amino Acid
|

The building block of proteins

Anaerobic
|

Existing in the absence of oxygen.

Analogous Structure
|

A structure that is similar because of evolution in response to similar selection pressures resulting in convergent evolution, not similar because of descent from a common ancestor.

Aqueduct
|

A watercourse constructed to convey water.

Atom
|

The smallest component of an element that retains all of the chemical properties of that element.

Atomic Mass
|

The mass of an atom. It is equal to the number of protons and neutrons of that atom.

Atomic Number
|

The number of protons in an atom.

Autopolyploidy
|

A polyploid individual will have two or more complete sets of chromosomes from its own species.

B

Base
|

A substance that provide hydroxide ions (OH–) and raise pH.

Binomial Nomenclature
|

The scientific system of naming each species of organism with a Latinized name in two parts; the first is the genus, and is written with an initial capital letter; the second is some specific epithet that distinguishes the species within the genus. By convention, the whole name is typeset in italics.

Biochemical Oxygen Demand
|

The amount of dissolved oxygen consumed by aerobic bacteria growing on the organic material present in a water sample at a specific temperature over a specific time period. Also called Biological Oxygen Demand.

Biodiversity
|

Variety of a biological system, typically conceived as the number of species, but also applying to genes, biochemistry, and ecosystems.

Biodiversity Hotspot
|

A concept originated by Norman Myers to describe a geographical region with a large number of endemic species and a large percentage of degraded habitat.

Biogeography
|

The study of the geographic distribution of living things and the abiotic factors that affect their distribution.

Biological Species Concept

|

A group of actually or potentially interbreeding natural populations which are reproductively isolated from other such groups.

Biology
|

The scientific study of life.

Biome
|

Large, distinct geographical regions of Earth's surface that are characterized by its specific climate, and plant and animal life.

Biosphere
|

The global ecological system that consists of living things, their environment, and the interactions inbetween.

Biotic
|

Of, pertaining to, or produced by life or living organisms.

Black Water
|

Domestic wastewater containing feces.

Buffer
|

A solution that resists a change in pH by absorbing or releasing hydrogen or hydroxide ions.

C

Carbohydrate
|

A biological macromolecule in which the ratio of carbon to hydrogen to oxygen is 1:2:1; carbohydrates serve as energy sources and structural support in cells.

Cell
|

The basic unit of a living organism, consisting of a quantity of protoplasm surrounded by a cell membrane, which is able to synthesize proteins and replicate itself.

Cellulose
|

A polysaccharide that makes up the cell walls of plants and provides structural support to the cell.

Chemical Bond
|

An interaction between two or more of the same or different elements that results in the formation of molecules.

Chemical Diversity
|

Variety of metabolic compounds in an ecosystem.

Chitin
|

Atype of carbohydrate that forms the cell walls of fungi, as well as the outer skeleton of arthropods (i.e. insects and crustaceans).

Chytridiomycosis
|

A disease of amphibians caused by the fungus *Batrachochytrium dendrobatidis*; thought to be a major cause of the global amphibian decline.

Clade
|

A group of taxa with the same set of shared derived characters, including an ancestral species and all its descendants.

Cladistics
|

A method used to organize homologous traits to describe phylogenies using common descendent as the primary criterion used to classify organisms.

Class
|

The category in the taxonomic classification system that falls within phylum and includes orders.

Climax Community
|

The final stage of succession, where a stable community is formed by a characteristic assortment of plant and animal species.

Cohesion
|

The ability of a substance to stick to other members of the same substance.

Commensalism
|

A symbiotic relationship between two species where one species benefits from a close prolonged interaction, while the other neither benefits nor is harmed.

Community
|

The set of populations inhabiting a particular area.

Competitive Exclusion Principle
|

No two species within a habitat can coexist indefinitely when they compete for the same resources at the same time and place.

Control
|

A part of an experiment that does not change during the experiment.

Convergent Evolution
|

An evolution that results in similar forms on different species.

Covalent Bond
|

A type of chemical bond where two atoms are connected to each other by the sharing of two or more electrons.

D

Dead Zone
|

Hypoxic areas in aquatic systems. It occurs when the concentration of dissolved oxygen (DO) falls to or below 2 mg of O2/liter. When this happens, aquatic flora and fauna begin to change behavior in order to reach sections of water with higher oxygen levels. Once DO declines below 0.5 mg O2/liter in a body of water, mass mortality occurs.

Deductive Reasoning
|

A form of logical thinking that uses a general statement to forecast specific results.

Denaturation
|

The loss of shape in a protein as a result of changes in temperature, pH, or exposure to chemicals.

Deoxyribonucleic acid (DNA)
|

Adouble-stranded polymer of nucleotides that carries the hereditary information of the cell.

Desalination
|

The artificial process by which salt water (generally sea water) is converted to fresh water.

Disaccharide
|

Two sugar monomers that are linked together by a peptide bond.

Dispersal
|

An allopatric speciation that occurs when a few members of a species move to a new geographical area.

Divergent Evolution
|

An evolution that results in different forms in two species with a common ancestor.

DNA Barcoding
|

Molecular genetic method for identifying a unique genetic sequence to associate with a species.

E

Eco-districts
|

Neighborhoods that reuse and recycle materials and significantly reduce the volume of solid waste and toxic chemical releases.

Ecology
|

The study of the interactions of living organisms with their environment.

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.

Ecosystem Diversity
|

Variety of ecosystems.

Electron
|

The subatomic particle having a negative charge and orbiting the nucleus.

Empirical
|

Verifiable by means of scientific experimentation.

Endemic
|

Limited to a particular area or region.

Environmental science
|

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.

Enzyme
|

Acatalyst in a biochemical reaction that is usually a complex or conjugated protein.

Equilibrium | A dynamic state of an ecosystem in which, despite changes in species numbers and occurrence, biodiversity remains somewhat constant.

Estivation
|

A state of animal dormancy characterized by inactivity and a lowered metabolic rate, entered in response to high temperatures and arid (dry) conditions.

Eukarya
|

The domain of life containing cells with nuclei and sub-cellular organelles..

Eutrophication
|

A process in which nutrients accumulate in a body of water, resulting in an increased growth of organisms that may deplete the oxygen in the water. It may occur naturally or as a result of human actions. This pollution usually causes algal blooms and bacterial growth, resulting in the depletion of dissolved oxygen in water and causing substantial environmental degradation.

Evaporation
|

The release of individual water molecules at the surface of a liquid, such as a body of water, the leaves of a plant, or the skin of an organism.

Evolution
|

A change in a population's genetic composition over successive generations.

Exergy
|

Exergy is a thermodynamic term that measures the quality or usefulness of energy, specifically defining the maximum amount of actual work an energy source can perform. While energy tells you how much power exists in a system, exergy tells you how much of that power you can actually use before inefficiencies and the laws of physics turn it into unusable waste heat.

Extinction
|

Disappearance of a species from Earth; local extinction is the disappearance of a species from a region.

Extinction Rate
|

Number of species becoming extinct over time, sometimes defined as extinctions per million species–years to make numbers manageable (E/MSY).

Extremophile
|

An organism that thrives in an extreme environment.

Exurbs
|

An urbanized area outside the typically denser inner suburban areas of a city, located at the edge of a metropolitan area.

F

Falsifiable
|

Able to be disproven by experimental results.

Family
|

The category in the taxonomic classification system that falls within order and includes genera.

Fat
|

Alipid molecule composed of three fatty acids and a glycerol (triglyceride) that typically exists in a solid form at room temperature.

Food Security
|

The state of having reliable access to a sufficient quantity of affordable, healthy food.

Food Web
|

A complex, overlapping network of multiple food chains that encompass the feeding relationships and energy transfer within an ecosystem.

Foundation Species
|

A species which often forms the major structural portion of the habitat.

G

Gene Pool
|

All of the alleles carried by all of the individuals in the population.

Genetic Drift
|

The effect of chance on a population's gene pool.

Gentrification
|

The process whereby the character of a neighborhood changes through the influx of more affluent residents and investment.

Genus
|

The category in the taxonomic classification system that falls within family and includes species; the first part of the scientific name.

Glycogen
|

The storage form of carbohydrates in animals.

Green Urbanism
|

The practice of creating communities that are beneficial to both humans and the environment.

Grey Water
|

Domestic wastewater (households, office buildings) that lacks substantial fecal contamination; Sources include sinks, showers, baths, washing machines and dishwashers.

Hard Water
|

Water with high mineral content.

Hardy-Weinberg Equilibrium
|

A population genetics theorem that states that allele and genotype frequencies in a population will remain constant from generation to generation in the absence of other evolutionary influences.

Heat of Vaporization | The amount of energy that must be added to a liquid substance to transform a quantity of that substance into a gas.

Homeostasis
|

The ability of a system or living organism to adjust its internal environment to maintain a state of dynamic constancy; such as the ability of warm-blooded animals to maintain a stable temperature.

Homologous Structure
|

A structure that is similar because of descent from a common ancestor.

Hormone
|

A chemical signaling molecule, usually a protein or steroid, secreted by an endocrine gland or group of endocrine cells; acts to control or regulate specific physiological processes.

Hydrogen Bond
|

A weak bond in which a hydrogen atom in one molecule is attracted to an electronegative atom (usually nitrogen or oxygen) in the same or different molecule.

Hydrophilic
|

A substance that dissolves in water; water-loving.

Hydrophobic
|

A substance that does not dissolve in water; water-fearing.

Hypothesis
|

A statement that explains an observation, phenomenon or scientific problem, and that can be tested by further observation, investigation or experimentation.

Hypoxia
|

Abnormally low oxygen content.

I

Inductive Reasoning
|

A form of logical thinking that uses related observations to arrive at a general conclusion.

Inheritance of Acquired Characteristics
|

An idea that describes the mechanism of evolution proposed by Lamarck in which traits acquired by individuals through use or disuse could be passed on to their offspring thus leading to evolutionary change in the population.

Insolation
|

The amount of solar radiation (sunlight) that reaches a specific area of Earth's surface over a set period of time.

Ion | An atom or molecule with a net electrical charge. The charge can be positive (cation) or negative (anion).

Ionic Bond
|

A type of chemical bond where two atoms or molecules are connected to each other by electrostatic attraction.

Ionic Bond
|

An atom or compound that does not contain equal numbers of protons and electrons, and therefore has a net charge.

Island Biogeography
|

The study of life on island chains and how their geography interacts with the diversity of species found there.

Isotope
|

Any of two or more forms of an element where the atoms have the same number of protons, but a different number of neutrons within their nuclei. Thus, isotopes have the same atomic number but a different mass number.

K

Keystone Species
|

A species whose presence is key to maintaining biodiversity in an ecosystem and to upholding an ecological community's structure.

Kinetic Energy
|

The energy of motion.

Kingdom
|

The category in the taxonomic classification system that falls within domain and includes phyla.

L

Lineage Species Concept
|

This species concept defines species as groups of organisms that share a pattern of ancestry and descent and which form a single branch on the tree of life.

Lipids
|

Aclass of macromolecules that are nonpolar and insoluble in water.

M

Macroevolution
|

A broader scale of evolutionary changes seen over paleontological time.

Macromolecule
|

A large molecule typically formed by the joining of smaller molecules

Macromolecule
|

Alarge molecule, often formed by polymerization of smaller monomers.

Macronutrients
|

Nutrients that the body needs in relatively large amounts. They include carbohydrates, proteins, lipids, and water.

Matter
|

Anything that has mass and occupies space.

Maximum Parsimony
|

An optimality criterion under which the phylogenetic tree that minimizes the total number of character-state changes (or minimizes the cost of differentially weighted character-state changes) is constructed.

Megalopolis
|

A group of metropolitan areas which are perceived as a continuous urban area through common systems of transport, economy, resources, ecology, and beyond.

Metropolis
|

A large city or a large continuous urban area formed when multiple separate towns and cities grow outward and merge together. They are a significant economic, political, and cultural area for a country or region, and an important hub for regional or international connections, commerce, and communications.

Microevolution

|

The changes in a population's genetic structure (i.e., allele frequency)/

Micronutrients
|

Nutrients the body needs in relatively small amounts. They include vitamins and minerals.

Migration
|

The movement of individuals of a population to a new location; in population genetics it refers to the movement of individuals and their alleles from one population to another, potentially changing allele frequencies in both the old and the new population.

Mimicry
|

An adaptation in which an organism looks like another organism that is dangerous, toxic, or distasteful to its predators.

Modern Synthesis
|

The overarching evolutionary paradigm that took shape by the 1940s and is generally accepted today.

Molecular Systematics
|

The methods of using molecular evidence to identify phylogenetic relationships.

Molecule
|

A chemical structure consisting of at least two atoms held together by a chemical bond.

Monomer | A single, small molecule that can chemically bond with other identical or similar molecules to form a larger chain - a polymer.

Monophyletic
|

Descending from a single ancestral species and containing all descendants of that single ancestor.

Monosaccharide
|

A single unit or monomer of carbohydrates.

Morphological Species Concept
|

A species concept that defines species by its observable physical characteristics; Often called morphospecies.

Mutualism
|

A symbiotic relationship between two species where both species benefit.

N

Natural Selection
|

The greater relative survival and reproduction of individuals in a population that have favorable heritable traits, leading to evolutionary change.

Neutron
|

A subatomic particle forming part of the nucleus of an atom and having no charge.

Niche | The unique set of resources used by a species, which includes its interactions with other species.

Nucleic acid
|

A biological macromolecule that carries the genetic information of a cell and carries instructions for the functioning of the cell.

Nucleotide
|

A monomer of nucleic acids; contains a pentose sugar, a phosphate group, and a nitrogenous base.

O

Obesity
|

When excess body fat accumulates to such an extent that it can have negative effects on health.

Octet Rule
|

States that the outermost shell of an element with a low atomic number can hold eight electrons.

Oil
|

An unsaturated fat that is a liquid at room temperature.

Order
|

The category in the taxonomic classification system that falls within class and includes families.

Organ
|

Collections of tissues grouped together based on a common function.

Organelle
|

A specialized membrane-bound structure found inside cells that carries out a specific life process (e.g. ribosomes, vacuoles).

Outgroup
|

A species or group of species that diverged before the lineage containing the group(s) of interest.

Overweight
|

Having more body fat than what is considered healthy.

P

Paleontology
|

The study of the forms of life existing in prehistoric or geologic times, especially as represented by fossils.

Parasitism
|

A symbiotic relationship between two species where one species benefits to the detriment of the other.

Peer Reviewed Article
|

A scientific report that is reviewed by a scientist's colleagues before publication.

Periodic Table of Elements
|

An organizational chart of elements, indicating the atomic number and mass number of each element; also provides key information about the properties of elements.

Persistent Organic Pollutants (POP)
|

Organic compounds that are resistant to degradation through chemical, biological, and photolytic processes.[

pH
|

The measure of the acidity (low pH) or basicity (high pH) of an aqueous solution.

Phospholipid
|

A major constituent of the membranes of cells; composed of two fatty acids and a phosphate group attached to the glycerol backbone.

Phylogenetic Tree
|

A branching diagram illustrating the potential evolutionary relationships among biological organisms or other entities in which the tree-maker hypothesizes share a common ancestor.

Phylogeny
|

The evolutionary history and the relationships among a species or group of species.

Phylum
|

The category in the taxonomic classification system that falls within kingdom and includes classes.

Pioneer species
|

The first species to appear in primary and secondary succession.

Point Sources
|

Any single, identifiable, and localized origin from which pollutants are discharged directly into the environment.

Polymer | A large molecule made up of many repeating monomer units bonded together in a long chain.

Polypeptide
|

A ong chain of amino acids linked by peptide bonds.

Polyploidy
|

A condition in which a cell, or organism, has an extra set, or sets, of chromosomes.

Polysaccharide
|

A long chain of monosaccharides; may be branched or unbranched.

Population
|

A collection of organisms of a particular species, sharing a particular characteristic of interest, most often that of living in a given area.

Population Genetics
|

The study of how selective forces change the allele frequencies in a population over time.

Postzygotic Mechanisms
|

Mechanisms of reproductive isolation that occur after fertilization.

PPB
|

Parts Per Billion

PPM
|

Parts Per Million

Prezygotic Mechanisms
|

Mechanisms of reproductive isolation that occur before fertilization.

Primary Succession
|

The succession on land that previously has had no life.

Prokarya
|

The domain of life containing cells that lack nuclei and sub-cellular organelles.

Protein
|

A biological macromolecule composed of one or more chains of amino acids.

Proton
|

A positively charged subatomic particle forming part of the nucleus of an atom and determining the atomic number of an element.

R

Relative Species Abundance
|

The absolute population size of a particular species relative to the population size of other species within the community.

Reproductive Isolation
|

When different evolutionary mechanisms, behaviors and physiological processes prevent members of different species from producing offspring, or ensure that any offspring are sterile.

Reservoir
|

An artificial and enlarged lake behind a dam, usually built to store fresh water, often doubling for hydroelectric power generation.

Resilience | The speed at which an ecosystem recovers equilibrium after being disturbed.

Resistance | The ability of an ecosystem to remain at equilibrium in spite of disturbances.

Ribonucleic Acid (RNA)
|

Asingle-stranded polymer of nucleotides that is involved in protein synthesis.

Rooted
|

Describing a phylogenetic tree with a single ancestral lineage to which all organisms represented in the diagram relate.

S

Saturated fatty acid
|

A long-chain hydrocarbon with single covalent bonds in the carbon chain; the number of hydrogen atoms attached to the carbon skeleton is maximized

Science
|

From the Latin scientia, meaning ""knowledge"".

Scientific Laws
|

A description of what happens in nature under specific conditions; They are often expressed mathematically.

Scientific Method
|

A method of discovering knowledge about the natural world based in making falsifiable predictions (hypotheses), testing them empirically, and developing theories that match known data from repeatable physical experimentation.

Scientific Theory
|

A coherent statement or set of ideas that explains observed facts or phenomena and correctly predicts new facts or phenomena not previously observed, or which sets out the laws and principles of something known or observed.

Secondary Metabolite
|

An organic compound produced by any lifeform which is not directly involved in the normal growth, development, or reproduction of the organism. Instead, they generally mediate ecological interactions, which may produce a selective advantage for the organism.

Secondary Plant Compound
|

A plant secondary metabolite.

Secondary Succession
|

The succession in response to environmental disturbances that move a community away from its equilibrium.

Shared Ancestral Character
|

A character on a phylogenetic branch that is shared by a particular clade.

Shared Derived Character
|

A character on a phylogenetic tree that is shared only by a certain clade of organisms.

Sister Taxa
|

A sister group or sister taxon, is made up of the closest relative(s) of another given unit in an evolutionary tree.

Slum Cities
|

The development on the outskirts of cities of unplanned shantytowns or squats with no access to clean water, sanitation, or other municipal services.

Solvent
|

A substance capable of dissolving another substance.

Speciation
|

Formation of a new species.

Species
|

The most specific category of classification; the second part of the scientific name.

Species Concept
|

A working definition of a species and/or a methodology for determining whether or not two organisms are members of the same species.

Species Richness
|

The number of different species in a community.

Species-area Relationship
|

Relationship between area surveyed and number of species encountered; typically measured by incrementally increasing the area of a survey and determining the cumulative numbers of species.

Specific Heat Capacity |

The amount of heat that must be added to one unit of mass of the substance in order to cause an increase of one unit in temperature.

Starch
|

A storage carbohydrate in plants.

Steroid
|

A type of lipid composed of four fused hydrocarbon rings.

Suburbs
|

The communities surrounding cities, typically close enough for a daily commute in, but far enough away to allow for more space than city living affords.

Surface Tension
|

The cohesive force at the surface of a body of liquid that prevents the molecules from separating.

Symbiosis
|

The long-term living together or association of two unlike organisms.

Sympatric Speciation
|

A speciation that occurs in the same geographic space.

Systematics
|

The study of organisms with the purpose of deriving their relationships.

T

Taxon
|

A single level in the taxonomic classification system.

Taxonomy
|

The science of finding, describing, classifying and naming organisms.

Temperature
|

A measure of molecular motion.

Thermocline | Layers of water with temperatures that are significantly different from those above and below it.

Thermoregulation
|

The maintenance of a constant internal temperature of an organism independent of the temperature of the environment.

Tissue
|

A group of cells (along with their extracellular matrix if any) that are similar in origin and function together to perform a specific job.

Torpor
|

A state similar to hibernation characterised by energy-conserving, very deep sleep.

Total Dissolved Solids (TDS)
|

The total amount of dissolved material in water.

Tragedy of the Commons
|

An economic principle that resources held in common will inevitably be overexploited.

Triglyceride
|

A fat molecule; consists of three fatty acids linked to a glycerol molecule.

U

Unsaturated Fatty Acid
|

A long-chain hydrocarbon that has one or more than one double bonds in the hydrocarbon chain.

Urban Heat Island Effect
|

A meteorological and climatological phenomenon in which urban areas experience significantly warmer temperatures than surrounding rural areas.

Urban Sprawl
|

The extension of low-density residential, commercial, and industrial development into areas beyond a city's boundaries that occurs in an unplanned or uncoordinated manner.

Urbanization
|

the study of the social, political, and economic relationships in cities.

V

van der Waals Interaction
|

The relatively weak attraction between neutral atoms and molecules arising from polarization induced in each particle by the presence of other particles.

Variable
|

A part of an experiment that can vary or change.

Vector
|

An organism that transmits a pathogen.

Vestigial Structure
|

A physical structure present in an organism but that has no apparent function and appears to be from a functional structure in a distant ancestor.

Vicariance
|

An allopatric speciation that occurs when something in the environment separates organisms of the same species into separate groups.

W

Wastewater Pretreatment
|

Screening and removal of sand and gravel.

Wastewater Primary Treatment
|

Settling or floatation to remove organic solids, fat, and grease.

Wastewater Secondary Treatment
|

Takes place when aerobic bacterial decompose of organic solids.

Wastewater Sludge
|

The concentrated organic solid produced during primary and secondary treatment.

Wastewater Tertiary Treatment
|

Occurs when bacteria decompose and filter nutrients.

Water Residence Time
|

The average time that a water molecule spends in a water reservoir.

Watershed
|

A drainage basin. An area of land in which all flowing surface water converges to a single point.

White-nose Syndrome
|

A disease of cave-hibernating bats in the eastern United States and Canada associated with the fungus *Geomyces destructans*.

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